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INSTITUTO DA CONSTRUÇÃO

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Emuze Fidelis, Fred Sherratt and Alfredo Soeiro (eds.)

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CONTENTS

AUTOMATED SPATIOTEMPORAL IDENTIFICATION AND DISSEMINATION OF WORK CREWS' EXPOSURE TO STRUCK-BY HAZARDS

Karsten W. Johansen[1], Carl Schultz[2], Jochen Teizer[1]

[1] Dept. of Civil and Mechanical Engineering, Technical University of Denmark (DENMARK)
[2]Dept. of Electrical and Computer Engineering, Aarhus University (DENMARK)

Abstract

The construction industry is among the most hazardous industries, and its continuously changing, and complex environment results in a labour-intensive task to plan and prevent hazards. The current manual safety planning procedures cannot be performed with a temporal resolution that represents all stages of the environment. This leads to unplanned durations and an increased responsibility for the individual workers to analyse and act accordingly to a situation. With this work, we propose an automated approach to identify and measure the amount struck-by falling objects hazard exposure to the construction tasks and their assigned work crews. The automated identification, dissemination, and digitization of hazard identification allows safety professionals to perform safety analysis every time the spatial situation of the construction site changes and introduces temporary safety equipment or suggests changes in the sequence of tasks to lower the exposure of workers to hazards. Additionally, it allows for a comparison between schedules, which is highly relevant with respect to digital twins, where alternative plans are generated based on historical knowledge about construction projects. The approach is described through a graphical and algorithmic approach, which is then validated in two case studies. The case studies reveal the potential and, at the same time, requirements for the scheduling of construction projects if automated approaches should realise their full potential.

Keywords: Automated prevention through design and planning, Digital Twin for construction safety, Hazard exposure identification and dissemination, Spatio-temporal safety analysis

1 INTRODUCTION

Construction is one of the most dangerous industries due to the continuous change in the construction environment. Over time, the previously safest route may have turned into a hazardous one, e.g., tools dropping from crews allocated nearby or above other work areas. Safety planning is currently a manual and labor-intensive task. In particular, the standard planning process only covers the overall site layout in a coarse temporal resolution because it would be impossible to generate a new safety plan for every state change of the construction site. Consequently, the workers are responsible, and must be aware of, consider, and adapt to, new hazardous situations that may not be a part of the safety plan due to the low temporal resolution available when undertaking initial safety planning. Pushing the safety responsibility to the individual worker results in thought-provoking safety statistics in construction. Additionally, some analysis tasks can be too complex for the current manual approaches to solve (e.g., extensive *struck-by-falling object* hazards). This often leads to a hard hat requirement that covers the complete construction site, even in areas where it is not strictly required. Furthermore, having the dangerous areas digitally modelled can allow sensor-based approaches to notify workers about the requirement of safety equipment (e.g., hard hats), and ensure that the workers conform to the requirements.

The complex and dynamic nature and the increasing interest in Digital Twins (DTs) demands an approach that can automatically perform safety assessment and enhancement when the project progresses, and changes on the construction site are recorded. The frequently gathered progress information can be processed and utilized to plan, act, and improve the safety situation for the construction project [1, 2]. This study will represent the DT with a 3D BIM (Building Information Modelling) model and a schedule, which assigns the work crews to the task. The schedule structure is inspired by the structure that is defined in [3].

This work proposes a novel automated algorithm that allows safety management to extract hazardous situations in the construction site based on the (spatial) 3D geometry and the (temporal) construction schedule. The algorithm performs a spatiotemporal analysis (i.e., considering both the geometry and the schedule information simultaneously) using the work crews' exposure to hazards from simultaneously occurring tasks and other work crews. We calculate how one crew exposes other crews to hazards based on an automatically generated workspace (i.e., the zone and location of the task the crew is assigned to in the schedule). The analysis will investigate *struck-by falling object* hazards (aka. overhead work). Most automated safety analysis studies have been performed with respect to *falls from height* hazards, as this is the deadliest hazard in the construction industry [4–11]. Nonetheless, *struck-by* hazards are responsible for the second most fatalities. This work finds inspiration in the approach presented in [12] but describes the hazard source and exposure regions with spatial artefacts that are generated based on the current spatial situation of the construction site.

The spatiotemporal analysis is based on temporarily existing spatial artefacts [13], which are semantically rich empty-space objects describing regions that emerge from a spatial situation. For example, when a crew is assigned to a task on a building object, then the footprint of the object becomes the surface of an extruded workspace spatial artefact. The workspace's impact on other workspaces can be determined through stepwise geometric operations, where the surrounding and related building elements' geometries are considered.

2 RELATED WORK

Safety planning is a complex labor-intensive task and can, therefore, not be carried out every time the construction site's spatial situation changes. The safety planning procedure is often referred to as Prevention through Design and Planning (PtD/P) and tries to remove the hazards with changes to the design (e.g., inserting temporary protective equipment like guardrails and safety nets), or changes to the schedule (e.g., reordering the scheduled tasks or crane lift paths). An alternative solution to the manual PtD/P is to automate the efforts, which can be divided into two categories, based on semantic or spatial analysis. In the first category, the safety engineers are, often based on patterns in a hazard database, guided through a safety evaluation sequence, where hazards can be identified [14], [15]. The other category is based directly on the geometry of the objects and safety regulations which enables the identify the hazards and their geometry. This approach allows the solution to inject safety protective equipment directly into the BIM model, which therefore becomes a part of the digital design [5, 7, 8, 10]. The second approach, which is based directly on the BIM model geometry and injection of protective equipment, demands less manual handling from the safety engineer, which is important, especially in the DT setting.

When the safety analysis is performed in a (semi) automated way, the software needs a way to represent the scoped rule of the safety regulation. Spatial artefacts [13, 16] can be used for this purpose as they represent empty-space regions that emerge and change based on the existence of BIM elements or situations in the 3D space. The spatial artefact approach was initially investigated for construction safety in [7, 17], allowing one to express the situation in greater detail, as they can be modelled with the inclusion of more than one BIM element. For example, in a situation where the operation space (i.e., the region where a crew will be situated to perform a task) can be modelled as the overlapping region of an enlarged version of the element footprint that the work is performed on and the surface, which the crew is standing on to perform the work. The details allow the analysis to be performed in a more realistic and detailed situation, as it also, dependent on the implementation, can model the fact that the crew cannot levitate (i.e., that the operation space should only be extended towards already existing surfaces).

There have been research activities in the *struck-by falling object* hazard type. As the *struck-by falling objects* hazard emerges from competing work crews, the approaches involve information about the active work crews and their workspaces. This information often comes from the schedule, but when the geometry of the workspaces must be determined, the approaches differ. [14] has a semantic approach, where a set of rules are checked based on the user's selection of analyzed hazards. In this approach, the exposed BIM elements light up if their spatial representation is exposed by a task that is performed simultaneously. Work crews may not only be situated inside the geometry of the BIM element that they are working on, but they would also often be placed in the surroundings of the element; thus, the geometry of the BIM element itself can be a help but is not enough to identify when and where workers are exposed to struck-by falling object hazards. In [12], zones are defined to represent the spatial representation of the workspaces, and those are activated or deactivated by the schedule. This way, the exposure is related to a zone that may contain the surroundings of the BIM elements as well. In [18], the approach relies on a rule-checking engine that identifies areas that are exposed by other work crews, but in do also offer a way to represent the worker´s trajectory paths, which enables the tool to identify hazards that are not just within the geometry of an exposed BIM element. It is important that the information that is utilized in automated hazard analysis tools stem directly from information that is readily available from the existing 3D BIM model and belonging schedule. as the additional modelling of zones, and worker trajectories may not be available at the time of analysis. Modelling this information can be a time-consuming procedure, that must be performed repeatedly due to the constant change of the construction sites' spatial situation. Additionally, too much manual handling does not conform with the vision of DTs, which will act and improve automatically based on the situation and gathered knowledge.

Together with automatization, open standards, and non-proprietary formats are key for the DT to exist. As the vision for the DT is that all the stakeholders can utilize the information and knowledge that is gathered in it, it must be able to exchange information with many different workflows. Likewise, it must be able to take information from as many workflows. Additionally, [19] investigated why the automated BIM-based safety enhancement tools remain in research and are still not widely used in practitioners' workflows. Lack of confidence, standardization, and fit to current workflows impede the widespread adaption. Industry Foundation Classes (IFC) is an initiative for open standard, platform-neutral Computer-Aided Design (CAD) data exchange in an object-oriented fashion. IFC is supported by most CAD and BIM tools and facilitates data exchange between different stakeholders with different workflows in a construction project. IFC has also been welcomed in the open-source community, where contributors have collaborated on IFC interfacing software that can read, write, and modify the IFC file format (e.g., the JavaScript-based plugin [20] and C++ and python-based [21]).

The usage of IFC can also be a way to tackle the issues of lack of standardization and fit to current workflows. The lack of confidence in automated approaches has also been addressed by researchers, for example, by this work´s authors [22], where an application can assess the automated safety analysis tool´s performance can be assessed in terms of soundness, completeness, and spatial correctness. The assessment is based on benchmark models and corresponding ground truth assessments. This approach can facilitate goal-oriented improvement of the algorithms for the developer. Furthermore, it helps to convince construction industry practitioners to adopt automated safety analysis approaches.

3 METHODOLOGY

This study is split into three different activities. The first activity is initiated by importing the construction situation and processing the geometries and schedule information to build a spatial representation of the construction situation for the time stamps described in the schedule (i.e., spatiotemporal representation). In the second activity the workspaces are defined and extracted from the spatiotemporal representations of the construction project. Additionally, this stage defines and extracts the *item drop space*, which in conjunction with the workspaces, creates the *struck-by falling object* hazard spaces. Finally, the third activity consists of exporting the identified hazard spaces in a way that is useful for construction practitioners but also useful in a DT setting. The three activities are visualised in Fig. 1 and are further elaborated in Sections 3.1, 3.2, and 3.3, respectively.

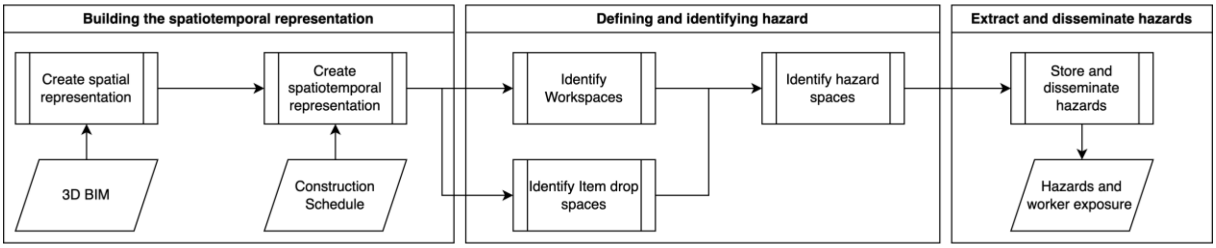


Fig. 1 Visualization of research approach, showing the three performed activities.

3.1 Building of the spatiotemporal representation

To create a spatiotemporal representation, it has been chosen to work with the open standard file format IFC, and the open-source python library IfcOpenShell to parse the geometries of the BIM elements. Each element is stored with its upwards-pointing surfaces, i.e., surfaces that can be walked on by humans, and on to which items or humans can fall onto. Additionally, the downwards-pointing surfaces are extracted, as these define regions that must be subtracted, e.g., when a wall is placed on a slab, it is the downwards-pointing surfaces that should be subtracted from the walkable space.

Once the spatial situation of the construction site has been extracted from the IFC, the temporal component is then added. In this work, it has been chosen to select a human interactable format for the schedule, namely Excel. The excel format is widely used in construction, and it is straightforward to export Comma Separated Values (CSV) from it, which can be interfaced with most applications and software development tools. The schedule pairs the BIM object with tasks, which individually have start and end dates. After parsing the schedule this information is added to the python object that also captures the geometry of the object.

The 4D BIM (3D geometry and schedule) representation in python now holds a list of BIM objects, and their planned start date and completion date, also referred to as the As-planned BIM. Based on analysis date (T_a) the 4D BIM allows the program to query the As-planned, As-Built, and Ongoing tasks shown and described in Tab. 1. These queries are used to build a spatial representation of the construction site at different dates, such that the analysis can be performed for the complete schedule duration in discrete steps.

Tab. 1 overview of 4D BIM queries inspired by [1], [2], where the analysis date refers to the time stamp that the analysis is performed for and BO is a set of all Building Objects.

Query	**Description**	**Definition**
As-built(T_a)	Elements whose tasks' end-dates (T_e) are before the analysis date (T_a)	$bo \in BO: end\_date(bo) < T_a$
Ongoing(T_a)	Elements whose tasks' start-dates (T_s) are before, and end-dates (T_e) are after the analysis date (T_a)	$bo \in BO: start\_date(bo) \leq T_a \leq end\_date(bo)$
As-planned(T_a)	Elements whose tasks' start-dates (T_s) are after the analysis date (T_a)	$bo \in BO: T_a < start\_date(bo)$

3.2 Definition and identification of hazards

Performing the analysis directly in the geometry of the BIM elements has certain drawbacks, where it cannot be expected that workers are only present within the object geometry, e.g., that workers are only located on the specified construction site slabs. Likewise, predefined zones lead to additional manual handling, as described in the related work (Sec. 2). Therefore, this work uses an approach where the analysis spaces emerge from the existence of BIM elements, but where the surrounding is also considered. These analysis spaces will, from now on be referred to as *spatial artefacts*, which is a way to express semantically rich regions of empty spaces that emerge from a spatial situation in the construction site [7, 13]. This work uses spatial artefacts to represent three kinds of regions, which is *workspaces*, *item drop spaces,* and *struck-by falling object hazard spaces.* The spatial artefacts will be defined and described based on Fig. 2, which illustrates a construction scenario consisting of four slabs and one wall. The sequence in which the building object is constructed is shown with the annotation on the building objects (i.e., T_s and T_e, capturing the start and end times of the construction task, respectively).

Workspaces

While the geometry of a workspace may differ based on the performed task, this work describes a definition of a workspace that is related to the cast-in-place structural work of building elements. Nevertheless, other workspace definitions can be added as specialized child classes that inherit the general parent space properties and relation to the analysis. For the cast-in-place workspace, referred to as just the workspace in the following, it is necessary to describe the nature of its emergence. Fig. 2 shows the spatial representation of these spaces in the fourth time step of the analysis. In this representation, one of the active workspaces emerges from the slab, and one emerges from the wall that are both under construction at T_a=4. Common for both workspaces is that they result from an enlargement of the upwards-pointing surface(s) in combination with the intersection of a lower existing building object. The intersection is reasoned with the fact that the work crew needs something to stand on to build the building object, and that it is natural to assume that it would be based on a surface that exists directly below.

Alg. 1 formalises the described procedure, where variables are shown in *italic* and inputted lists in **bold**. The dilate()-function in line 3 refers to the standard Minkowski sum operator, which extends the polygon region, and the intersection()-function in line 6 returns the overlapping portion of the polygons. The subtract()-function in line 7 returns the difference, and ^-operator represents a concatenation of two lists. Line 6 consequently appends the new workspace to the resulting list S.

Alg. 1 Algorithm for workspace extraction

```
Input: OBO (a sorted list of ongoing building objects, based on z-offset),
       EBO (a sorted list of as-built building objects, based on z-offset)
Output: S (a list of workspaces)
S = []
for each BO in OBO:
    WS_Polygon := BO.Top_polygon.dilate(Work_distance)
    for each EBO in EBO:
        S := S^[ WS_polygon.intersection(EBO.Top_polygon)]
        WS_polygon := WS_polygon.subract(EBO.Top_polygon)
return S
```

The workspaces can, in this way, also be limited in height, which could be used for access analysis, for example, to investigate if and how much scaffolding would be needed. In this study this aspect is not included, and the workspaces are not limited by a maximum height, and it is therefore assumed that the work crews can reach with ladders or mobile scaffolding. Additionally, these workspaces can be used in automated reasoning and analysis of activity and progress, such as [23, 24].

Item drop spaces

The purpose of the *item drop space* is to determine where an item or object that originates from a workspace would be able to drop. Fig. 2 illustrates an *item drop space* in analyzing the fourth time step of the construction example. The illustrated *item drop space* emerges from the active *workspace* that emerges from the task of building the wall element at the top. The space gradually grows with an angle, which means that the size of the *item drop space* will increase with the distance from the workspace that it originates from (i.e., creating the cone-formed shape).

Alg. 2 show how the item drop spaces are extracted. The angular_dilation()-function returns a dilated version of the polygon, where the dilation amount equals $\tan(\theta_{drop\ angle} * distance)$. If the elements are already built, the algorithm will subtract its geometry (i.e., the dropping item cannot go through existing elements). On the other hand, if the building object is in progress, the algorithm appends the dilated version to the list of item drop spaces.

Alg. 2 Algorithm for item drop space extraction

```
Input: AWS (a sorted list of active workspaces, based on z-offset),
       BO (a sorted list of all building objects, based on z-offset),
       EBO (a sorted list of as-built building objects, based on z-offset)
Output: S (a list of item drop spaces)
S = []
for each WS in AWS:
    IDS_Polygon:= WS.Top_polygon
    Z_WS:=WS.top_Z
    for each BO in BO:
        IDS_Polygon:= angular_dilation(Z_WS - BO.top_Z)
        if BO in EBO
            IDS_Polygon:= IDS_Polygon.subtract(BO)
        else if BO not in EBO
            S:=S^[IDS_Polygon]
return S
```

The recursive analysis allows the item drop space artefact to describe its impact on other workspaces all the way down to the bottom of the construction model if it is not removed by existing elements. In the end, it reaches the ground, which always exists, and the subtraction will consequently return an empty polygon, that cannot generate further artefacts. Nonetheless, until it is removed, it can impact workspaces that were not identifiable by the human eye, especially in more complex BIM models.

Struck-by falling object hazard space

After the automated extraction of both workspaces and item drop spaces, it is possible to extract the potential struck-by falling object hazard space artefacts. The way that it is extracted is to loop through the item drop spaces and find their overlapping regions with the active workspace artefacts. The illustration of the result of this procedure is shown in Fig. 2, which shows that the work crew, who are working on the slab, is exposed to items that are accidentally dropped by the work crew working on the wall task.

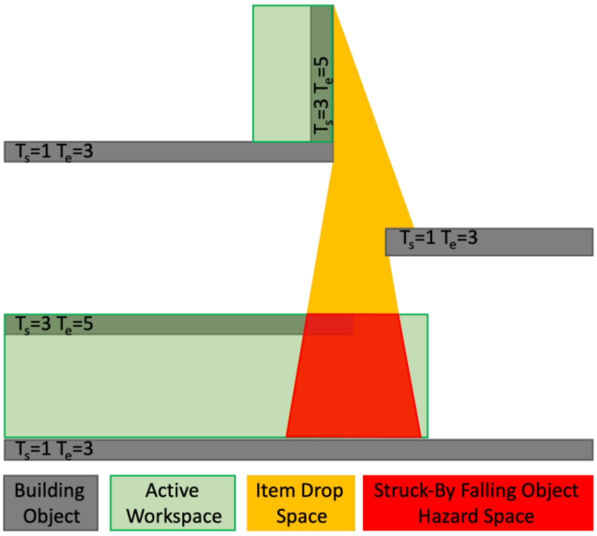


Fig. 2 visualization of the proposed struck-by falling object hazard analysis in a simplified building scenario showing the emerging spatial artefacts.

3.3 Extraction and dissemination of identified hazards

Automated safety analysis for construction is not currently being widely adopted in the industry, as mentioned previously. Some of the reasons for this are that there is a lack of confidence, but also a lack of a fit with, and support for, the current workflows of construction practitioners. Therefore, this work bases its output on IFC, which can be used in almost any CAD tool. This strategy consequently enhances the incoming BIM model with spatial artefacts, which are captured with the IfcSpatialZone class. This enables the practitioner to investigate when and why the hazard zones appear and potentially mitigate these hazards using safety nets and guardrails that are equipped with nets.

Besides capturing the analysis result in the BIM file, it also provides a selection of overall Safety Key Performance Indicators (SKPI), which enable the construction management to rapidly assess whether a construction plan´s amount of struck-by hazard exposure exceeds the expected or even to compare two different construction approaches. The latter is especially relevant in a DT setup, where different construction approaches are captured in what is referred to as alternative plans in [1] and [2]. To provide the overview, the SKPI for *struck-by falling object* hazards are captured for each individual time step of the construction schedule (i.e., when the geometry of the environment changes), and as an accumulation of the overall exposure. Both numbers are based on the normalization of the exposed area compared to the total amount of active workspaces.

4 CASE STUDIES

This section describes how the proposed *struck-by falling object* hazards analysis has been used in two case studies. The case studies have been used to validate the approach and to propose requirements for the schedule and construction scenario. The two case studies are based on two different models with corresponding schedules and are further described in the following two subsections.

4.1 Case study high-rise

The first case study consists of a low-complexity BIM model illustrated in Fig. 3. The construction schedule consists of two crews per element type, i.e., two crews building slabs, two crews building columns, and two crews building walls. The schedule follows topological rules, which ensure that a slab on level L is not built before the columns are built on Level L-1. The building comprises seven stories, each consisting of nine columns, four slabs, and eight walls. The construction process is planned to take around 100 days.

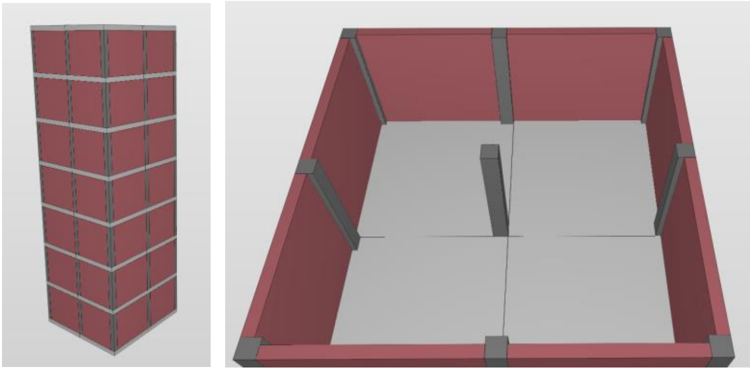


Fig. 3 Visualization of construction scenario in the high-rise case study

The analysis results consist of the two plots shown in Fig. 4, where the upper plot captures the normalized spatiotemporal *struck-by falling objects* hazard exposure for the construction scenario in each time step of the schedule. The normalization is captured based on the exposed hazardous area over the total area of the active workspace, multiplied by the hazard-exposure time over the total duration of the hazard-exposed task. The second plot captures the cumulative hazard exposure, such that an overall degree of hazard exposure in the construction project and schedule can be compared to other schedules or even other projects.

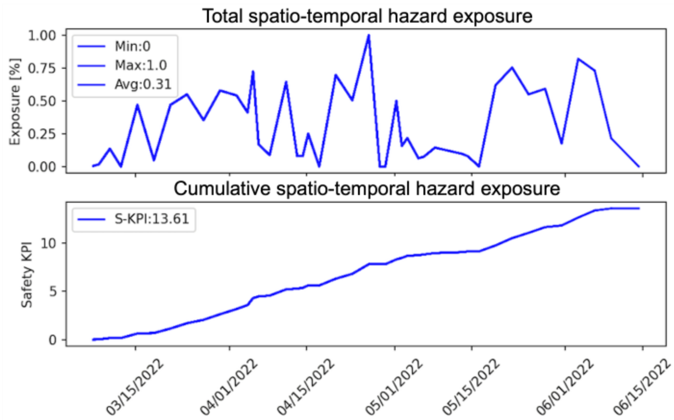


Fig. 4 Resulting spatiotemporal struck-by falling object exposure for the high-rise case study.

4.2 Case study school building

The second case study is based on a structural model of the Autodesk school model shown in Fig. 5, and a schedule that has been created for the EU-funded research project COGITO. The schedule is based on construction zones, which means that elements within the individual zones are constructed simultaneously. The zones are split by stories, which means that there is no work performed on different building stories at the same time. Below each slab, there are columns and concrete beams that are scheduled to be constructed in the same period as the slab they support.

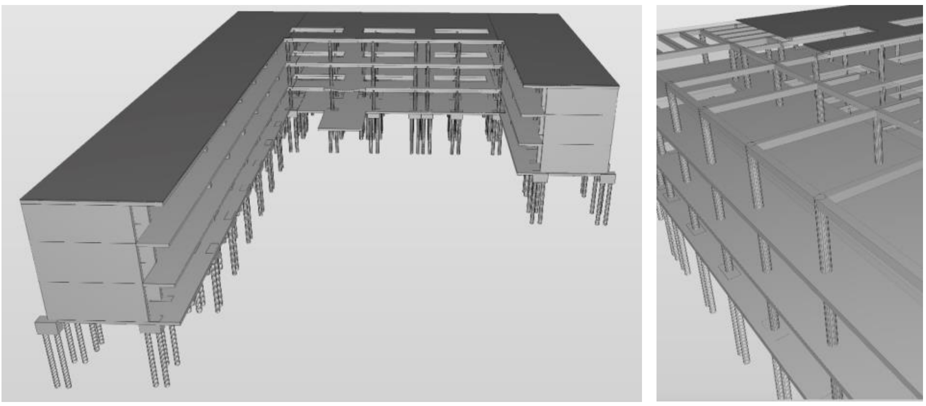
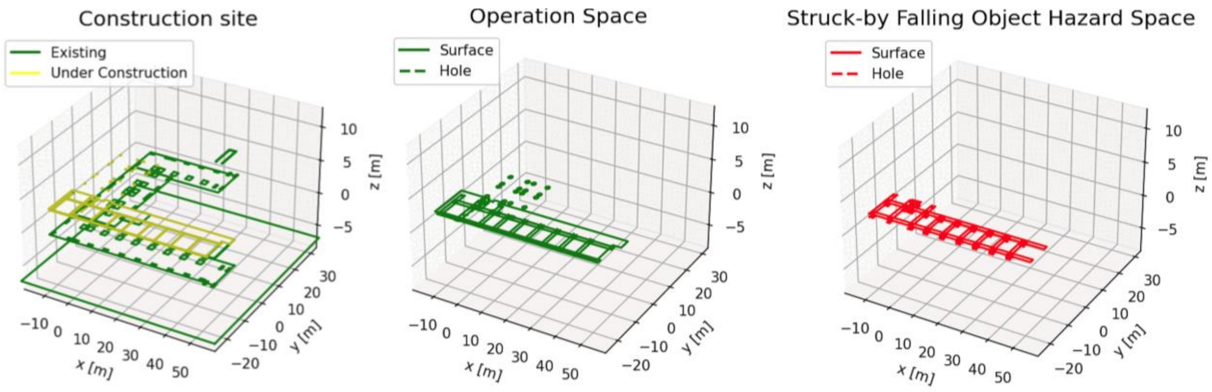


Fig. 5 Visualization of construction scenario in the school case study



a) Spatiotemporal situation b) Active operation zones c) Struck-by hazard zones

Fig. 6 Illustration of spatial artefacts for T=23/12/2009

Fig. 6 illustrates the resulting spatial artefacts that are used to compute the work crew's inter-exposure. The algorithm produces the visualized results for each time stamp, and this is produced for the time stamp representing 23/12/2009, where the yellow elements in Fig. 6 (a) are under construction, which results in the active operating zones in Fig. 6 (b). As the slab, accordingly to the schedule, is being built simultaneously with the supporting beams below it, it introduces a hazard for the work crew below. The overlap can represent that the formworks are planned to be removed from the beams, while the formwork is installed for the slab. Based on the revealed information, it is possible to investigate whether the slab task should be postponed until the beam task has been completed, or if this is a mistake in the schedule. In both cases, the revealed information can be used to prevent hazards or identify mistakes in the schedule, potentially creating problems in the construction process.

Fig. 7 shows the same information as described in the high-rise case study, but this figure also shows that the amount of exposure is low compared to the other results. The decreased exposure is first a sign of the increased project footprint, which means the increased size of work areas and, consequently, a decreased normalized exposure. Secondly, the decreased exposure is a result of the decision to disallow work to be undertaken on two different stories simultaneously. Thus, the exposure that is shown here is a result of the beams being planned to be constructed within the same task as their supporting slabs. This work is not about assessing whether a schedule is realistic, complete, and correct, but about identifying and measuring the hazard exposure that is created by competing work crews in an automated approach and informing the construction management about it. This way, they can investigate and change the schedule if the schedule is incorrectly modeled, or alternatively test an alternative construction approach.

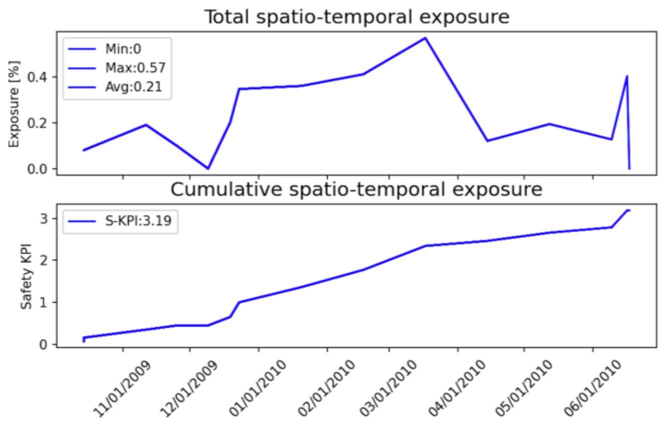


Fig. 7 Resulting spatiotemporal struck-by falling object exposure for the school building case study.

Tab. 2 Processing time for each case study using Apple M1 Max CPU with 32 GB memory.

Case study	Number of BIM Objects	Processing time
High-rise	153	39 seconds
School	896	65 seconds

The *struck-by falling object* analysis is performed on a laptop equipped with the Apple M1 Max processor and 32 GB of memory. The processing time for both case studies is presented in Tab. 2, and includes creating a spatiotemporal representation of the construction project, extracting the spatial artefacts, and disseminating identified hazards. The table presents the processing time that has been produced for this study, which does not include any runtime optimization; thus, the numbers can be improved.

5 CONCLUSION AND FUTURE WORK

This work proposes a novel automated approach to identify and measure the struck-by falling object exposure of work crews in a Digital twin-inspired 4D BIM-based construction situation. The approach is based on spatial artefacts capturing spatial regions that stem from the construction elements and their planned activities. Throughout this work we define new spatial artefacts for modelling *struck-by falling object* hazards and provide a detailed description of their extraction from the spatiotemporal construction situation.

Even though this study is based on 4D BIM models, it is highly motivated and inspired by the increasing interest and maturity of digital twins, where autonomous approaches are demanded to keep up with the update rate and flow of information. In the digital twin vision, is it also proposed that the planning component will propose alternative schedules based on the progress of current and previous projects. These alternative plans would need to be assessed and compared in terms of safety as well as cost and time. While the case study results in this work yields different numbers based on the different project and thereby get more difficult to compare, it is straightforward to compare two different plans for the same project. Besides being able to compare different schedules, the proposed work also enables the construction management to identify, if work crews are scheduled to work on different tasks in close vicinity, which is not desirable for progress, but especially in terms of safety.

Currently, the proposed analysis does not include the areas which are traversed when the work crew is not actively working within their designated workspace, for example, when entering the area in the morning or gathering material. Modeling these areas would mean that information about the location of onsite storage and construction crew trailers needs to be included in the analysis. It is envisioned to extract this kind of information from the construction site layout and incorporate it in the hazard analysis. Additionally, an onsite tower crane would also be a potential source of dropping items, which could also be the proposed analysis. Including the crane would, although, demand information about where and when the crane is operated. Generally, including more information in the hazard analysis consequently increases the demand for the input information.

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INNOVATIVE INTEGRATION OF MODERN TECHNOLOGIES FOR HEALTH AND SAFETY DECISION MAKING IN THE CONSTRUCTION INDUSTRY

Abdulkadir Ganah[1], Godfaurd John[1]

[1] *School of Engineering, University of Central Lancashire, Preston, PR1 2HE (UK)*

Abstract

Health and Safety (H&S) has been one of the key issues in the design and implementation of projects within the construction sector. At the design stage of a project, usually designers are accused of failing to appreciate most of the construction processes that will optimise safety and minimise cost. Therefore, clients and other stakeholders are apprehensive as to whether the designer's input should be fully integrated through other known ways. Also, within a continuation in the downstream end (i.e., construction and facilities management) professional processes used are not fully appreciated by designers. As such these sets of practitioners need to learn fully from each other and integrate their knowledge and skills to close the existing knowledge gap among practitioners. Modern technological innovations have given us new ways of understanding and finding solutions to such existing problems with most professionals working in a collaborative way. Such collaborative ways can enhance learning and cross pollination of professionals within an organisation and across organisations. However, the evidence through data collection is not captured across projects. This conceptual paper aims to integrate modern Artificial Intelligence (AI) and other software applications (such as BIM, IoT, and Digital Twins) to be used within the construction industry setting to understand and augment the learning of all practitioners. An exploratory qualitative research approach through literature review is used in the development of the conceptual framework for the implementation of H&S management that will inform future detailed developments of this proposed innovative approach.

Keywords: Health and Safety; IoT; AI; BIM, Digital Twins, Innovation, Integration; Construction

1 INTRODUCTION

The construction industry is one of the high-risk sectors because of the workplace related accidents that quite often occur because of the complex and dynamic nature of the construction projects [1]. The industry has historically been associated with a higher risk of workplace injuries and fatalities compared with other industries. According to the Health and Safety Executive in the UK, in 2021/22, the construction sector had the highest rate of fatal injuries to workers, with around a quarter of fatal injuries to workers in 2021/22 being in the sector [2]. In the USA, over the past ten years, the construction industry has contributed about 20% of all fatalities, despite employing only 4% of the workforce [3]. The rate of deaths and fatalities in the construction industry is five times higher than rates in other manufacturing industries [4]. Recent international statistics show that there has been no significant decrease in the number of fatalities and deaths over past five years [5].

Farmer [6] pointed out that poor and low investment in and adoption of innovation has been one of the key issues that has led to mediocre performance of the current construction industry in the UK. The construction industry has widely been criticised for low productivity, inefficiency, and reluctance to adopt to technology [7]. The construction industry has been slower to adopt digital technologies compared with other industries like banking, finance, retail, and healthcare [1], [8]. However, the construction industry has been making progress in recent years, and there are several digital tools and technologies available to help improve efficiency, productivity, and safety on construction sites.

Nowadays, Artificial Intelligence (AI) significantly transforms industries such as communications and trade. Knowledge-based systems, robotics, optimisation computer vision, machine learning and other AI subfields have been successfully applied in manufacturing, aerospace, and allied industries to achieve more profit, efficiency, safety, and security. Although the potential benefits of AI application in the construction industry are well recognised, there are many challenges related to AI which still exist and need to be resolved.

In recent years, there has been a growing recognition of the need for the construction industry to embrace technological innovations to improve its performance. Governments, industrial bodies, and stakeholders have been pushing for greater investment in research and innovation [9].

The COVID-19 pandemic has also highlighted the need for the construction industry to embrace innovation and digital technologies. The pandemic disrupted supply chains, forcing the industry to adopt new ways of working, and accelerating the adoption of technologies such as virtual meetings and remote collaboration tools [10]. While the construction industry in the UK still faces significant challenges in terms of productivity and efficiency, there is growing recognition of the need to invest in and adopt innovative technologies and innovations to improve performance and deliver better outcomes [6].

The rest of the paper is divided into the research methodology, health and safety, the perspective of the construction sector, innovative technologies, integration, and a conceptual model development, before discussion and conclusion.

2 RESEARCH METHODOLOGY

This paper is a conceptual idea that will develop the disparate areas that are required for integration to be made among emerging Information Technology (IT), concerning construction personnel health and safety, well-being, and its management, using the developing power of AI in achieving the end solution. An exploratory qualitative research approach through literature review is used in the development of the conceptual framework for the implementation of H&S management [11], [12]. As such three distinct literature reviews were done, one comprising literature on the emerging technologies, a second on health and safety management, and the last literature is on a *person-environment fit* model that has taken root in the environmental social space. The first concerns the modern IT capabilities, as well as the power of AI. The second concerns health and safety practices, concerns, and challenges within organisations, with links to the theoretical bases of the environmental theory, and its associated applications.

This research used certain search engines and the following databases: ScienceDirect, Emerald Insight, and Web of Science with free-text keywords related to subfields and the construction industry to achieve the focus of the research. These keywords include health, safety, integration, innovative, technologies and BIM.

As the literature review was not a systematic one, the last 15 years (since the emergence of BIM concept in academia) was the baseline since the construction sector has existed for an exceedingly long time. Value judgement was used for the selection of the papers which fit the research themes of historical, conceptual, development, principles, and applicability [13]. These were the dominant themes that were relevant to developing what is now part of the literature review in this paper.

3 HEALTH AND SAFETY FOR CONSTRUCTION INDUSTRY

Health and safety is an especially important functional area in all organisations. When it is effectively managed and health and safety processes are working, an organisation's projected image is valued by competitors, as well as admired by the wider built environment. However, if health and safety is compromised, the connotation it has on the organisation's business functions is usually negative in impact that is far reaching and difficult to rectify or made better within a limited time domain. As such it is imperative that organisations working independently or collaboratively should have a hold on the way they carry out health and safety, whether such an organisation be large or small. Innovative approaches and solutions to identify, understand and manage such health and safety concerns are required that are not easily found in the way health and safety is currently imagined. Although health and safety measures are widely accomplished within all manufacturing industries, in the construction industry conditions cannot be controlled in terms of a "pure" production process as it is known. As such, health and safety become paramount [14].

Through investments in people, processes, and equipment, clear safety policies, communication, leadership, and commitment to health and safety, a positive collaborative safety culture should be ingrained within the company ethos. Collaboration can be aided using structured processes, techniques, and cutting-edge digital technologies [15].

On the other hand, organisations and their members have a fundamental stake in how well characteristics and (capabilities) of the person and the environment of the organisation fit one another. Organisations wish to select persons who will best meet the demands of the job, adapt to training and changes in job demands, and remain loyal and committed to the organisation. Achieving these goals in a systematic manner requires a taxonomy of characteristics and (capabilities) of actual and potential organisational members and of the organisational environment and its tasks (e.g. [16] and [17]).

Person-environment (PE) fit model can be created using different theoretical perspectives. One unique feature of the framework is its operationalisation-the assessment of the P and E components along commensurate dimensions [18]. The concept of *PE* reflects the insight that it is not the capabilities of a person or the affordances of the environment as such which determine their quality of life in their environment, it is the relation between capabilities of the person and environment.

Because behaviour is always conducted in an environmental context with its unique affordances and constraints, behavioural competence (performance) must be viewed as an outcome of the person-environment transaction. Nonetheless, the relative strength of personal versus environmental determinant of competent performance may vary. Thus, it is possible to group types of behavioural competence into rough inner determined and outer-determined subgroups [19].

There are several methodological problems that remain to be addressed in PE fit theory. The objective measurement of the person's skills, abilities, and needs and of the environment's demands and resources continues to be elusive. The assessment of subjective measures of P and E also requires more methodological development. Scales need to be developed which demonstrate that the P and E measures are not contaminated by each other. A taxonomy of theory-based dimensions of P and E also needs to be developed [18]. Operationalising the PE framework concerning health and safety issues will involve a lot of data capture and analysis, for which the seamless integration of modern technologies will be highly significant [20].

4 INNOVATIVE TECHNOLOGIES

There are myriads of IT technologies which upon can assist in the way the management of work processes on construction site are achieved. Among such technologies are AI, Internet of Things (IoT), and Digital Twins (DT) that we want to evaluate and focus our discussion upon for the development of a conceptual research approach.

Technology is an innovation if the user has not encountered its benefits and its values. However, innovative technology is not an oxymoron when viewed from the perspective that such disparate technologies, when integrated together for higher values, gives us something that has not yet been considered within their usage values.

Adoption of such innovative technologies such as AI, Building Information Modelling (BIM), IoT, Digital Twins DT, Robotics, Virtual Reality (VR), Augmented Reality (AR), Machine Learning (ML), Wearable Devices, Eye Tracking, Radio Frequency Identification (RFID), and Laster Scanning and LiDAR may have better beneficial values when integrated for better functioning values [21], [22]. However, the focus of this research paper is on digital twins (BIM & IoT), and AI.

4.1 Digital Twins (BIM & IoT)

Sensors as the basic unit of data capture instrument, with the use of cloud as the repository, with the aim of using the data within the IoT domain wherein technologies can be fully automated to achieve some form semblance. Sensors and 'things' cannot fully 'talk' to each other seamlessly without some form of automation powered by AI, which human intervention can 'play' with in real time [23]. Hence, there is a need to appreciate fully how such technology will enhance work processes in construction concerning issues of health and safety.

Digital Twin (DT) is gaining momentum in industries like manufacturing, aerospace, and the mechanical sector. Adoption of DT by many industries, sectors, and services has started to emerge with the recent development of IoT [24] and the development of the fifth generation (5G) technology standard for broadband cellular networks. The main concept of DT and IoT is connecting and collecting data about the physical objects to their virtual counterpart and vice versa. However, in construction there is an inertia as to its relevance and benefits for contemporary projects and products. If we deconstruct DT, and its definition, we are already using all the technologies within the construction industry, as independent standalone innovation. However, the concept behind DT is what we have not yet embraced, which may require human intervene in decision making, as well as automating some of the processes. Though the uptake of DT is slow, one issue is that we still have a silo mentality toward their application in construction. However, considering the facts that the next group of leaders, managers, CEOs movers and shakers within the construction industry will be ‘kids’ who have grown up with X-box, Nintendo, and Zelda’s, a transformation is emerging, as they would be ‘relaxed’ with such innovative technologies. If the industry approach be radically improved from what it is now, to something close to what they have encountered as kids in their virtual world with continuous improvement, the need for integration of some of the technologies will follow.

Digital Twin technology has been made possible by advances in computing power, data analytics, and IoT not forgetting BIM. BIM digital twins can be beneficial in improving H&S in construction industry. BIM models created during the design phase of a construction project can be used to create a virtual replica of the building or structure. By using this virtual model, the construction team can identify potential safety hazards and take steps to mitigate them before construction begins. BIM model can be used to simulate construction sequences and identify potential conflicts or hazards, such as workers working at heights or in confined spaces. This can help to reduce the risk of accidents and injuries on the construction site. During the construction phase, BIM models can also be used to monitor and manage H&S. For example, sensors and other IoT devices can be embedded in the construction site to collect data on noise levels, air quality, and other environmental factors which can impact worker safety. This data can be used to identify and address potential risks in real-time. Additionally, BIM models can be used to train workers on safety procedures and protocols before they begin working on the construction site [25]. This can help to ensure that workers are prepared to handle potential safety hazards and reduce the risk of accidents.

4.2 AI

The impact of AI on the construction industry is wide and varied. Mostly what we experience of AI is the first iteration that people tend to attribute to the power of AI. Issues of AI-Bots that are application specific to optimise functions equate with the number of queries that have been given/done within known problem areas that AI can be used. In construction the main areas of AI application include IoT, especially in the downstream end of the construction industry. For example, the optimisation of resources through proper AI efficiency.

Nowadays, AI significantly transforms industries such as communications and trade. It can be defined as the field of computer science and engineering which focuses on creating machines and systems that can perform tasks that typically require human-like intelligence, such as perception, reasoning, learning, and problem-solving [26] . While AI is about creating intelligent machines and systems, it does not aim to replicate human intelligence entirely but rather to augment it by providing tools and technologies that can perform tasks that are beyond human capability or perform them more efficiently and accurately.

Knowledge-based systems, robotics, optimisation computer vision, machine learning and other AI subfields have been successfully applied in many industries to achieve more profit, efficiency, health and safety, and security. For H&S in the construction industry, AI technologies focus on enhancing H&S for site workers, such as a system that alerts site personnel with a message about the possible hazards, thereby minimising risks. With improved efficiencies, the technology can lead to advances in H&S, as the technology with robotics can be used to evaluate sites and complete dangerous tasks for humans [27].

However, the potential benefits of AI application in the construction industry are well recognised but there are many challenges related to AI which are still exist.

5 INTEGRATION

The integration of people, technology, and process is essential in ensuring health and safety in construction sites. This approach involves the uses of a systematic and coordinated way to manage and implement health and safety measures. The following sub-section discusses these key elements in detail.

5.1 People

People are the wellspring of what we do when we have work to achieve and complete the goals that are set out in our project objectives. Without the employees’ input in turning disparate resources into the product through the project, it is almost impossible to achieve our goals. Although IT automation has helped in most processes there are still issues of interpretation of the integrated processes for good decision making. Hence the competencies required for such operative and their leaders need to be sound for value to be created when we do our projects.

Leadership is paramount for an effective and efficient project and its health and safety concerns. Management of health and safety is about the people’s knowledge and understanding about their job processes and how they integrate technology with these processes in a safe and structured environment, as well as minimising the health and safety risk associated with their jobs. The leader should be focussed in driving his/her ideas through a well-oiled and robust team of players. Without a transformational leader in charge, who see the benefit of AI as the link in integrating these technologies we would not succeed. For example, the AI-Bots, which are used currently in other industries for queries and answer, can be adapted to meet issues of building regulations, violation of Construction, Design and Management (CDM) regulations, as well as violation of construction site contraventions. Hence the people can be just administrators [28].

5.2 Technology

So many technologies have emerged that are utilised in other industries that have not yet taken root in the construction sector. Some of these technologies include wearable devices that monitor heart rate, respiration, and body temperature, which can help detect early signs of fatigue or exhaustion, as well as alert supervisors to potential safety hazards. Additionally, smart safety vests or helmets equipped with GPS and sensors can help track worker movements and notify them of nearby hazards or unsafe conditions [29]. Such devices can be linked using IoT to a digital model where hazard areas are identified with the use of digital twins. Despite most of these technologies being mature and diffused in other industries, there is an absent of their diffusion within the construction sector. Construction inertia may be due to failure to understand how to get these technologies ‘talking’ to each other. Therefore, with advancements of technology and the life cycle realisation of the project in one holistic environment, a vast amount of the health and safety data can be generated, collected, and stored directly in a single environment. With the aid of artificial intelligence, this data can help construction site personnel and managers, designers, clients, end-users, and all other stakeholders involved in the design, delivery, and use of a facility in making the right and correct decisions regarding health and safety issues which may arise [7].

5.3 Process

Some of our processes within the built environment need formulation as some may not be ‘*fit for purpose*’ due to changes in the way we design or build things. Perhaps revisiting the development of these processes and finding new ways of approaching the ‘old’ problem may aid us in coming up with better understanding emerging from the appraisal [30]. In most case, practices developed from the evolving work pattern have existed from the start of the process type. However, over time there may come innovation which requires a rethink of these processes, of which AI is an example. Hence new strategic process must be reformulated incorporating the innovation. For example, the drawing of plans has moved from the basic technical drawing, through 2D CAD, into BIM. Similarly, components manufacturing has moved from the workers in a controlled environment into 3D automated printing. Thus, AI can be another innovation which may be disruptive in nature, hence requiring process rethink. Using a known model in developing this innovative integration of using AI reside in the Lawton *person-fit environment* model approach and within a well-developed application [31], [32].

5.4 Optimisation

Optimisation involves improving the efficiency or effectiveness of a system or process by fine-tuning certain parameters or variables within the system or process as data becomes available over time for every successful completed project [33]. It is critical to ensure the health and safety of the employees and reduce the risk of accidents and injuries on construction sites. It is usual to say that once a problem has been analysed and solution found, there is a need to refine the solution through various optimisation cycles such that it can be practically used within the field of application envisage.

Optimisation is an ongoing process that requires the continuous evaluation and refinement of solutions to ensure they are effective, efficient, and sustainable within the field of application. This involves a commitment to innovation, investment in technology and resources, and a culture of continuous improvement and learning.

6 TOWARDS AN AI DECISION SUPPORT HEALTH & SAFETY MANAGEMENT

Fig. 1 gives a high-level schema of how the integration of technologies can be conducted, considering the known processes, as well as new processes will be used in developing the integrated approach. People are considered as part of the integrated environment, for without the person, this approach cannot function effectively. As such, using the Lawton's [19] *person-environment fit* model, its principles and concepts as the premise, and the starting point for this integrated approach, decisions can safely be made by those working within the construction environment. AI together with IoT will ensure that a commensurate scale is used when developing the organisation *PE* fit required through the mapping done to capture the required data measures.

After data collection using IoT, as well as known conventional data collection methods, the data is cleaned, then standardised and structured for database inclusion. The standardised data will be added to the dataset, with the App and AI running seamlessly for the purpose for which they have been designed or the programmes developed. The AI/ machine learning App would have been trained for pattern recognition, for health and safety hazards, risks, incidents, site safety event types, as well as expert domain construction knowledge. A bit of Lawton's [19] *person-environment* will have also been built into the integrated approach, recognisable within the form of AI decision criteria.

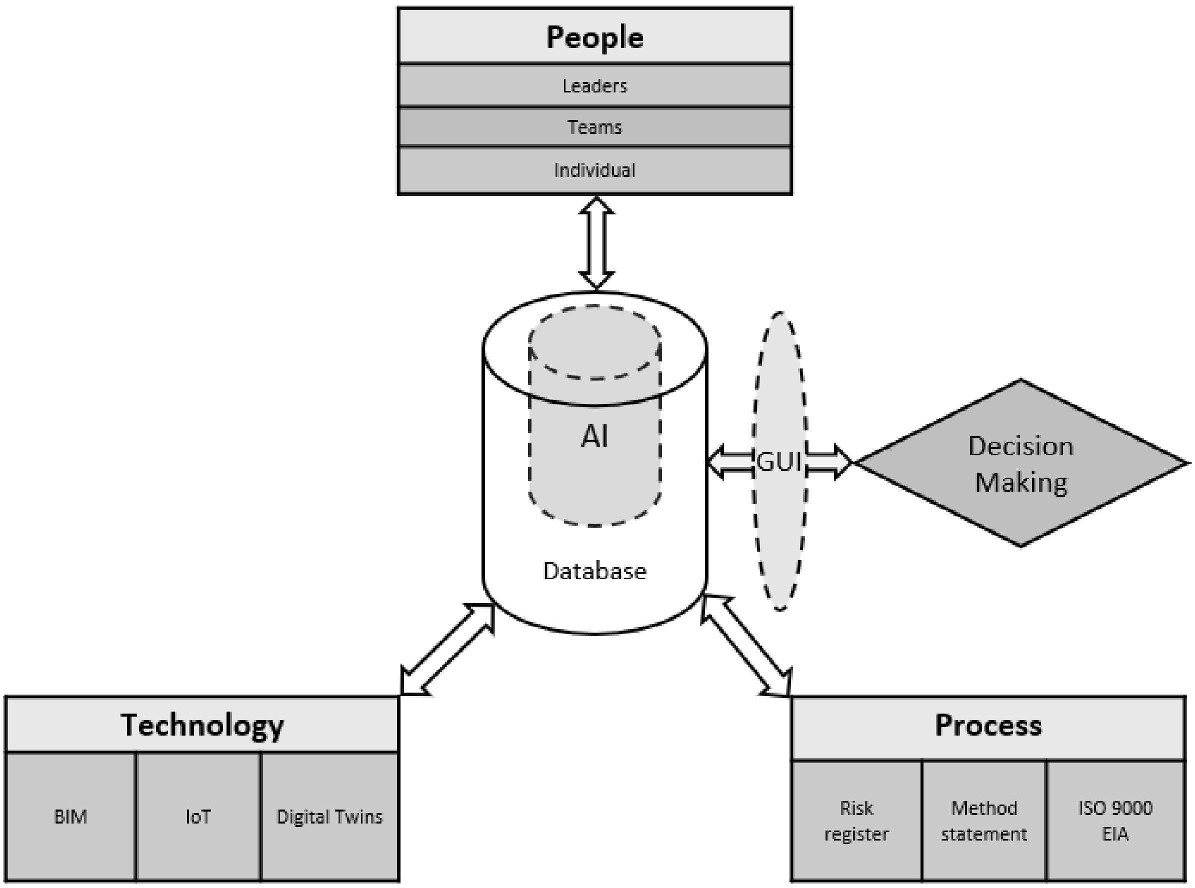

Fig.1: Conceptual representation of digital integration for construction

The AI technology can search the database with a command from the user through the graphical user interface (GUI) for similar issues and analyse each health and safety incidents with all scenarios, with the best possible solution suggested to the decision maker. The speed and accuracy of AI tools for mining data cannot be compared with those of human and other tools. Time in health and safety issues is paramount and key for saving lives and money. AI technology save much of time. With an optimisation algorithm or App as part of the full suite within the framework envisage, the AI machine learning approach would continuously learn by optimising the solution space, with new safety risk challenges, and health and safety issues that are arising as the site work changes, as well as from one site experience to the next the possibilities are many. AI increases the value of health and safety management by supplying all the possible answers to the raised questions and solving problems that would otherwise require substantial development time [34].

7 DECISION MAKING

For one to be able to make the right decision in real time, there is a need that the operative or the decision maker/team must have competencies in different fields which will aid in making an informed decision [35]. That means the decision made should be credible interpretation of data and text mining, as well as the field of specialism, say project management, health and safety, quantity surveying or environmental engineer. Combining the specialism of the decision maker, as well as the information mining from the disparate technology's issues, better understanding of a phenomenon with specific knowledge can be generated which will be an original creative thought from AI aided approach. Hence, the decision maker will not just be an abductive individual but supported by unambiguous evidence from AI support.

AI can assist to analyse the data collected from sensors, cameras, and other data collectors installed on the construction site to detect potential hazards or risky behaviours of workers. It can also provide real-time alerts and recommendations to the personnel to prevent accidents and injuries. Moreover, AI can assist in predicting and managing risks related to environmental factors such as weather conditions, geological conditions, and natural disasters. This can help the project team to take proactive measures and adjust their plans accordingly to avoid any risks and hazards.

AI assistance will involve gathering measurement in the characteristics (i.e., intrinsic, or extrinsic) of a person through machine learning, by analysing data from social media, online surveys, and other digital platforms. Patterns and trends in data can be identified to measure some of these characteristics.

8 DISCUSSION

Within this paper the concept, principles, and usage of emerging technologies have been developed, although most of such technologies are seen as disparate. A conceptual understanding was generated from Fig. 1, gives an insight into the workings of the proposed model.

The data to be collected comes from the site operatives, designers and stakeholders that will have adverse impact on the site construction process. The data from these operatives are mapped and structured for eventual inclusion into the database. Also, data arising from the changing nature of the BIM artifacts, on construction operations, as well as method statements, and risk registers will be collected into the centralised database. An organisation that has existed from some time will also have historical data as their corporate memory, which is also to be harvested for the dataset that is envisage.

To consolidate all parts of the collected data into a single centralised location and maintain a comprehensive health and safety information (i.e., records, documentation, policies, processes, etc), a mapping process is required between the resultant structured data from the already described processes using the OWL Ontology [36], of which this will be the subject of another paper.

9 CONCLUSION

The premise for this position paper is that processes that are considered independent with the health and safety domain can be improved through the idea of integration of technology, processes, and people. Integration of people has been present all the time but capturing the soft people's issues are not so apparent. In this paper a concept was thought out which would when fully developed give a clear indication about how such concept can be operationalised for the benefit of the construction industry. Therefore, a good deal of research is required for such a position to be attained. One of the biggest and most significant industries in the world is construction, yet compared with other sectors, it has been reluctant to incorporate AI technologies. While there are undoubtedly advantages to employing AI in construction, such as better safety & health, more efficient processes, and lower costs, there is also several difficulties which must be resolved. The requirement for accurate and trustworthy data is one difficulty. Construction AI systems require precise and trustworthy data to function properly. Nevertheless, the data in the construction sector is notoriously complex and disorganised, which can make it challenging to create efficient AI models. Another issue is the lack of qualified personnel who can run and maintain AI systems. The paucity of competent personnel in the construction sector is well recognised, and it is made much worse by the lack of people who are familiar with AI technologies. It might be challenging to develop efficiently and maintain AI systems without skilled people. Regulatory compliance presents another difficulty. Like any innovative technology, AI systems in construction are subject to several laws and guidelines. Failure to comply may have legal and financial repercussions, and it can be a complicated and time-consuming process. BIM, IoT, and digital twins can enhance health and safety in the construction industry by spotting potential problems, keeping an eye on them in real-time, and supporting workers in their training needs. Although the construction industry can reap substantial advantages from AI, IoT, BIM, and Digital Twins in terms of health and safety, certain hindrances must also be explored and resolved to achieve those benefits. As technology progresses, we can anticipate further breakthroughs in the construction sector that will facilitate digital transformation and enhance future operations.

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TECHNOLOGY ADOPTION PROTOCOL: A PROCESS TO ADOPT A NEW TECHNOLOGY TO MITIGATE SAFETY IMPACT OF LAST-MINUTE CHANGES

Wei-Hsuen Lee[1], John Gambatese[1], Matthew Hallowell[2], Chukwuma Nnaji[3]

[1]School of Civil and Construction Engineering, Oregon State University, Corvallis, USA
[2]Civil, Environmental and Architectural Engineering, University of Colorado Boulder, Boulder Colorado USA.
[3]Department of Construction Science, Texas A&M University, College Station Texas USA

Abstract

Technology is widely used in many industries and the construction industry has started to incorporate many technologies during the work process. Some technologies are specifically designed help the construction industry improve worker safety performance, such as proximity alert systems, automated flagger assistance devices, and automated cutting protection. It is critical for the successful use of technology that the functions of the technology are matched to the targeted requirements. Currently-available technology adoption processes incorporate many essential predictors to help construction industry organizations evaluate whether adopting a technology is beneficial. However, current technology adoption processes are typically designed for general situations, not for specific safety situations such as when last-minute changes occur. A last-minute change is an unexpected change that happens at the last-minute/end of a work operation when a limited response time is available, which may lead to unsafe decisions by workers. This research introduces a technology adoption protocol to aid construction industry organizations in determining whether the technology is appropriate to mitigate safety issues caused by last-minute changes. The researchers reviewed current technology adoption processes and critical factors in the adoption process, then modified and developed an existing process into a technology adoption protocol specifically for coping with hazards related to last-minute changes. Adoption factors in the updated technology adoption protocol were assessed by experts using the Delphi method to confirm consensus amongst the experts that the factors are valid. The technology adoption protocol developed consists of three main steps, a Preliminary Feasibility Evaluation, Technology Assessment, and Pilot Test/Field Assessment, to guide the construction team to adopt the right technology to address the impact of last-minute changes. The research results contribute a rigorous process for the construction industry to assist decision-making when considering whether to adopt new technology to mitigate safety issues related to last-minute changes.

Keywords: Last-Minute Change; Safety; Construction Industry; Technology Adoption Protocol.

1 INTRODUCTION

Many different types of technology are widely used in work industries. The construction industry has been identified as getting a late start in deploying new technologies in its work processes. Safety inspections in the construction industry have traditionally relied on workers' or managers' ability to identify hazards [1]. Moreover, conditions on the construction site are dynamic and complicated, which creates a high likelihood for safety issues and risks to be ignored or missed by workers or managers. However, technologies designed specifically to address safety can help the construction industry identify hazards on construction sites [2]. For example, proximity alert technology can alert heavy equipment operators that there is another worker or object close to the heavy equipment. Although many new or developing technologies can help the construction industry improve safety performance, based on research by the Center for Construction Research and Training (CPWR), only a few construction contractors utilize new technologies in their projects [3]. Therefore, adopting new technologies is an important topic for the construction industry.

Given the dynamic nature of construction, last-minute changes often occur on construction sites. The research team defined a last-minute change as "a change that occurs or manifests at the work face when there is limited time available to plan for and address the change" [4]. A last-minute change can also be considered an unexpected deviation from the plan or conditions at the last minute. After a last-minute change occurs, a worker or manager who is impacted needs to assess the dynamic risk. If the assessment is not appropriate, the action taken may cause unsafe acts or behavior and result in an injury to the worker. For example, when a worker unknowingly walks into the path of heavy equipment, and neither the worker nor the operator notice they are getting close to each other, a last-minute situation is created in which the worker is at risk of being struck by the heavy equipment. In this case, the impacts of the last-minute change could be mitigated by technology adopted for the work operation (i.e., a proximity alert system) [5]. Another example of a last-minute change is when a worker is working diligently at the end of a work shift, or near the deadline to get work completed, and an unexpected change occurs that increases the risk of injury. The worker is put in the position of making a decision about safety under the stress of wanting or having to complete the work promptly. Given the mental pressure to complete the work, the worker may make an unsafe decision. Prior research reveals that working under pressure and improvisation are precursors to serious injury and fatality incidents [6] [7]. A wearable device that prompts the worker or manager to make an appropriate decision may be applicable in this case [8] [9]. The research team identified a total of 49 technologies that are potentially applicable to last-minute changes. The technologies can be organized into the following six categories: communication/mobile computing, sensing/monitoring, visualization, automation, site control/site access, and artificial intelligence. A complete list of the technologies is available in [4].

2 LITERATURE REVIEW

Many commonly-used and newly-developed technologies are available for the construction industry to improve their safety performance, but the application of these technologies is still inadequate in the construction industry [2]. Based on previous research, technologies were classified into six categories: communication/mobile computing, sensing/monitoring, visualization, automation, site control/site access, and artificial intelligence. Communication technology, such as a quick response (QR) code, allows workers to obtain information related to the tagged item to perform safety analyses when conditions have changed [10]. Sensing/monitoring technology, such as a weather sensor and wearable device, can detect environmental situations and track physiological conditions in real-time [8]. Visualization technology, such as virtual reality (VR) and augmented reality (AR), can help designers and safety managers recognize potential hazards during the design phase [10]. Automation technology can perform tasks in extreme conditions to keep workers away from hazards [2]. Site control/site access technologies, such as an automated flagger assistance device (AFAD) and work zone intrusion alert technology (WZIAT), are proven to enhance safety performance when exposed to live traffic [11] [12]. Artificial intelligence has high potential applications for construction safety because it is expected to identify all unsafe behavior automatically [13].

Even though the researchers revealed that technology can be used for safety performance on the construction site, there is a lack of knowledge in the present archival literature regarding how technology can be used to mitigate the potential negative impacts of last-minute changes. Moreover, while examples of technology adoption protocols presently exist, such as that shown in Fig. 1, no examples of protocols for effective adoption of technologies specifically to address safety implications related to last-minute changes were found.

To fill the gaps in knowledge and practical resources, the researchers conducted a study to create a technology adoption protocol that can help construction companies identify an appropriate technology to mitigate safety issues related to last-minute changes. With this goal in mind, the research aimed to identify and include potential technology adoption factors, involve an evaluation for applicability to last-minute changes on construction sites, and create a technology adoption protocol for construction companies that is effective, accurate, and feasible for use in practice. The new technology adoption protocol is expected to be a powerful and beneficial tool for the construction industry when adopting new safety technologies for construction projects.

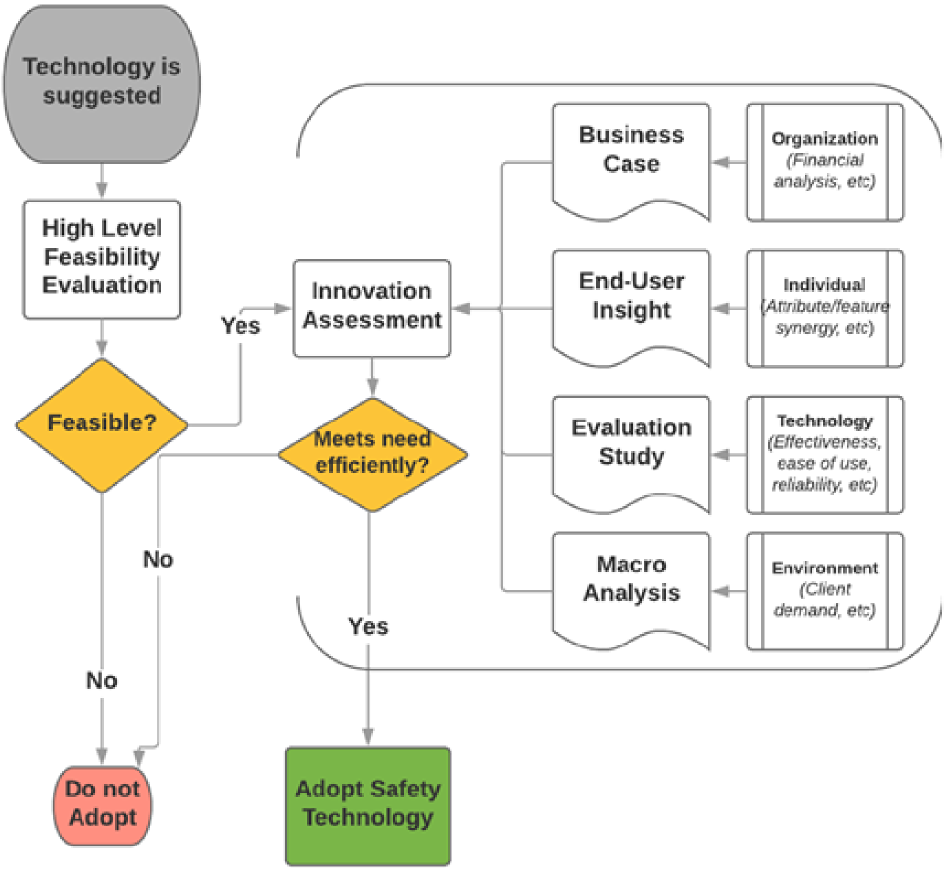

Fig. 1: Current technology adoption protocol [14]

3 RESEARCH DESIGN AND METHODOLOGY

The researchers chose a research design consisting of an expert panel and the Delphi process to achieve the goals of the research. The Delphi process is an interactive and systematic research method allowing experts to provide independent judgment on a topic. Forming an expert panel is the first step in the Delphi process. The researchers first identified potential experts and then evaluated, based on their educational background, work experience, involvement in professional organizations, and record of authorship, whether the potential experts were qualified to provide input on the topic. The qualification process was performed through an online survey. The second part of the Delphi process involved determining the discussion topic. In this research study, technology adoption factors were the main topic of discussion. In the last part of the Delphi process, experts independently provided input for each identified technology adoption factor in multiple rounds of surveys.

After the expert panelists were identified, the researchers asked all experts to provide their independent opinion on each factor regarding its importance to technology adoption. The technology adoption factors were identified from previous studies. The previous study separated factors into four categories: organization, individual, technology, and environment. The organization-related factors evaluated whether the organization had the plan, budget, or benefits to adopting the technology. At the same time, the individual-related factors determined the application issue of the technology. Moreover, the technology-related factors checked the functions of the technology. Lastly, the environment-related factors evaluated external issues if the technology was adopted [14]. While another research mentioned different category, vendors' attributes, which focused on the factors of the technology vendor [15]. Experts would review all these identified factors.

A rating scale from 1 to 5 was used, where 1 = extremely unessential, and 5 = extremely important. Then, the researchers summarized the experts' ratings and, in the second round of the Delphi survey, presented an anonymous summary of the ratings to the expert panelists. The panelists were then asked to review the summary ratings, and use the summary to consider whether to revise their initial ratings in the first round of the survey. The process of reviewing the summary results and re-evaluating their responses was repeated two times in the study. After the responses from the second round were summarized, the researchers determined whether group consensus was achieved regarding the importance of each technology adoption factor. The researchers set the criteria for reaching consensus to be when the mean absolute deviation of the factor rating is equal to or less than 1.0. If panel consensus regarding the importance of a technology adoption factor was achieved, the factor was retained for inclusion in the adoption protocol. If consensus was not achieved for a factor or the median rating of the factor was equal to or less than 2.0 in the final round (i.e., rated less than moderate importance to technology adoption), that factor was dropped from the analysis [16].

The research protocol and target population were submitted to the Institutional Review Board (IRB) at Oregon State University for review and approval for research involving human subjects. IRB approval was obtained, after which data collection commenced.

4 RESULTS

The background and expertise of each panelist based on the experts' responses to the demographics questions in the survey are shown in Table 1. All of the experts who participated in the research met the minimum requirements to qualify as experts by following the instruction from a study [16]. Thus, all of the experts were retained and included on the panel.

In a meeting with the panelists facilitated by the researchers, the researchers and expert panelists initially discussed the current technology adoption protocol, shown in Fig. 1, and previous research to determine what steps should be included in the new technology adoption protocol. The researchers and experts concluded that the new technology adoption protocol should consist of three main steps: preliminary feasibility evaluation, technology assessment, and pilot test/field assessment for applicability to last-minute changes. An illustration of the protocol steps and decision points is shown in Fig. 2. The following sections present the information associated with each step.

Table 1 Expert demographics

Panelist ID	Highest Degree	Years of Experience	Professional Registrations	Committee Memberships	Number of Employees	Positions
P1	MS	21 – 25			> 10,000	ESHQSS Integrator / technical advisor
P2		26 – 30	CSP, CHST		2001 – 5000	Senior VP of EHS
P3	BS	11 – 15	None	None	5001 – 10,000	
P4	BS	26 – 30	Professional License Mechanical Engineer-California	None	> 10,000	Construction Manager
P5	MS	> 30	CMIOSH	None	2001 – 5000	Corporate HSE manager
P6	None	6 – 10	None	None	> 10,000	EHS Manager
P7	None	< 5	None	Member, ABC National Safety & Health Committee	2001 – 5000	Corporate Safety Director

P8	MS	< 5	LEED GA, E.I.T.	None	> 10,000	Consultant
P9		26 – 30	None	None	> 10,000	Construction Automation Specialist
P10	BSCE & MSCE	6 – 10	None	None	> 10,000	Principal Staff Engineer - Technical
P11	None	< 5	None	None	> 10,000	
P12	None	16 – 20	None	None	5001 – 10,000	HSE Director
P13	None	21 – 25	None	None	5001 – 10,000	HSE Director

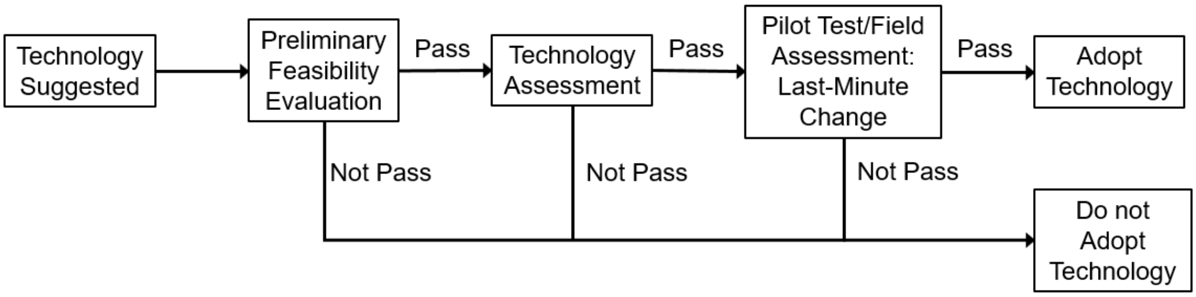

Fig. 2: Protocol steps for evaluating technology for possible adoption for last-minute changes (Adapted from [14] and [15])

4.1 Preliminary Feasibility Evaluation

The first step, Preliminary Feasibility Evaluation, provides a quick check of whether the technology is a potential target technology for the construction industry. The evaluation contains two short answer and eight yes/no questions. The first two short answer questions ask for the technology's name and the target application or use case for the technology. These two questions are also included in the second and third steps of the protocol for the same purpose. The next questions in this evaluation step consist of eight yes/no questions derived from the identified technology adoption factors based on the experts' experience and opinions, shown in Table 2. These questions mainly focused on factors related to cost, usage, and effectiveness issues. If the answer to any of these eight questions for the suggested technology is "no," the technology does not pass this evaluation step and it is recommended that the technology not be adopted. But, if the suggested technology passes this evaluation step (i.e., answers to all yes/no questions are "Yes"), the technology will move to the second evaluation step for a highly detailed assessment. The specific questions included in the full preliminary feasibility evaluation document are available in [4].

Table 2: Preliminary feasibility evaluation questions (Extracted and adapted from [4])

1.	Does the technology have potential capabilities to prevent or mitigate last-minute changes?
2.	Is the capital cost of the technology affordable for the organization?
3.	Are there any potential cost savings from using the technology?
4.	Is the cost of operating and maintaining the technology affordable for the organization?
5.	Is the technology easy to use?
6.	Is the technology proven to be reliable in applications it is being considered/ evaluated for?
7.	Is the technology scalable across the organization at the enterprise level?
8.	Can the technology be used on multiple projects and on local sites?

4.2 Technology Assessment

The second evaluation step, Technology Assessment, is the main part of the technology assessment and consider many adoption factors in detail. Based on categories found in the literature review, the researchers decided to evaluate all identified technology adoption factors through the Delphi process.

In the Delphi process, as described above, the researchers provided an evaluation form to the expert panelists and the panelists input their opinions regarding the importance of each factor. The first round of the Delphi process showed that consensus was reached on most of the factors, but the mean absolute deviation of the rating for some factors was close to the established consensus threshold. After the panelists reviewed the anonymous summary data and discussed it amongst the panel without telling the other panelists their ratings, the researchers asked panelists to provide input for the second round of the Delphi process. Based on the result from the second round of the Delphi process, the mean absolute deviation of the rating decreased for those factors with the mean rating absolute deviation close to the set threshold. Technology adoption factors in the technology assessment step are included and shown in Table 3. However, there were a few factors, such as technology brand and direct competitors adopting similar technology, that received median ratings of 2 or lower; these factors were subsequently dropped from the identified factor list.

After determining the appropriate factors to include in this evaluation steps of the adoption protocol, the researchers identified scales for use by the protocol users to rate each factor when implementing the protocol. A scale from -3 to 3 points was adopted, where -3 represents extremely negative factor presence and 3 represents extremely positive factor presence. An “I don’t know” option was also included. This scale enables the protocol user to provide their evaluation of the technology with respect to each adoption factor. For the given scale the consider 44 factors, the maximum possible point range will be from -132 to 132. If there are any “I don’t know” (IDK) responses selected, the maximum possible points will range from (-3)*(44 – number of IDK responses) to (3)*(44 – number of IDK responses). The protocol user then sums the score from each factor to obtain a total score for this evaluation step. In order to pass this evaluation step, the total score must be over a threshold established by the construction company. If many IDK responses are selected, the assessment is invalid and the technology should be re-evaluated when the required information is available. If the total score is negative or very low, the suggested technology should not be adopted. Conversely, if the sum of the factor scores is high or reaches the targeted score, the suggested technology passes this technology assessment step and moves on to the last evaluation step. The full Technology Assessment document is available in [4].

Table 3: Technology adoption factors (Extracted and adapted from [4], [14], and [15])

Technology Adoption Factor Category	Example Technology Adoption Factor
Organization	Capital cost of technology
	Competitive advantage
	Level of compatibility with current processes
	Observability
	Organization culture
	Organization’s general overall attitude
	Potential cost savings from using technology
	Safety budget within organization
	Top management degree of involvement
	Having an adoption plan in place
	Organization has an adoption and implementation partner
	Having a site champion for each project site
	Buy-in from the project manager
	Paying for ongoing maintenance cost
	Projects will not pick up the budget unless they can pass the cost on to the owner
	Corporate office will not pick up the budget unless they can pass the cost on to a project
	Worker involvement in selection
Individual	Ease of use
	Training required for optimum performance
	Individual innovativeness
	Technical capabilities of users
Technology	Technology durability
	Technology reliability

	Triability
	Versatility
	Technical attributes and features included
	Complexity of technology
	Integration with existing systems/work processes
	Use in hazardous areas
	Use in remote locations
Environment	Client demand
	Government policy and regulations regarding technology
	Industry standard for using the technology
	Industry-level change required for technology adoption
	Partners adopt similar technology
	Technical support from manufacturer
	Technical support required for optimum performance
Vendor	After sales service
	Guaranty
	Warranty
	Training service
	Maintenance service
	Relationship & Motivation program
	Vendor: size of organization

4.3 Pilot Test/Field Assessment: Last-Minute Change

The last step in the adoption protocol, Pilot Test/Field Assessment: Last-minute Change, is the part that helps the construction company determine whether the suggested technology can mitigate safety issues related to last-minute changes. The assessment questions were designed and discussed amongst the researchers and expert panelists based on the panelists' experience and knowledge of safety and technology usage on construction sites. The questions in the assessment were separated into four parts: (1) technology development, (2) technology applicability to last-minute changes, (3) technology alert, and (4) technology decisions and actions, shown in Table 4. The technology development section contains questions related to the technology itself, such as "Is this technology ready to use," "Is this technology easy to use," and "What type of control in the hierarchy of controls is the technology" [4]. These questions can help evaluators check and test the basic background of the technology in the field. Next, the technology applicability to last-minute changes section includes questions to evaluate the technology's ability to respond to or prevent last-minute changes. The questions focus on whether the technology can detect, comprehend, or project the safety issues caused by last-minute changes, and whether environmental impacts from the weather affect the technology's ability to detect last-minute changes. In this context, "comprehend" means the technology has an ability to recognize a hazard that exists and classify the type of hazard. Also, "project" refers to the ability to estimate and predict outcomes of safety issues caused by last-minute changes. The next set of questions address the technology alert that is provided by the technology to alert workers or any impacted people when hazards caused by last-minute changes are present on the construction site. The last section of questions focuses on the decisions and actions that the technology can make. In this section, the evaluator can determine whether the technology can make decisions or take actions to address the impact of last-minute changes. After the field pilot test and evaluation are completed, the suggested technology should be adopted if the result reaches the target established by the construction company. The target is based on the number of questions which are answered in the affirmative. On the other hand, if the result does not attain the target, the suggested technology should not be adopted. The full pilot test/field assessment document is available in [4]. Once the suggested technology passes the pilot test, this technology would be qualified as a safety technology that can improve safety performance and protect workers from hazards related to last-minute changes on construction projects.

Table 4: Pilot test questions (Extracted and adapted from [4])

Part 1. Technology Development	
1	What is the extent of development of the technology (Technology Readiness Level)? (Possible answer: TRL1 to TRL 9) [4] [17] [18]
2	Is this technology ready to use?

3	What is the level of automation (LOA) of the technology? (Possible answer: 1 to 10) [19]
4	Is the level of automation of this technology enough for the usage purpose?
5	Is this technology easy to use?
6	Does this technology integrate with existing technologies?
7	What type of control is the technology? (Possible answer: PPE, administrative, engineering, substitution, elimination)
Part 2. Technology Applicability to Last-minute Changes	
8	Does the technology have the ability to monitor site conditions and work operations?
9	Does the technology have the ability to detect last-minute changes?
9.a	If Yes to Question 9, what kind(s) of last-minute change can the technology detect? (The answer type in this question a is short answer)
9.b	If Yes to Question 9, does the technology detect and act upon last-minute changes within an appropriate time?
10	Does the technology prevent SIFs due to last-minute changes?
11	Does the ability of the technology to detect and respond to last-minute changes provide a positive impact?
12	Does weather impact the technology's ability to detect and respond to lastminute changes?
13	Does the technology have the ability to comprehend safety hazards resulting from last-minute changes? Note: In this context, comprehend means to determine that a hazard exists and to identify the type and nature of the hazard.
14	Does the technology have the ability to project the safety risk from last-minute changes? Note: In this context, projecting the safety risk means to estimate and foresee the consequences of worker exposure to the hazard based on injury frequency and severity.
Part 3. Technology Alerts	
15	Does the technology have the ability to send alerts to affected workers and/or those who oversee the work?
15.a	If Yes to Question 15, what kind(s) of alerts does the technology send? (The answer type in this question is a short answer (e.g., visual, audio))
15.b	If Yes to Question 15, does the technology send alerts to affected workers and/or responsible parties within an appropriate time?
15.c	If Yes to Question 15, does the alert work well enough to warn workers?
Part 4. Technology Decisions and Actions	
16	Does the technology have the ability to identify options/alternatives for mitigating the impacts of last-minute changes?
16.a	If Yes to Question 16, does the technology identify options/alternatives for mitigating the impacts of last-minute changes within an appropriate time?
17	Does the technology have the ability to decide which option(s) to select to mitigate last-minute changes?
17.a	If Yes to Question 17, does the technology make the decision within an appropriate time?
17.b	If Yes to Question 17, what kind(s) of decisions can the technology make? (The answer type in this question a is short answer)
17.c	If Yes to Question 17, are the decisions effective for preventing serious injuries and fatalities (SIFs)?
18	Does the technology have the ability to implement the selected action(s) after making the decision?
18.a	If Yes to Question 18, does the technology take action within an appropriate time?
18.b	If Yes to Question 18, what kind(s) of actions can the technology make? (The answer type in this question a is short answer)
18.c	If Yes to Question 18, are the actions effective for preventing serious injuries and fatalities (SIFs)?

* All questions are yes/no questions except the potential answer type is mentioned in the question.

5 CONCLUSIONS AND RECOMMENDATIONS

The applicability and effectiveness of technology for improving construction safety has been proven and the construction industry can benefit from technology. Many changes, including some at the last-minute, may occur on construction sites due to their dynamic and complex nature. A hazard due to a last-minute change may only allow a very short time for response, and the worker may not be able to react in that very short time. Hence, the assistance provided by technology can play an important role in mitigating the impacts of safety hazards and preventing worker injuries and fatalities. Nevertheless, the application of technology in the construction industry for this purpose is still low to non-existent. Therefore, the use of technology in the construction industry needs to increase to reinforce worker productivity and safety performance while eliminating safety hazards and preventing injury/fatality incidents. In order to help construction companies select technologies that match the desired capabilities and use cases, an appropriate technology adoption protocol is necessary. This research study used an expert panel and the Delphi process to collect professional input on applicable technology adoption factors to determine which factors should be included in a new technology adoption protocol. A construction company can use the new protocol to determine whether it should adopt a safety technology. If the selected technology meets the requirements addressed by the protocol, such as organization, individual, and environmental factors, it is anticipated that the technology will help improve safety performance associated with hazards caused by last-minute changes.

The technology adoption protocol developed by this research study does not include a benchmark of what score achieved in the Technology Assessment evaluation indicates an acceptable technology. Similarly, the protocol does not indicate the kind and amount of answers in the Pilot Test/Field Assessment document that signify a positive result. The expert panel suggested that the construction organization should define these targets since the technology application and use cases vary between construction organizations. Thus, construction organizations need to make decisions based on the type of last-minute changes and hazards anticipated. Future research should develop a standard target score and rubric for these two documents to make this new technology adoption protocol more convenient and comprehensive.

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ISAFE: AUTOMATED CONSTRUCTION SAFETY MANAGEMENT PLATFORM

Chansik Park[1], Mehrtash Soltani[1], Akeem Pedro[1], Jaehun Yang[1], Doyeop Lee[1]

[1] School of Architecture and Building Science, Chung-Ang University, Seoul 06974, Republic of Korea

Abstract

The construction industry poses a significant risk of accidents and injuries, making it one of the most hazardous sectors. While safety regulations and guidelines have been implemented, accidents and fatalities still occur with alarming frequency. This underscores the inadequacy of traditional methodologies for construction safety management in addressing these risks. This paper proposes the iSAFE platform, an automated safety management solution that covers various stages of construction safety management, including before, during, and after the work process. iSAFE offers 4D Building Information Modeling (BIM)-based risk assessment and safety planning, virtual reality (VR), and 360-panorama-based Training to enhance planning and training in construction job sites. During the work process, the iSAFEGuard encompasses technological monitoring advancements by incorporating over 100 unsafe detectors using Computer Vision (CV) and Internet of Things (IoT) sensors. This results in a more robust worker and job site monitoring process, proactively enabling safety managers to monitor safety compliance with less hands-on experience on the job site. Finally, after the work process, the iSAFEIncentive builds a new safety culture by integrating blockchain technology with CV. This approach incentivizes workers based on their safety behavior at job sites, promoting safe work practices and improving job site safety. The iSAFE platform presents a comprehensive and automated approach to safety management encompassing all safety management procedure phases. Its goal is to introduce a new paradigm and vision with a more efficient and reliable method to reduce injuries and fatalities resulting from accidents at construction job sites.

Keywords: AI, computer vision, blockchain, construction safety management, planning, training

1 INTRODUCTION

Construction safety management can be divided into three stages: before, during, and after work. However, current practices within these stages are associated with several issues. For instance, in the before-work stage, manual procedures and document-based data may lead to unreliable training and time-consuming processes, which can be problematic. Additionally, the monitoring methodology during work is often inefficient, which can result in numerous injuries and fatalities at job sites. Furthermore, these problems are compounded by a lack of positive safety culture, making it a significant challenge for organizations to maintain a safe working environment and improve productivity throughout all stages of the work process *[1]*. In the subsequent sections, various problems associated with current practices in construction safety management will be explored.

1.1 Current Safety Management Practices

1.1.1 Before Work/ Safety Planning-Training

Construction projects can be complex and risky, with many potential hazards that must be considered [2]. Without proper safety planning and training, workers may be at risk of injury or death [3]. In addition, workers may not be aware of the specific risks associated with their tasks or may lack the knowledge and skills needed to perform their duties safely. Therefore, safety planning and training are critical components of any construction project, helping to identify potential hazards and develop strategies to mitigate them [4].

Document-based risk assessments frequently use in the construction industry to identify potential hazards *[2]*. However, these assessments are not without their challenges. One of the primary difficulties is that they may not capture all of the risks associated with a given project, leaving workers vulnerable to unanticipated hazards. Additionally, these assessments may not be tailored to the specific work plan and site situation, increasing the potential for accidents and injuries. Furthermore, even when safety plans are developed, they are often not utilized during construction, leading to confusion and increased risks. To create safer work environments and reduce the incidence of accidents and injuries, it is crucial to address these challenges by developing comprehensive and site-specific safety plans, providing updated planning to workers, and ensuring that safety plans are adhered to throughout the project *[3]*. The construction industry encounters an additional predicament concerning standardized training programs that lack sufficient preparation for the hazards and risks associated with individual worksites. *[4]*. Additionally, training programs that are solely classroom-based or rely on short toolbox meetings may not provide workers with the hands-on experience and practical knowledge they need to perform tasks safely *[5]*. These challenges can increase the risk of accidents and injuries on the job. To overcome these problems, it is important to prioritize site-specific, interactive, and practical training methods that equip workers with the knowledge and skills to perform their tasks safely and confidently.

1.1.2 During Work/ Safety Inspection and Monitoring

Even with proper training and planning, neglecting safety risks can still occur in the construction industry, leading to accidents and injuries during the work process *[6]*. To minimize this risk, a proactive safety approach must be established that prioritizes safety through regular inspections, ongoing training, and clear protocols. By doing so, the industry can reduce accidents caused by negligence and promote a safer working environment *[7]*.

Safety inspection and monitoring are essential for identifying and addressing potential hazards in the construction industry [8]. It is crucial to monitor the unsafe behavior of workers to minimize risks in construction sites. Safety managers must constantly keep a watchful eye on workers to address the factors mentioned above. However, this manual monitoring process requires safety managers to be physically present at construction sites to identify potential hazards or non-compliance with safety rules. It is a time-consuming process that heavily relies on safety managers' experience and competence. This can lead to delays in identifying and addressing potential hazards, increasing the risk of accidents and injuries [12]. In addition, Implementing safety rules and monitoring Personal Protective Equipment (PPE) compliance in large and complex construction sites is expensive and impractical. Hence, there is a need to incorporate technological advancements to ensure the real-time safety of workers at hazardous elevations and reduce the workload on safety managers who monitor workers on-site [9]. The following section discusses issues related to after-work safety management in the current approach.

1.1.3 After Work/ Safety Performance Assessment

Recording manual inspection results in a paper-based format is always repetitive and subject to error [10]. Current information management in the construction industry is highly vulnerable to data falsification because of the general usage of centralized data management systems; their data security and management rely heavily on a central node [11, 12, 13]. In addition, data from construction industry accident records show that safety accidents are often caused by mistakes or negligence of safety rules. Safety management is crucial in promoting safety measures and workers' occupational safety, which can significantly affect unsafe behaviors. To improve safety behaviors, it is important to implement effective incentive programs. Scholars have found that safety policies, punishment, and a safe environment can positively influence workers' behaviors. However, conflicting objectives between safe and production goals can lead to workers ignoring safety measures and rendering incentives ineffective [14].

To address the above problems, this study proposes a framework of a robust and comprehensive solution, named iSAFE platform, for construction safety management. iSAFE comprises three modules:

1) iSAFE module to assist in safety planning and training before the work phase.

2) iSAFEGuard module to monitor the construction site for rule compliance during the work.

3) iSAFEIncentive module to measure safety performance and provide incentives after work phase for encouraging safe behavior.

2 RESEARCH METHOD

Several academic articles have been disseminated to confront the difficulties above, which may culminate in a transformative advancement in construction safety management. Such progress may be realized through the technological enhancement of the iSAFE platform. These papers cover most technical parts and implementation of this platform, from planning, training, monitoring, and blockchain technology for storing safety performance data and incentive token-based applications. In terms of planning, one paper discusses the use of generative planning to identify optimal locations for construction safety surveillance cameras in a 4D BIM environment [15]. Another paper proposes an approach for hazard identification that integrates 4D BIM and accident case analysis [16]. Regarding training, some articles suggest new methods for safety training using immersive technologies such as cross-platform VR and extended reality. One recent paper presents an artificial intelligence (AI)-based safety helmet recognition system to enhance the safety monitoring process [17]. In terms of monitoring, several papers propose new approaches to iSAFE for fall prevention and worker safety using Internet of Things (IoT)-based monitoring, CV, and other technologies [24-28]. Finally, some articles explore the potential of blockchain for construction safety management, including a proposed network concept model for reliable and accessible fine dust management at construction sites and the use of blockchain for scaffolding work management [18, 19]. Table. 1 presents the different components within the iSAFE platform published in academic journals.

Table. 1: Published papers related to the development of the iSAFE platform.

No	Subject	Research Title	Summary	Main Technology	Journal Name	Ref
1	Training	Cross-platform virtual reality for real-time construction safety training using immersive web and industry foundation classes	The paper proposes a VR training program for construction safety that can be accessed from multiple platforms.	VR, Web technology, Industry classes	Automation in Construction	[17]
2	Planning	A hazard identification approach of integrating 4D BIM and accident case analysis of spatial–temporal exposure	The paper proposes a novel hazard identification approach through spatial–temporal exposure analysis.	4D BIM	Sustainability	[15]
3	Planning	Generative planning for construction safety surveillance camera installation in 4D BIM environment	The paper proposes a generative planning method for installing surveillance cameras in construction sites using 4D BIM technology.	4D BIM	Automation in construction	[16]
4	Planning	Suggestions for improving South Korea's fall accidents prevention technology in the construction industry: focused on analyzing laws and programs of the United States	The paper proposes suggestions for improving fall accident prevention technology in the South Korean construction industry by analyzing the laws and programs of the United States.	Analysis of laws and programs	Sustainability	[20]
5	Monitoring	Computer Vision Process Development regarding Worker's Safety Harness and Hook to Prevent Fall Accidents: Focused on System Scaffolds in South Korea	The paper proposes a computer vision system to prevent fall accidents by monitoring worker's safety harness and hook in construction scaffolds.	CV	Advances in Civil Engineering	[21]
6	Monitoring	Fall prevention from scaffolding using computer vision and IoT-based monitoring	The paper proposes an IoT-based monitoring system that uses computer vision to prevent fall accidents from scaffolding.	Internet of things, CV	Journal of Construction Eng and Management	[22]
7	Monitoring	Fall Prevention from Ladders Utilizing a Deep Learning-Based Height Assessment Method	The paper proposes a fall prevention system that uses deep learning for height assessment.	Deep learning	IEEE Access	[23]
8	Monitoring	Tag and IoT based safety hook monitoring for prevention of falls from height	IoT-based safety hook monitoring system to prevent falls from height.	Internet of things	Automation in Const	[24]
9	Monitoring	Utilizing safety rule correlation for mobile scaffolds monitoring leveraging deep convolution neural networks	Mobile scaffold monitoring system that uses deep convolution neural networks to correlate safety rules.	Deep convolution neural networks	Computers in Industry	[25]
10	Blockchain	Blockchain-based network concept model for reliable and accessible fine dust management system at construction sites	The paper proposes a blockchain-based network model for fine dust management in construction sites.	Blockchain	Applied Sciences	[18]
11	Blockchain	Leveraging blockchain for scaffolding work management in construction	Blockchain-based system for scaffolding work management in construction.	Blockchain	IEEE Access	[19]

3 INTRODUCING THE ISAFE PLATFORM

The iSAFE encompasses all phases of the safety management system, from pre-work, during work, and post-work. In the pre-work stage, conventional classroom training has been identified as a significant challenge in safety planning. To address this issue, the proposed solution involves a 4D Building Information Modeling (BIM)-based risk assessment & safety planning and virtual reality (VR) & 360-panorama-based training. The iSAFE platform is designed to incorporate these technologies to provide a comprehensive solution during work phase presents additional safety challenges in inspecting and monitoring safety performance for a large workforce on complex job sites. As discussed, the current manual inspection method is inefficient. Computer vision (CV) and sensor-based technologies are recommended for safety inspection and monitoring to overcome this issue. The iSAFEGuard platform encompasses these technological advancements, resulting in a robust worker and job site monitoring process. This proactive solution would enable safety managers to monitor safety compliance with less hands-on experience on the job site.

In the post-work phase, document-based activities are critical for satisfying legal requirements and evaluating safety performance. However, collecting this data in hardcover data sheets makes it difficult to assess workers and evaluate their safety performance. This is especially true when numerous workers are working at job sites. To overcome this challenge, iSAFE proposes the iSAFEIncentive, a blockchain, and AI-based safety reward performance assessment system. By integrating this advanced technology with CV, the entire ecosystem of rating performance of workers and companies can be improved. Furthermore, the token-based incentive technology would reward workers and companies for good safety performance, with workers receiving tokens from safety managers and companies receiving tokens from regulatory inspection governmental agencies. Fig. 1 illustrates the existing challenges in construction safety management and the proposed solutions offered by iSAFE.

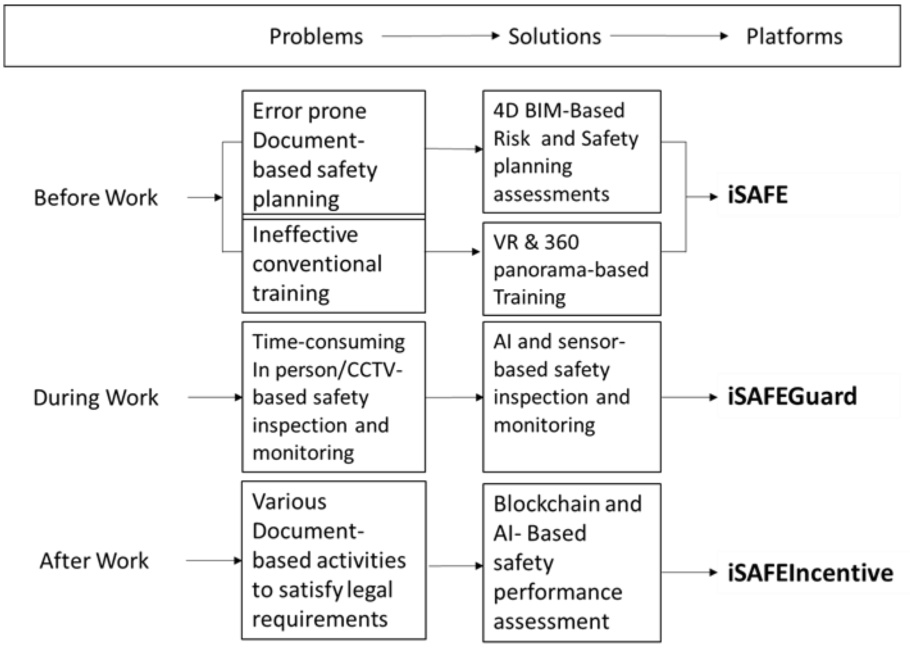

Fig. 1: Problems and suggested solutions related to construction safety management.

The iSAFE platform offers a comprehensive solution streamlining safety management activities, including planning, training, monitoring, and reporting. As depicted in Fig. 2, the iSAFE platform utilizes advanced technologies such as 4D BIM, Digital Twin, augmented and VR, AI, and blockchain to automate the safety management cycle. The following sections provide additional details on each one.

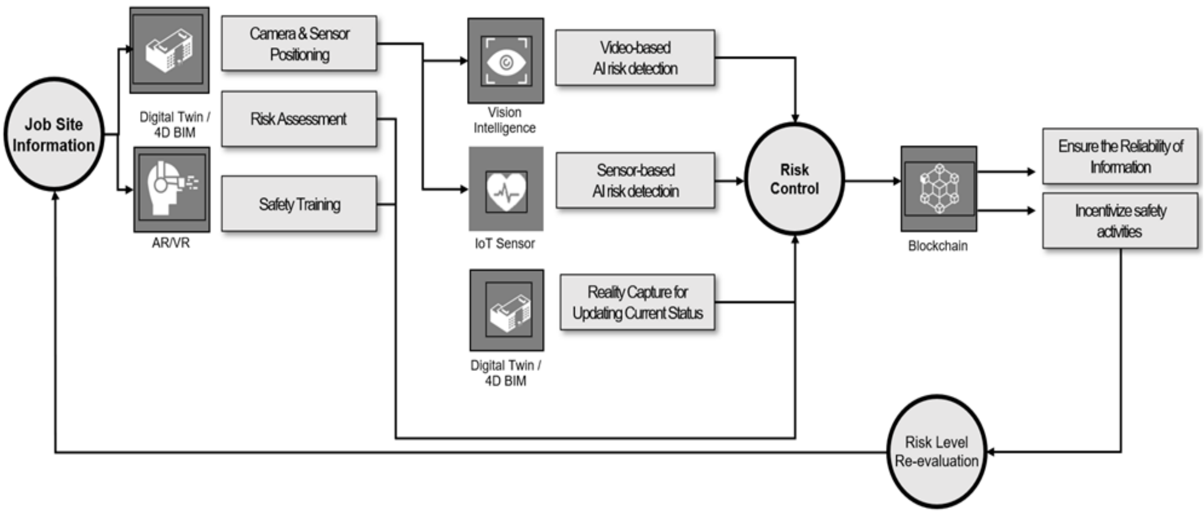

Fig. 2: iSAFE platform framework.

3.1 iSAFE (Planning/Training)

Safety planning is a crucial part of the construction process on job sites. Several activities, if conducted in parallel, may trigger risks and hazards. To tackle this issue, iSAFE provides an efficient work plan by combining the risk assessment database and specific construction job site conditions into the BIM model. It Identifies the specific potential hazard situations and prepares prevention methods. Some of the functions of the systems include pre-risk assessment of the job site, safety information sharing amongst workers and training, and remote site inspection and instruction. Fig. 3 demonstrates the iSAFE (Planning/Training) framework and its technological functions. The following sections will discuss the performance of the iSAFE planning and training.

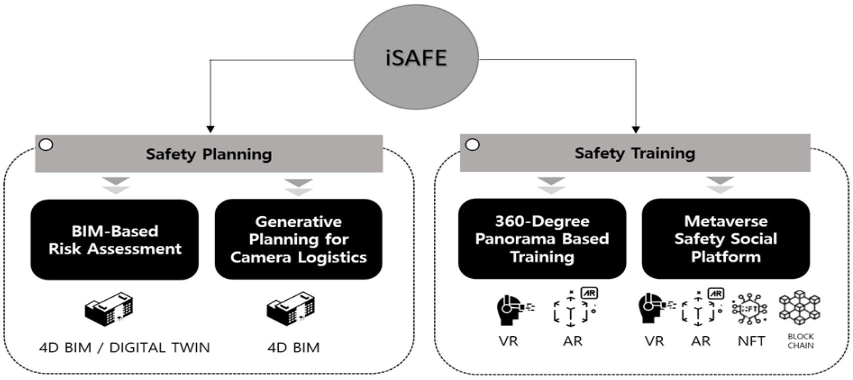

Fig. 3: iSAFE (Planning/Training) framework.

3.1.1 iSAFE Training

Traditional training methods may not keep pace with evolving technological and industrial practices, leading to worker frustration, disengagement, and ill-preparedness to tackle emerging challenges. Conversely, real-time learning offered in iSAFE utilizes a segmented approach, providing workers with tailored training and work instructions, resulting in efficient and customized education that enhances worker performance and engagement. Situated learning reflects new technological and industrial advancements, ensuring workers are well-equipped to handle emerging challenges. It utilizes technologies such as Digital Twin / 4D BIM and AR/VR. Workers can access this education from iSAFE's high-fidelity virtual environment, which reflects daily job site conditions. Additionally, iSAFE's planning toolkits combine risk assessment databases with construction job site characteristics to provide an efficient work plan and identify potential hazards. Options for surveillance camera locations are also generated to facilitate remote monitoring and AI-based risk detection during work. Fig. 4 shows how educational content and instructions can be accessed at a job site.

Fig. 4: Reality capture view of iSAFE Training.

3.1.2 iSAFE- Planning

iSAFE planning is another advanced functionality of the iSAFE platform. Its algorithm is integrated with BIM and provides in-depth work report-based daily/weekly schedule information linking, work plan information extraction, and risk & change visualization rule development. After uploading the work schedule in the BIM application, the algorithm will evaluate all the parallel work to find any contradiction job that their same time happening may result in danger. As it appeared in Fig. 5-A, activities such as painting and welding, any job defined near the opening or edge will be highlighted in the red zone to provide visualized risk zone to workers. All these adjustments will be made based on different rule compliance, and the algorithms are easily tailored to apply various rules and codes. iSAFE planning also offers a new framework for camera planning in construction, which includes functions such as selecting the appropriate camera type and positions based on the construction schedule by integrating into BIM 4D. A simulated viewpoint of the camera view in BIM is demonstrated in Fig. 5-B. Camera placement in construction is typically done manually, which can be time-consuming and costly [16]. This approach provides a cost-efficient, accurate solution with improved visualization by integrating BIM. The subsequent section elaborates on the monitoring capability of the iSAFE platform throughout the construction process stage.

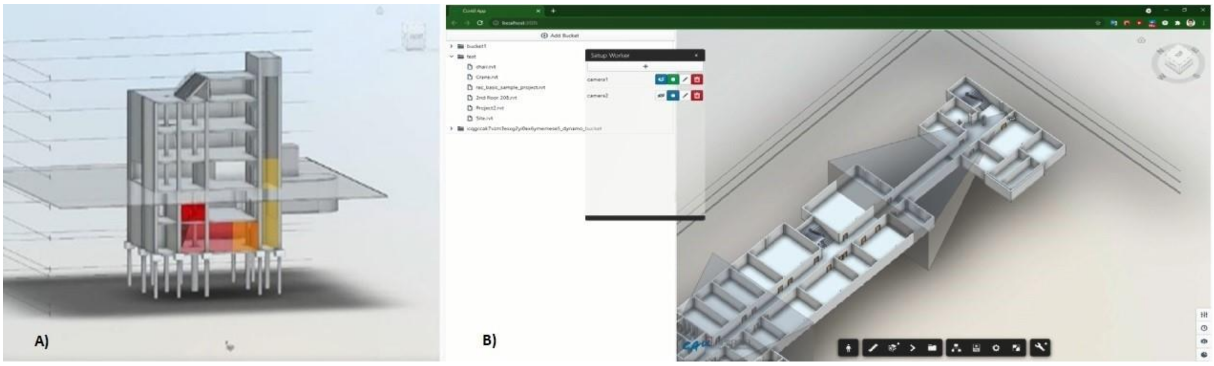

Fig. 5. A) Visualized risk zones in BIM B) Simulated version of the camera view in BIM.

3.2 ISAFEGuard (Monitoring/Inspection)

Despite efforts to plan for safety and provide training, unpredictable hazards can still occur during construction due to unsafe behaviors, unsafe working conditions, and violations of regulations. To address this persistent problem, iSAFEGuard has been developed as a technological solution utilizing video-based AI and sensor technologies to detect and prevent accidents and injuries on construction sites proactively. As it appeared in Fig. 6, using AI, VC, sensors, VR, and wearable devices, iSAFEGuard provides a comprehensive solution that detects and alerts safety managers and workers to take proactive measures to prevent accidents and injuries. The following sections explain the computer vision technology and sensor-based technologies of the iSAFEGuard.

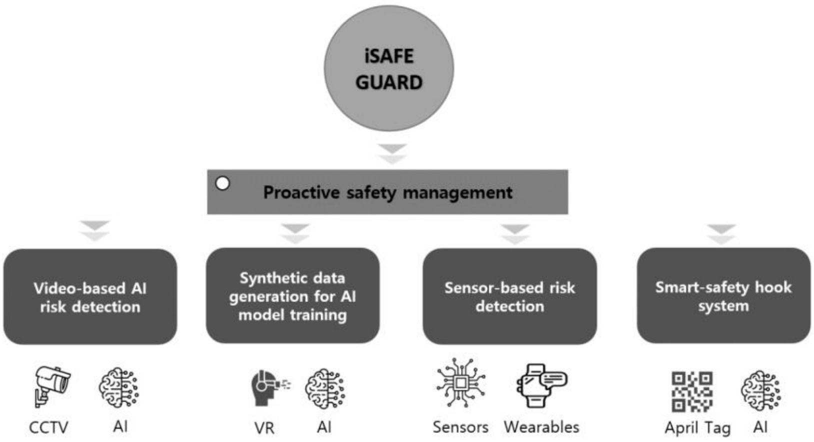

Fig. 6: iSAFEGuard's technological functionality.

3.2.1 ISAFEGuard/Computer Vision

One of the fundamental features of iSAFEGuard is its video-based AI risk detection platform, which utilizes a deep neural network model for hazard detection. This system consists of over 120 unsafe behavior detectors trained with synthetic and real data for various types of hazards, such as falling from a height, being hit by an object, collapsing, fire, and being struck by equipment. The detectors can examine all tools and monitor individuals working with various equipment, including scaffolds, ladders, staircases, forklifts, etc. This model is designed to identify unsafe behaviors, working conditions, and violations of regulations in diverse scenarios. To develop this model, large datasets are collected and processed to train and validate the system before deployment. The research project has been conducted to accumulate real site data, approximately 1 million images with location information (i.e., bounding boxes and polygons). In addition, a dataset augmentation technique using synthetic images was applied to overcome difficulties in collecting real-site images, such as difficulties in directing dangerous situations. The system utilizes a state-of-the-art model in the computer vision domain, considering detection speed and accuracy, to enable real-time site monitoring, and identifying any unsafe conditions or behaviors that may pose a risk to workers. Fig. 7 depicts two examples of iSAFEGuard unsafe activity detection scenarios associated with scaffold and ladder jobs.

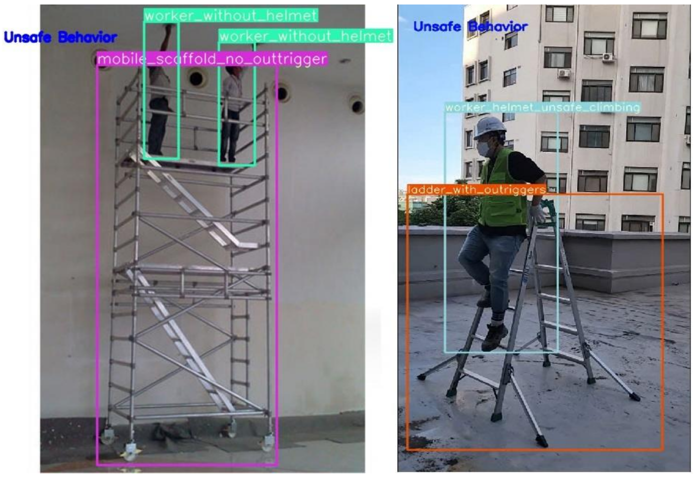

Fig. 7: Unsafe detection scenarios related to scaffold and ladder jobs.

3.2.2 Sensor-based Risk Detection

Certain limitations, such as blind spots, occlusion, and limited coverage, constrain standalone vision-based monitoring technologies. To address these issues, iSAFEGuard proposes an innovative solution that combines vision and the IoT to create an intelligent smart safety hook. Sensor-based technologies such as the Hybrid Gateway, Smart Safety Hook, Smart Watch, and Location Sensor Dashboard improve construction safety management. As shown in Fig. 8, the Hybrid Gateway transfers the data from safety and environmental sensors in real-time. The Smart Safety Hook and Smart Watch detect and alert workers to potential safety hazards. The Location Sensor Dashboard tracks workers' activities to identify potential safety hazards, allowing supervisors to take corrective actions. The subsequent section describes the iSAFEIncentive technology, a token-based incentive system that rewards workers and companies based on their safety performance.

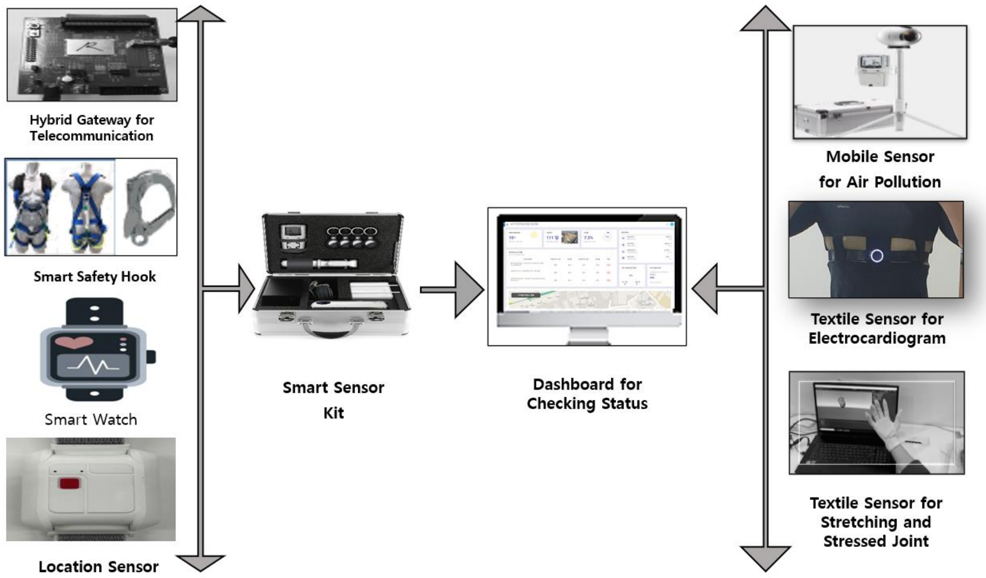

Fig. 8: Sensor-based technology worker's behavior detection.

3.3 ISAFEIncentive (Data Management/ Token-Based Rewards System)

The iSAFEIncentive aims to transform the safety culture of the construction industry by incentivizing and rewarding safety performance, shifting the focus from blame and punishment to a collaborative worker-driven approach. By leveraging cutting-edge technologies like CV, AI, blockchain, and IoT, iSAFEIncentive streamlines safety inspection and reporting circumventing conventional methods' subjective and time-intensive nature. This includes using decentralized identifier certificates, computer vision, and smart contracts to verify and reward safety performance. Tokens are issued to workers, safety managers, and contractors based on their safety ratings. This system enables regulatory bodies to evaluate companies based on their safety performance ratings. Governmental agencies use the token-burning process to ensure sustainability and effectiveness. The iSAFEIncentive platform promotes worker-led safety management, providing the reliability of safety information, facilitating safety level evaluation and compensation, and ultimately improving safety performance and culture in the construction industry.

4 DISCUSSION

The iSAFE platform can play a crucial role as a safety solution to prevent accidents in construction job sites. This platform provides three critical safety barriers that aim to improve the safety culture within the entire industry and prevent accidents.

The first barrier, the iSAFEIncentive incentive, promotes a safety culture among workers, improving the industry's safety. The incentive rewards workers with positive safety behaviors and a high safety rating. Ultimately, the whole company's performance is rated based on the safety ratings of every worker, and the information is reported to safety agencies and regulatory bodies. Companies with higher safety risks receive incentives, like how workers are rewarded for safe behavior.

The second barrier involves providing proper planning and training sessions, usually mandated by companies and contractors. Effective safety planning is also crucial to understanding the risks and hazardous activities involved in the work. iSAFE provides robust and comprehensive training materials based on the type of work and activities involved and can visualize dangers and hazards in BIM format [15,17].

The third barrier involves real-time monitoring of workers and job sites. Both experienced and inexperienced workers may become negligent towards safety rules, particularly when tired, working on complicated tasks, or in a rush. In addition, a lack of adequate human resources, such as safety inspectors, can make monitoring all workers on a large job site challenging. iSAFEGuard provides great opportunities for companies to monitor workers and inspect any defects at job sites that may put workers at risk. Early detection of unsafe behaviors or workers significantly reduces the chances of risky situations. The system can alarm workers and safety managers about dangerous activities, ensuring the highest levels of safety in the workplace [21, 22].

5 CONCLUSION

This paper presents a developed and implemented iSAFE platform for digital infrastructure to enhance safety management in construction projects. The proposed system has been transformed into a functional prototype and tested in real-world construction sites. Collaboration with industry stakeholders, including vendors and software developers, was undertaken throughout the development process to ensure practicality and compatibility. The research encompasses technology development and practical implementation to evaluate the system's effectiveness and feasibility. Detailed information regarding the development and implementation, including methodologies and technical specifications, is provided in the paper. The goal is to bridge the gap between theoretical concepts and practical application by offering a thoroughly developed and tested blueprint.

To conclude, the iSAFE platform offers a comprehensive approach to safety management, covering all phases of the safety management system. By leveraging advanced technologies such as 4D BIM-based risk assessment, VR & 360-panorama-based Training, CV, sensor-based technologies, and blockchain, the iSAFE platform offers a proactive solution to safety challenges faced in the pre-work, during work, and post-work phases. The platform is designed to seamlessly fit into construction practices, offering server-based, edge-based, and mobile-based solutions. Additionally, the token-based incentive technology encourages workers and companies to prioritize safety performance, resulting in a safer and more efficient job site.

In future development, our plan entails integrating training data with our risk assessment technology during the planning stage. This integration aims to enhance the availability and practicality of training materials for workers by coupling training data with real accident cases. The objective is to increase workers' awareness of risk factors and provide them with more comprehensive and relevant training materials.

The limitation of this proposed solution is that the iSAFE platform while offering safety measures for construction job sites, faces challenges in implementation and raises concerns regarding privacy and data security. Integrating the platform into existing operations can be complex and time-consuming. Furthermore, the collection and analysis of worker data raise privacy and security issues, necessitating the establishment of proper protocols to protect sensitive information.

6 ACKNOWLEDGMENT

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A DATA-DRIVEN METHOD FOR HAZARD ZONE IDENTIFICATION IN CONSTRUCTION SITES WITH WEARABLE SENSORS

Kepeng Hong, Jochen Teizer

Dept. of Civil and Mechanical Engineering, Technical University of Denmark (DENMARK)

Abstract

Hazard zone identification plays a significant role in designing construction site layouts and preventing construction accidents. The existing identification methods require laborious and empirical predefinitions. Despite the emergence of some automatic hazard zone identification algorithms, they still heavily depend on stagnant regulations and rules. Thanks to the development of real-time location systems and sensor technology, the trajectory data of construction workers and equipment can be precisely collected and stored. Such data can facilitate understanding workers' and equipment's activity patterns, thus further improving the dynamic recognition of hazardous behaviors and areas. In this work, we introduce a data-driven method to automatically identify and predict potential hazard zones in the construction site. The algorithm is implemented on a digital twin platform to retrieve location data and generate real-time hazard index maps. The method consists of the following parts: (a) construction site sensor data collection and processing, (b) worker and equipment data analysis (e.g., speed, acceleration, and trajectory), and (c) hazard zone identification algorithms development. For validation, we implement the method on one railway construction project in Karlsruhe and compare the result with the close-call incidents map. This real-life case study partially demonstrates the effectiveness and accuracy of our method under the constraints of currently limited project data. On the basis of this work, further study can be conducted on the aspects of workers' behavioral patterns and prediction model selection.

Keywords: construction safety, data-driven method, digital twins, hazard zone identification, real-time location sensing.

1 INTRODUCTION

Construction sites are widely recognized as one of the most dangerous workplaces. The rates of fatality and non-fatality accidents are significantly higher than in other industries. A report on the labor statistics in the EU shows that more than a fifth of all fatal accidents took place in the EU within the construction sector of which, depending the country, up to 15 percent relate struck-by equipment or other object incidents [1]. Traditionally, Health, Safety, and Environmental (HSE) managers define the construction hazard zone in advance and observe the workers' safety performance based on the predefined hazard zone. However, the construction site's dynamic and changeable features bring challenges to the static and top-down approach to delineating the hazard zone area.

The emergence of the Digital Twin (DT) even in construction allows – at some point in future time – HSE managers to proactively monitor and interfere with potential hazards at construction sites in real-time [2]. A DT can first be a virtual representation of a real-world product or system (aka. physical twin). By integrating data from the Internet of Things (IoT) with Building Information Modeling (BIM), project stakeholders can add valuable information to a Digital Twin Platform (DTP) of the construction site for viewing and controlling the on-site events and processes. Through various sensing technologies, such as Real-time Location Sensing (RTLS) [3, 4] or vision-based sensors [5], the DT can retrieve contextual information. These are, for example, trajectories of resources, incl. workers or equipment, or image-based point clouds of a work terrain they traverse in. Such (trajectory) data can then be analyzed using hazard detection algorithms that predict future work states, and in case applicable, avoid potentially dangerous situations. These algorithms pose a research gap, because they rely so far on basic data analysis and visualization [5]. Instead, proposed are additional criteria, such as the capitalization of a priori-known safety rules [6] or real-time data of too close proximity distances [7]. Such algorithms can then be powerful when implemented on a DTP as they can provide real-time personalized feedback to the HSE managers, equipment operators, and workers, and proactively detect and avoid personal harm or other collateral damage.

Nevertheless, a DTP still heavily relies on predefined input (e.g., safety distance, hazard zone predefinition) from HSE managers, which undermines the effectiveness of real-time hazard detection and feedback. At the same time, spatial-temporal data from workers can reveal their behavioral patterns related to surrounding contexts. Therefore, we aim to utilize the historical and real-time workers' location data on the DTP for Hazard Zone Identification (HZI) so that the predefined hazard zone can be adjusted on time. Previous studies have utilized the location data or behavioral patterns of construction workers to analyze the safety condition at the construction site. For instance, Li et al. apply a crowd-sourced density map method to classify construction site zones for workplace safety [8]. Yang et al. analyze abnormal patterns of workers' gait cycles to infer workplace safety hazards [9]. Golovina et al. use heatmap for recording, identifying, and analyzing interactive hazardous near-miss situations between workers on foot and heavy construction equipment [10]. So far, these approaches only focus on one certain aspect of the temporal-spatial data for hazard prediction and have only been tested on locally stored data, without further integration with real-time data on a DTP.

In this work, we focus on developing a method of updating hazard zone maps using only location data from construction workers. We derive the visiting frequency, speed patterns, and stay duration for each spot from the aggregate spatiotemporal data of workers. With the fusion of the visiting frequency, speed patterns, and stay duration, we calculate the hazard index for each spot. The algorithm is expected to be integrated into DTP so that it can fetch real-time location data and predict the hazard index map. In this work, we use the persistence model for hazard prediction for simplicity.

Our contributions are listed as follows:

- We establish a framework of a DTP for construction site hazard zone prediction using only location data from the construction workers. The whole process of data collection, communication, analysis, and feedback is defined in the framework.
- We analyze location data (e.g., visiting frequency, speed abnormality, and stay duration), revealing human behavioral patterns to infer the contextual workplace safety conditions.
- We develop an algorithm for hazard zone prediction using a persistence model. The algorithm uses the spatial-temporal information of the construction workers as input data. It derives a hazard index for each spot, which can be used to supplement a predefined hazard zone map.

2 METHODS

In this work, we conduct a case study on a railway construction project at Karlsruhe. As shown in Figure 1, the method adopted in this study consists of three consecutive steps. First, we define the framework and workflow of DTP. Subsequently, we analyze and conclude the behavioral patterns of workers from the location and vision-based data, based on which we develop the algorithm for the HZI. Lastly, we implement the algorithm using the dataset to generate the hazard index map. The hazard index map is further validated via comparison with the close call incidents occurrence map. Close calls refer to incidents that nearly turned into an accident, which is defined by Occupational Safety and Health Administration in 2016 [11]. Proximity analysis is a specific method to detect close call events at the construction site [7]. When workers are too close to the path of the heavy equipment, the proximity-based events will be recorded in terms of location and timestamp. Despite various types of hazards (e.g., falls for lack of guard rails, struck-by due to obstacles), we can only partially validate the results of the hazard zone using the proximity-based close call analysis with the mere input of location data.

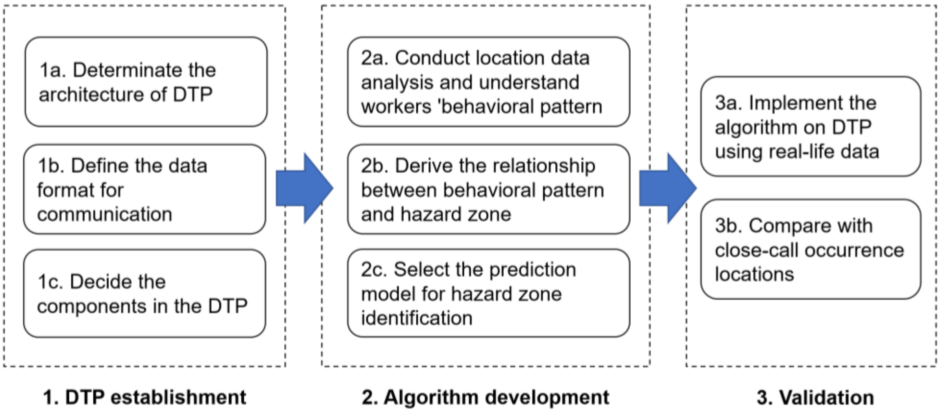

Figure 1: Methodology for the development of DTP and HZI algorithm.

3 DIGITAL TWIN PLATFORM

DTP is where the on-site location data is received and processed. We define the overall framework, data format, and components of the DTP.

3.1 Framework

Figure 2 presents the overall framework and workflow of receiving data, processing data, and returning feedback on the DTP. The framework comprises three parts: real-time location data collection at the construction site, data preprocessing, and real-time hazard map generation. The RTLS system at the construction site reports all relevant event data (e.g., equipment ID, personal tag ID, location coordinate, timestamp) to the DTP. After the DTP receives the data, preprocessing module (PPM) reduces the noise in the data, converts the geographic coordinate to the local coordinate, and derives other required information (e.g., speed). The preprocessed data is the input for the HZI algorithm, which is elaborated on in the next section.

We adopt the Message Queuing Telemetry Transport (MQTT) protocol as the data communication protocol in the DTP. MQTT is an OASIS standard messaging protocol for the Internet of Things. It is designed as an extremely lightweight publish/subscribe messaging transport that is ideal for connecting remote devices with a small code footprint and minimal network bandwidth [12].

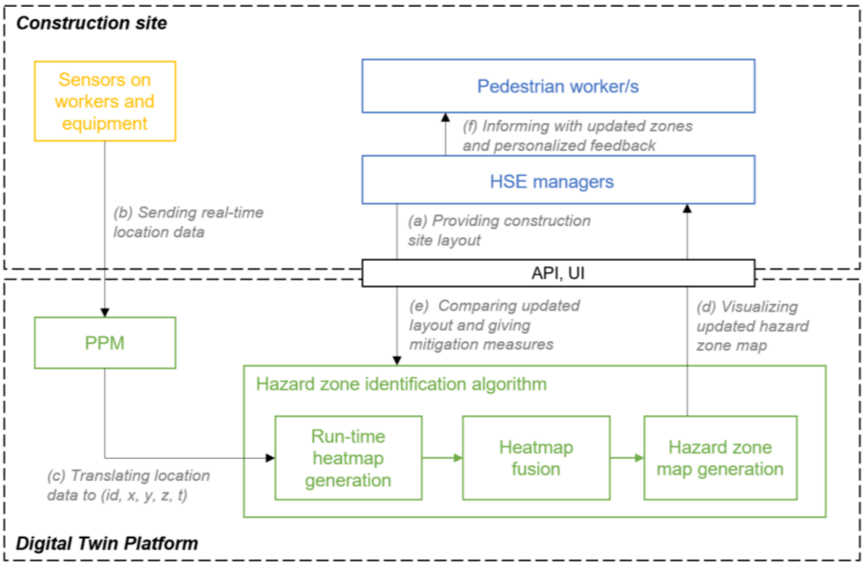

Figure 2: Framework and workflow of receiving and processing location data on the DTP.

3.2 Components

The IoT component of the DTP captures data from the physical objects in the real world. Continuously recording data from sensor tags, such as Real-time Kinematic Global Navigation Satellite System (RTK-GNSS), placed or installed on pedestrian workers and dangerous equipment, can yield a valuable source of spatial and temporal information that is needed for analyzing too close proximity events of such objects to each other.

For instance, the Karlsruhe railway construction project applied RTK-GNSS sensor system consisting of a base station and rovers for real-time resource location data collection. The employed RTK-GNSS can provide cm-level location accuracy, which is essential for monitoring workers' safety at construction sites [13].

As a further element of the DTP, the information displayed on a User Interface (UI) should be designed distinctively for multi-level users. These include but are not limited to equipment operators, pedestrian workers, and HSE managers. HSE managers, for example, may have access to the real-time trajectory data for each piece of equipment and workers and a full analysis of the recorded raw data. In contrast, workers should have access to only their trajectory and their personalized feedback.

The DTP therefore consists of modules responsible for data gathering, processing, analysis, and visualization. The functionalities of the different modules are listed as follows:

- a data preprocessing module that translates data from the RTLS system into the input data for the HZI algorithms,
- a proactive safety monitoring module that analyses trajectory and heatmap in the work environment, where the HZI algorithm is implemented, and
- a UI module that visualizes the safety analysis provides personalized feedback and assists decision-making processes.

4 HAZARD ZONE IDENTIFICATION ALGORITHM

The heatmap is often used to compare with the predefined construction site hazard map and analyze the visiting frequency of different spots in the construction site. Figure 3 shows an example of visiting frequency heatmap, where the construction site is divided into 1 m x 1 m cells, and the count of unique visits is shown inside each cell. The visiting frequency can indicate the hazard degree of each spot at the construction site, i.e., the cells that have been visited more tend to have less hazard degree.

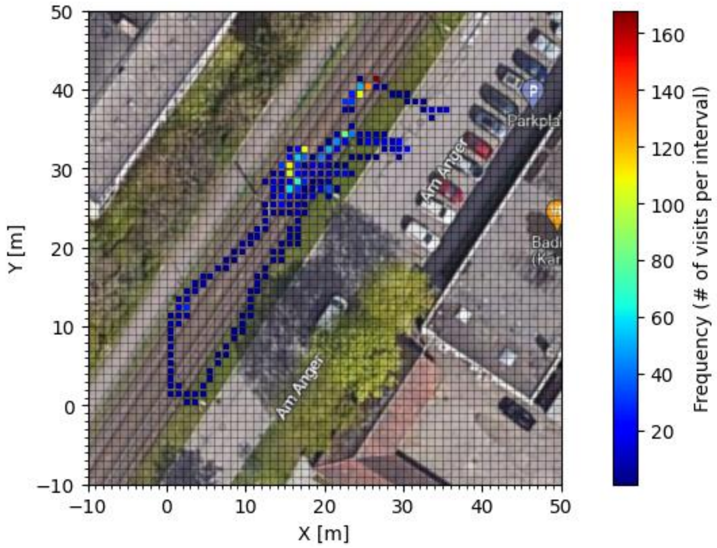

Figure 3: Frequency heatmap of all workers visiting the spots at the construction site (the site is divided into an occupancy grid of 1 m x 1 m cells).

The HZI algorithm uses real-time location data as input and generates the hazard zone map after each time interval. We initially observe and analyze the speed patterns of the workers at the construction site. Figure 4 shows that the speed of construction workers is within a range between 0 and 0.68 m/s. However, we notice that there are two noticeable speed changes during the observation. In this work, we define a speed above 0.68 m/s as speed abnormality. We investigated when and where the changes occurred based on the frames captured by the surveillance camera on the construction sites. As shown in Figure 5, at T = 50 s and T = 70 s, the workers change their speed to keep their distance from the path of the concrete truck. These speed abnormalities tend to occur when workers enter a hazardous area or when the equipment is close to workers. Therefore, it is plausible to infer a correlation between the worker's speed abnormality and their proximity to the hazard area.

In addition to the speed abnormality, maximum stay duration at one region can also indicate the safety condition of the region. From the observation and inference, we conclude the following hypotheses,

Hypothesis 1: Construction workers, after safety training, can recognize and avoid the hazards at the construction site. Given the dynamic feature of construction sites, the real-time location information of construction workers can convey the latest information regarding the hazard zones at the construction site, which still needs to be identified at the predefined construction hazard zones.

Hypothesis 2: Construction workers conducting the same types of work tend to follow the same routes and behavioral patterns. When they get close to hazard zones, they respond similarly, such as adjusting speed and reducing stay duration.

Hypothesis 3: We use the persistence model for hazard zone prediction in the algorithm, which assumes the consistent state of the construction site for the adjunct time intervals.

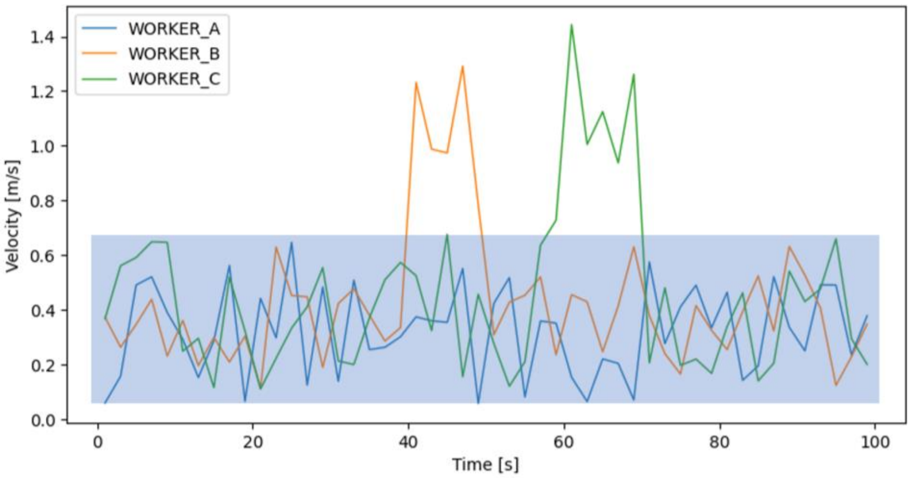

Figure 4: Automatically generated speed patterns of the construction workers.

Figure 5: Visualization of the ‘speed abnormality’ (note: manual annotation of colors).

Figure 6 explains the workflow of the HZI algorithm. The construction site is divided into cells, and the algorithm aggregates the spatial and temporal data from the workers in the cell. For each cell (C_{ij}), the visiting frequency (VF), speed abnormality count (SA), and maximum stay duration (SD) are added up and normalized over all the cells at the construction site. For each cell visited, we calculate the hazard index (HI) of the cell (C_{ij}) at a given time T. The hazard index is then normalized over all cells. The higher hazard index indicates a higher incident risk in the area.

$$HI_{C_{ij}}^{T} = \frac{\sum_{T-\Delta T}^{T}(SA_n - SD_n)}{VF_n}$$

With the persistence model, the hazard index for each cell at the next interval ($T, T + \Delta T$) is considered the same as the hazard index at the given time T.

$$HI(T, T + \Delta T) = HI(T)$$

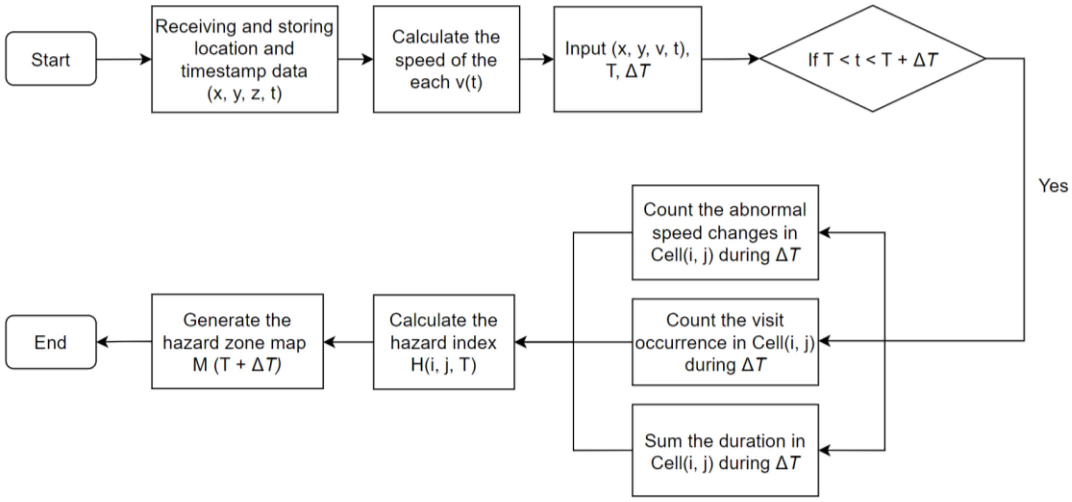

Figure 6: Hazard zone identification algorithm workflow.

5 RESULTS

The dataset for the Karlsruhe project was collected by Real-time Kinematic-Global Navigation Satellite System (RTK-GNSS) modules, which contain location and timestamp data of four tags, respectively, one concrete truck and three workers. As shown in Table 1, the entire dataset spans fifteen minutes, with each tag sending its latitude, longitude, and elevation information every second. A close call analysis was conducted in the previous study, and the close call occurrence locations can be compared with the algorithm's hazard zone map.

Table 1: Overview of an extracted part of the dataset collected from the Karlsruhe railway project site.

Identification	Count (No.)	Start time	End time	Date
WORKER_A	910	13:05:09	13:20:18	09-Jul-2022
WORKER_B	910	13:05:09	13:20:18	09-Jul-2022
WORKER_C	910	13:05:09	13:20:18	09-Jul-2022
CONCRETE_TRUCK_A	910	13:05:09	13:20:18	09-Jul-2022

We simulate the real-time data communication process using an MQTT broker and establish a DTP on a local server. We implemented the HZI algorithm on the data collected at the Karlsruhe railway construction project. The location and timestamp data of three tags are used as input, and the time interval ΔT is set as 10 minutes. Figure 7 shows the input data, the intermediate heatmaps, and the hazard index map generated from the algorithm.

The close call incidents are based on the proximity between workers and heavy machinery, which can be caused by unscrutinized layout arrangement of the construction site or latent surrounding hazards (e.g., obstacles on the pedestrian's pathway). Therefore, a close call incidence map can indicate the potential hazard spots at the construction site. We adopt the close call detection and analysis algorithm developed by Golovina et al. [7]. When the workers are within the protective envelope of the equipment, the events will be recorded. In our case study, we define a proximity-based close call event as when workers are within the one-meter protective envelope outside the vehicle, as shown in Fig. 5.

We compare the hazard index map with the close call incidence map during the interval. As shown in Figure 8, the comparison indicates that the location of close call incidents is around the high hazard index area. However, the locations of close call incidents only partially overlap with the area with a higher hazard index, which can result from factors such as the delay of worker reaction. Due to the limited amount of data, bias exists in both the hazard index map and the close call incident map. Further algorithm validation should be carried out on the dataset with broader time windows and diverse data types.

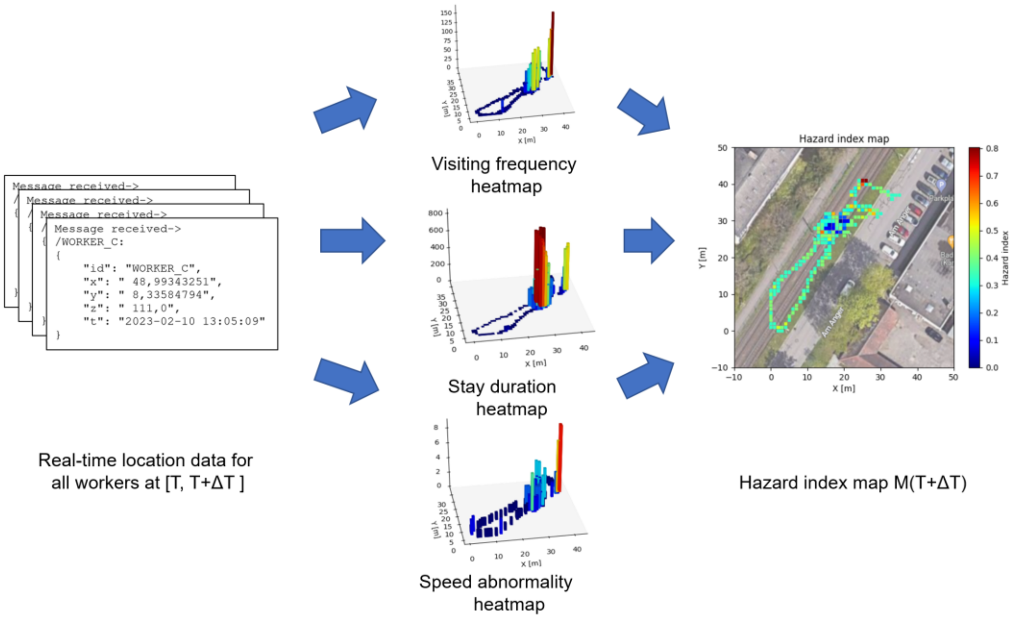

Figure 7: Results from the hazard zone identification algorithm.

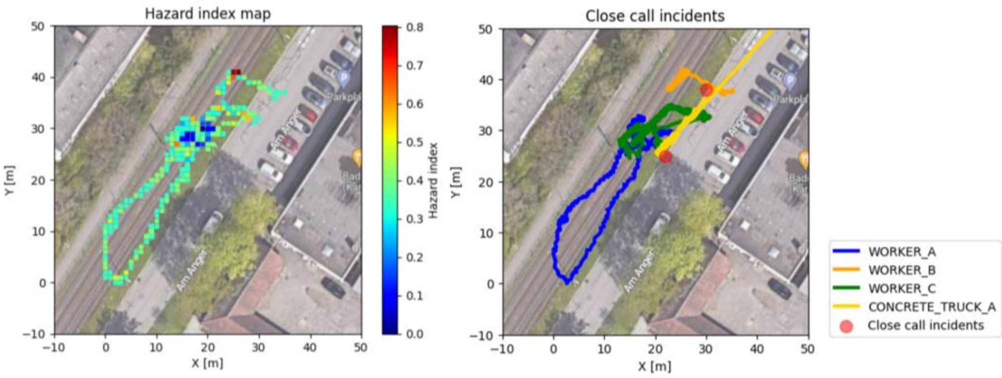

Figure 8: Comparison between the hazard index map and close call incident map.

6 DISCUSSION

The novelty of this work is to propose an algorithm to identify and predict the hazard zone at the construction site based on behavioral patterns derived from workers' spatial-temporal data. Implemented on the DTP, the algorithm can process on-site data and return results to the HSE managers in real time to support hazard meditation and decision-making. Due to the constraint of limited data availability, the accuracy and effectiveness of the algorithm can only be partially validated in this study. The HZI algorithm must be further validated with expert knowledge and other hazard detection methods, such as BIM- and vision-based methods.

The algorithm is built on the hypotheses as mentioned above and assumptions. Improvements in the algorithm are expected in the aspects of the prediction model and semantic enrichment. The prototypical algorithm uses using persistence model for simplicity, which assumes the consistent state of the construction site in the adjunct time intervals. The prediction model should include historical data for comprehensive assessment and robust performance in further research. It requires access to historical data storage on the DTP.

Regarding semantic enrichment, additional data can be integrated into the algorithm. Supplementary data, such as work type and experienced level, can help us better classify the behavioral patterns of construction workers. For instance, workers of certain work types should follow similar routes and schedules, whose trajectories can be grouped for investigation. Basic contextual information can also semantically facilitate our understanding of trajectories so that we can categorize the zones at the construction site. Workers' behavior is expected to differ in the rest area and working area, and the algorithm is supposed to focus on the working area.

7 CONCLUSION

In this work, we developed the concept of a DTP and implemented RTK-GNSS an automated HZI function using real-time location data from the construction site. Using spatial-temporal information, the algorithm can derive construction workers' general behavioral patterns (e.g., speed and stay duration), from which we can infer the hazard status of the surrounding environment. The prototypical algorithm fuses visiting frequency, stay duration, and speed abnormality for the prediction of the hazard index at each spot on the construction site using a persistence model.

We test the DTP and algorithm using the data from a real-life railway construction project. The framework and workflow prove to be viable. We compare the hazard index map with the location of close call incidents that occurred during the time interval. However, under the constraint of limited data availability, the hazard index map generated from the algorithm can only be partially validated compared with a proximity-based close call occurrence map. Further validation is expected with more input data and other hazard identification approaches.

8 ACKNOWLEDGEMENT

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A FRAMEWORK FOR ASSESSMENT OF RESILIENCE AGAINST AIRBORNE VIRUSES IN THE DESIGN, CONSTRUCTION, AND MAINTENANCE OF FUTURE BUILDINGS

Amna Salman[1] and Anoop Sattineni[2]

[1]*Assistant Professor, McWhorter School of Building Science, Auburn University (USA)*

[2]*Associate Professor, McWhorter School of Building Science, Auburn University (USA)*

Abstract

SARS-CoV-2/COVID-19 (Severe Acute Respiratory Syndrome Coronavirus-2/Coronavirus Disease 2019) has affected all trades in the built environment, but Facilities Management (FM) divisions were hit the most. Many measures were taken, however, most of these were reactive measures and their effectiveness is not fully known. There is a need for proactive measures to assure the health and safety of building occupants in future outbreaks, epidemics, or pandemics. Current research proposes layers of defense in the post-pandemic era for the new buildings which should involve close collaboration among the architects, facility managers, mechanical engineers, healthcare professionals, epidemiologists, virologists, and builders. This research aims to create a standardized framework that can be used for the design, construction, and maintenance of future buildings. The research is divided into three phases; the first phase is comprised of interviews with subject matter experts (SMEs) to identify key indicators that could mitigate the spread of airborne viruses; the 2nd phase consists of content analysis followed by thematic analysis of the collected data to create a final list of validated indicators, and; the third phase consists of creating the standardized framework that designers and facility managers can use in times of crisis. The purpose of the study is to create an instrument that can be used to evaluate whether a building is properly designed and equipped to ensure the health and safety of building occupants against an outbreak/epidemic/pandemic. The standardized framework presents all modifications in the design, construction, and maintenance of future buildings.

1. INTRODUCTION

SARS-CoV-2/COVID-19 (Severe Acute Respiratory Syndrome Coronavirus-2/Coronavirus Disease 2019) has affected all trades in the built environment, but facilities management (FM) divisions were hit the most. Current research proposes layers of defense in the design and construction of future buildings [1]. Buildings in the post-pandemic era should be designed after close collaboration between architects, facility managers, mechanical engineers, healthcare professionals, epidemiologists, virologists, and builders [1]. Morawska et al., (2020) recommended: (1) increasing ventilation rates; (2) avoiding air circulation; (3) using air cleaning and disinfection devices, and 4) reducing the number of people in the buildings. Since viruses spread through surfaces, future designs may involve touchless doors, faucets, elevators, etc. Previous studies found three main categories to mitigate the spread of COVID-19 that could be applied in the design and construction of future buildings i.e., building systems, technologies, and HVAC systems [2]. The building system category suggested the use of botanical air filtration systems, natural ventilation, air purification, and cleansing for improved indoor air quality. The technologies were mainly for monitoring purposes whereas HVAC retrofitting required improved ventilation, filtration, dilution, and use of UV lights in the ducts and/or rooms [2–4]. The list continues especially if one is proposing changes in the design, construction, and maintenance of future buildings. Most of the spread of the virus took place indoors, where facility managers had taken reactive measures to control the virus [4]. However, currently, no checklist was found in the existing literature that can be used to proactively measure the building's level of safety against an outbreak/epidemic/ pandemic.

The recent pandemic reveals that airborne viruses were a secondary consideration in the design, development, construction, and management of existing public and commercial buildings [5]. COVID-19 is not the first airborne virus and will not be the last one. Therefore, the design and construction of future buildings need to identify the risk of disease transmission and create more resilient buildings [6].

Megahed & Ghoneim (2021) proposed the creation of a multidisciplinary team for the development of such guidelines while keeping the latest scientific results in mind. Reducing transmission through modified heating, ventilation, and air conditioning (HVAC) systems and changes in the building design are potential solutions. The current literature proposes a series of elements that can reduce the transmission indoors i.e., ultraviolet germicidal irradiation (UVGI), bipolar ionization, vertical gardening, indoor plants, building materials, as well as smart technologies that tend to mitigate the infections of communicable diseases [6]. Another study measured the role of natural ventilation in a building. It concluded that the size and fraction of window openings can substantially increase the outdoor air exchange rate during moderate and warm seasons resulting in a 10% decrease in the risk of disease transmission [7]. The current literature has discussed a series of building controls that can contribute to virus mitigation but are scattered. It also demands the development of guidelines for the design and construction of future buildings and the compiling of all the elements. This will help designers, contractors, and facility managers to create a more resilient built environment. The developed framework will apply to commercial buildings excluding labs, utility buildings, and data centers. The applicability of the framework is limited to buildings in the United States only.

2. LITERATURE REVIEW

The COVID-19 pandemic had a major impact on the functionality of buildings and it is important to understand the challenges facility managers faced during the pandemic to keep the occupants safe [2]. Different organizational leadership took various measures to protect building occupants. U.S. Centers for Disease Control and Prevention (CDC) stated three main ways of virus transmission: (1) Contact Transmission: spread through direct contact like a handshake or hugging etc.; (2) Droplet Transmission: Spread through inhaling droplets of the virus. This can happen when a person is standing close to the infectious person and; (3) Airborne Transmission: Inhaling droplets or particles containing the virus that can be suspended in the air for a longer period [8]. The most critical mode of transmission is an airborne transmission which cannot be mitigated even by following the CDC guidelines [4,9]. The current literature presents different strategies and requires strong collaboration between architects, builders, facility managers, mechanical engineers, and healthcare professionals to design a comprehensive framework for reducing virus spread in buildings [1]. The following review of literature investigates airborne virus spread, and mitigation strategies, and presents a need to rethink building design in the post-pandemic era.

2.1 Airborne Virus Transfer

The virus transmission through the airborne route can only occur if the virus can live outside of the host, withstand external conditions, and be transported to a new host through wind, airflow, or other routes [10]. The effect of evaporation, light, humidity, and temperature on the concentration and virality of the pathogen indicates the threat of the airborne route [10]. There are many different types of airborne viruses like Tuberculosis, Chickenpox, Mumps, Measles, etc. However, drugs and vaccines were able to control them. The SARS-CoV-2 outbreak has given a new impetus to research on this subject. Although vaccines have been developed for COVID-19, data shows that vaccine is not enough to prevent the spread [9]. In addition, there is a threat of different strains which may be more fatal than the existing virus.

Wang et. al. (2021) shows the airborne transmission of respiratory pathogens that can spread through small respiratory aerosols, float in the air, and infect people over a short or a long distance from the infected person. The Amoy Garden case is a strong example of the airborne transmission of the virus. The study analyzed the temporal and spatial distributions of 187 positive cases in the Amoy Garden housing complex during the 2003 SARS outbreak in Hong Kong. The researchers studied the association between the location (building, floor, and direction the apartment unit faced) and the probability of infection using logistic regression. The spread of virus-laden aerosols generated by the index patient was modeled with the use of airflow dynamics and computational fluid dynamics (CFD) [11]. The study concluded the airborne nature of SARS viruses. Figure 3 shows the vertical travel of the SARS virus in a multi-story residential building through the airborne route [12].

Besides the 2003 SARS outbreak, the vertical outbreak of COVID-19 has also been reported in many high-rise residential buildings [13]. One of the studies confirmed that the outbreak took place through the flushing of toilets, which generated viral aerosols that were diffused into different apartments through wastewater stacks. The spread was also aided by bathroom extraction fans, wind shear, and temperature and humidity variance [13]. Building materials also play a vital role in virus transmission. Scientists detected COVID-19 aerosols for up to three hours in the air, up to four hours on a copper surface, up to 24 hours on cardboard, and up to two to three days on plastic and stainless steel [14]. Hence, the architects can design or recommend materials that do not retain the virus particles for a longer duration.

2.2 Engineering Controls

There have been several reports and publications in the United States since March 2020 that proposed several changes in HVAC operations to limit the spread of the virus indoors [4,15]. Ventilation refers to providing fresh air to a space or room. It has been given importance since it plays a vital role in removing or distributing the virus-laden exhaled air from the primary source [15]. Morawska et al., 2020 recommend 1) increasing ventilation rates; 2) avoiding air circulation; 3) using air cleaning and disinfection devices, and 4) reducing the number of people in the building. Although the best way of ventilation is through natural ventilation, it depends on the climate and function of a particular area and needs to be decided on a case-by-case basis [16]. Recirculation of heated/cooled air is very energy efficient, however, during an outbreak, it can be very risky for building occupants as it will spread the virus pathogens to different areas [2,15].

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has also provided filter sizes that should be used in HVAC systems to avoid airborne transmission. Research shows that the smallest COVID-19 virus is 0.1µm (micrometer), through the infected person's breathing [17]. However, droplets through cough or sneezing are >1µm [17]. ASHRAE recommends using the MERV-14 (Minimum Efficiency Reporting Values) filter, which is 90 % efficient in capturing particles 1µm- 3 µm [15]. On the other hand, HEPA (high-efficiency particulate air) filters are 99.97% efficient and accurate in capturing airborne virus particles [15]. Modeling studies of non-healthcare settings using filters MERV 13 or above have shown a reduction in aerosol inhalation transmission with the recirculated air [18]. A study of aerosol removal by four portable HEPA cleaners in an active classroom (128 m^3) with well-mixed air showed a 95% reduction in particles 0.01–10 µm after 37 minutes [19]. However, current systems are not designed to withstand the pressure drop created by the higher-rated filters, and this can cause the failure of the whole system. Hence there is a need for better systems in future buildings that are capable of handling high-rated filters and even HEPA filters in times of need.

2.3 Design and Construction of Post-Pandemic Buildings

Research has demonstrated that most people contract COVID-19 via indoor airborne transmission, especially in crowded and poorly ventilated environments. Thus, maintenance of optimum air quality and proper interior design is necessary to eradicate the spread. This challenges the traditional design and construction approaches that are created for social interaction. The spatial layout of the building is important but after the pandemic, there is a need for innovative design for interior spaces which can be modified in case of an outbreak [6]. Studies have been conducted to evaluate the time of survival of different airborne viruses on various surfaces. The survival of the COVID-19 virus on surfaces varies based on the material. A study compared the stability and decay rates of the COVID-19 virus on copper (99% copper metallic plate), cardboard, stainless steel, and plastic. The study highlighted that after four hours on the copper surface, no detectable levels of the SARS-CoV-2 virus were found [6,20,21]. However, it lasted on plastic, stainless steel, and cardboard for 3, 2, and 1 day, respectively.

In addition, preventing virus spread can be done through hygienic surfaces. Different flooring materials exist, such as bamboo, cork, and engineered timber on which the virus lives only for a few hours. Wood contains extractives, such as flavonoids, tannins, aldehydes, phenolic acids, terpenoids, alkaloids, terpenes, etc. These wood chemicals enable antimicrobial actions against microbes [20].

Post-COVID-19 buildings may also consider the use of bipolar ionization systems. Bipolar ionization technology, also known as needlepoint bipolar ionization (NPBI), is the method of charging particles to clean the air. These devices use electrostatically charged plates to produce negatively or positively charged ions. The ions then attract and capture certain airborne particulates and pathogens including COVID-19 (Figure 1) [22].

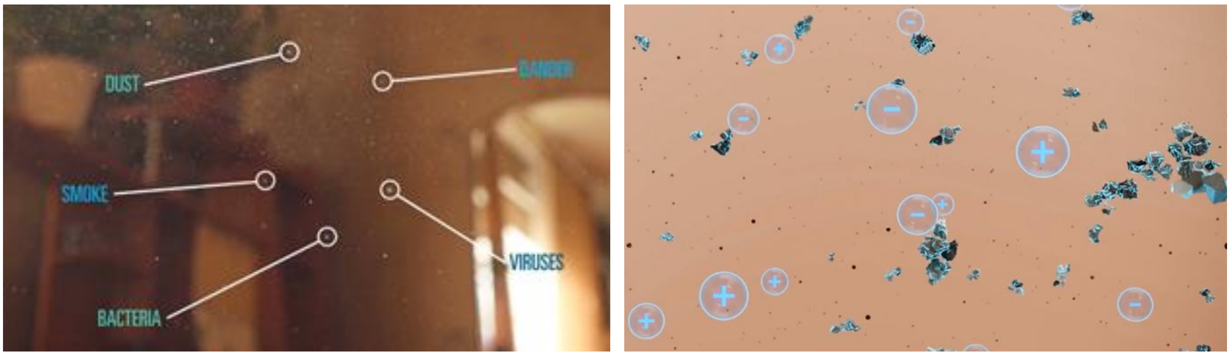

Figure 1: Bipolar Ionization (Adapted from Bipolar Ionization, 2022)

3. METHODOLOGY

A qualitative research methodology approach was adopted to achieve the research goals. Data was collected through one-on-one interviews with the Subject Matter Experts (SMEs). The SMEs were divided into four main groups namely, medical experts, mechanical engineers, architects, and facility managers. Emails were sent to 30 experts. Out of 30 experts, 15 responded and agreed to participate in the study. Interviews were scheduled and recorded. The medical experts assisted in determining the virus spread, its size, travel patterns, and overall behavior. Mechanical engineers guided on the mitigation strategies through the HVAC and plumbing systems. The architects supported the overall design changes for future construction. Whereas facility managers offered expertise for the operations phase of the building. Semi-structured interviews were conducted, and each participant responded to questions from their area of expertise. All participants were either industry professionals or associated with academia. All participants from industry had 10+ years of experience whereas all participants from academia had a Ph.D. degree with 5+ years of industry experience.

The interview data were analyzed through thematic analysis, which is a method of analyzing themes and patterns in the data sets (Tracy, 2019). Each interview was recorded and then transcribed using the software 'Rev.com'. The data recordings were played several times to ensure accuracy between the audio clips and the auto-generated transcripts. For detailed data analysis, an iterative approach was used. Tracy, 2019, defines the iterative approach as, "a reflexive process in which the researcher visits and revisits the data, connects empirical materials to emerging insights, and progressively refines his/her focus and understandings". The main inquiry was kept in mind during the process, i.e., "What is it I want to know according to research objectives, questions, and theoretical points of interest" [23]. The first step was the data immersion phase in which the transcribed data was read and reread multiple times. In the second phase, codes were generated. "Coding is the active process of identifying data as belonging to or representing, some type of phenomenon" [24]. The same code names were given to data explaining the same phenomenon. During the next step, themes were generated with similar codes and then further divided into major categories (Figure 2).

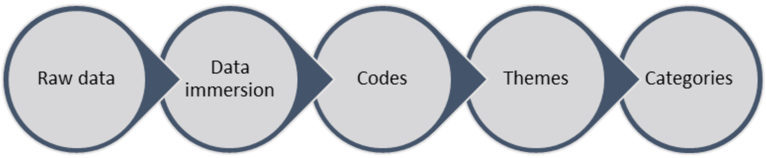

Figure 2: Data analysis steps

4. RESULTS

Data analysis comprised six phases. The first phase was the data immersion phase, and the main purpose was to get familiar with the raw data and prepare it for data analysis. Based on Phase-I, a mind map of major criteria discussed during the interviews was prepared, which helped in further determining the codes (Figure 3). Phase 2 consisted of generating initial codes (Figure 4). Phase 3 consisted of reviewing the codes and determining the empirical themes from the coded data. Phases 4-6 were iterative phases trying to establish the final themes and categories from the generated codes. The final categories generated from the data analysis were HVAC Systems, air quality, bathroom design, and touchless building systems. Cleaning and disinfection, adaptable design, and building commissioning. These categories were further refined to create a framework of proposed modifications to be implemented in the design, construction, and maintenance of future buildings (Table 1).

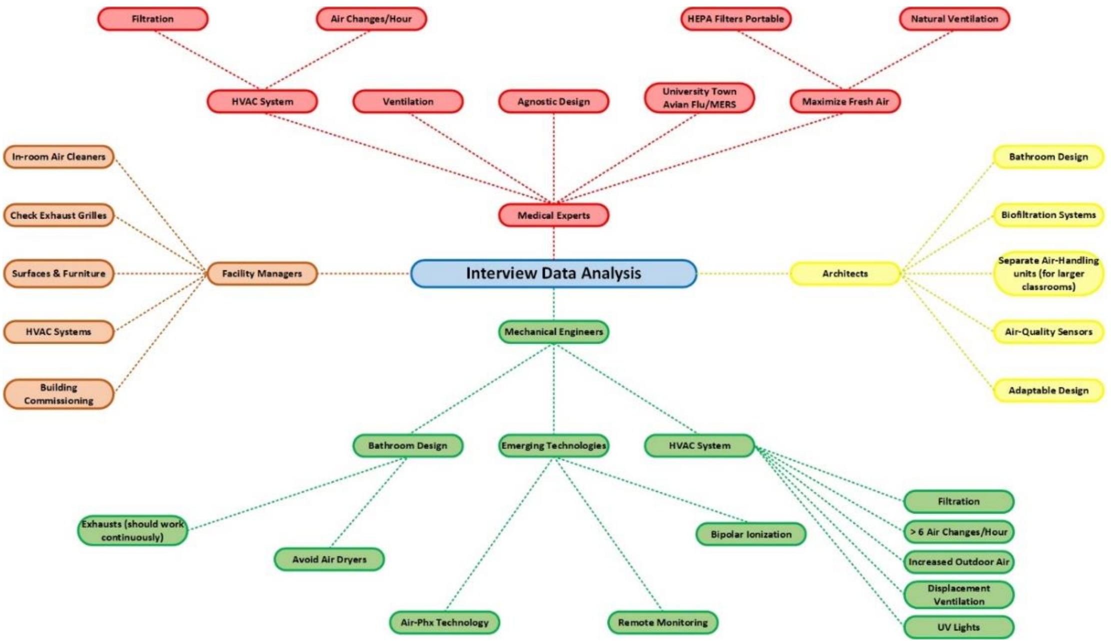

Figure 3: Mind map of the interview data

4.1 Interview Results

4.1.1 Medical Experts

Medical experts shared knowledge about different kinds of airborne viruses and how building researchers should plan for similar crises like the COVID-19 pandemic. According to medical experts, the world has seen many outbreaks and each one of them has been different than the other. Some are more contagious at the beginning, and some are contagious towards the end of the illnesses. Severe Acute Respiratory Syndrome-I (SARS-I) was one of the viruses which were contagious in the end. In addition, SARS-I immediately made the contracted person sick, forcing them to seek medical help. For that reason, the spread was slow and was confined to China and Hong Kong only. The experts also presented the idea of “Agnostic Design” meaning that the framework should be designed for mitigating all kinds of viruses and bacteria. To determine the Agnostic design principles, implementation of engineering solutions is a must. Legacy Air conditioning and heating systems need to be redesigned to match the demands of better indoor air quality (IAQ).

4.1.2 Architects

Architects focused on the design modifications of the building and proposed touchless systems in the building. For example, foot-operated elevators and touchless entrances for common areas. Some participants emphasized the benefits of biofiltration systems to improve indoor air quality whereas all architects proposed modifications in bathroom design. It was recommended to avoid the use of an air hand dryer since it disperses the aerosols, instead, provide multiple hand-free towel dispensers, especially in bathrooms with high traffic. Some changes in large lecture rooms were also proposed; separate air handling unit, remote IAQ monitoring, and multiple entrances. Adaptable/flexible design was a common proposal among all architects.

4.1.2 Mechanical Engineers

Mechanical engineers mainly focused on the building's heating and cooling systems. The experts explained the significance of high-rated filters. MERV-13 is the minimum filter rating that the experts recommend in the HVAC design work. To get that rating, it needs to remove at least 90% of particles in the 3-10 µm range, 85% of particles in the 1-3 µm range, and 50% of particles in the 0.3-1 µm. MERV-16 filters out more than 95% of the particles in all three of those ranges. In addition, mechanical experts also recommended the following: (1) maximum fresh air, (2) separate air handling units in high-density areas like a large lecture hall (3) flush the air after every use: Pre- or Post-Occupancy Flushing Strategy, (4) Use Ultraviolet Germicidal Irradiation (UVGI) in the ducts, (5) Use of hydrogen peroxide to kill the virus, (6) Bipolar ionization, (7) An exhaust above every toilet so that the aerosols are immediately pulled from the environment, (8) Effective room air distribution, (9) Directional airflow from clean to potentially contaminated areas, (10) Keep relative humidity 40-60% RH and, (11) Increase ventilation rates.

4.1.3 Facility Managers

The facility managers focused on the maintenance of the facility and recommended finished surfaces that are easy to clean. According to facility managers, one of the major challenges during the recent pandemic was making sure the building systems are working properly. In the HVAC system, for 100% outdoor air, the dampers needed to be opened, which was a big challenge since some of them were stuck. The facility management organizations had to hire third-party testing and balance representatives to check every damper in the organization. The facility managers suggested the following criteria: (1) prescribed recommendations tried to increase outdoor air in the building to the point that the equipment can handle, (2) remote monitoring, (3) hiring test balance contractors, (4) terminal cleaning, (5) UV air cleaning, (6) UV-C disinfection lighting, (7) vapor or dry hydrogen peroxide, and (8) easy to clean surfaces and use materials that do not hold the virus for an extensive period.

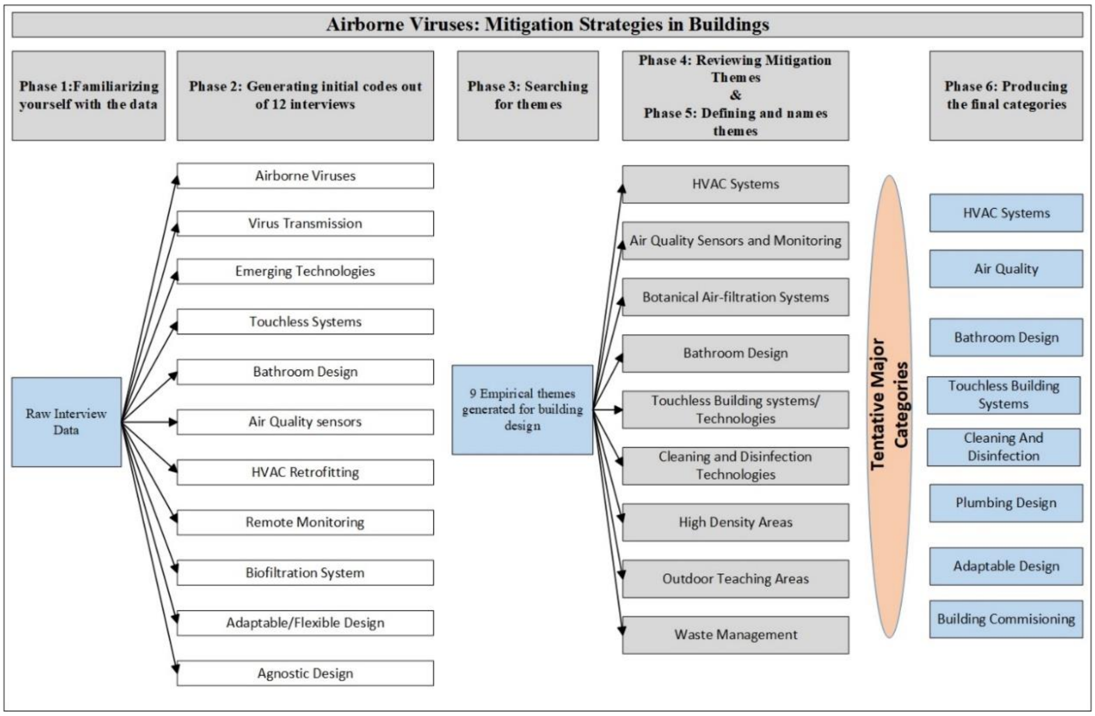

Figure 4: Codes and themes generated through data analysis

Table 1: Framework for the design, construction, and maintenance of future buildings

Category	**ID**	**Description**
A. HVAC System		
	A1	Operable windows if possible
	A2	MERV 13 or higher rated filters
	A3	A system capable of MERV 13
	A4	Check filters to ensure they are within the service life and appropriately installed
	A5	Install HEPA or MERV 16 filters at recirculated air ducts.
	A6	Seal the edges of the filter to limit bypass.
	A7	Clean HVAC intakes daily
	A8	Maintain outdoor airflow rates for ventilation
	A9	Consider installing UV germicidal irradiation (UVGI) in mechanical ventilation paths or upper room applications to indirectly treat air through convective air movement
	A10	Limit/disable re-entry of contaminated air/ demand-controlled ventilation.
	A11	Flush the building for two hours before occupancy in the morning and after occupancy in the afternoon/evening.
	A12	Monitor and maintain relative humidity levels, preferably to RH 40–60%.
	A13	Consider the use of portable room air cleaners with HEPA filters
	A14	If room fans are utilized, take steps to minimize air from fans blowing from one person directly at another individual.
	A15	Deposition Method
B. Adaptable Design and Finishes		
	B1	Reduce density and/or increase spacing of seating
Bathroom Design	B2	Bathroom designs-touchless entries
Bathroom Design	B2	Increase required footage for hallways, entryways, etc.
	B4	Botanical air filtration systems
	B5	Provide outdoor lecture theaters
	B6	Provide flexible seating design for normal operations and during socially distant spacing for an outbreak
	B7	Prioritize easy-to-clean materials when selecting replacement furnishings.
	B8	Install physical barriers such as clear plastic partitions where proximity cannot be avoided
	B9	Replace or modify restroom stalls/partitions to make partitions floor to ceiling where fire safety and proper ventilation are not an issue.
	B10	Signage placement in seating areas, hallways, and elevators
	B11	No-touch trash cans should be installed
	B12	Minimize the use of high-touch or difficult-to-clean finishes and equipment
	B13	Provide touchless hand soap, and clean towels or air-dry hands.
Bathroom Design	B14	Disconnected drainpipes for waste management
	B15	Vent toilets separately where possible
	B16	Exhaust above every toilet
C. Air Quality		
	C1	Volatile Organic Compounds (VOCs) Reduction Methods
	C2	Microbe and mold control
	C3	Advanced/Portable air purifiers
	C4	Source Control Strategies

	C5	IAQ Monitoring
	C6	Sensors/ IoT system
	C7	AI/ML/DL system for Building Automation
D. Touchless Building Systems		
	D1	Utilize IoT technology (RFIDs) to reduce touch points.
	D2	Touchless Entrances
	D3	Sound recognition/ face recognition for doors and offices
	D4	Entry card sensors for big lecture theaters
	D5	Replace light switches with motion sensor controls or phone-based application controls
	D6	Change elevator controls to voice or mobile phone actuated.
	D7	Touchless faucets
E. Cleaning and Disinfection Technology		
	E1	Hydrogen Peroxide-Air Phx Technology
	E2	Utilize ultraviolet C (UVC) during non-occupied hours for sterilization
	E3	Check for bacterial growth in the cooling and water tower condensers
	E4	Bipolar Ionization
F. Mental Health		
	F1	Availability of Greenery and Gardens
	F2	Availability of outdoor common spaces
	F3	Availability of common indoor spaces maintaining social distancing
	F4	Availability of port spaces
G. Energy Efficiency		
	G1	Energy-efficient HVAC system
	G2	Regular inspection for leaks in building shells and ducts
	G3	Natural ventilation control system
	G4	Advanced sensor and technology
	G5	Promotion of sustainable and alternative energy sources
	G6	Use of energy-efficient appliances
H. Continuous Building Commissioning		
	H1	Verify that HVAC systems are working as designed regularly
	H2	Quality of water system provided in the building
	H3	Check for particulate accumulation on filters, and replace filters as needed
	H4	Check for bathroom exhausts and vents to work properly
	H5	Ensure ventilation systems work properly
	H6	Check ultraviolet lamp, and replace bulbs as needed (If applicable)

5. Conclusion and Future Research

Current research shows that there have been great action delays in controlling global disease outbreaks. COVID-19 is not the first pandemic and will not be the last one. This paper presented a framework for the design, construction, and maintenance of future buildings. The framework is in the form of a series of modifications that experts had suggested. Data was collected through interviews with subject matter experts. Interviews were conducted with medical experts, architects, mechanical engineers, and facility managers. At present, there is no systematic framework or set of guidelines that building owners and/or facility managers can use to critically assess a building's readiness in an outbreak/pandemic. This paper has identified the major criteria and indicators that can mitigate the spread of airborne viruses. The future goal of this research is to develop a building readiness index that ranks each indicator according to its importance. The proposed index system will be a powerful, easy-to-use rating tool that would identify each critical element that should be modified in the design, construction, and maintenance of future buildings.

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SMART SOCIETIES? THE POSITIONING OF PEOPLE WITHIN ISO SMART CITY STANDARDS

Katerina Prevelianaki[1], Fred Sherratt[2], Christian Henjewele[1] and NezHapi Odeleye[1]

[1]*School of Engineering and the Built Environment, Anglia Ruskin University, UK*

[2]*Construction Safety Research Alliance, University of Colorado at Boulder, USA*

Abstract

Smart Cities seem to be a natural goal for the current Fourth Industrial Revolution. Emerging in the global construction industry as Construction 4.0, the digitization of how we build inevitably combines with resultant smart built environments to create a bright new future in which technology promises to solve all of society's ills. However, how smart things actually are for the people who live, work, and play in such environments can be questioned. With the human-centric Industry 5.0 already emerging as a counter to the technologically deterministic Industry 4.0, what can be technologically achieved and has been prioritized thus far should now be reconsidered, with a focus on what can and should be put in place to bring effective improvements to citizens' quality of life. Here, a model based on the human-centric difference between output and outcome is used as a lens to unpack how smart reprioritizes and reshapes different aspects of our built environments. The globally agreed standards produced by ISO are used as the data for a critical discourse analysis focused on the key built-environment element of transportation. This analysis revealed inconsistencies and challenges in the positioning and valorizing of smart within social spaces, and highlighted inefficiencies in international smart city guidance. Those working within the built environment should be aware of the potential consequences the unquestioned prioritization of smart can bring to our industry, many of which may be unintended, as the rush for smart continues to be shaped by a technological rather than a people-focused narrative, resulting in a technologically advanced city of little benefit to its citizens.

Keywords: human-centric, ISO standards, smart cities

1 INTRODUCTION

Smart cities continue to enthuse both built environment professionals and city leaders worldwide. However, 'smart' continues to be an elusive term which is only vaguely defined, and until recently was dominated by technology in myriad forms. Yet in recent years, a more human centric approach to smart has come forth which aims to bring quality of life to its citizens [1], although technology arguably remains central to this quality of life – albeit through delivery rather than being the end goal in and of itself. Despite a vast array of literature, confusion around smart city criteria and how to optimally measure 'smartness' remains [1], and this poses a problem.

City leaders, architects and all built environment professionals are developing cities for their people, and by virtue their responsibilities for creating the short and long term visions of the city alongside running/allowing more technical aspects (such as development permissions), they are intrinsically part of the construction industry. Regardless of the particular roles of people in construction, we are all now involved to varying extents with the construction of smart cities, and thus there is a shared interest in successfully building them for the benefit of all people in construction as well as those we serve.

City leaders and built environment professionals often look to international guidance in efforts to build their smart city. One such framework with international applicability is from the widely recognised International Organisation for Standardisation (ISO) which in 2019 released their Smart City standards. These standards provide indicators through which a city can develop and track its progress towards its 'smart' status and guide the industry's decision making on how to achieve that. However, a close analysis of these standards reveals areas of shortcomings and inefficiencies in its guidance towards smartness, such that it can undermine the success of relevant initiatives undertaken by cities which follow the standards' guidance.

This paper presents a critical analysis of the ISO standards, and particularly the Transportation Theme, through a citizen-focused lens. It also adopts a critical view of how smartness is defined and measured by the indicators, and discusses the identified gap between the ISO guidance and literature/practice. This paper also argues that technology, although needed, it is not smartness itself, and recalibrates the narrative to focus more on people, their quality of life and how these elements are currently measured. This comes in time with the latest discussions on Industry 5.0 [2] which also attempts to shift the focus from technology being panacea to making humans more visible in all processes. This work is informative to city leaders, regulators, planners and all those involved with the decision making and realisation of smart cities and their initiatives. The paper recognises that people of construction working at various capacities with smart city initiatives, and thus the analysis presented here adds a critique to the complexities and challenges that need to be managed, as the world moves forwards with smart cities.

2 SMART SOCIETIES NEED SMART OUTCOMES

2.1 What is a smart city?

Defining a smart city is no simple task. Smart has become a buzzword, something for city leaders to chase, capture and use in their city operations and marketing, yet remains obfuscated in both practice and research. A widely accepted definition for a 'smart city' has yet to be established, making evaluations and comparisons problematic. Commonly, definitions focus on technology and technology use within the city and its operations [3]. This can include the use of technology in linking city services [4] or simply equate a prominent technological presence with smartness, effectively using the mere presence of technology itself to evidence the smartness of the city.

Such technocentric definitions have been criticized [5], not least because technology is not smart by default. More nuanced definitions have consequently been developed; For example that proposed by Giffinger et al., which also forms the foundations of many others, states that a smart city is based on the connection of human and social capital along with Information Technology Information (ICT) infrastructure, able to achieve sustainable economic development and higher quality of life [6]. Another definition by Townsend describes smart cities as '…places where information technology is combined with infrastructure, architecture, everyday objects, and even our bodies to address social, economic, and environmental problems' [7, p.15]. In similarity with Giffinger et al., this holistic definition takes a pragmatic approach to reality, seeking to incorporate real-world problems and solutions [8]. Indeed, as Prevelianaki et al. [9] have argued, smartness does not inevitably come from the technology itself but is in fact found in the quality of life achieved from having utilized the technology appropriately – this approach therefore focuses on smart *outcomes* from a situation and necessitates a more detailed consideration of smart within real-world contexts.

2.2 Why outcomes matter

Placing outcomes in the center of a definition of smart enables a refocus on the human within the city. This approach, as set out by Prevelianaki et al. [9], finds excellent fit with the emerging Industry 5.0 [2] which brings a human-centric challenge to the technocratic dominance and determinism of Industry 4.0.

To give an example of an outcome-focused application of smart, consider the use of 'smart' parking mobile technology applications (Apps). These Apps use technology to enable drivers to identify available parking spots at their destination before they even arrive there. In this example, the goal (parking) is ultimately the same no matter how smart the city is. In the absence of a smart parking App, drivers can potentially spend considerable time driving around an area in search of a free parking space. The use of an App is able to eliminate this wasted time and effort by locating and sharing a vacant space with the driver – directing achieving the goal. Therefore it is not the actual goal or the technology used to achieve it (the App) which is smart but rather the actions taken (or not) to achieve an outcome that actually makes something smart.

Borrowing from Project Management, output can be defined as the end product delivered by a project [10]; essentially it is the end product created by a process. These same theories would define an outcome as 'the changed circumstances or behavior that results from the use of an output' [10], which would basically constitute the impact (i.e. changed behavior) created through the use of the output – the end product of the process. Putting these definitions into context using the above smart parking App example, the 'equation' would calculate as shown in Fig. 1, where parking is the service to be achieved, and the smart parking App is the ICT.

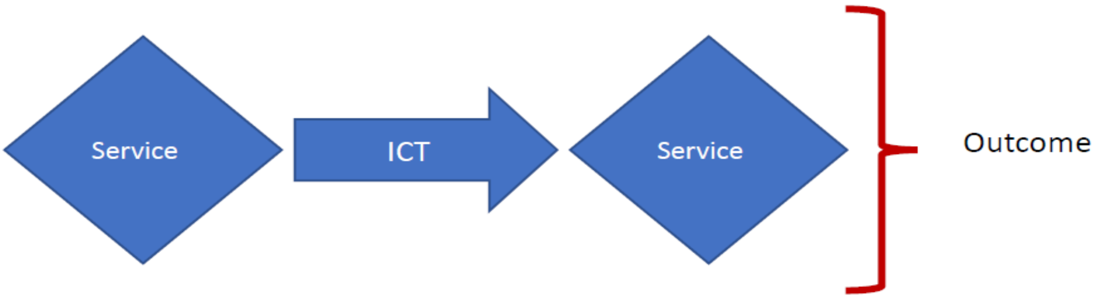

Fig. 1: Smart Outcome

It is of course perfectly possible to park with or without the use of an App and so the end service remains the same, but it is instead the outcome which makes a significant difference here. The car has been parked either way, but has the smart technology made it easier? Has less time been spent driving around? Has less time been spent to find the parking spot? Is the environment less polluted because less fuel has been used? Has the entire process been more efficient and effective? This is what smartness should deliver as its outcome – goals that prioritize the experience of the human in the city. Thus an outcome model of smart can be defined as 'a process which through the use of advanced technology returns a more efficient, effective and sustainable outcome'.

2.3 Measuring smart using ISO Standards

Given the quest to be smart, many cities seek ways through which their smartness can be demonstrated in robust ways [5]. One of the globally recognized bodies to propose a framework for smart is the International Organization for Standardization (ISO).

There are three relevant standards relating to Smart Cities. The ISO 37120 Indicators for City Services and Quality of Life (QoL ISO) is an umbrella standard which includes ISO 37122 Sustainable cities and communities - Indicators for Smart Cities (SC ISO), and ISO 37123 Sustainable cities and communities - Indicators for Resilient Cities. The relationship between the standards can be seen in Fig. 2.

Fig. 2: ISO Standards for Smart Cities and its umbrella standards [11]

The ISO 37120 City Services and QoL standard is expected to be in effect until 2023, following the traditional life cycle of 5 years. The two sub-standards were both published in 2019, a year after the umbrella standard that they complement. These three standards are collaborative in nature and propose indicators and methodologies at a regulation level.

ISO define a smart city as:

> *'city that increases the pace at which it provides social, economic and environmental sustainability outcomes and responds to challenges such as climate change, rapid population growth, and political and economic instability by fundamentally improving how it engages society, applies collaborative leadership methods, works across disciplines and city systems, and uses data information and modern technologies to deliver better services and quality of life*

to those in the city (residents, businesses, visitors), now and for the foreseeable future, without unfair disadvantage of others or degradation of the natural environment' [11, p.2].

This definition is highly ambitious in its scope, seeking to incorporate and include all potential aspects of smart including sustainability, technology, quality of life, society engagement, economic and political stability among others. However their smart city indicators as stated within ISO 37122 (Sustainable Cities and Communities – Indicators for Smart Cities) are perhaps not so inclusive. Indeed, they often reveal a preference for technology, both relied upon to achieve measurable goals but also to some extent seen as contributing to smart by its very presence in the city. This focus on technology reflects the earliest definitions of a smart city (e.g. Hall et al. [12]) and fails to incorporate more human-centric or output focused evaluations, making these smart city indicators in need of recalibration towards Industry 5.0. With many cities looking to the ISO standards for guidance in their 'smart journey', it is perhaps timely to evaluate their contribution from this alternative perspective; To evaluate their effectiveness and potential impacts and consequences for the people who will soon work, rest and play in the smart societies of the not-too-distant future.

3 METHOD

Effective evaluation of the ISO Smart City Standard necessitates documentary analysis of the Standard itself. Given the aim of this study, this analysis will be inevitably critical as it seeks to evaluate and consider the positioning of people therein. A critical discourse analysis [13] will enable this process to be undertaken rigorously and in-depth and is thus a highly appropriate methodological approach to this work. Due to the nature of this analysis, no claims are made to generalizability, and validity and reliability are demonstrated by the detailed explication of the research and articulation of the analytical process.

Due to constraints of space, in this paper only one theme from the ISO Smart City Standard is considered, that of transportation, and particularly indicator 19.4 ''Number of bicycles available through municipally provided bicycle-sharing services per 100 000 population'' is unpacked here within that theme. Transport is a vital aspect of any city and one that has considerable impact on its citizens in terms of outcome, and so its consideration is able to make a useful contribution to wider discussions in this space.

4 FINDINGS AND DISCUSSION

The specific indicators found within the ISO 37120 City Services & Quality of Life and ISO 37122 Smart Cities with relation to the Transportation Theme are shown in Table 1.

Table 1: Transportation indicators [11]

ISO 37120 City Services & QoL (QoL ISO)	ISO 37122 Smart Cities (SC ISO)
19.1 Kilometers of public transport system per 100 000 population (core indicator)	19.1 Percentage of city streets and thoroughfares covered by real-time online traffic alerts and information
19.2 Annual number of public transport trips per capita (core indicator)	19.2 Number of users of sharing economy transportation per 100 000 population
19.3 Percentage of commuters using a travel mode to work other than a personal vehicle (supporting indicator)	19.3 Percentage of vehicles registered in the city that are low-emission vehicles
19.4 Kilometers of bicycle paths and lanes per 100 000 population (supporting indicator)	19.4 Number of bicycles available through municipally provided bicycle-sharing services per 100 000 population
19.5 Transportation deaths per 100 000 population (supporting indicator)	19.5 Percentage of public transport lines equipped with a publicly accessible real-time system
19.6 Percentage of population living within 0,5 km of public transit running at least every 20 min during peak periods (supporting indicator)	19.6 Percentage of the city's public transport services covered by a unified payment system
19.7 Average commute time (supporting indicator)	19.7 Percentage of public parking spaces equipped with e-payment systems
19.8 Transportation profile indicators	19.8 Percentage of public parking spaces equipped with real-time availability systems
	19.9 Percentage of traffic lights that are intelligent/smart
	19.10 City area mapped by real-time interactive street maps as a percentage of the city's total land area

	19.11 Percentage of vehicles registered in the city that are autonomous vehicles
	19.12 Percentage of public transport routes with municipally provided and/or managed Internet connectivity for commuters
	19.13 Percentage of roads conforming with autonomous driving systems
	19.14 Percentage of the city's bus fleet that is motor-driven

4.1 Indicator 19.4: Number of bicycles available through municipally provided bicycle-sharing services per 100 000 population

4.1.1 General Considerations

This indicator attempts to promote municipal bike sharing systems (BSS) for smart cities to adopt. This is achieved by cities providing bike sharing systems whereby bicycles are '*available through self-serve docking stations, or person-operated docking stations, located throughout a city, where bicycles can be rented as needed. Users should be able to rent and return bicycles to any docking station within the bicycle-sharing system. Municipally provided bicycle-sharing services shall refer to bicycle-sharing services funded and operated by the city. This shall also include bicycle-sharing services operated under a license or contract agreement with the municipality, such as public-private partnerships*' [11, p.47].

This indicator is calculated '*as the total number of bicycles available through municipally provided bicycle-sharing services in the city (numerator) divided by 1/100,000 of the city's total population (denominator). The result shall be expressed as the number of bicycles available through municipally provided bicycle-sharing services per 100,000 population*' [11, p.47]. Data for the bike sharing services can be obtained via the sources in relevant city departments which oversee and collect data on bike shares.

The benefits that the SC ISO seeks to achieve are for cities to be able to provide an alternative mode of transport, be that public or private. The standard also believes that if cities are able to provide a municipal bike sharing system, users will be encouraged to take up biking as a regular mode of transport while also removing any barriers that might deter users from using a bike, such as cost, theft and repair [11]. Presumably, the BSS would also bring the consequential benefits of more eco-friendly city transport, able to reduce emissions as well as congestion, and potentially improve air quality, although these are not specifically stated for this indicator, or in the overall theme of Transport in which it most appropriately belongs. Ultimately, *'this indicator provides municipalities with a measure of the availability of bicycles in the bicycle share system'* [11, p.46]

There is no doubt that using bikes as a mode of transport can have very clear benefits to the citizens, city, and government, and are well established in literature. Benefits include improvement of the air quality, reduction of car use, health improvement and notably, as bikes are an eco-friendly mode of transportation they can help reduce emissions [14,15,16].

The benefits of the use of bikes as a mode of transportation are not disputed here; yet what has the potential to be problematic is how this SC ISO Standard chooses to communicate the implementation of BSS to city leaders, and how that might impact consequential initiatives that can have adverse consequences for all involved – the city, the city leaders, and the (bike) users. A key issue is that all that is provided is the calculation deemed appropriate and adequate for the purpose of increasing bike use as an alternative mode of transportation. However, this calculation alone fails to capture the real and actual use of bikes, the uptake of the BSS initiative by the citizens and more importantly, any actual difference this initiative makes to the citizens' lives (the outcome of the BSS). The latter is a significant factor if one wants to measure the 'smartening up' of cities; Regardless of any advanced technology and investments utilized, if a smart city initiative has failed to make a (significant) positive difference in its citizens' lives, has it really smartened up?

More detailed guidance (or even direction to robust guidance) on how to implement a successful BSS is again lacking and this absence can be problematic. The Standard simply states that the number of BSS-provided bikes present in the city needs to be analogous to the city's population, with little other guidance or advice given to help city leaders and all those involved to develop a successful bike scheme. Yet the implementation, use, challenges, and success factors of BSS in cities has been extensively researched and is able to provide useful insights for city leaders engaging with a BSS initiative for their city. For example, it has been established that BSS schemes are quite nuanced, and their implementation as well as their uptake very much depends on various different factors which city leaders ought to be aware of if they want to develop/expand their BSS – those collated by Todd et al. [15] and shown in Table 2 which comprehensively shows the myriad variables that influence the use of BSS in a city. Thus, although a large volume of bikes in a city which the indicator seeks is surely positive, but there is much more to a successful BSS than quantity of bikes.

Table 2: variables that influence use of BSS in cities [15]

Variable		Relationship	Paper
BSS Factors	Number of Stations	Positive	Faghih-Imani et al. (2014), Médard de Chardon et al. (2017)
	Station Density	Positive	Médard de Chardon et al. (2017)
	Station Capacity	Positive	Tran et al. (2015), O'Brien et al. (2014)
	Distance to Station	Negative	Tran et al. (2015), Bachand-Marleau et al. (2012)
Socio-Demographic	Population	Positive	Médard de Chardon et al. (2017), Faghih-Imani et al. (2014), Tran et al. (2015)
	Income	Positive Negative	Fishman et al. (2014), Roy et al. (2019), Woodcock et al. (2014), Bachand-Marleau et al. (2012)
	Age	Positive	Fishman et al. (2014), Zhang et al. (2016)
	Gender	Male	Fishman et al. (2014), Zhang et al. (2016), Goodman and Cheshire (2014), Murphy and Usher (2015)
	Jobs	Positive	Tran et al. (2015), Woodcock et al. (2014)
	Education	Positive	Fishman et al. (2014), Shaheen et al. (2013)
	Ethnicity (White)	Positive	Buck et al. (2013)
Weather/Climate	Rainfall	Negative	Corcoran et al. (2014), Miranda-Moreno and Nosal (2011)
	Windspeed	Negative Insignificant	Corcoran et al. (2014), Miranda-Moreno and Nosal (2011)
	Air Pollution	Negative	Campbell et al. (2016)
	Temperature	Insignificant Positive	Corcoran et al. (2014), Faghih-Imani et al. (2014)
	Humidity	Negative	Faghih-Imani et al. (2014)
Topography	Slope	Negative	Frade and Ribeiro (2014), Mateo-Babiano et al. (2016)
	Altitude	Negative	Tran et al. (2015)
Cycling Infrastructure	Cycling Infrastructure	Positive	Fishman et al. (2014), Faghih-Imani et al. (2014), Buck and Buehler (2012), Mateo-Babiano et al. (2016)
Other	Public/School Holidays	Insignificant	Corcoran et al. (2014), Brandenburg et al. (2007), Borgnat et al. (2011)
	Helmet Requirement	Negative	Médard de Chardon et al. (2017), Fishman et al. (2014), O'Brien et al. (2014)
Temporality	Weekday/Weekend	–	Faghih-Imani et al. (2014), Faghih-Imani et al. (2017), O'Brien et al. (2014), Zaltz Austwick et al. (2013)
	Season	–	Ahmed et al. (2010), Faghih-Imani et al. (2017)
	Time of day	–	Faghih-Imani et al. (2017), O'Brien et al. (2014)

4.1.2 Infrastructure and Safety

Appropriate bike infrastructure is not only a condition for cities implementing a BSS initiative [17], but the absence or limited presence of bike paths and lanes can be a deterrent to use and uptake of bike use [18]. To the contrary, cities that demonstrate a dedicated bike infrastructure observe a greater use of their BSS [19]. The size of the BSS system also influences users' inclination to rent a bike, as well as the total number of users [20], which highlights even more the need for a well-designed bike path system. Furthermore, safety is directly linked to infrastructure and in cases this is limited, concerns for collision with motorists are a major deterrent of any bike use for citizens around the world [18].

The literature makes a clear case of a need for appropriate infrastructure to facilitate use and enable safety of the users of BSS as well as motorists. Safety concerns, in fact, are stated as one of the largest barriers to BSS [21], yet the SC ISO indicator is unconcerned with both safety and infrastructure. Without purpose made infrastructure, bike users must share the roads with motorists, but safety concerns mean that such use should perhaps not be encouraged by ISO in their vision for the cities of tomorrow. Instead, bike infrastructure is considered within ISO's sister standard, ISO 37120 for City Services and Quality of Life (QoL ISO). Under the same Transportation Theme (Theme 19), the QoL ISO has an indicator to help the city to measure and control the development of infrastructure for bikes. In particular, the indicator 19.4 *Kilometers of bicycle paths and lanes per 100 000 population* in the QoL ISO [22, p.69], states that a city should measure the length of the bike paths and lanes in relation to its population. The indicator suggests that the greater the length of the bike lanes and paths, the better the infrastructure is, but length is linked to the population of the city.

This calculation proposal seems a little odd, as by correlating length of bike path kilometers to city population is an interaction which can lead to ambiguous and inaccurate results, depending on the city itself. Specifically, the indicator might score poorly or inaccurately against cities with dense population rates, where a large number of people live in a smaller area. This would create a distorted result to the proposed measurement ratio (length of bike lanes/100,000 population). Are densely populated cities inherently less smart, simply because the length of the bike paths is not proportional to its population? This is what this indicator would suggest. One could, however, argue that a city with a dense population will also have a large population which would automatically mean greater length of bike paths, as the indicator suggests. However, the proposed calculation has an inherent cap on the length of the bike paths, as the city's overall space can reach certain limits, but its population does not. This also brings in the discussion city expansion patterns. The QoL ISO calculation (length of bike lanes/100,000 population) assumes that cities will expand their catchment area as the population increases. This, however, might not be geographically possible for all cities or accurately reflect the way cities expand. Indeed, in recent years, and with equity and sustainability in mind as land is a finite source, cities also expand upwards, not always outwards [23]. This results in effectively greater population density which reduces the 'ISO score', as previously mentioned. Is it the case then, that the more skyscrapers a city builds, the less smart it becomes? Furthermore, the QoL ISO flatly states that more kilometers is a positive thing, however no consideration is given as to the location of these bike paths. Connectivity of the bike paths and lanes, and the parts of the city which they make accessible for this mode of transport is a significant factor which users consider when deciding whether to engage with a BSS. Nevertheless, literature confirms that it is not the length of the bike network that matters, but that a network has been created and is well maintained [24]. As such, these sister indicators, although certainly encouraging positive infrastructure development, do so without including key considerations or thorough planning, thus posing a challenge to city leaders and those in the built environment who are involved with city infrastructure.

4.1.3 Topography and Climate

A further consideration for BSS is the city's topography and climate, which can also directly influence the use of bikes. Topography features such as downhill/uphill roads are shown to have a negative correlation with the BSS use, and bike users will dislike inclines more than 4% and will entirely avoid inclines more than 8% [24]. For example, users in Barcelona used the BSS bikes only to go downhill and would leave the bikes there - the bike accumulation at the downhill road grew into a distribution problem, for which the city had to take action to resolve [24]. In a similar scenario, Brisbane was found to have significantly more downhill roads than uphill, which also affected the users' bike patterns [19]. In cases where topography is challenging, the use of electric bikes can help overcome these issues, with the caveat that they are more costly than traditional bikes [24].

The weather of the city also plays a significant role in bike use as well as patterns of use [25]. For example, it has been recorded that bike use patterns tend to decrease during times of or in areas with rainfall [26]. Temperature also influences BSS uptake [15]; People can be less likely to choose this mode of transportation in adverse weather conditions or uncomfortable temperatures (be they high or low).

For the SC ISO to recommend a mode of transportation that will not, and in some cases simply cannot, be used equitably in all cities world-wide, and to consider that a measure of smartness seems a little unfair. From an outcome perspective, that topographical and climate related factors can play a significant role in the success of relevant schemes should also be considered. Advice and guidance for city leaders to support them in planning an appropriate BSS according to their city's unique topography would be a useful addition here. Does global location dictate smartness? Without adjusting the BSS system to topography specifications, the ISO allows for the global location to dictate the smartness and makes city leaders victims of their city's topography, evidently, a rigid approach that doesn't seem smart or fair.

4.1.4 Access points and Convenience

Convenience and access points are also factors that score high in deciding whether to use a BSS. Users are less likely to use the BSS if the access points are not convenient or close to their destination/starting point [15]. Proximity of residential addresses to access stations has a very strong influence on deciding whether to use the BSS [18], as well as the population density near the docking stations; the higher the population density, the greater the BSS use [27]. Density of docking stations themselves can have a positive correlation to BSS use, meaning the more docking stations in the city, the greater the BSS use [28, 20]. If not in close proximity, users are generally willing to walk to the nearest access station for around 500m [29,30], a factor that is integral when city leaders and those in the built environment need to consider when planning for the BSS network.

It is important to mention here that there are three types of docking stations: a) fixed permanent, where there are designated racks for bikes to lock to, b) fixed portable, an advanced level fixed permanent station where there are portable modular blocks using solar power (thus no installation needed beyond placing the modular blocks in the desired location), and c) flexible, where bikes carry a lock mechanism and do not require a docking station [24]. The SC ISO, does specify that ''*Users should be able to rent and return bicycles to any docking station within the bicycle-sharing system''* [11, p.47], but does not specifically exclude other types of BSS schemes that do not require docking stations. Either BSS type has its pros and cons when it comes to access points. If the city chooses to have docking station from which users can collect/drop off bikes, these access points will need to be carefully located within the city to increase convenience of use. If, on the other hand, the BSS is free floating, then this poses an even bigger issue of unreliability. Users can never know in advance whether they will be able to find a bike at the location they need it, which might prevent them from using the BSS altogether. This type of BSS can also result in careless behaviors, such as littering the city with bikes deserted at inappropriate spaces, a phenomenon most recently seen with shared e-scooter systems [31].

Travel time is yet another factor on which people decide on their transportation options [18], individuals will simply prefer an alternative option if biking does not save them any time. Consequently, access points, network of bikes lanes, distribution of bikes and their density need to be strategically placed not only within the city, but also within the overall transportation network. A well-connected network of bike paths with appropriate catchment and access points is crucial and one which the SC ISO standards should consider before simply extending the length of bike paths to justify the population correlation, or place thousands of bikes which may not be used.

4.1.5 Vision

Cities around the world have different features, characteristics and needs, and so it is only natural that they will also have different goals they will want to achieve by implementing a BSS scheme. These goals could vary from improving the air quality, to promoting biking as a means of (alternative) transportation, reduce congestion and emissions, encourage bike use instead of cars in short, downtown trips, to beautify the city and many more [24].

Understanding the areas which a city aims to improve via the BSS scheme is crucial as it will directly impact how the BSS network is designed, who are its users and what is its intended use in the context of the entire city transport system. Conversely, if the system is not designed with its goals in mind, it might struggle to achieve them, and/or use precious resources and funding inefficiently and reap little rewards.

Literature indicates that cities mostly aim for the BSS to be used in conjunction with other public transportation. Indeed, a study by Yang et al. [32] evidenced that BSS usage patterns showed extensive BSS use near metro stations, indicating the scheme was a good solution for the last mile problem. On the other hand, individuals who do use the bikes, are in their majority switching from walking or using another mode of public transportation [18, 24, 33], while levels for those switching to bikes from cars are reported as disappointingly low [18,24]. It is clear that if cities wish to achieve results, they will need to carefully plan how to develop their BSS, particularly when some of their goals are challenging, such as reduction of car use in certain areas.

Therefore, the question city leaders should be asking themselves, is what is their vision? This might certainly vary depending on the city and country, but it’s important to know what the end goal is – and ideally the outcome for their citizens. It is not clear whether the SC ISO envisions BSS to be used as a reliable mode of transport which citizens will prefer over cars or other public transportation, or if the BSS should only be used for short distances in between other public means, or something in between.

The proposed SC ISO measurement (number of bikes/100,000 population) is therefore lacking and falls short in two ways; First, it does not include any guidance, advice or even acknowledge any success determining factor, despite the fact that these are very well established in literature and real data studies. It can be irresponsible, wasteful and misleading to propose such indicator(s) without providing additional direction or even drawing attention to factors that can have a profound impact on both the city and its people. Secondly, the proposed measurement (number of bikes/100,000 population) discounts any other quantitative or qualitative factors and imposes a one size fits all approach (it doesn’t matter what needs, goals, or characteristics a city has, it’s smart as long as it can present a number of bikes which satisfies this fraction?). Ultimately, the use of a single measurement suggests that the ISO considers smartness to be the mere presence of a BSS, regardless of usage rates or any actual impact and outcome they do or do not have in the lives of the citizens.

5 CONCLUSIONS

Literature makes it clear that developing the infrastructure and the BSS itself are far more nuanced than this indicator suggests. Although the indicator aims to encourage bike presence (and consequently use) in the city, its crude approach via presence and quantification alone does not address any of the proven and well evidenced factors and considerations that would help this initiative become successful. Output has dominated over outcome.

Formulaic measurements such as the one proposed in this indicator offer a technocentric result with little meaning or use, all the while remaining blind to other, more valuable, well proven and impactful methods of success. It is interesting to highlight that the literature and case studies which prove and establish the BSS system nuances (many of which are cited in this paper) had already been published well ahead of the ISOs' publication year. Yet, neither the QoL or the SC standard considered these. This suggests a continued reliance within the underlying concept of smartness and has resulted in a technocentric focus that is encouraged and perpetuated through these standards. Yet one size does *not* fit all; The SC ISO can certainly not cater with specific details to every single city worldwide, but in setting out a smart city vision for cities to follow, it should attempt to ensure that city leaders are aware of all the necessary nuances that might affect the BSS initiative by at least providing some advice, or even better, informative guidance, so city leaders can succeed and learn without having to fail first.

Ultimately, what is the vision the city wants to achieve? Certainly, the vision can't be to simply buy and release on the streets a large volume of BSS bikes and hope for the best. Endless, senseless construction/technology for the sake of construction/technology is not the answer. Investing large sums and using labour to build city parts which potentially do not achieve their intended goals, and which cause more problems than offer solutions, do not really make for a valuable contribution to the built environment the world over. Investments that ultimately do not make the city better/smarter are a waste of resources (monetary and otherwise) in a world which is quickly running out of resources. While this particular indicator focuses on bikes, when extrapolated to look at the bigger picture of the city as a whole, it becomes clear that we need to (re)consider the kinds of projects the construction industry is asked to undertake, and what vision is the industry building towards. We need not make our cities simply smart, we need to make our planning, design and construction also smart, and thus enable built environment professionals and the people they serve to be placed firmly at their heart.

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MENTAL WELLBEING THROUGH PEOPLE-FOCUSED DESIGN

Sinéad Gilmour[1], Simon D Smith[2]

[1]Civic Engineers, Glasgow, UK
[2]School of Engineering, University of Edinburgh, UK

Abstract

With rapid global urbanisation, focus must turn towards the people who are – and will be – inhabiting the cities of the world. However, for the effective curation of beneficial urban spaces, an understanding of how the built environment impacts occupants' not just physical, but mental wellbeing is needed. This is important as it will enable personnel within the sector to incorporate mental wellbeing effectively within design – holistically bettering the lives of many.

From a critical realist standpoint, a qualitative study consisting of seven semi-structured interviews with construction development sector personnel, informed by a review of literature surrounding the topic of mental wellbeing and the built environment, was conducted to establish the current ways in which mental wellbeing is viewed and implemented within urban development projects. This further aimed to deepen an understanding of the barriers faced in the implementation of mental wellbeing measures for construction projects within an urban development setting. In light of these findings, the study additionally aimed to establish a common framework, designed to facilitate the effective and holistic incorporation of good mental wellbeing into urban development projects.

Findings show that while mental wellbeing is appreciated as a complex phenomenon, there exists an inherent lack of understanding of the depth to its complexity and subsequent residency within urban development projects. Mental wellbeing's position within the sector is affected by a number of barriers that affect its consideration within people focussed design. Via a thematic analysis, and through the identification of four key themes – Knowledge, Complexity, Ease, and Motivation – these barriers consist of intangible characteristics that inhibit any consideration and assessment of mental wellbeing, along with a lack of incentive to do so due to risk, financial, and belief constraints seen within the structured construction industry. The findings exposed an inadequate understanding of eudaimonic (functioning) against hedonic (feeling) aspects of mental wellbeing within urban development projects, which prevents a subtle and holistic understanding of how wellbeing, and mental wellbeing, is manifested within an urban environment.

With these findings, a common framework was developed to address the incorporation of both eudaimonic and hedonic elements of mental wellbeing within urban development projects to enhance the depth in which the concept exists within design.

Keywords: mental health, wellbeing, urbanisation, design

1 INTRODUCTION

With nearly 70% of the world's population forecasted to be living within a city by 2050, Zhang (2016) has emphasised that record numbers of people are currently relocating to an increased urban life. This shift has resulted in rapid urbanisation and its impact upon health is a growing problem. The built environment's relationship with people's physical health has long been investigated, however, despite the rising number of people residing within cities, as stressed by Dong & Qin (2016), research surrounding its impact upon its peoples' mental wellbeing is lacking.

This issue can be set against the backdrop of the United Nations Sustainable Development Goals (UN SDGs), established and adopted by all United Nations member states in 2015. SDG goals 3 and 11 focus on health and wellbeing and sustainable, resilient cities, respectively. This push for change requires a need to refocus cities around their inhabitants.

In 2013, Silderberg and Lorah reported on the growing realisation of a 'people-focused' ideology within the urban development sector, spurred on from the evident failures and displacements seen from late 20th century urban architecture. This was further emphasised by Schooling et al. (2020), who recognised the importance of 'making place' in a holistic manner within the urban development field. Explained by Platt & Medway (2020), these efforts centre around focusing upon the needs of people within beneficial urban spaces and call for a more holistic assessment of built form, space and use. This has been accompanied by calls for wider considerations of inclusivity and diversity within the urban environment, sparking campaigns such as the UK's Institution of Civil Engineers' *Inclusive Cities* – seeking to address key imbalances within its cities such as male-orientated designed spaces and safety and provision for night city workers. Echoing the calls from the ICE, Galasso et al. (2021) heightened attention towards the risk of unbalanced impacts upon the marginalised and most vulnerable groups within cities. Thus, these efforts recognise the importance of a diverse group of people within cities.

1.1 The missing link – motivation for research

Evidently, within the urban development realm, there has been a potential shift in the way urban spaces and their communities are viewed. Through the procurement of social factors within projects, the benefits of curating people focused design can be seen. However, there still lies a distinct absence within the literature on *how* the built environment impacts its occupants' mental wellbeing. That it does impact is generally accepted: Abbott (2011) indicated the link between occupants' likelihood of mental illness whilst living within an urban setting. Their findings suggest that a link existed between increased numbers of schizophrenia and occupants' residency within an urban place. More recently, Buttazzoni et al (2022) report on a new field of *neurourbanism*, a multidisciplinary field that considers the effects of urban living on neurological processes, but its work seems yet to filter to built environment planning, design and delivery. Thus, a number of problematic questions remain.

1.2 Problem definition and research intentions

Leading on from the above discussion and consideration of key parts of the relevant literature, the problem investigated and reported on here can be encapsulated thus:

The urban development sector exists so as to enable the built environment to facilitate and better the lives of people. However, without an appreciation of how mental wellbeing is considered within design, the success of people focused urban design falters. This is important: the rise of placemaking initiatives yields the questions of how the sector is focusing its designs on people and how it plans on continuing to design for the rapidly rising urbanised world? Without a clear understanding of the current state of mental wellbeing within the urban development sector in terms of its image and implementation, its acknowledgement, progression and future within the field is hindered. Yet, with the acknowledgement of the stance of mental wellbeing and methods of implementation within urban development projects, an appreciation of its nature within the field can be achieved. This will ensure its progression and security as a critical part in enabling the future wellbeing of the rapidly urbanising world.

1.2.1 Research questions

1. How is mental wellbeing is currently viewed and implemented within urban development projects?
2. What are the potential barriers to the curation of positive mental wellbeing within urban development projects?
3. Can a common framework be established to effectively implement mental wellbeing strategies within urban development projects?

1.3 Contribution and beneficiaries

This investigation consequently yields a wide pool of beneficiaries – further promoting the importance of this study. As shown, investigations into the value of place and people focused design cover a range of sectors and thus, a deeper understanding of the built environment's effect upon mental wellbeing will be benefitted by many. Voiced by Fincher, et al. (2016), the need for centring urban form around people is not simply held in the minds of researchers, but small-scale neighbourhoods, communities, through to regions. Thus, this study will aim to explore the ways in which mental wellbeing is viewed and implemented within urban development projects. Outcomes, in the form of recommendations and frameworks, will strive to help urban sector developers visualise the premise of mental wellbeing in design, enabling them to seamlessly incorporate it into people focused projects. This will ensure the continued growth of people focused design – bettering the lives of the rapidly growing urban environment.

2 RESEARCH APPROACH AND DESIGN

A conference paper is not the place to explore in detail the appropriate philosophical and methodological nuances of attempting to explore the research questions posed above. But with a clearly subjective ontology and interpretivist epistemology, the researchers also accept that the subject of this work – the physical built environment – leads to a critical realist perspective, and this has guided the research approach. Such an approach also helps in avoiding axiological pitfalls, though the researchers were continually aware that their own personal values can easily impact upon the interpretations and manner of communicating the outcomes.

2.1 Data collection

It was quickly concluded that within the realms of qualitative research methods, the use of interviews to gather data was deemed the most appropriate. The aims, being to fundamentally explore the stance of mental wellbeing within the urban development sector and subsequently to establish a common framework to be used, exemplified the need for interviews. The use of interviews, as highlighted by Fellows & Lui (2015) provides a two-way avenue of data collection, compared to survey methods inducing only a one-way narrative. This entails a degree of verification from the interviewer to the interviewee such that the data obtained are understood correctly and not merely recorded as the sole product of the researcher's perspective. Thus, with the flexibility of a two-way corridor of data transfer, interviews allow for the exchange of meaning. This is critical in exploring the ways in which mental wellbeing is implemented and viewed in the urban development sector as it is well suited for exploring human behaviour and perception. Thus, for this study, data collated through the interaction and acknowledgement of personnel within the field aimed to yield holistic and enriching results, helping to satisfy the research aims.

Semi-structured interviews were chosen that followed a skeleton format, allowing the interviewer to guide the conversation through focal points yet, still permitting open-ended answers to be received. Due to the subjective and complex nature of mental wellbeing, the open-ended structure allowed for non-constrained views to be voiced whilst still ensuring their residency within the scoped domain. This degree of flexibility ensured an exploratory aspect of the research design remained throughout the data collection – thus, making semi-structured interviews advantageous compared to, say, structured. Structuring the interviews too crisply risks narrowing the scope of analysis and yielding a more explanatory design. However, the semi-structure did allow for some degree of structure. This allowed the interviews to generate consistent results and avoid the scope becoming too wide – potentially yielding unspecified and meaningless data.

The interviews were conducted between January and March 2021 via the online platform Microsoft Teams. Despite the pandemic-induced restricted contact, the interviews were still able to be conducted face-to-face, and seven interviews were held with professionals in the built environment sector. An overview of the participant list is seen in Table 1. Their duration lasted approximately 30 minutes. In line with semi-structured interview practice, prior to interviews, all respondents received an interview guide consisting of the general research topic and the outlined areas of conversation to be discussed during the interview. Once more, bias is to be addressed. It could be argued that pre-conceived opinions could be voiced surrounding the questions. However, given the restricted timescale, providing a short interview guide ensured that the interviews consisted of partially structured, concise and relevant content. The interviews were designed to last adequate time for relaxation to be achieved as it was recognised that the subject of mental wellbeing was personal.

The interviewees were selected by purposive sampling in order to gain a widespread view on the concerned topic of research. Shown in Table 1, the different types of interviewees ranged from planning to more engineering orientated side of the sector. Choosing to conduct purposive sampling, instead of allowing respondents to volunteer, avoided unnecessary volunteer bias. Respondents who volunteer for interview are subject to potential bias as they are at risk of possessing pre-conceived opinions on the subject and thus, volunteer with intent (Fellows & Lui 2015). However, the use of purposive sampling is recognised to have its shortcomings. Bias can be introduced into the sample courtesy of the researcher. By acquiring samples by selection, the researcher may entail results that they desire to obtain, subjecting them to ethnocentrism. However, as discussed, through the research design and theoretical approach outlined, efforts were made to reduce ethnocentrism such that its presence was deemed insignificant as the researcher maintained awareness of their stance when collecting and analysing the data.

Table 1 *Overview of purposive sample for semi-structured interviews*

Participant Number	Professional Role	Planning or Engineering Background
1	Manager	Planning
2	Consultant	Planning
3	Manager	Engineering
4	Design Engineer	Engineering
5	Design Engineer	Engineering
6	Co-ordinator	Engineering
7	Manager	Planning

2.2 Data analysis

The interviews were transcribed from the audio recordings as permitted by participants and analysed using thematic analysis via the software nVivo 20.

In thematic analysis, the researcher aims to identify patterns present in their data set and identify themes. However, it is to be made clear that the presence of a theme is not equated necessarily to quantity. Rather, the theme must be of importance within the data set to the researcher. By ensuring prevalence was outlined through importance of the theme, the author aimed to mitigate theme prevalence through quantifiable measures, although it is recognised that these may be concurrent.

In using theoretical thematic analysis techniques, the types of themes are to be identified. As laid out by Braun & Clarke (2006), themes can either be of semantic or latent nature. This entails a choice of the level at which the themes are identified within the data and thus, changes the nature of the research design. Semantic themes are identified by the researcher and presented as literal occurring themes. Conversely, the identification of latent themes calls for a more interpretive approach allowing for a synthesis of not only their presence but reasons for their residency within the data set. Braun & Clarke further outlined (2006), that an effective research design will yield only one of the two. Thus, semantic level themes were chosen for the analysis. This aligns with the critical realist standpoint adopted in the research design as the analyst can interpret the findings whilst presenting them in a realist manner. Identifying latent themes would reside within a more constructivist research design allowing for the exploration of their meaning rather than just presence.

With the structure of the analysis curated, the method of analysis followed the six-step thematic analysis method laid out by Braun & Clarke (2006). It is noted that whilst not intended to be a strict set of rules for thematic analysis, following the six steps ensured that the analysis was thorough and structured – yielding more robust conclusions.

3 RESULTS AND DISCUSSION

Primary consultation of the gathered data found that the interviews held a diverse but interconnected collection of semantic themes. Thematic analysis requires the repetitive study of the data set, ensuring the analyst revisits all parts of the data set numerous times. With familiarisation, four key themes emerged in the domain of mental wellbeing:

- *Knowledge* – the current understanding of mental wellbeing and recognition that further knowledge of mental wellbeing itself is needed in order to understand how it sits within urban development.
- *Complexity* – the realisation that there are many factors and inter-relationships within the way in which mental wellbeing resides and how it is to be managed.
- *Ease* – as a counter to complexity, the desire to simplify the nature of mental wellbeing and how it might be managed.
- *Motivation* – that getting designers and developers to allow for mental wellbeing in their projects is not straightforward.

In making sense of these themes, below, we see a number of sub-themes, or micro-themes, emerging that also require consideration. Figure 1 summarises the themes and their connection to sub- or micro-themes.

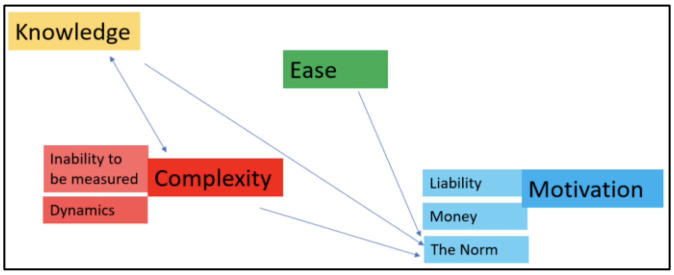

Figure 1 *Thematic map of interview data*

3.1 Knowledge

Identified through the sense of respondents' awareness of mental wellbeing within an urban development setting. Primarily, the theme presented itself from respondents' shared perception of mental wellbeing with a commonality present in how mental wellbeing was effectively "dealt with in design". The theme was named such so that findings allowed for the definition of mental wellbeing within the urban development sector to be explored.

Often, overt references to aspects such as "*social connection*", "*cycling*", "*integrat[ing] areas of seating...of planting*" were mentioned throughout the interviews. Explicitly, when discussing the ways mental wellbeing was embedded within design, one respondent said, "*things like, you know, seating, cycle stands and space and trees, plants*". It is interesting to note the commonality of this thought process as respondents indicated that it was a shared acceptance that by incorporating greener and more connected spaces, their efforts ultimately benefitted people's mental wellbeing. This notion echoes the calls from Pfieffer & Cloutier (2016) that the implementation of open greenspaces may directly increase happiness by incorporating design features that actively promote social interaction (i.e., integrating seating).

However, by unpacking the data, the analysis suggests that there lies a fragmentation between the theory and subsequent knowledge within the field. Interestingly, this issue was conveyed by personnel from the front line 'practice' side of the sector – expressing the presence of an imbalance between theory (knowledge) and practice (guidelines). One remarked that "*sometimes the official guidance can be slightly behind [the theory]*" with another saying, "*this is very challenging, especially 'cause the timelines are different for publications, so it may be that you publish your development plan and then you have a national policy coming out the year after you publish the development plan, and it is not that easy to update*". Struggling with differing levels of insight into whether procedures are up to date with policy emphasises the presence of the theme of Knowledge. Subsequently, it illuminates the reality of fragmented knowledge within the field, thus presenting a barrier – how are people to implement it into design if there lacks a coherent relationship between theory formed, knowledge gained, and practice implemented? Personnel within the sector seem to hold a common view of what constitutes mental wellbeing; however, they are disadvantaged when implementing it due to inconsistent, insufficient guidelines and a subsequent lack of accepted knowledge.

3.2 Complexity

The theme of Complexity was established through the re-occurrence of the intricacy and barriers surrounding mental wellbeing within the urban development sector as expressed by respondents. Whilst it was established that a commonly held view of better mental wellbeing equated to the involvement of greener and more connected infrastructure, as distinguished by Lauwers et al. (2021), this nevertheless presents a somewhat fractured narrative of the steps needed in urban development projects to constitute better mental wellbeing. Essentially, mental wellbeing was highlighted as a fundamentally difficult premise to grasp and it could be suggested that the lack of awareness shown by respondents was, in fact, revealing the complexities involved with mental wellbeing.

These complexities were further considered to form two subsequent micro-themes: *inability to measure* and *dynamics*.

3.2.1 Inability to measure

Comments such as "*Obviously [it is]...something that's difficult to measure*" and mental wellbeing being "*not really a parameter as such*" demonstrate the acknowledgement of the challenges of quantification. Such views mirror those in the literature: Dodge et al., (2012), suggesting that mental wellbeing, or more generally, the measurement of 'wellbeing' is not something that can be easily executed. Why? For one, as argued by Sherratt (2018) the literature on 'wellbeing', before the mental component is even considered, is particularly hazy, with a distinct lack of concrete data present to constitute its 'definition'. With the absence of a universal definition of wellbeing, a lack of knowledge is highlighted once again. Aware of this lack of knowledge, respondents' answers echo that of Dodge et al., (2012), who stress that the incomplete definition of wellbeing leads to its weak ability to be effectively measured parametrically. These findings echo another view held by a respondent who voiced that the measurement of mental wellbeing was "*really dependent on having some sort of measure to start with...how do you go about saying "What are the key things?"*" with the commencement of such measurement involving "*a jumping off point for what [the key things] might look like*." Thus, it is perhaps not surprising that respondents seemed to struggle to define mental wellbeing, leading to a rather hazy response in their efforts to incorporate it into design.

Wellbeing's measurement *"...is a really difficult one. Is it sort of like a happiness scale - like how happy people are with something?*" Here, the respondent is seen to show the apparent inability to confidently outline a method of measurement for mental wellbeing, with the proposal of a happiness scale. However, to simplify such a concept endangers the complexity being lost and thus, its measurement being flawed. The questioning of the measurement method can also suggest a lack of knowledge from the respondent, yet the instinctive measurement of mental wellbeing with a happiness scale suggests an attempt to simplify to counter its complexity.

This concept of measurement by simplification is possibly explained by the context of the predominantly quantitative and objective field of designing, planning and executing urban development projects. However, mental wellbeing cannot be easily measured in an objective manner, and it is here that the urban development field is seen to falter. As highlighted by Giupponi and Thomson (2020), the subjective element of mental wellbeing lends itself to enhancing its complex nature and consequently, explains its inability to be measured.

3.2.2 Dynamics

Dynamics presented itself as a micro-theme through responses that signified the complex wider culture of the urban development sector. Responses indicated that whilst measurement was challenging, the circumstances and wider culture in which mental wellbeing resided presented significant challenges too. There appear to be two sides to this issue.

Internal dynamics of design teams

Those who worked directly within the urban development field commonly voiced an 'us vs them' dynamic, regarding architects and engineers. Interestingly, this dynamic was voiced strongest by one respondent working outside the technical engineering team but was present on the planning side. Certain, striking quotes from the interview include:

"*These people are engineers, they're not planning theorists, they are not architects, where architects will be much more grounded in all of these sort of idealisms about what makes a good place and what makes a place a positive and happy place to live and work, promotes health and wellbeing, you know*."

"...an engineer will argue that they're protecting your wellbeing, but there's a psychological implication to that, and it gives a sense of 'this is a dangerous space where we have to have [guard] rails up to protect us..."

"*I think also, an engineer would argue, they make the place safer and better and so, better for your wellbeing. But I think a planner or an architect or an urban designer might have a different view*."

Such responses mirror claims from Chiberg & Jensen (1991) regarding the dynamics of small group communication, which can encounter significant trouble due to differing personnel coming together in a close-knit environment. This further emphasises a hurdle over which the incorporation of mental wellbeing into design is seen to face: repeated use of words such as 'they' and 'these people' emphasises an 'us vs them' dichotomised culture, illuminating not just fragmented knowledge, but also divided team structures.

External relationship between the design teams and the wider community

The thematic analysis exposed another barrier faced by mental wellbeing implementation within design: the community. The external relationship was depicted by respondents in ways such as "*the local community*" who, "*designing for 'all'...then they usually have conflicting needs*". The addressing and fulfilment of these conflicting needs was framed as "*the challenge of striking a balance*" and the effort of doing so effectively the act of "*juggling*". Here, the words of 'challenge', 'juggling' and 'balance' highlight the theme of Complexity as it shows that the dynamic of designer and community entails an intricate relationship. Interestingly, these views hold an arguably negative undertone with the inclusion of the community seen as a 'juggling' act, suggesting it to be a manoeuvre not very easily completed. This suggestion is further voiced by Close and Loosemore (2014) who highlight how the construction industry still view the community as a liability in the implementation of their projects. Unfortunately, if this group is treated as a burden, with its presence seen as a hindrance to the overall success of a project, how can the consideration of the community's mental wellbeing even begin to hold significance within design?

3.3 Ease

Further analysis suggested a counter-theme to Complexity, which allowed the barriers faced, or otherwise, in the implementation of mental wellbeing in design to be explored further. *Ease* was established due to the inherently widespread association of increased mental wellbeing with the idea of permitting everyday actions to be easily completed and the ability to make "*people's lives more manageable and enjoyable*." As seen in the previous section, the complexity of mental wellbeing instigated its simplification within design – and it is from this simplification that the theme of Ease was derived. Whilst initially the concept of 'ease' was considered as simply possessing positive connotations for mental wellbeing (its incorporation linked to 'ease of living'), the analysis yielded the emergence of its negative nature as well. Herein lies a significant outcome of the analysis, with two sides – positive and negative.

3.3.1 Ease as a positive construct

A dominant aspect of discussion was the concept of mental wellbeing linking to a desire of achieving 'liveability' within a design. Respondents were shown to link the idea of people-focused strategies with liveability with one referring to the background strategy of their city as the 'Living Strategy' – focusing upon the liveability of a city. Deepening the knowledge of this concept, another referred to "*the concept of liveability*" as asking questions such as "ho*w well does this place function? And where can people thrive?*" Respondents tended to link the concept of liveability with the novel premise of "*the idea of 20-minute neighbourhoods*". When pressed further, these new neighbourhoods were described as "*these liveable neighbourhoods...where people can achieve everything they need to achieve to work within a 20 minute sort of radius*," with their goal being to "[*make] people's lives more manageable and enjoyable*."

The answers alluding to the ease of everyday functions and tasks equating to better mental wellbeing echo Aristotle's concept of eudaimonic wellbeing – the sense of positive 'functioning' of humanity – and thus, illuminates Ease's role in the portrayal of mental wellbeing in an urban development context. The incorporation of eudaimonia allows for a richer definition of wellbeing to be established: for good wellbeing to be achieved there is a requirement to not only feel good, but to also function. However, in contrast with obvious correlations held between green spaces, ample seating areas and good mental wellbeing, respondents showed a more muted appreciation of the eudaimonic aspect of mental wellbeing. Their efforts framed mental wellbeing in a more hedonic manner within design with the use of physical interventions like greenspace and ample seating recognised to promote people to feel better in the space. Whilst it is recognised that the responses did not explicitly reference Aristotle's dual theory of wellbeing, their recognition of wellbeing forming a multifaceted nature is still evident – although arguably quietly.

3.3.2 Ease as a negative construct

These muted tones amplify a significant part of the thematic analysis that sees the premise of Ease link the themes of Knowledge and Complexity and essentially mobilise the final theme of Motivation. The suggestion of eudaimonic wellbeing in the interviews highlight the complexity of wellbeing. Incorporating the eudaimonic element within design requires the addition and consideration of another layer: it forces personnel within the field to drift from their ideals of happiness scales and ample seating to face a complex, multifaceted phenomenon that holds a valid, and essential place within the urban development sector. It has been established that through the themes of Complexity and Knowledge that there is arguably a link between the complex nature of mental wellbeing and the subsequent lack of knowledge possessed in the field. However, recognising the contrast between the deafening tones of hedonic initiatives against the innately muted tones of eudaimonic ones, calls into question whether this added complexity is exposing a reluctance within the sector. Incorporating an additional layer of complexity onto a concept that is currently hazily understood and defined suggests the encumbrance of major obstacles and difficult procedures to be conducted.

Herein lies the intrinsic link between the theme of Ease and Motivation. The thematic analysis not only enabled the identification of potential barriers faced by the incorporation of mental wellbeing into design but once identified, allowed for the exploration of their causes.

3.4 Motivation

Motivation was identified through the appreciation of the ways in which mental wellbeing is implemented and the current view of its state within design held by the respondents. This macro-theme encompassed the micro-themes, money, liability and the construct of 'the norm'. They represent distinct obstacles met in the implementation of mental wellbeing within the urban development field.

3.4.1 Liability

The micro-theme liability was a striking element to the macro-theme of Motivation as from the interview responses, simply the introduction and presence of mental wellbeing in design was viewed as "*a risk*". A common response emphasised the inflexibility of the current structures for design in urban development projects with "*large projects...very much [following] the process*" with the added point that "*it's important in terms of the contractual elements that [following guidelines] happens – there isn't much flexibility in terms of that process*". Highlighting the rigidity of design protocols within the sector, the responses result in a clear indication that mental wellbeing is not something that is easily implemented into design – as the current procedures do not currently allow adequate flexibility. This agrees with the claim from Loosemore (2016) that identifies rigidities enforced in formal institutions are one of the challenges experienced by promoting social procurement within the construction industry.

3.4.2 Money

Emerging alongside this micro-theme lay the subject of financial means and the discussion of money within the sector. The micro-theme of money indicated a clear connection with the overall theme of motivation as it was voiced as a major barrier in implementing mental wellbeing with a respondent's "*second challenge*" having to prove "[*mental wellbeing] in terms of [financial] benefit to the client*". Their view formed the opinion that "*it's only once you can prove that there's money involved, and that it's beneficial for money that people take it seriously and actually change*".

3.4.3 The Norm

This explicates the link between the two micro-themes liability and money as both allude to the rigidity of structures and ideas present within the sector. Hence, this illuminated a third part to the macro theme of Motivation – in the form of the recognised 'norm'. Respondents tended to frame the incorporation of mental wellbeing into design only being possible if there were changes to the current procedures and thought processes present within industry. One respondent referenced the incorporation of active travel in the hopes of bettering mental wellbeing by stating that the "ve*hicle and drivers have to get used to the idea that they have to think about more things other than just other vehicles*". Introducing more 'people-focused' designs suggest an appreciated need to change the standard norm with one respondent voicing "*I think people and, whether it be engineers or whether it be just the general public, there can be some people that can be a bit reluctant to the idea of, you know, changing the thought process*". This reluctance, again, echoes the rigidity present within the sector in terms of current procedures and links these micro-themes cohesively.

It is the emergence of the micro-theme of the norm that ultimately highlighted one of the key barriers faced: the presence of mental wellbeing within a stagnant industry that is lacking motivation to change. However, upon closer inspection, this absence of motivation to change could arguably stem from something larger than mental wellbeing itself. Fundamentally, the investigation of mental wellbeing within the built environment is an immature field (Loosemore, 2016). Thus, it could be argued that by no fault of their own, the industry resides within a field that contains no significant amount of evidence-based research surrounding mental wellbeing in the specific context of the built environment and hence, personnel are left with a lack of knowledge of correct ways to incorporate it. This lack of knowledge is also partnered with the substantial barrier of the inherent complexity of mental wellbeing and thus, results in a problematic combination in the efforts of incorporating it into design. Their lack of motivation stems from a knowledge base that only extends to the boundaries of what industry considers 'the norm' – an urban development sector that is incredibly structured, procedures orientated and codes dependent. It is the breaking of these boundaries that will see a hope for the effective incorporation of mental wellbeing into urban development designs.

4 THE FRAMEWORK

The findings of this research suggest the importance of framing both eudaimonic and hedonic aspects of mental wellbeing. Fundamentally, the muted tones of eudaimonia in contrast to hedonic implementations exist as the core of this framework. The link present between the complexity of mental wellbeing, a lack of knowledge of its eudaimonic and hedonic aspects and inconsistent implementation into design has been established.

The framework is presented in Figure 2 and is presented as a dichotomised model, aiming to yield a holistic incorporation of mental wellbeing. Through this, it recognises the complexity of the problem it aims to solve. Therefore, its aim is to provide a baseline for the incorporation of mental wellbeing in this holistic manner within urban development projects, on which further research will advance.

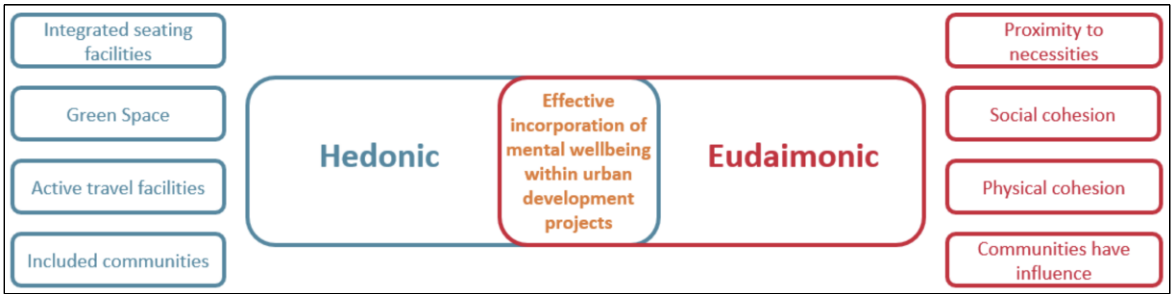

Figure 2 *Suggested framework for the holistic incorporation of mental wellbeing within urban development projects*

5 CONCLUSIONS

This paper presented an investigation into understanding how mental wellbeing is currently viewed and implemented within urban development projects. The investigation hoped to identify barriers to the implementation, and establish a framework for designers and developers to better incorporate and allow for mental wellbeing in their projects.

It is evident that mental wellbeing resides within the industry as a complex, multifaceted concept that struggles to be effectively measured in an objective, consistent nature. Despite this, efforts have been made to incorporate it through primarily physically led methods in the form of greener, more connected and actively promoting spaces. Efforts like these illuminated the goal of urban development projects to better mental wellbeing by ensuring their occupants felt good. Thus, in line with Aristotle's definition of wellbeing, a hedonic framing of mental wellbeing, the premise of feeling good, is seen to currently lie within the sector. However, furthering its perception within the field, whilst not as domineering, personnel were found to view the premise of better mental wellbeing equating to ensuring that urban development projects were constructed in a way that enabled 'easy living'. Thus, the findings illuminated a subtle eudaimonic framing of mental wellbeing within the sector allowing people to function well in proximity to their necessities.

Through providing a common framework, this research exposed the current hindrances met by the implementation of mental wellbeing within the urban development sector. Existing as a complex phenomenon, simplified unduly within a complex environment, mental wellbeing faces severe financial, risk and belief constraints. Thus, the framework acts to visualise the complexity of mental wellbeing within an urban development setting. Its implementation would contribute to the successful, holistic consideration of urban space occupants' mental wellbeing alongside the promotion of Local Place Plans.

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EVALUATING THE EFFECTIVENESS OF VIEWPOINT SOFTWARE ON QUALITY ASSURANCE IN CONSTRUCTION

Kenneth Lawani[1], Gregor Munn[1], Billy Hare[1], Iain Cameron[1]

[1]Glasgow Caledonian University, Construction & Surveying, School of Computing, Engineering & Built Environment, Glasgow (Scotland)

Abstract

Some fairly recent high-profile safety-related failings have left a damaging mark on the construction industry's image. Two commonly referenced failings in the UK are the Oxgangs Primary School masonry wall collapse in Edinburgh, and the Grenfell Tower fire. Both incidents were the results of systemic failures in delivering quality and safety on projects. The role of the Principal Contractor includes taking ownership and responsibility of delivering safe and high-quality projects. This necessitates the Principal contractor to implement safe methods of quality management that improves quality and safety culture. This paper evaluates the adoption of 'Viewpoint' - a construction technology package which is effective for quality assurance, with particular focus on 'Field View' and 'Viewpoint For Projects'. The study used existing projects as case study and engaged seven industry practitioners working for a UK based Principal Contractors through semi-structured interviews to evaluate the effectiveness of the adoption of Viewpoint for quality assurance. The findings demonstrate the benefits of the adoption of Viewpoint in terms of quality management, inspection check sheets and reporting non-conformance. Also, having a common data environment for sharing submissions and drawings significantly increased the quality of the Information Management and managing design for safety.

Keywords: Innovation, technology, research projects, etc.

1. GENERAL APPROACH

One of the most important issues facing the construction industry is related to poor quality in the buildings and the built infrastructure. Quality in construction have subjective interpretations by individuals [1], but fitness for purpose and conformance to specifications are generally used in the construction industry [2]. However, the perception of the Chartered Quality Institute (CQI) on quality means constantly pursuing excellence: making sure that what your organization does is fit for purpose, and not only stays that way, but keeps improving. The difficulty surrounding the issue of quality assurance in construction stems from the inability to have a unified or an exact definition of it [3]. That is why issues considered as below standard in construction are commonly labelled as defects, errors or non-conformance. Quality assurance has been a very topical subject in the construction industry with some recent events in the UK (The Grenfell Tower and Oxgangs Primary School) highlighting the serious consequences of poor quality, resulting in reputational damage of the construction industry [3]. Quality installation failures in the cladding were found to be the primary cause of the rapid spread of flames at the Grenfell Tower [4], while the Oxgang School wall collapse which resulted in the closure of other schools was linked to serious failures in procurement, design, and construction [5]. It is estimated that 6% to 15% of all construction costs are as a result of rework of defective components, and 5% of these costs are detected during maintenance [6]. The root cause of these errors is widespread and there are suggestions that 54% of these errors could be attributed to human factors e.g. poor workmanship or insufficient supervision [6].

Generally, quality management is conducted on site in the form of inspections, control, and assurance. Quality inspection is used during the construction timeline to identify errors which can be reported via a non-conformance or defect notice, while quality assurance is useful in eliminating the need for non-conformances and to allow for a smooth construction phase with any errors that are identified, swiftly resolved. Due to external pressures such as budget and sequencing of work or programme, quality assurance cannot always be guaranteed in the industry [1], and the lack of timely resolution could result in safety-related problems within the built environment. Creating a single 'synergistic' management system towards improving both safety and quality performance in construction could be the way forward [7], but this strategy can sometimes prove difficult to implement on site. Study shows that the nature of competitive bidding amongst contractors for construction projects (cutting safety and quality budgets to win the job) could have some impact on safety or quality management as the contractor strives towards maintaining a healthy profit margin for the project [7]. This paper evaluates the efficiency of Viewpoint, a cloud-based construction technology and offline mobile solution used for snagging, SHEQ, non-conformance, to improve quality assurance in construction as opposed to the traditional pen and paper approach which is slow in terms of execution and decision making, prone to errors, and not timely.

2. BACKGROUND

Viewpoint is a collaborative project management solution that integrates team members during the lifecycle of projects regardless of role. ‘Viewpoint for Projects’ is a document management system that simplifies project documentation, while Viewpoint ‘Field View’ is used in the field for snagging, forms and permits, project delivery and handover; as an enabler of informed decision-making and enhanced project efficiency [8]. Viewpoint for projects is useful in enhancing the connection between the office and the field, by adding more value, increased transparency, reducing risk during design, construction, and handover. The document control feature allows for the sharing, controlling, and management of drawings, specifications and schedules, contracts, daily logs, and mission critical reports. Viewpoint for projects provides the tools and mobile capabilities to improve project profitability, visibility for clients, risk management, and allows for the effective collaboration of project teams in real-time throughout the entire project lifecycle [8].

From the contracts point of view, the Joint Contract Tribunal (JCT) which is an industry standard of contract that is traditionally used during the procurement phase allows for limited contractor design. With this type of contract, there is no standard for the contractor to provide specifications of quality, but the JCT outlines the contractor’s requirement in providing a construction phase plan which outlines aspects of quality, although these plans do not guarantee a standard of detail that must be followed. Therefore, the JCT could potentially leave the employer in a scenario where they are not able to effectively configure a plan to manage and apply quality systems on site [9]. However, Clause 2.1 (in terms of quality) sets a standard of work to be expected by a skilled tradesperson or contractor and that all works must follow the supporting documents put in place by the contractor and designer. As opposed to the JCT, the New Engineering Contract (NEC) emphasizes the significance of quality and the contractor is required to implement site-specific Quality Management policy and plans. This plan allows the client to express their views in the process of establishing a standard for quality, and how quality issues should be achieved [10].

Quality management in construction encompasses the total management of quality and products, whilst ensuring the product is as per scope of works set out by the client and executed within budget and timeframe [11]. This includes ensuring quality control during construction, and compliance of the product in accordance with the material and workmanship outlined in the specification documents. It is suggested that 35% of people believe that poor management is the main reason for poor quality [11]. It is believed that devoting resources to preplanning, making available the requisite time to undertake tasks correctly the first time, engagement of leadership and involvement at the workface, and encouraging and empowering workforce to take pride in their work are potential strategies that could promote both safety and quality concurrently [12, 13]. For quality management to be successful, inspections must be carried out by competent personnel with the right ability, skill, and knowledge of the product being inspected [14]. Competent Quality Managers should oversee quality management, and the quality department should work towards improving the standard of quality management, thereby improving the success of a company’s projects. A Quality Manager should be responsible for overseeing the completion of quality audits, conducting and reviewing quality plans, and the training of on-site operatives [14, 15]. Therefore, promoting a positive quality culture, where workers and managers are encouraged to achieve high levels of quality assurance, and to remain motivated whilst addressing the challenges faced is fundamental to the successful application of quality control [3]. These could inherently improve overall site and project safety, health, and wellbeing of the workforce.

Quality culture is the pattern of habits, beliefs, and behaviour regarding quality [16], and these values, beliefs and hopes that are promoted and developed within members of an organisation in relation to their work leads to the delivery of high-quality products and services and improved total quality management [17]. The benefits of improved quality management which is reliant on efficient management of project delivery are associated to project profitability, improved company image, and safety which are some of the factors that the industry struggles with. Construction companies place significant emphasis on encouraging the self-reporting of safety issues and there is a general perception that the recording of non-conformances which is regarded as the failure to conform to specifications or requirements presents an image of poor quality and poor project management [18].

The adoption of the Inspection test plan (ITP) that details how the quality of a particular set of works is managed based on drawings and identifying a set of warranties, inspections, and specifications for ease of examination of the product is part of the overall project quality management system. An ITP could be considered as the job's quality assurance tool used to inspect all works that are undertaken to ensure compliance with the standards set out in the specification towards improving client-contractor relationships. Rumane (2017) suggests that inspections are an efficient and productive way to ensure all materials, systems, and workmanship applied on site are to the required standards. Although the sign off sheets are an efficient inspection method, they are however not adequate enough and it is ideal to accompany that with an Inspection Test plans throughout the process rather than at the end of the cycle [3]. With the use of ITPs and check sheets to manage quality, cases of onsite health and safety can be easily managed. Viewpoint allows for the digitized, consistent and automated quality processes (i.e. inspections and tests including associated drawings and specification sheets could be uploaded online) with the main contractor and client having real time update with the ability to evaluate performance, analyze trends, and access compliance [8]. The adoption of the ITPs throughout the build process rather than at completion allows for the defects/errors to be identified and rectified, resulting in lower costs and improved safety, quality, and duration of the construction project [12].

The cost of quality in construction is the value of incurred costs associated with the maintenance geared towards achieving high quality and client satisfaction. Existing study suggests that the benefits of better quality outweigh the costs, however, increased quality cannot be achieved without an increase in cost and the benefits to the company from increased quality will not necessarily compensate for the additional cost involved [19]. The cost of quality is considered to be much more than the cost of reworks, as it also translates to loss of customers, loss of market share, and other unforeseen costs [19]. The CIOB estimates that up to 2.5% - 5% of construction costs are associated with remedial works [3], and considering the tightly squeezed low profit margins of the construction industry of 1-3%, the costs of poor quality can have detrimental effect on the project's profit margins and the need to get it right the first time becomes invaluable [12]. Although it is almost impossible to get the full project right the first time, the most effective way to prepare for and counteract poor quality could be the adoption of Viewpoint towards improving the Total Quality Management (TQM) plan. This is important because quality in construction can often be viewed as time consuming and tedious (e.g. with under staffing), and this results in quality tasks being disregarded or rushed (lack of inspection) which results in poor workmanship [20]. The short durations that subcontractors have on specific projects and the lack of continuity [21] could potentially compromise the health and safety of the entire project if there are no structured approach in place to monitor quality. Therefore, the adoption of Viewpoint as a technology capable of improving the workers' efficiency [21] and making efficiency gains related to quality is considered significant in the construction industry [3, 22].

3. METHODS

This paper adopted the qualitative approach towards evaluating the effectiveness of Viewpoint for improving quality assurance [23]; whilst developing some level of understanding for the subject under consideration and to allow for more comprehensive response from the participants using semi-structured interviews [24, 25]. The involvement of participants reflecting on case studies was essential towards understanding the complexity of issues in a real-life scenario [26]. The participants' experiences were based on their direct involvement in case studies with a major UK principal contractor with established understanding into the effectiveness of Viewpoint for quality, quality assurance, snagging, and safety improvements. This builds on the detailed knowledge of the users and their organization's experiences in the adoption of the software across multiple projects. The profile of the participants involved in the semi-structured interviews (via MS Teams) include Senior Project Managers, Quality Managers, and Engineers involved in the regular use of the software across projects (Table 1). The participants were sent a description of the study, proposed interview plans, rationale for contacting them to participate in the study, privacy information, and a consent form regarding voluntary participation in line with approved ethical guidelines.

Table 1: Participant information

Participant	Role	Years with employer	Years of Experience
A	Quality Manager	2	22
B	Site Engineer	5	5
C	Senior Engineer/Mgr	3	20

D	Site Manager	5	5
E	Site Engineer	5	6
F	Senior Site Engineer	12	12
G	Head of Digital Construction	3	25+

The emerging themes from the semi-structured open-ended interviews were aligned to extant literature to develop a robust understanding of the effectiveness of Viewpoint as a software for improving quality assurance in construction. The interview questions focused on two aspects/features of Viewpoint – 'Viewpoint for Projects' and Viewpoint 'Field View' to reflect the participant's own perceptions and experiences of using the software [27]. The Viewpoint for Projects is a cloud-based project collaboration tool deployed by contractors to communicate, control, manage, and share information with relevant parties such as the client, authorities, design teams, subcontractors, and the principal contractor. Field View is part of the organization's aim to become fully digital whilst going paperless because it allows for the ease of information/data population and sharing of documents. As part of the organization's quality management policy, Inspection Test Plan (ITP) are used to manage quality by highlighting the relevant specifications, drawings and contractual responsibilities in terms of tests, materials, and requirements of warranties of the product. Field View is used to develop the ITPs through the use of Inspection Check Sheets (ICS). The interviews were recorded on MS Teams with the live captioning feature enabled for the audio recordings. The live captioning allows for the automatic generation of transcripts when a meeting is recorded, and when the meeting language is set to English. Thematic analysis was used to explore the data by identifying themes relevant to the research topic and these themes were grouped into nodes with the array of nodes aggregated together to reflect the views of the participants [28]. The steps adopted in generating the themes involves patterns of shared meaning, underpinned by a central meaning-based concept that emphasizes a uniting idea on main contractor quality, quality assurance, health and safety, and snagging [29]. This concept is based on the six steps of data analysis proposed by [30] which includes familiarization of data by the researcher; generating codes; combining the codes into themes; reviewing the themes; determining the significance of the generated themes; and reporting the findings. This whole process involved a continuous questioning and querying of the assumptions made that are relevant in the interpretation and coding of the research data to generate creative and interpretive stories about the data based on the researcher's thoughtful engagement with the interview transcripts and the analytical process [29].

4. FINDINGS AND DISCUSSIONS

4.1. Impact of Viewpoint on Main Contractor Quality

The participants' responses on the impact of Viewpoint on quality issues from their perspective as main contractors focused on the adoption of the Field View and Viewpoint for Projects, see Table 2.

Table 2: Impact of Viewpoint on main contractors' quality

Field View	**Viewpoint For Projects**
Quality Management	Common Data Environment
Inspection Check Sheets	Drawing control
Non-conformance Reports	

The participants believed the adoption of Viewpoint had a positive impact on quality indicating that the adoption of both Viewpoint for Projects and Field View were beneficial. However, the adoption of Viewpoint for Projects seemed to be most favoured as it is considered that the adoption of Field View offered marginal improvements on the quality of construction. The overall perception of the participants is that the impact of Viewpoint on quality is dependent on your site role and responsibilities. The benefit of adopting Viewpoint for Projects on quality in construction is evident on the available 'common data environment' useful for sharing submissions and drawings, thus improving communication and engagement amongst key duty holders resulting in significant increase in the quality of the Information Management and assessment of safety in design [31] in accordance with the UK Construction and Design Management (2015) Regulations. Due to the ease of real-time information sharing, there are consistency in the level of information being shared amongst the teams resulting in the management of quality issues, ease of communication with sub-contractors with any design changes, revisions or updates accessible to all parties involved. Therefore, the common data environment has positively improved information sharing, quality of construction and safety of the construction projects and this could be a proactive approach geared towards managing construction safety [32].

However, the participants suggested that the adoption of Field View slightly improves quality when compared to Viewpoint for Projects. Although the integration of the quality check sheets within Field View is beneficial, it thus seems like a ‘one size fits all’ document, and integrating some level of flexibility or add-ons within the software might be more beneficial to the users in terms of tailored quality checks. Furthermore, the addition of the quality management features within Field View streamlines the processes and improves efficiency because the inclusion of inspection check lists and non-conformance reports can be easily recorded onsite with pictures, compared to the more traditional methods. Due to the common data environment, the inclusion of pictorial information improves the level of understanding and communication that allows members of the team to review the reports and design changes, making it easier and beneficial for addressing and managing any health and safety critical features identified [33]. The adoption of Field View provides flexibility in reviewing other existing works because of the common data environment capabilities within Viewpoint, and this allows non-site-based workers access to site information which is useful for raising technical queries (TQs), non-conformances, hot works permits and permits to dig thereby improving collaboration and conflict management within projects [34].

4.2. Viewpoint in Quality Assurance

The systemic quality-related failures within the construction industry have been addressed by [35, 36]. The perception of the participants on the role of Viewpoint in mitigating quality assurance issues for principal contractors and sub-contractors are shown in Table 3, with emphasis on quality culture, SHEQ and quality related tasks.

Table 3: Role of Viewpoint in Quality Assurance

Principal Contractor	**Sub-contractor**
Up-to-date Drawings: up-to-date building information; improved confidence when assessing quality	Little to no impact on sub-contractors quality
Quality records: inspection check sheets; Non-conformance reports	Potential for increased efficiency: sub-contractors do not use it enough to full potential; training requirements
Increased efficiency	

The practitioners strongly believe that Viewpoint for Projects have a major impact on quality assurance for their organization due to its ability to ensure that the site teams have real-time access to the requisite up-to-date information (including revised drawings) required to build to approved construction standards rather than changes and revisions communicated via emails. The emphasis on the adoption of technology in construction is considered pivotal to the future of the construction industry [3], and the participants believe that lack of adoption of these types of technology is not fit for today’s industry. The use of Viewpoint for Projects contributes to efficiency gains within organizations when logging quality records and it is suggested to be highly beneficial for the organization and standard working practices, for example accessing up-to-date drawings and building information, and similarly SHEQ information via Field View.

Participants highlighted the significance of the adoption of Viewpoint as a quality assurance tool (based on ISO-19650) for principal contractors because of the common data environment but are yet to realise such gains with sub-contractors. The result of this could be traced to the lack of technological adoption, culture of resistance to change within the construction industry, and the heavy workload which can often impact on the commitment of sub-contractors to principal contractors’ procedures [21]. Some of the limiting factors to these cultural changes could be associated with the lack of training and upskilling within the supply chain and the principal contractor’s success or failure often relies heavily on sub-contractors and how they are managed. Overall, the participants agreed that the adoption of Viewpoint positively improved the organization’s method of measuring quality in terms of transparency between principal contractor and sub-contractor, keeping track of what non-conformance reports were identified, what has been closed off, and what inspections have been conducted and when. This allows the principal contractor to evaluate site performance and that of the sub-contractors in terms of workmanship and onsite health and safety towards achieving optimum quality in project delivery. Participants also suggested that the impact that Viewpoint can have on subcontractors’ quality is dependent on the sub-contractor’s size, ability to adopt and understand the technology, and the quality standards.

The significance of creating and maintaining positive quality culture is key to achieving optimum total quality management [15], and improved onsite safety because many industry failings have been the direct result of poor-quality culture [37]. The participants broadly agreed that the adoption of Viewpoint by their organization has positively impacted their quality culture due to the ease of access to the quality records and trends. However, to maximize efficiency, businesses should be striving towards upskilling their workforce through training and education. The participants indicated that Field View has had major impact on SHEQ in terms of the versatility that Field View offers and the efficiency it adds to SHEQ forms (inclusion of drawings, pictures of quality issues) for non-conformance reports which can be communicated in real time with the subcontractors to action and resolve quality-related issues in a timely manner

4.3. Field View for Health and Safety

The capabilities of Field View include accessing health and safety information inherent to the project, inspections, quality control, daily reports and punch list issues. The adoption of Field View in the delivery of projects ensures greater project control, real time accurate information capture and transparency on safety-related issues, quality, and defect management. Whilst quality standards of assurance are key factors in the success of a job, continuously improving health and safety is fundamental to the success of any project. However, there are opposing views from participants that the high standards of health and safety that are imposed on workers can sometimes be considered a distraction to the quality plan. That is why the implementation of an integrated quality plan in synergy with the health and safety plan is crucial in the survival of a construction organization now more than ever [3]. The downside of the inspection test plans (ITP) to identify errors which are reported via non-conformance or defect notice during the construction timeline is the requirement for a competent team to keep up with the volume of information and details. ITPs are also thought to be time consuming, and can be difficult to strike a balance between the priorities of the contractor and subcontractor as per quality, health and safety, and project schedule issues. Therefore, issues of poor quality which negatively impacts the image and profits of the organization also impacts on the overall project health and safety. Participants therefore believe Viewpoint has positively impacted their method of measuring quality performance and also useful for assessing health and safety related issues including Safety Environmental Observation Reports.

4.4. Viewpoint for Snagging

Every construction project requires the cooperative effort of several workers and stakeholders with each one having their own perspectives and interests, and the coming together of these different actors for the successful completion of the project involves managing different expectations and most importantly, minimizing building defects [7]. It is suggested that the primary indicators of construction quality are percentage cost of rework and rate of construction defects [12]. It is important that defects are identified early and Field View is useful as a snagging tool integrated within the common data environment. Field View's level of transparency between contractors is the key to improved snagging because of its increased mobility, ability to pictorially capture the snag and the contractor is able to add evidence of the snag and the remedial works undertaken. This feature is also a driver for sub-contractors to undertake their works to a higher standard because the duty holders involved have real-time access to the information. The identification and ease of location of snags with increased detail is another major advantage as the snag can be superimposed onto a drawing to identify the exact location and the study participants believe this feature removes any potential conflict the contractor might have in their assigned jobs. This feature has improved communication and resolution between the principal contractor and sub-contractors on issues of non-conformance (resulting from design, poor quality culture, and poor workmanship) by increasing job profitability and improving safety while sticking to the project quality plan and reducing repair costs. It is important to state that the adoption of Viewpoint as a technology for snagging becomes useful and beneficial to organizations when competent people, right processes and positive change of culture are embedded as the norm within the organization.

5. CONCLUSIONS AND RECOMMENDATIONS

The adoption of Viewpoint for quality assurance for all parties involved from the principal contractor and subcontractor suggest that the implementation of the technology is fundamental to improving workers' efficiency and quality gains in construction projects. The focus on the adoption of Viewpoint (Field View) as a snagging tool for identifying and resolving defects early can result in savings in project cost, improved standards of quality, and improved project safety. However, the true potential and impact of Viewpoint on quality in construction can only be achieved when organizations revolutionize existing quality culture that is endemic in the industry and work towards improving construction safety. The adoption of Viewpoint as a tool for identifying and resolving non-conformance resulting from design errors and poor workmanship is a significant development in quality management through the use of technology because recent quality failures from the construction industry has led to construction companies increasing the use and adoption of construction technology to maximise their performance, efficiency, and safety capabilities. Furthermore, there is perceived administrative burden on users that are site-based regarding the adoption of new technology, with older workers not keen to learn and embrace the adoption of the software. Similarly, sub-contractors struggle with the adoption of this technology due to time and resource pressures and the resistance of buy-in from operatives in learning new methods of quality assurance. This is why targeted and role-specific training is essential for operatives because of their differing levels of competency and their understanding of new technology useful for minimising information overload whilst maximising the capabilities of this software to improve quality and safety of projects.

Limitation – the data source for this study is limited to participants from same company but with slightly differing perspectives on the adoption of Viewpoint as a technology across multiple projects. Therefore, the views of the research participants may not be a fair representation of the industry as a whole.

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EXAMINING BIM-BASED AUTOMATED RULE-CHECKING TECHNIQUES IN CONSTRUCTION

Adeeb Sidani[1], João Poças Martins [2], Alfredo Soeiro[3]

[1]*CONSTRUCT – GEQUALTEC, Faculty of Engineering (FEUP), University of Porto, PT*
https://orcid.org/0000-0002-0570-1207
[2]*Built CoLAB; CONSTRUCT, Faculty of Engineering (FEUP), University of Porto, PT*
https://orcid.org/0000-0001-9878-3792
[3]*CONSTRUCT – GEQUALTEC, Faculty of Engineering (FEUP), University of Porto, PT*
https://orcid.org/0000-0003-4784-959X

Abstract

Research and Experimentation prove that construction safety planning and preparation during the Design phase significantly impact the safety of the construction workers. Construction work is an extensive and intense process consisting of several stages and activities that run simultaneously. The nature of the construction activities is dangerous and risky. Hence, construction workers' health and safety are threatened. However, previous studies claim that Designers and Architects are more concerned with the aesthetics of the building than with safety issues. In addition, they often lack construction safety knowledge, which is essential to effectively mitigate or reduce construction risks through design. This short review examines the Automated Rule checking tools that mainly assist in design for safety or Prevention Through Design (PtD) using BIM to oversee and mitigate construction risks during the construction phase. Based on a systematic review related to BIM-based health and safety practices, and after filtering the 99 collected articles, 19 articles related to Automated Rule checking were included in this short review. Findings suggest that the primary approach to preventing construction risks through design is creating an automated safety rule-based knowledge library for designers to automatically check the BIM models for specific safety risks. Moreover, assisting in construction safety planning and explaining the construction risks to designers and architects.

Keywords: Automated Rule checking; Construction Health and Safety; Prevention Through Design (PtD); Design for Safety; Building Information Modelling (BIM).

1. INTRODUCTION

Persistent health and safety procedures are applied to avoid construction accidents in the AECO (Architectural, Engineering, Construction and Operation) sector. Nevertheless, construction labour has the most serious accident and death rates among other sectors (Ahn et al., 2020).

In 2019, Occupational Safety and Health Administration (OSHA) registered around 200 thousand injuries related to construction work (Labor, 2019). The AECO sector is responsible for 9.5 fatalities per hundred thousand full-time workers. Similarly, one in five worker fatalities was in the AECO sector (Labor, 2019). According to the U.S. Department of Labour, Bureau of Labour statistics, the major causes of accidents and injuries are stuck-in, falls, struck-by-objects, and electrocution. These causes were responsible 2019 for 58.6% of the deaths of AECO workers (Labour, 2019). Furthermore, fatalities related to falls, slips, and trips increased from 805 in 2020 to 850 in 2021, representing a 5.6% increase in 2021 in all industries. The construction sector accounted for 370 of these fatalities in 2021, an increase of 7.2% from 2020, when there were 345 fatalities (Labour, 2022). Construction-related work is responsible for 951 fatalities in 2021 in the U.S., considered the second most occupational death in 2021 (Labour, 2022).

According to Wang's accident causations theory, five accident causations factors are responsible for accidents occurrence (Wang, 2018). These causation factors are Personal factors, Unsafe actions, Environment and Heredity, Management, Job factors, and conditions. Thus, organisation members must have safe environments and implement safety knowledge based on specific and detailed safety training to avoid risky behaviours before on-site construction. Moreover, the work site should constantly be supervised and monitored to prevent accidents (Wang, 2018).

The traditional safety approaches depend on manual supervision and monitoring. Hence, traditional approaches incorporate a lot of human errors and misjudgement (Eleftheriadis et al., 2017). There is an urgent need to shift to more digitalised and automatised prevention methods to overcome these traditional approaches that most construction industry still relies on (Zhou et al., 2015). Building Information Modelling (BIM) is one of the most promising tools being heavily investigated and implemented. BIM approaches, along with different contributions to the AECO sector, have the ability to assist in the automation of the safety management and coordination of the AECO sector (Eleftheriadis et al., 2017). Other research areas involving BIM for safety in the AECO sector are the usage of BIM in safety education and training (Clevenger et al., 2015). BIM for visualisation may facilitate the worker's and the student's skills to understand and identify construction concepts (Sidani, Dinis, et al., 2021; Sidani, Matoseiro Dinis, et al., 2021). Alongside safety automation, visualisation, training and education, BIM tools are widely utilised in various safety fields in the AECO, such as safety planning, monitoring, design for safety, safety inspection, and safety at the facility and management phase (Clevenger et al., 2015).

This review examines the present investigation in the field of BIM-based construction safety and Automated Rule Checking. Consequently, answering six essential questions provides an overview of the current interventions, objectives, targeted risks, targeted groups, hardware and software, assessment methods, standards, and regulations utilised to develop BIM-based Automated Rule Checking applications for safety in construction. The questions are as follows:

Q1. What are the main target groups?

Q2. What are the major risks being targeted by the BIM-based Automated Rule checking?

Q3. At which stage of the Project life cycle is the BIM-based Automated Rule checking implemented?

Q4. Which standards and regulations are being followed?

Q5. What tools and programs are used to fulfil the requirements of the intervention?

Q6. What are the limitations of BIM-based Automated Rule checking?

2. METHODOLOGY

The current review is based on a systematic review of BIM-based solutions for construction health and safety. The systematic review was performed with the leading electronic databases for scientific literature in multidisciplinary, construction and safety areas. The search underwent a snowballing technique examining the articles' references to investigate relevant studies from another electronic database that were not gathered during the search (Wohlin, 2014). Three keywords were used for the search: ("Construction, Occupational Health and Safety, and Building Information Modelling"). Furthermore, the authors considered the alternative expressions of each keyword, such as work health and safety, risks, accidents, and BIM.

After collecting the articles, the second step of the systematic review was screening the articles. Afterwards, the authors excluded conferences, reviews, discussions, and unpublished articles based on well-structured inclusion and exclusion criteria. Likewise, Studies not related to the AECO sector were rejected. 99 articles were considered adequate for the review, among which 19 articles targeted the fields of Automated Rule Checking for construction safety. Figure 1 mentions the number of fields each article targeted, considering that some articles mentioned more than one field totalling 129 fields targeted by the 99 articles. The search was performed in 2022, and the articles collected were up until August 2022. The authors did not consider any initial date.

The following sections demonstrate the results of the collected articles. All the listed questions are addressed following a discussion of the main findings, limitations, and the most promising tools to be considered, conclusions and future considerations.

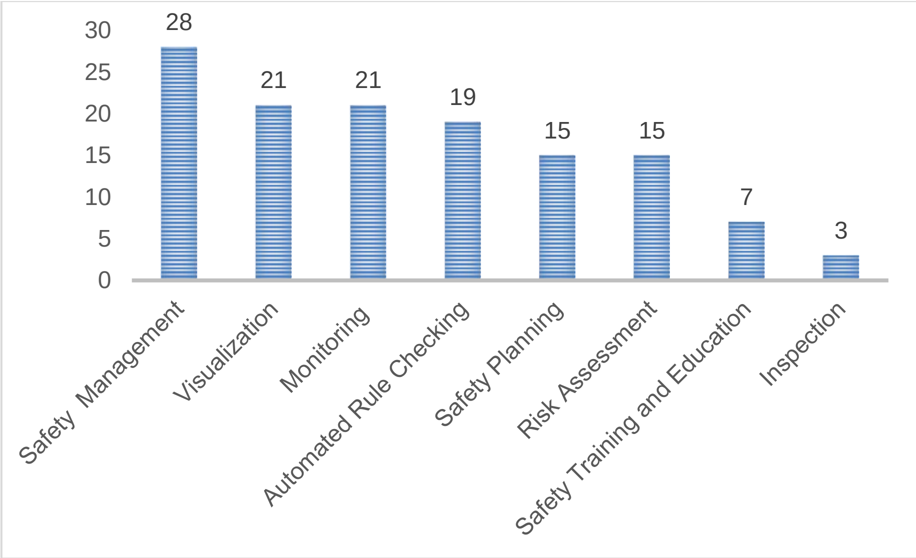

Figure 1. *Literature review results: Number of mentions for Safety Fields*

3. RESULTS

In order to facilitate the organisation of the information obtained from the 19 collected articles in the field of automation rule checking, the results will be categorised based on the six questions mentioned earlier.

3.1. Main Target Groups

The three main target groups that the authors focused on in their interventions are presented in Fig.2: Safety managers, with 11 mentions (Ji & Leite, 2018; Khan et al., 2019; Kim et al., 2018; M. Li et al., 2018; Malekitabar et al., 2016; Shen & Marks, 2016a; Wang et al., 2015; Yang et al., 2022; S. Zhang et al., 2013; S. Zhang, Boukamp, et al., 2015; S. Zhang, Sulankivi, et al., 2015), Designers/Architects with ten mentions (M. A. Hossain et al., 2018; M. M. Hossain & Ahmed, 2019; Ji & Leite, 2018; Khan et al., 2019; Lu et al., 2021; Rodrigues et al., 2021; Yuan et al., 2019; S. Zhang et al., 2013; S. Zhang, Sulankivi, et al., 2015; Zhou et al., 2021), and finally construction managers with three mentions only (Kim et al., 2018; B. Li et al., 2022; Y. Zhang et al., 2021). It is important to note that the final number is 24 mentions. Some articles focused on more than one target group. Also, some articles mentioned designers, and others referred to them as Architects in order to generalise the naming of the authors referred to them as Designers/Architects.

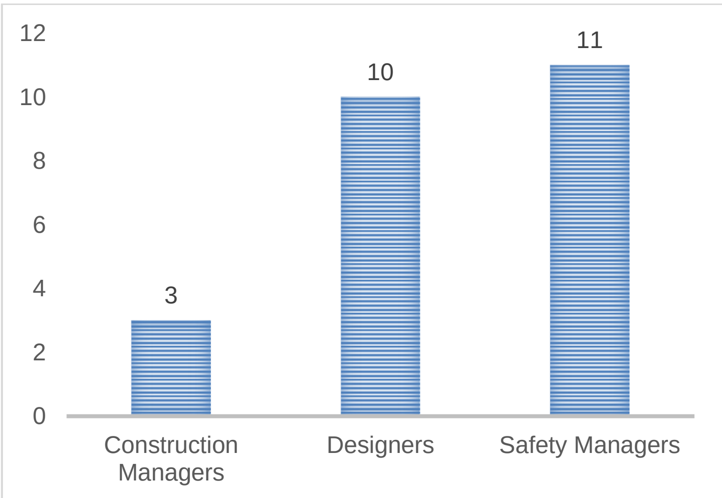

Figure 2. *Target Groups*

3.2. Major risks

Automated Rule Checking collected articles focused on ten major risks Fig.3. The articles represented the risks differently. Some mentioned work-related risks such as excavation, roofers, carpenters, and masonry work. Others mentioned risks related to machinery and tools such as cranes, scaffolding, or other heavy machinery. The rest mentioned risks, such as falls, electrocution, being caught in between, and caved in, among others. The authors of this paper merged some of the risks of the same nature. For example, excavation and underground-related risks are considered the same as caught in between, caved in, and risks resulting in working in confined spaces. Similarly, scaffolding-related work was considered as falls. The highest number of mentions occurs for Falls, with nine (M. M. Hossain & Ahmed, 2019; Kim et al., 2018; B. Li et al., 2022; Malekitabar et al., 2016; Rodrigues et al., 2021; Wang et al., 2015; Yang et al., 2022; S. Zhang et al., 2013; S. Zhang, Sulankivi, et al., 2015); following was excavation and underground related work with five mentions (Khan et al., 2019; M. Li et al., 2018; Malekitabar et al., 2016; Wang et al., 2015; Y. Zhang et al., 2021); general construction site risks were mentioned twice (M. A. Hossain et al., 2018; Yuan et al., 2019), and the rest of the risks were mentioned only once. It is worth mentioning that various articles targeted several risks, resulting in a total of 27 risks.

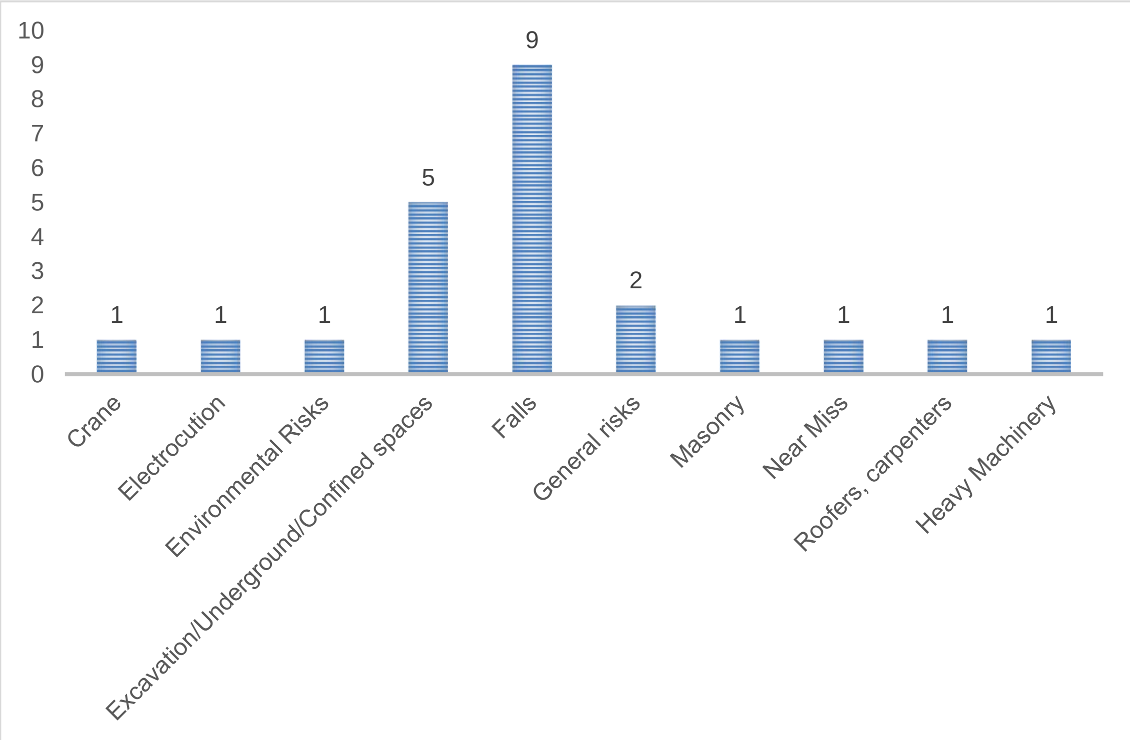

Figure 3. *Major Targeted Risks*

3.3. Construction phase

Only three construction phases were mentioned (Fig.4). The majority implemented in the Design Phase with nine mentions (M. A. Hossain et al., 2018; M. M. Hossain & Ahmed, 2019; Lu et al., 2021; Malekitabar et al., 2016; Rodrigues et al., 2021; Yuan et al., 2019; S. Zhang et al., 2013; S. Zhang, Sulankivi, et al., 2015; Zhou et al., 2021), Pre-construction with six mentions (Ji & Leite, 2018; Khan et al., 2019; Kim et al., 2018; M. Li et al., 2018; Wang et al., 2015; Y. Zhang et al., 2021), and the construction phase with five mentions (B. Li et al., 2022; Shen & Marks, 2016b; Yang et al., 2022; S. Zhang, Boukamp, et al., 2015; Y. Zhang et al., 2021).

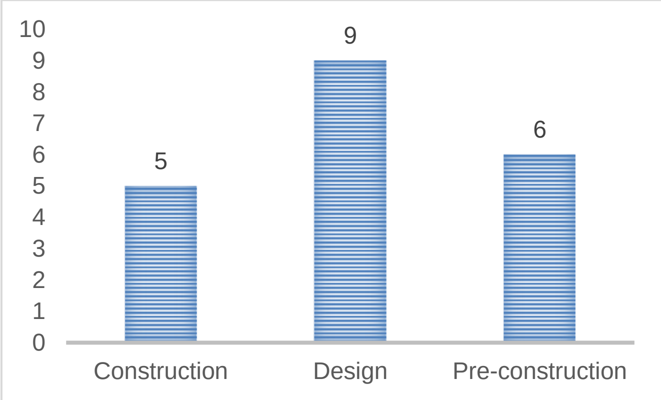

Figure 4. *Construction Phases*

3.4. Standards and Regulations

Only 14 out of the 19 collected articles mentioned standards and regulations that their work was based on, as shown in Table 1. Most authors implemented OSHA regulations or national/local regulations. Some authors used specific parts of OSHA. For example, Ji based their work on ASME B30.3- 2016 Edition “Tower Cranes” (Ji & Leite, 2018). While other others referred to OSHA for best practices (Rodrigues et al., 2021; Wang et al., 2015; S. Zhang, Boukamp, et al., 2015). Tab.1 summarises the results.

Table 1. *Standards and Regulations*

Article Title	Standards and Regulations
Construction safety risk drivers: A BIM approach	• OSHA - The National Institute of Occupational Safety and Health (NIOSH) has conducted a study on Fatal Accident Circumstances and Epidemiology (FACE) • OSHA comprises 70 ‘‘fatal facts” that fall in the category of construction accidents Iran’s safety code • International Risk Governance Council (IRGC),
Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modelling	OSHA - Standards and industrial best practices OSHA 1926.652 (a)(1)
Automated tower crane planning: leveraging 4-dimensional BIM and rule-based checking	OSHA - **ASME B30.3- 2016 Edition** “Tower Cranes” and Occupational Safety and Health Administration (OSHA) electronic code of federal regulations **(e-CFR) Title 29, Part 1926**, Subpart CC – “Cranes & Derricks in Construction.”
BIM-based fall hazard identification and prevention in construction safety planning	OSHA
Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules	• OSHA • Construction Industry Best Practices” • Construction Safety Alliance - Examining Causes of Construction Injuries and Defining Best Practices That Improve Safety Performance, Construction Information Quarterly, Chartered Institute of Building, Ascot, U.K., 2004”
Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)	• OSHA - regulations and industry safety best practices • OSHA regulation 1926, • The Occupational Injury and Illness ClassificationManual, and Construction Solutions Database.
Excavation Safety Modeling Approach Using BIM and VPL	OSHA
Safety plugins for risks prevention through design resourcing BIM	• OSHA - Occupational Safety and Health Administration and good practices guidelines • Portuguese safety legal regulations (DL273/2003 and DL 41821/1958) and the OSHA 1926–501 (2019). • Regulation no. 101/96 of April 3 (Portaria no. 101/1996)
An automated safety risk recognition mechanism for underground	• Guidelines for tunnelling risk management • Assessment of the Safety of Tunnels” construction technical manuals

construction at the pre-construction stage based on BIM	
Design-for-Safety knowledge library for BIM-integrated safety risk reviews	Building Regulation in the UK
BIM-integrated construction safety risk assessment at the design stage of building projects	• BLS Injuries, Illnesses, and Fatalities (IIF) program • Census of Fatal Occupational Injuries (CFOI) of the IIF program • Survey of Occupational Injury and Illness (SOII) of the IIF program • 2010 Standard Occupational Classification (SOC) system • BLS Occupational Employment Statistics (OES • RSMeans Data
Towards a unifying domain model of construction safety, health and well-being: SafeConDM	BG Bau 100 regulation
Developing an automated safety checking system using BIM: a case study in the Bangladeshi construction industry	• Bangladesh National Building Code (BNBC-2006) • Bangladesh Labor Acts (BLA- 2006),
Accident prevention through design (PtD): Integration of building information modeling and PtD knowledge base	• Mandatory provisions of project construction standards (building construction part) • The standard for safety inspection of building construction" in China, • Safety regulations, documents, and best practices

3.5. Hardware, software, and Data Exchange Formats

Most articles listed the BIM software used, the languages in which they created the algorithms or risk databases, and the Model checker programs. In addition, the authors listed the data exchange format used. Table 2 summarises the hardware, software and data exchange formats employed or developed by the authors and the file formats that the authors adopted.

Table 2. *Hardware, Software and Data Exchange Formats*

Title	Tools
Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling (Wang et al., 2015)	• Algorithms were developed in Matlab™ • Commercially available terrestrial laser scanner • GIS
A BIM-based identification and classification method of environmental risks in the design of Beijing subway (Zhou et al., 2021)	• Autodesk Revit • Safety evacuation design toolbox (SEDT) • 3Dmax • Navisworks • 3D GIS Engine "Citymaker Server V7.0." • FDB (feature database)
Automated tower crane planning: leveraging 4-dimensional BIM and rule-based checking (Ji & Leite, 2018)	• Autodesk Revit • Microsoft Excel • Solibri Model Checker v9.7 (SMC) • IFC data exchange format
Towards a unifying domain model of construction safety, health and well-being: SafeConDM (B. Li et al., 2022)	• Autodesk Revit • Graphisoft Archi- CAD • IFC data exchange format
Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA) (S. Zhang, Boukamp, et al., 2015)	• The SemanticWeb Rule Language (SWRL) • IFC data exchange format
Accident prevention through design (PtD): Integration of building information modeling and PtD knowledge base (Yuan et al., 2019)	• Autodesk Revit • Microsoft Access is used to create a PtD knowledge base for safety risks related to design, laying the foundation for the automatic detection of PtD. • Microsoft Visual C# • A plug-in based on Revit was developed in this research to implement the automatic inspection of rules,

Design-for-Safety knowledge library for BIM-integrated safety risk reviews (M. A. Hossain et al., 2018)	• Microsoft's C# (build the DfS rule-based knowledge library) • Reasoning Engine reads BIM-compliant digital models in IFC format and comprises a set of safety-checking algorithms. • MySQL • IFC data exchange format
BIM-integrated construction safety risk assessment at the design stage of building projects (Lu et al., 2021)	• Autodesk Revit 2018 plugin was created • Revit API to develop Windows Presentation Foundation, • C# language for further development based on Microsoft Visual Studio 2017.
Safety plugins for risks prevention through design resourcing BIM (Rodrigues et al., 2021)	• Revit API, "Job Hazard Analysis" (JHA) plugin developed, • C# language • "SafeObject" plugin
Semantic IFC data model for automatic safety risk identification in deep excavation projects (Y. Zhang et al., 2021)	• Autodesk Revit • ArchiCAD • Construction Risk Identification System (CRIS) Prototype
Developing an automated safety checking system using BIM: a case study in the Bangladeshi construction industry (M. M. Hossain & Ahmed, 2019)	• Autodesk Revit • Solibri Model Checker (SMC 2014). • IFC data exchange format
Near-Miss Information Visualization Tool in BIM for Construction Safety (Shen & Marks, 2016a)	• Autodesk Revit • Open application programming interface (API)
An automated safety risk recognition mechanism for underground construction at the pre-construction stage based on BIM (M. Li et al., 2018)	• SPSS20.0 software for cluster analysis • SQL database software is used to store the safety risk knowledge • BIMQL, which is an open query language for building information models, combines • IFC standard database with the BIM-cloud by designing a set of query systems. • Backus-Naur Form method, engineering information in the BIM models can be well read in the BIM platform
Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules (S. Zhang et al., 2013)	• Tekla Structures
BIM-based fall hazard identification and prevention in construction safety planning (S. Zhang, Sulankivi, et al., 2015)	• Tekla Structures that incorporate the safety rule-checking algorithms • IFC data exchange format
BIM-Driven Automated Decision Support System for Safety Planning of Temporary Structures (Kim et al., 2018)	• A decision-making engine was created to support decision-making for scaffolding. • Created Simulation Engine
Excavation Safety Modeling Approach Using BIM and VPL (Khan et al., 2019)	• Autodesk Revit • Visual programming language (VPL) • Hummingbird • Rhino - Grasshopper (plug-in)

3.6. Limitations of Automated Rule Checking

Limitations can be classified into six categories. The first category refers to limitations related to the BIM models. In general, the models need to be developed to a relatively high maturity stage. In addition, models often contain inaccurate, incomplete or incorrect information, need to be more automated to reduce the manual efforts needed for modelling work and scheduling, require more safety design elements and natural constraints of the construction sites still cannot be accurately modelled, thus, lacking the realism of construction sites (M. A. Hossain et al., 2018; M. M. Hossain & Ahmed, 2019; Ji & Leite, 2018; Khan et al., 2019; Malekitabar et al., 2016; Shen & Marks, 2016a; Yuan et al., 2019; S. Zhang et al., 2013; S. Zhang, Boukamp, et al., 2015; S. Zhang, Sulankivi, et al., 2015; Zhou et al., 2021).

The second category refers to safety risks-related limitations. The databases and libraries for risks are lacking. Most authors targeted one or few risks because they could not access extensive safety databases. In addition, automation of risk detection should be increased for multiple scenarios and needs to include environmental and spatial analysis. Similarly, the detection of dynamic safety hazards is missing. Still, manual efforts are needed to contextualise safety rules into computer language and complex and complete algorithms to refine safety risks are required. Model checkers still lack the integration of safety regulations and standards (M. A. Hossain et al., 2018; M. Li et al., 2018; Rodrigues et al., 2021; Wang et al., 2015; S. Zhang et al., 2013; Zhou et al., 2021).

As a third category, there are limitations related to the case studies. These are mostly related to one risk in a single construction site or a controlled environment. More complex case studies should be done with more risks and a variety of construction site typologies (M. M. Hossain & Ahmed, 2019; B. Li et al., 2022; Malekitabar et al., 2016; Wang et al., 2015; S. Zhang et al., 2013; S. Zhang, Sulankivi, et al., 2015).

The fourth category includes limitations related to the steep learning curve of implementing Automated Rule Checking tools and procedures. Not all personnel involved in the construction work have the same educational level, modelling experience, or using digital tools. Thus, Automation Rule Checking makes it very difficult for some workers to understand and extract the required information. Visualisation of the Automated Rule Checking information is also considered a limitation, and there is a need to introduce immersive tools in order to facilitate training, education, and visualisation (M. M. Hossain & Ahmed, 2019; Khan et al., 2019; Shen & Marks, 2016a).

The fifth category refers to limitations that result from the interoperability of the file exchange formats. Most of the authors used IFC as the preferred data exchange format. Nevertheless, IFC presented interoperability issues. Moreover, IFC needs to be expanded to target more risk types (S. Zhang, Boukamp, et al., 2015; S. Zhang, Sulankivi, et al., 2015; Y. Zhang et al., 2021).

The sixth and final category includes limitations related to Standards and regulations. Most of the authors were able to verify models for compliance with some of the regulations related to construction safety. However, most of the rules are not verifiable due to limitations in available software tools, modelling development practices or in the nature of the rules themselves (M. M. Hossain & Ahmed, 2019; Yuan et al., 2019; S. Zhang et al., 2013).

4. DISCUSSIONS

Designers and Safety Managers were mentioned in 21 out of 24 by the authors, leaving Construction Managers with only three mentions, as shown in Fig. 2. This shows a clear trend favouring Architects/Designers and Safety Managers before construction works. Moreover, the Pre-construction and Design phases were mentioned 15 times out of 20, and the Automated Rule Checking tools were used only five times during the construction phase.

Several articles did not contain any reference for regulations, standards, or best practices. The OSHA regulations had ten mentions. Precisely, the authors selected specific chapters and topics to include in their work.

The most mentioned BIM modelling tool was Autodesk Revit, with ten mentions, while Tekla structure and ArchiCAD were less common and were mentioned twice and once, respectively.

Considering Rule checking programs, Solibri Model Checker was mentioned twice (M. M. Hossain & Ahmed, 2019; Ji & Leite, 2018). Six authors created different model-checking tools (M. A. Hossain et al., 2018; Khan et al., 2019; Kim et al., 2018; M. Li et al., 2018; Y. Zhang et al., 2021; Zhou et al., 2021). Five authors created plugins (Lu et al., 2021; Rodrigues et al., 2021; Shen & Marks, 2016a; Yuan et al., 2019; S. Zhang, Sulankivi, et al., 2015), as described in Table 2.

Regarding Data Exchange Format, the authors mentioned IFC the most, with almost no other Data exchange format mentioned, as shown in Table 2.

5. CONCLUSION

Automated Rule Checking seems a promising approach to improve safety levels in construction. Investigation in this field is currently expanding, and more model-checking tools, safety libraries, databases, and best practices are being created, facilitating the execution of Automated Rule Checking techniques. Furthermore, standards, regulations and best practices are being translated into computer languages, enabling the implementation of more risks. It is believed that the advancement of Artificial Intelligence automated Rule checking for safety will involve more risks that are hard to translate to machine languages.

Automated Rule checking still faces some limitations. First, the environment of construction sites is constantly changing, so it may not be possible to automatically check all unsafe conditions in a BIM model in real-time. Moreover, manual effort in rule interpretation is still required for rule translation into machine-readable code. Furthermore, there is still a lack of safety and risks databases regarding modelling, reports, best practices, and algorithms. More immersive training and visualisation tools are required to assist with the steep learning curve and enable construction workers to clearly understand the models, risks, and prevention methods. The interoperability issue of IFC is improving, but it is still necessary to incorporate safety risks. Finally, standards and regulations should be modified to facilitate the adaptation to computer language.

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THE MATURITY MODEL OF IMMERSIVE TECHNOLOGY APPLICATIONS USED FOR SAFETY TRAINING IN CONSTRUCTION: A SCIENTOMETRIC ANALYSIS

Farisya Abu Bakar[1], Clara Cheung[2], Akilu Yunusa Kaltungo[3], Saeed Reza Mohandes[4] and Eric Lou[5].

[1]PhD Candidate, Department of Mechanical, Aerospace and Civil Engineering (MACE), University of Manchester, M13 9PL, UK.
[2]Senior Lecturer in Project Management, Department of Mechanical, Aerospace, and Civil Engineering (MACE), University of Manchester, M13 9PL, UK.
[3]Senior Lecturer in Reliability and Maintenance Engineering, Department of Mechanical, Aerospace, and Civil Engineering (MACE), University of Manchester, M13 9PL, UK.
[4]Postdoctoral Research Associate, Department of Mechanical, Aerospace, and Civil Engineering (MACE), University of Manchester, M13 9PL, UK.
[5]Reader in Project Management, Department of Engineering, Manchester Metropolitan University, M15 6BH, UK.

Abstract

Though there is growing interest in the utilisation of immersive technologies (ImT) for improving the effectiveness of safety training in construction projects, limited research has been conducted to assess the organisational readiness of adapting ImT for this purpose. This study aims to identify the prevalent maturity models (MMs) used in evaluating maturity level for ImT application in construction, through a systematic literature review (SLR). The study found that most studies were published between 2019 and 2021; and showed that United Kingdom, China, and Australia, have the highest rankings in the development of maturity models for ImT application in the construction industry. The mapping of 23 selected papers demonstrated that the current maturity model research used for ImT application is applicable to 18 objectives such as safety training and visualisation and communication. The paper revealed that many researchers have been focusing on developing new models rather than using or enhancing the existing ones. The findings of this study could enable researchers and practitioners to understand the status of using maturity models to assess the readiness of ImT application in construction.

Keywords: Technology readiness levels; Immersive technologies; Construction safety; Occupational safety and health; Maturity model.

1. INTRODUCTION

Safety training is one of the most common interventions to improve safety performance in construction. Indeed, effective training was identified as a critical success factor in some of the earliest studies on safety interventions (Tezel et al., 2021). Several studies have identified safety training as a factor for reducing the rate of unsafe acts and behaviours. Solís-Carcaño & Franco-Poot (2014) found that workers with minimal safety training and weak safety culture are more prone to accidents. Tam & Fung (2012) discovered that mandatory training increases construction employees' interest in safety. Hence, workers receiving safety training is critical to the development and management of safety programs. Ho & Dzeng (2010) demonstrated that appropriate safety instruction has the capacity to encourage safe behaviour. Kaskutas et al. (2013) concluded that employees who had undergone safety training established more effective safety communication practices. In other words, an effective constructing safety training programme with standardised rules for planning, management, and administration could improve safety performance by decreasing the accidents frequency (Getuli et al., 2021).

Nevertheless, construction projects are now facing increasing demands to keep up with the various pressures, needs, and objectives in safety training practices, which require the utilisation of innovative materials, methods, and technologies to establish adequate training skills that are compatible with project requirements (Mouchi et al., 2011). To meet these needs, the construction industry is beginning to embrace immersive technologies (ImT), so as to minimise the risks and complexities associated with conventional safety training in construction projects. A considerable amount of previous research suggest that integrating ImT into safety training programmes is an effective way of boosting training efficiency and quality, by capturing trainees' attention and reinforcing learning in construction related safety training (Chen et al., 2013; Sacks et al., 2013; Zhao & Lucas, 2015). According to Alizadehsalehi et al. (2020), ImT represents a 360-degree area in which to expand reality or to build new universes using virtual reality (VR), augmented reality (AR) and mixed reality (MR). Each of these technologies is constantly evolving in order to assist employees in simulating real-world scenarios and train them in a safe and engaging immersive training environment.

ImT has an advanced approach that can help employees gain training experience in a more engaging and personalised manner within a risk-free environment (Jeelani et al., 2017; Noghabaei et al., 2020), allowing organisations to improve the effectiveness of safety performance throughout construction projects. Immersive training can help in keeping learners' safety knowledge and skills up to date so they can handle complex or new hazards. For example, VR systems have conventionally concentrated on boosting the sense of vision, but recently VR technology has expanded to encompass wearable headset technologies that are putting a greater emphasis on audio feedback using headphones (e.g., demolition sounds), and on physical simulations for materials (e.g., rigid bodies, joints, characters, robots) (Grassini, 2020). Trainees can obtain knowledge-based safety training through a gamified scenario that includes active exploration and human-computer interaction (Gavish et al., 2013). This gamification also allows trainees to experience the entire project, including its interior and outside locations, with a much greater realism (Ahmed 2019).

The development of ImT application takes time but most importantly depends on organisation readiness. Due to the complexity of such developments, collaboration with other organisations is required to acquire, develop, and exchange various types of knowledge, information, and other resources. Therefore, organisations almost never innovate in isolation (Charles Edquist, 2013). Other businesses (suppliers, customers, competitors) may be included in these organisations, but they may also include universities, research institutes, investment banks, schools, government ministries, and so on. Organisations frequently establish relationships with other types of organisations through their innovative activities; thus, viewing innovating firms as isolated, since individual decision-making units face fierce challenges and delays (Charles Edquist, 2013). In this research context, the successful implementation of ImT for construction safety training requires large financial and human resource investments. Identifying, analysing, and comprehending elements (i.e., capability attributes) and stakeholders that influence the organisation, both internally and externally, is necessary for successful management (Clarke & Flitcroft, 2013). Therefore, to support organisations in evaluating their readiness for deploying ImT in safety training, developing an ImT readiness model in this context could help them to conduct these analyses.

As a process improvement safety training method, the maturity model helps organisations understand their existing capabilities and provides a systematic path to improve their capabilities to reach higher maturity levels (Facchini et al., 2019). In a variety of industries, maturity has different definitions. Maturity is a concept that describes the gradual development of project management systems and processes that can be used to assess an organisation's capabilities and provide a route for improvement (Pennypacker & Grant, 2003). In terms of technology development, maturity is considered as a process management tool that streamlines all processes, demonstrating that maturity models (MMs) and their definitions are industry-specific (Tocto-Cano et al., 2020). Even though ImT has been shown to improve training performance and the ability to identify potential hazards on a construction site more effectively, and that many MMs have been developed in the construction industry, little research has been conducted to determine their readiness for ImT application in construction safety training. This suggests the idea that even though MMs share fundamental similarities, their definitions vary and provide different meanings considering the context. In this regard, there is a clear need for research to be carried out the construction MMs to develop a definition for the ImT application in safety training development context. It is intended that the maturity model adopted by the study reflect the capability attribute perspective in terms of people, processes, technology, and finances. This perspective is suitable for evaluating the organization's readiness when it comes to invest resources in training method for construction safety. Hence, this study begins by reviewing the extant literature on ImT applications for safety training in the construction industry. The study identifies the prevalent MMs available, and the approach used in evaluating maturity levels for ImT applications in construction. The study aims to address the following research question:

- What is the current state of maturity model deployment for ImT applications in the construction industry?

2. METHOD

Based on the research question, a systematic literature review (SLR) was used to identify relevant publications as well as assess their quality, using well-defined procedures (Khan et al., 2021). It is distinguished from traditional reviews and comments by its specific and systematic methodology. This research was designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement, which provides guidelines to facilitate the reporting of SLR. Although PRISMA is not an evaluation tool for determining SLR quality, it can provide both researchers and practitioners with evidence-based insights about a specific topic or research problem (Petersen, 2019).

2.1 Identification of relevant studies

In order to identify publications that are relevant to the use of MMs for ImT application in construction, a meticulously constructed set of keywords was formulated for searching the significant literature databases. For this SLR, Scopus database was selected due to its multi-disciplinarity and size. To optimise the refinement process, filters were specifically designed for the titles, abstracts and keywords. Collectively, the filters were utilised to identify relevant publications (Moore et al., 2019). As it was difficult to identify relevant publications when using “safety training”: as a keyword, it was initially removed from the search formulation process. During the identification process, the initial idea to include the keyword "health and safety" was scrapped. This is because most publications only concentrating on the maturity model for organisational change, with no mention of ImT. While this review is intended to determine the maturity model used for the ImT application in safety training. Figure 1 illustrates the search string used in the study.

2.2 Study Selection

Figure 1 summarises the three stages of the SLR process used in this study. A paper retrieval process related to the maturity model used for ImT application in construction was filtered according to exclusion criteria. This was carried out as follows:

i. The initial stage of exclusion aided in the identification of relevant publications from a wide range of subject areas. To be precise, a complete examination of the literature covering engineering, computer science, social science, and management subject areas were selected as a foundation for this research, to establish the possibility of developing these topics further.

ii. The second stage of exclusion involved a quick review of the title, abstract and keywords in order to eliminate publications that did not discuss the maturity model for ImT application in construction, hence considered irrelevant to the target topic area. The review only focused on studies written in English language, with full-text reviews available. Papers that merely discussed the ImT application in construction without proposing any maturity model were deemed ineligible for review. The publications that met these criteria were then put through Mendeley reference management software for identification of possible repititions, which then yielded 23 papers for further evaluation and analysis. At this point, table outlines were constructed.

iii. The concepts in the category research content emerged gradually by analysing the publications. Each publication was classified with keywords, summarising the content in a coarse way. The final concepts are subsequently explained as follows:

    a. Concept/construction: publications where a maturity model is developed (conceptual) or constructed (design-oriented),
    b. Description: publications where existent MMs are described for presentation purposes or as applicable methods or instruments,
    c. Mapping/comparison: publications where existing MMs are compared and mapped to each other or to other maturity evaluation concepts,
    d. Assessment: publications where the maturity of industries, organisations, etc. is assessed (not the assessment, in terms of validation, of the model itself),

e. Transfer: publications where an existing maturity model is applied to another domain or research field without changing the model or developing a new one,
f. Empirical study: publications where an empirical study (qualitative, quantitative, and mixed) has been conducted to develop, apply, or validate MM, assessments, or other purposes,
g. Theoretical reflection: publications where theoretical implications of MMs are discussed; for example, applicable theories, measurement approaches, theoretical benefits, and others.
h. Others: publications that could not be classified into any of the aforementioned concepts.

Based on these premises, 23 publications published between January 1998 and March 2022 were initially retrieved using the Scopus search string formation. The Scopus database was used because its literature is indexed from a variety of disciplines, journals are ranked by their h-index, and content is chosen for scientific quality as well as a technical infrastructure to guarantee full coverage (Baas et al., 2020). An extra filtration process was utilised during the screening process to ensure that all extracted publications were related to the study's objective. This stage led to the removal of publications that were published between 1998 and 2000, owing to the misalignment with ImT application in the construction industry and in the context of maturity model, hence did not address the primary research objective.

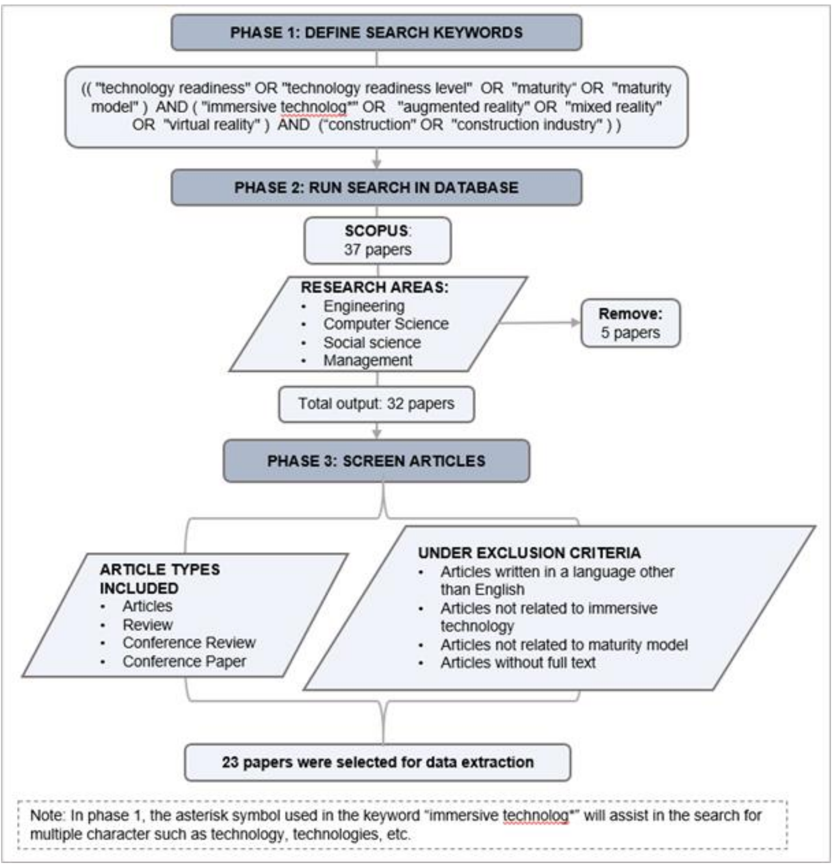

Figure 1: Four-stage SLR process.

2.3 Scientometrics analysis

The papers selected from Scopus were subjected to scientometric analysis. The VOS viewer software was used to build and visualise bibliometric networks based on citation, bibliographic coupling, co-citation, or co-authorship connection indicators throughout the specified topic area from journals, researchers, or individual publications (DeGroote, 2023). This approach helps researchers to identify particular concerns, generate subject themes within a given area, and specifically, determine the amount of representation of relevant studies within the field. This, in turn, makes it easier to identify important research streams and future research objectives. This analysis approach was employed in this study to gain deeper insights into and comprehension of the phenomena under scrutiny within a range of studies (Adekunle et al., 2022).

3. RESULTS AND DISCUSSIONS

The final sample included 23 publications that presented the maturity model used for ImT application in the construction industry. These publications comprised 22 original research (i.e., 20 journal and 2 conference publications) and 1 review publication. Figures 2a, 2b, 2c and 2d illustrate the total number of publications by year, country, subject areas, and papers that related to developed MMs, which may provide an indication of how much research has contributed to the deployment of MMs for ImT application in construction.

To get an overview of the trends in MMs research, the papers in the study were analysed by the year of publication. The publications were evenly distributed over the years until 2018 (with an average of one paper per year), as can be seen from Fig. 2a, after which the number begins to rise gradually. The development of the maturity model for ImT in construction began in 2000 with the assessment studies on VR applications; the library-based approach, straightforward translation approach and database approach, which were used as tools to improve construction processes for data organisation. Although the development of a maturity model for ImT application has been established since 1998, there are no publications relating to the maturity model for ImT application in construction for that timeline. One of the reasons for this underrepresentation is that the concept of ImT was still undergoing notable development, with education and training as the main area of application (Mencke et al., 2017). The number of yearly publications stayed around one until 2018. In 2019, it appears that the subject began to garner attention and there was a considerable increase in the number of publications. This is demonstrated by additional papers in 2019 and 2021, which produced 3 and 8 papers, respectively.

In Figure 2b, China and the United Kingdom (UK) generated the most papers based on the first author of the paper published, contributing four publications each. A reasonable justification would be that the UK has been leading the research and technology advancement in visualisation for a number of years. According to the Institute of Personnel (2020), digital learning was extensively available in the UK prior to the COVID-19 outbreak, with more than 200 businesses offering online learning for adult learners with low to intermediate abilities. Meanwhile, three publications originated from Denmark, with nations such as Australia, Canada, Vietnam, France, etc., contributing one publication each.

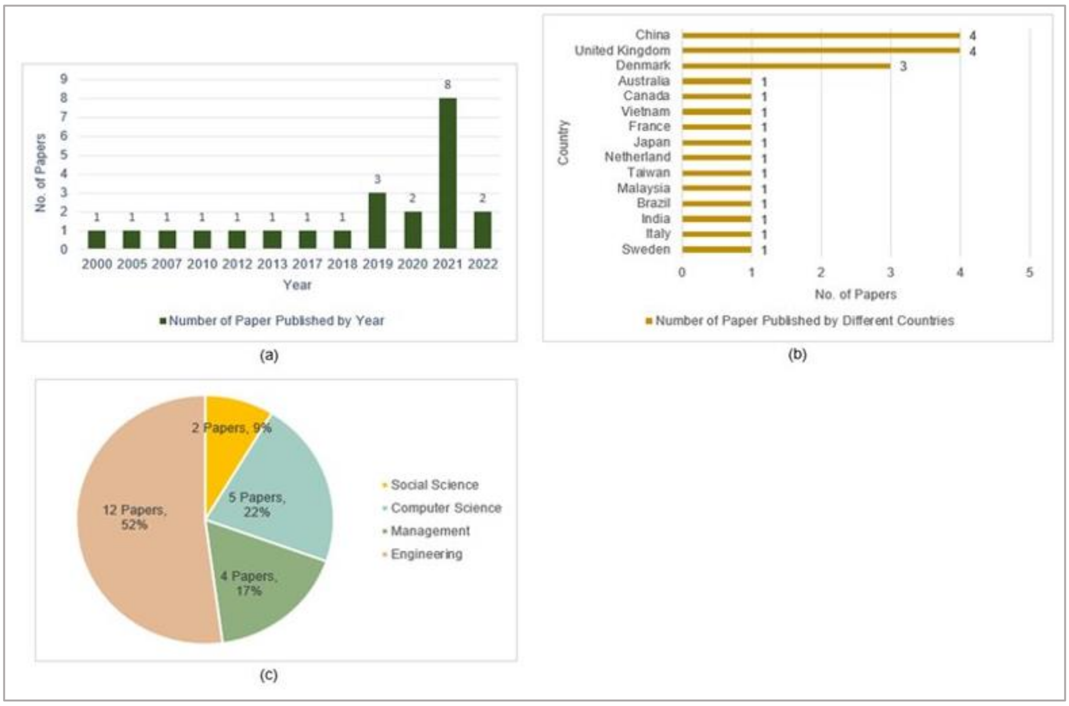

Fig. 2: Descriptive data: (a) Distribution of papers by year, (b) Distribution of papers by different countries, and (c) Distribution of papers by subject area

Fig. 2c shows the distribution of publications across four of the most relevant subject areas, where it can be seen that engineering (12 papers, 52%) was the most contributing subject area, then followed by Computer science (5 papers, 22%). Management (4 papers, 17%) subject area had the third highest contributions to maturity model for ImT construction. Social science (2 papers, 9%) appeared as the least contributing subject area, based on the database and search strings applied in this study.

The matrices in Fig. 3 link the maturity model development concept (8 domain contents), the model application objective (18 application domains) and the model validation method (7 domain methods). The colour in the circle corresponds to the number of publications found for a given combination. The maturity model objective categories in the middle can be read in combination with the charts on the left and right. The bottom left chart in matrices shows the relationship between the maturity model development concept (refer 2.2 for the description) and the maturity model objective, while the right side shows the relationship between the method used to validate the model and the maturity model objective. The matrices show where the studies are concentrated. It indicates that the primary maturity model approaches for ImT application in the construction industry have mainly focussed on safety training among empirical studies and concept/construction research content, which released 2 papers in each area. The matrix on the opposite side shows the combination of the maturity model approach and model validation method. Researchers used questionnaire surveys (5 publications) to validate the MMs for a variety of purposes, including safety training, virtual learning environment, digital technologies, decision-making, and maintenance and quality management. The findings showed that the second most popular data collection approaches were via interviews and experiments, with 4 publications in each category.

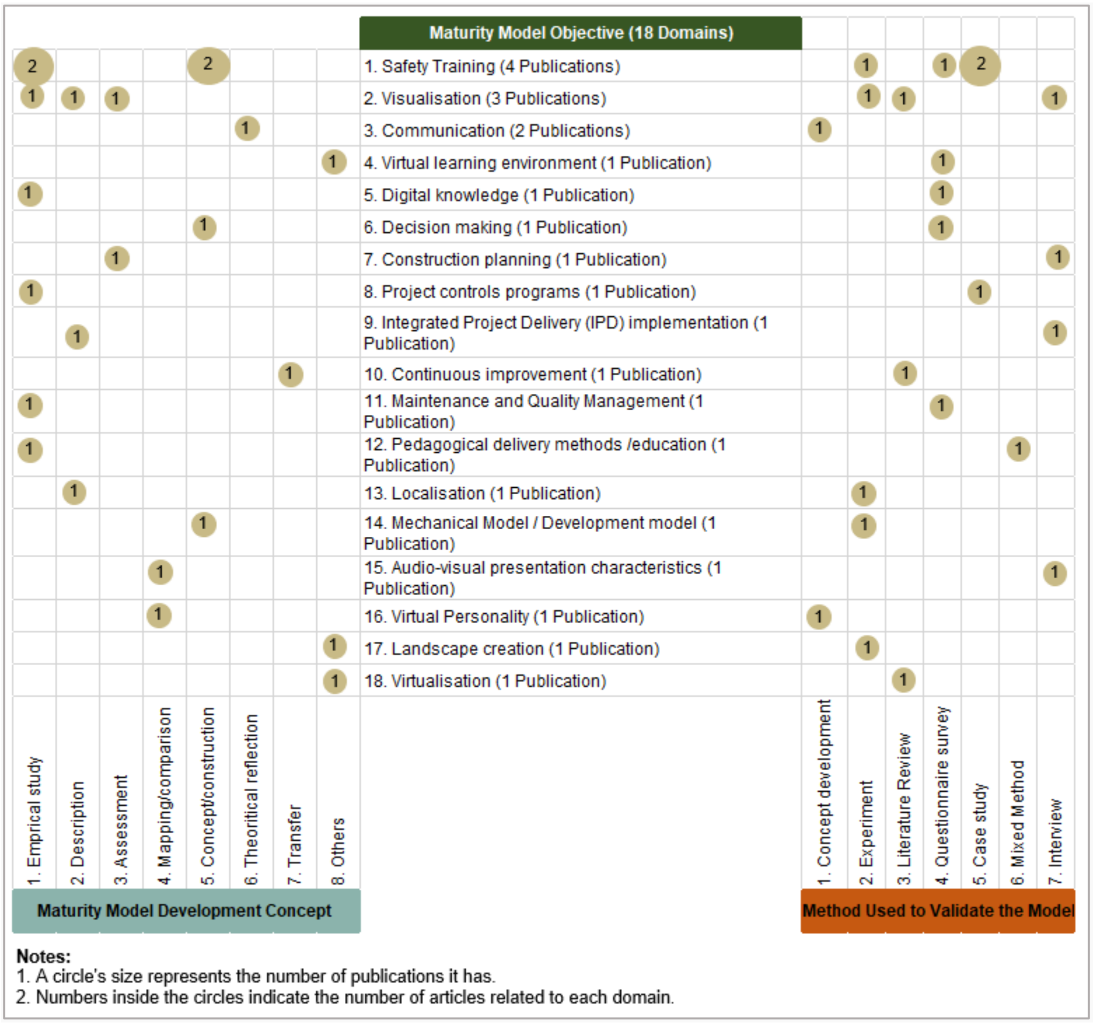

Fig. 3: Relationship between model application objective, maturity model development concept and method used to validate the model.

Meanwhile, Fig. 4 depicts the relationship between the maturity application objective, developed maturity model, and model validation status. The majority of MMs are still undergoing validation. Interestingly, even though four publications demonstrate their objectives for safety training, these MMs introduce new concept, including three publications that require further validation and one publication that has been validated. Other publications, on the other hand, have been dominated by their own concepts in developing model and have certainly not been validated. The paper revealed that many researchers have focused on developing new models rather than considering the use or enhancement of existing ones. A large number of researchers with their own (own/other) maturity model is not surprising given the limitations of research publications or non-academic application reports. These models do not look holistic or systematic due to their limited understanding (Olugboyega O & Windapo A, 2019). This makes it difficult to assess the reliability and robustness of the model. It is also difficult to identify the best model for a given problem. Moreover, the lack of standard benchmarks makes it difficult to compare models objectively. The Quality Management Maturity Grid (QMMG) and Building Information Modelling (BIM) model are the most recognised MMs. The other types of MMs, although widespread in practice, seem hardly significant for research. The matrices also showed that the BIM maturity model was mentioned in two publications about mechanical model and continuous improvement. One validated publication referenced virtual personality and was covered by Maslow's hierarchy.

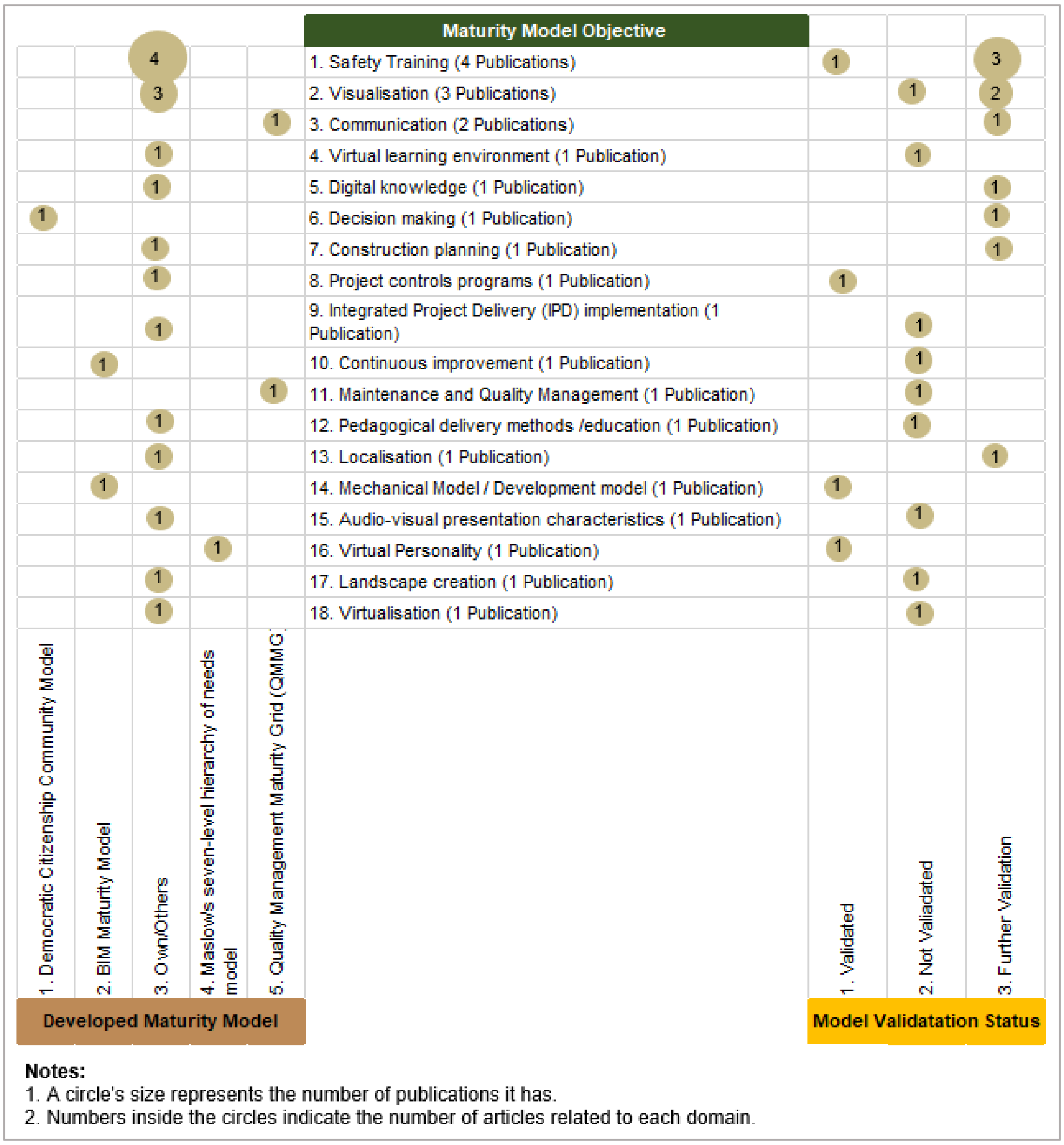

Fig. 4: Relationship between maturity model objective, developed maturity model, and model validation status.

Fig. 5a shows an overlay visualisation used to optimise academic research trends using keywords from the literature between 2014 and 2022. This helps to identify the target subject areas where the maturity model has been applied over the past decade, which in turn, assist researchers to find future research directions. As shown by the colour key in the map's corner, the keywords are colour coded according to the publication year. The circle's colour denotes the time period when the keyword was most frequently used; darker colour indicates more prevalence in older studies, while lighter indicates most recent studies. The keyword "virtual reality" was centred in the map and had the strongest relationship with the other keywords. As can be seen, it’s larger size of the circle covered the largest number of journals, and it’s the linkage covered to a variety of subject areas in the construction industry.

In studies conducted prior to 2012 and up to 2014, terms such as "computer assisted design", "computer simulation", and "visualisation" were more prevalent, indicating that researchers paid greater attention to these themes. Between 2016 and 2018, the majority of publications were related to engineering education, augmented reality, and technological readiness. From 2018 to 2022, there is a new path in academic concentration is indicated by keywords like "e-learning", "architectural design," and "safety training," which emerge while the "building information model" remains to appear in a recent publication indicates that researchers are exploring the potential of ImT in the architecture and engineering in the construction sector.

As shown in Fig. 5b, it was observed that MMs have recently migrated to ImT application areas involving "technology readiness" along with "virtual reality" and "safety training" from 2020 onwards. The keywords colour code indicates their similarities and relationships, while the size of the circle suggests weighting which is a function of documents, citations, or occurrences (Jan van Eck & Waltman, 2022). This close map has provided a twofold direction, that the "virtual reality" keywords have a strong link with "technology readiness" and the far distance yet shows an initiative effort between "technology readiness" and "safety training". It also indicates that, despite the widespread use of virtual reality in the construction industry, current research on developing a maturity model for ImT applications for safety training is still in its early stages in recent years.

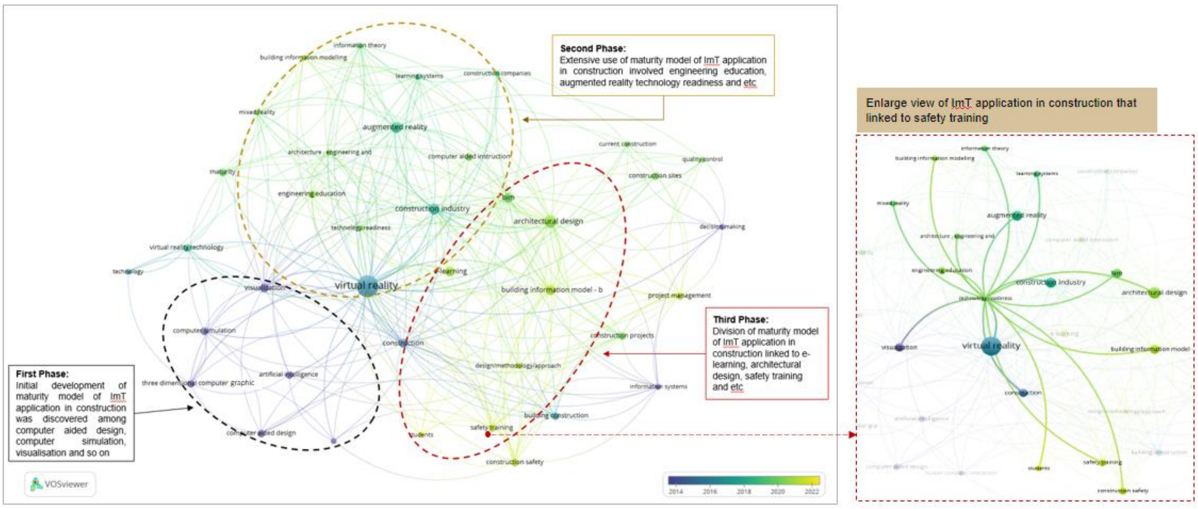

Fig. 5: Overlay visualisation (a) use keywords to explore trends over time and (b) extend view keywords related to safety training.

For evaluating the maturity level of immersive training, an assessment and evaluation instrument is needed. It is worth noting that a recent study has shown that the Technological Readiness Levels (TRL) model is being applied extensively across the world to assess the technological readiness of opportunity-driven projects (Judi HRL, 2022), but none of the papers has been evaluated on this model during the review process. This model was originally proposed by the National Aeronautics and Space Administration (NASA) as a type of measurement system for assessing the maturity level of a particular technology (Dixon et al., 2018; Salazar et al., 2020). The scale originally had seven levels but was subsequently upgraded to a nine-level scale, ranging from level 1 (basic observed and reported) to level 9 (actual system proven through successful mission operations) (Uflewska et al., 2017). The TRL scale is regarded as an effective tool to assist the successful deployment of technology. This is useful in the context of product design, where teams must plan, know how long it would take to advance to a certain level of TRL, and project the resources required (Islam, 2010). Moreover, it would also be useful for appraising the stakeholder role (people), management procedure (process), technology (infrastructure) and cost (financial), as clients need to evaluate how big an investment could be, or what impact a technology may have. Although it has been developed and much research have advocated for its application in several industries such as nuclear, manufacturing, and aerospace, its use in the construction industry is still limited. Thus, further investigation is required.

4. CONCLUSIONS

Effective safety training is critical for safety performance and outcomes. However, training interventions have not consistently resulted in the expected gains for worker safety readiness. The systematic review conducted here discovered not only the status but also trends of MMs that focus on ImT application in the near future. 23 publications from Scopus database were consulted, with most of them being published between 2019 and 2021. The review also revealed that the majority of the studies investigating the development of MMs for ImT application in the construction industry originated from United Kingdom, China, and Australia. Furthermore, the study found that MMs of ImT application in construction have 18 different objectives, and safety training is the most studied objective. In particular, most of the MMs developed for evaluating the readiness of ImT for safety training focused on developing new models rather than building on existing well-established MMs (e.g., CMMs). Yet, most of those new models have not been validated. In addition, based on the scientometric analysis of this study, it indicated that there is a growing number of MMs of ImT application in safety training in recent years. All these suggested that more research is needed in this area to evaluate the effectiveness of adopting ImT in safety training.

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IDENTIFYING SCENARIOS FOR ROLE-PLAY IN CONSTRUCTION HEALTH AND SAFETY EDUCATION

Dr. David Oswald

Senior Lecturer, RMIT University, Melbourne, Australia

Abstract

There is an unclear consensus into the most effective methods of teaching, training, and educating construction health and safety. Within construction workplace training and construction tertiary education, researchers have called for greater use of participatory methods. Role-play is an innovative participatory technique that could be used within both workplace training and tertiary education. This study aims to identify scenarios where role-play could be effectively used in construction health and safety education. A review of health and safety studies that have used role-play was undertaken. This helped inform where role-play could be effectively implemented within construction. The results found that role-play had been effectively used for teaching in: daily workplace practical skills, coping with crisis or emergency situations, mental health training and transferring of safety knowledge. These four themes can be translated into the construction sector, since the industry requires an abundance of practical skills, experiences accident and emergency situations, has a poor record with mental health, and still requires effective ways to transfer safety knowledge. It is recommended that future construction research work implements and evaluates role-play techniques used within these identified scenarios of practical construction skills, emergency situations, mental health training, and safety knowledge transfer.

Keywords: role-play, role play, higher education, training, safety

1. INTRODUCTION

Health and safety (H&S) education and training are fundamental in creating a safe working environment [1] [2] [3]. In prior work, it has been contended that passive pedagogical methods should be replaced with training techniques that encourage participation of construction employees [4] [5]. Similarly, within construction education in the tertiary sector, it has proposed that there should be greater use of more participatory teaching methods including: role-play [6], problem-based learning [7], and interactive teaching methods [8].

Role-play has been highlighted as a way of equipping construction students with the skills required for the profession through an active learning environment that balances theory and practice [6]. Despite having promise as a teaching method, role-play has not received attention in construction research studies. Indeed, there is a clear lack of understanding into the use of role-play within construction safety education. To begin to fill this gap in knowledge, this study aims to: identify role-play scenarios that could be successfully implemented for teaching construction safety. This insight could also be useful for identifying and informing role-play scenarios for construction workplace H&S training.

2. HEALTH & SAFETY TRAINING AND EDUCATION

Occupational health and safety (OHS) professional education has advanced significantly in recent years with certification of OHS practitioners and professionals, the development of an OHS Body of Knowledge, and an accreditation of OHS professional education at universities [2]. The relevance of H&S education and training is not only limited to OHS professionals, with prior research identifying different safety leadership behaviours to support training managers and leaders [9], as well as identifying the different H&S training needs that operators and managers have [10].

Previous H&S literature has evaluated types of OHS training, examined the role of the trainer, and highlighted limitations, drawbacks, and challenges in the delivery of effective OHS training (see [11] [12] [13] [14]). While within the body of OHS literature, innovative learning methods such as team working, real-life case studies, and blended learning have been found to being useful techniques for teaching OHS [15], there is still a lack of clear consensus within research on the most effective ways to teach H&S. This lack of understanding remains problematic for the construction industry, who have high accident rates and a variety of degree programs, including civil engineering and construction management, where construction H&S education is vitally important.

Within the construction sector, training sessions are one of the most common ways to transfer safety knowledge [16]. Previous studies have investigated various types of training including: first aider training and safety knowledge [17], mental health training [18], virtual reality safety training [19] and supporting emergency management training [20]. However, despite efforts to educate and train, the construction industry remains one of the most dangerous places to work [21] [22] [23]. There are physical health conditions emerging from noise, dust, and heat [24], mental health conditions arising from high demands and lack of resources [25], and safety incidents that can be observed through the high accident rates within the industry [4].

Training methods that are active, rather than passive, have been associated with stronger impacts on OHS awareness [26]. One active approach of training and teaching is through the use of role-play techniques. There are challenges to navigate with role-play, such as students not engaging in the role-play [27], potential embarrassment, and poor acting skills [28]. However, role-play has been proposed as a potential effective teaching approach for the construction industry [6], which requires both theoretical understanding and practical skills. It also has been recommended that further research into construction health and safety training is required [29] and that the tertiary educational sector needs to participate as one of the remedies for OHS training reforms in the construction sector [30]. By exploring the potential use of role-play as a training and educational tool, this study will begin to address a knowledge gap and contribute to the body of construction H&S literature.

3. RESEARCH METHODS

A review was undertaken to gather insight for the implementation of role-play within construction safety teaching, training, and education. The review aimed to identify relevant articles on both role-play and health and safety. A search on Google Scholar of articles since 2012 included the terms: 'role-play safety'; 'role-play health'; 'role-play hazards'; 'role-play accident'; and 'role-play risk'. Both the hyphenated 'role-play' and 'role play' were used in these searches. Google Scholar was chosen as the primary database, as relevant health and safety papers would be in multidisciplinary fields. To supplement this approach, the database 'A+ Education', was also searched since role-play educational approaches were of interest, as was 'Elsevier ScienceDirect', since leading health and safety journals, such as Safety Science, are within this database.

The articles that were included had to have used role-play within health and safety research. There were 37 articles identified that met the inclusion criteria of this relevance to health and safety research, as well as being in English and published in a peer-reviewed journal. All articles were scrutinised for meeting this inclusion criteria, with some articles excluded, such as Matthews et al.'s [31] conference paper on role-play in a mental healthcare setting and Dohaney et al.'s [32] book chapter on the use of role-play in a volcanic crisis (since both not published in a peer-reviewed journal). The articles that met the inclusion criteria were thematically analysed to identify key themes on where and how role-play methods were being used for health and safety education. The outcomes of these studies were also captured within this analysis. There were four key themes that emerged from the data, which were labelled: 'role-play for daily practical skills'; 'role-play for crisis or emergency situations'; 'role-play for safety knowledge and interventions' and 'role-play for mental health training'.

4. FINDINGS

The results found 37 peer-reviewed articles that involved role-play methods for health and safety. The papers were predominately within the healthcare sector (23), though other sectors were represented such as the military [33], manufacturing and transportation sectors [34]. Other role-play work explored public safety within society, such as child safety [35], vulnerable people in public [36] and safety in disaster situations [37]. Within the construction sector, there was only Martin et al.,'s [38] work, who argued that the use of role-play in engineering ethics education is an effective way to broaden case studies, with participants considering multiple perspectives due to the role-play, including safety. Aside from this study, there were no relevant articles found within the construction sector, highlighting a clear gap in knowledge. The following subsections provide an overview of the results (and relevant papers) on the four key themes that emerged:

4.1. Role-play for day-to-day practical skills

Role-play teaching methods were often used to educate students on practical skills that they would need when entering to workplace. For example, within the healthcare sector coached role-play (with goal-setting) proved an effective approach to teach medical students an interview examination that covers suicide/depression and safety amongst other topics [39]. Further, the use of role-play has been recommended as an effective educational method in teaching students the SBAR (Situation-Background-Assessment-Recommendation) technique [40] [41] [42], which is a standard tool for building effective communication to avoid errors that could endanger patient care.

Other studies within the healthcare sector, concluded that: the role-play simulation is an effective educational approach for teaching handover techniques [43], that role-play had a positive impact on improving medication communication skills for future clinical practice [44], that physiotherapy students reported their confidence and preparedness for clinical placement higher post role-play intervention [45] and that role-play was found to being a cost-effective method that provided a unique learning experience which allows for the incorporation of non-verbal interactions of care [46].

Role-play has also been successfully adopted to improve teamwork. For example, Ferrero et al. [47] designed a role-playing game to foster stakeholder collaboration in Water Safety Plans. In healthcare, participants reported improved understanding of an unfamiliar and challenging role-play scenario that required collaboration, communication, and situational awareness to improve patient safety and reduce risks [48]; and amongst community health volunteers role-play resulted in positive experiences, teamwork spirit, learning from one another, and increased motivation [49].

4.2. Role-play for crisis or emergency situations

Role-play has also been found to be useful in situations of emergency and crisis. For example, Thomson et al. [50] developed a simulation-based emergency training course involving role-play for new psychiatry residents, who need to rapidly acquire the clinical and team-working skills to manage psychiatric emergencies. The training was well-received with statistically significant increases in confidence in both non-technical skills and clinical skills found between pre-course test and post-course test results.

Research into time-critical situations, such as telephone conversations in the emergency department [51] [52], revealed that participants reported the role-play approach had increased their confidence, knowledge, and that the less experienced were able to learn from the more experienced. Other time-critical studies also found positive shifts of self-perceived abilities, such as research into role-play for educating tertiary geoscience students to forecast and mitigate a volcanic crisis, as well as delivering media releases, and real-time, high-pressured, press conferences [37]. In situations where there is loss in emergency situations, it has been found that role-play scenarios led to a self-reported increase in comfort, knowledge, and competence in communicating difficult news of death and poor prognosis to family [53].

4.3. Role-play for safety knowledge and interventions

Role-plays were found to being effective teaching methods for transferring safety knowledge to vulnerable members of the community, such as the intellectually disabled and children. For example, through role-play all students with a moderate intellectual disability learnt safety skills when lost in the community [36]. Another study (see [54]) investigated individuals with Williams syndrome (where increased sociability towards strangers is displayed leaving them socially vulnerable and potentially unsafe). Prior to a role-play intervention, only 14% of participants walked away from a stranger. This rose to 62% following role-play safety skills adopted from the role-play.

Studies into food safety for children found that role-play could significantly improve attitudes and skills of school children with food safety [35], especially when coupled with high levels of parental knowledge [55]. Role-play has been effectively used to significantly increase the level of knowledge of school-age children into the prevention of child sexual violence [56]. It has also been used help evaluate training children gun safety skills [57] and has been proposed as form of treatment following a traumatic experience, since it can allow children to experiment with different roles and gain control of their experience to feel safe again [58].

Within healthcare, it has been reported role-play teaching approaches for 'speaking up for safety' early in a nursing students' tertiary education can have important psychosocial implications for their confidence, empowerment, and success [59]. Further, role-play has been effectively used as a safety intervention through the implementation of a WHO Surgical Safety Checklist (see [60]). The role-play led to both high completion rates and high staff satisfaction. In another study on nursing students, hazard prediction scores were found to being significantly higher in the role-play group, demonstrating safety knowledge transfer [61]. Significant increases in safety knowledge have also been found in other non-healthcare settings, including the manufacturing and transportation sectors, following role-play training [34].

4.4. Role-play for mental health education and training

Role-play was also reported as an effective technique for mental health education and training. For example, role-play was found an effective approach for mental health providers serving the military [33] and was a highly effective pedagogy for nurse bullying [62].

In a study on nursing for psychiatrically ill patients, Dawood [63] (2013) reported that although doing a role-play can create initial fears and anxiety amongst students, the process of role-play brought many benefits including: improved communication, active participation and teamwork, the integration of theory and practice of psychiatric nursing, as well as overcoming fears, doubts, and anxiety around real-life nursing care practices.

Role-play provided participants with both an initial exposure to individuals with mental health challenges, and an opportunity to repeat and refine their skills. For instance, a role-play involving students in a hearing voices scenario, and provided an opportunity for them to practice their skills in preparation for their first mental health clinical experience [64]. Whilst a repeated practice of virtual role-play improved teacher's communication skills for intervening with bullying.

It has also been proposed that virtual role play had benefits over traditional as scenarios could be replayed multiple times [65], that the effectiveness of virtual reality simulation or traditional clinical role-play scenarios do not differ [66], and that repetition of online role-play was useful for effectively learning for mental health communication skills [67].

5. DISCUSSION

This review of literature aimed to identify where role-play had been effectively used in broader health and safety studies to inform potential avenues for use within construction health and safety education, teaching, and training. The healthcare sector was clearly the most advanced in terms of having a growing body of literature on the use of role-play as a teaching method. The results revealed four main themes where role-play was used for teaching. These included: performing daily practical skills within the workplace; coping with crisis or emergency situations; mental health training; and improving safety knowledge.

When considering using role-play as a teaching method, it is initially important to identify the scenario that role-play could be effectively implemented. These four themes above highlight where role-play could be potentially used within sectors, such as construction, that have yet to develop a body of knowledge on role-play for teaching, training, or education. For example, role-play has been found in broader literature, particularly in healthcare, to be useful for teaching students' practical skills within the workplace, as well as improving their confidence and preparedness for the workplace. While within healthcare this was for sector-specific tools, such as SBAR [40] [41] [42], this could translate to daily practical tools used within the construction sector, such as undertaking a role-play teaching how to do Safe Work Method Statements or pre-task risk assessments.

As well as these daily practical skills, role-play has been successfully used as a teaching method for crisis and emergency scenarios. For instance, studies found role-play useful for time-critical communication in an emergency [51] [52], delivering real-time, high pressured new conferences during a natural disaster [37] and for delivering difficult news of death and poor prognosis to family [53]. These scenarios all have potential to also be of use within the construction sector. For example, in the event of an accident on a construction site, an emergency phone call scenario would likely emerge. There could also be media interest if the accident was significant, or the construction project was under public scrutiny. Thus, role-play techniques for teaching how to deal with the media could also be of use. Considering the high fatality rate in construction, as well as other major injuries that occur, there is also potential for construction professionals to have to deliver difficult news to family.

Serious accidents and injuries can have a significant mental health toll for those involved. Within this review, mental health training was another topic that role-play techniques were found useful for. This included those being trained to deliver mental health training [33], working with those that are mentally ill [63] [64] and dealing with workplace bullying [62]. Considering the construction industry has significant mental health challenges [68] and has vulnerable workers, such as apprentices who could be targeted for bullying [69]; role-plays on the topic of mental health could be a very useful teaching, training, and educational technique for the construction sector.

Other potential role-play scenarios that emerged from the review included the transfer of safety knowledge. Studies have successfully used role-play to educate safety to those vulnerable in the community, such as the mentally ill [36][54] and children [35] [56]. Role-play was also found to being successfully used for the transfer of safety knowledge in organisations [34], as well as for safety interventions [60] and to improve hazard identification [61]. Teaching safety knowledge, interventions and hazard identification are also clearly relevant to the construction sector, due to its poor health and safety record. These topics are therefore also identified as potential scenarios where role-play could provide an effective learning approach.

6. CONCLUSION AND FURTHER RESEARCH

The first step in successfully using role-play in teaching and training is to identify scenarios for the role-play. Within construction safety education, there is very limited understanding into how role-play could effectively teach health and safety, despite other sectors, such as healthcare having developed a growing body of knowledge within this space. This study aimed to use the knowledge gathered in other more advanced sectors to inform potential scenarios for role-play teaching in construction health and safety. The results found that those considering implementing role-play techniques within construction education should consider role-play for: daily workplace practical skills (e.g. SWMS), coping with crisis or emergency situations (e.g. serious accident), mental health training (e.g. bullying) and transferring of safety knowledge (e.g. hazard identification). It is recommended that future construction research work implements and evaluates role-play techniques used in these identified scenarios.

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INCREASING CONSTRUCTION SAFETY THROUGH VIRTUAL REALITY

Peter Mésároš[1], Ivica Završki[2], Nicolaos P. Theodosiou[3], João Poças Martins[4], Marcela Spišáková[1], Pavol Kaleja[1], Zvonko Sigmund[2], Matej Mihić[2]

[1]Technical University of Košice, Faculty of Civil Engineering (SLOVAKIA)

[2]University of Zagreb, Faculty of Civil Engineering (CROATIA)

[3]Aristotle University of Thessaloniki, Department of Civil Engineering, School of Technology (GREECE)

[4]University of Porto, Faculty of Engineering (PORTUGAL)

Abstract

The construction industry generates jobs for large numbers of people and makes up about 12 percent of the global gross domestic product (GDP). Even though labour conditions vary widely throughout the world, construction represents one of the most dangerous industries. Construction safety intends to prevent people from dying or becoming injured. International Labour Organization estimates that losses of GDP due to this type of accidents represent about 4% of GPD. On the other hand, every construction site is different, unique. It is influenced by many internal and external factors that affect the execution of construction works. The proper training and teaching process can lead to the reduction of occupational accidents and hazards. The education system is increasingly part of the digital transformation of society, which can take advantage of its benefits and opportunities. We are witnessing society's demand for online education and increasing people's digital skills in the field of health and safety in construction.

The aim of the paper is to present an interactive educational tool for the design of a safe construction site using a universally interoperable virtual environment which was developed as part of an educational project supported by the Erasmus+ program. Training tool allows to identify the safety risks during the implementation of construction works and propose measures for their elimination in virtual reality. The emergence of possible safety risks is identified in six groups of scenarios (e.g. fall hazard, tripping hazard) describing 18 dangerous situations on the construction site. A significant benefit of the developed tool is its dynamic dimension, which allows each user (instructor, teacher) to create their own hazard scenarios and their own construction site environments by building information model. The developed educational tool can be used without installing additional software, only with the support of an internet browser on any device (smart phone, PC, tablet).

Keywords: Construction, safety, education, virtual reality, digitization

1. INTRODUCTION

Architecture engineering and construction (AEC) belongs to an important part of the European Union (EU) economy. AEC activities contribute to about 10% of GDP in the European Union and create 20 million jobs [1]. On the other hand, AEC presents represents a dangerous working environment for all stakeholders. In addition, it is characterized by the following features:

- each building and each construction site are unique,
- more contractors are interested in construction project implementation,
- more contractors and subcontractors participate in construction process,
- construction process requires its own production place (construction site),
- construction process has stationary character – people, machines, products „follow“ the construction,
- construction process requires many workers – in terms of number of workers, as well as professions,
- main construction works (earthworks, foundations, framework) are influenced by weather conditions,
- relatively long duration of construction – project implementation.

These aspects confirm the fact that AEC represents one of the most dangerous industries from the point of view of occupational health and safety. The construction site is a dynamic and complex environment, which makes it difficult to manage and monitor. Ensuring a safe working environment, i.e. the construction site and the construction process, prevents working accidents and even deaths. It is a socially actual issue. According to the Occupational Safety and Health Administration (EU-OSHA) in 2020, more than a fifth of all fatal accidents at work in the EU took place within the construction sector [2]. It also represents an economic problem, costing about 4% of world GDP [2]. In the XXI. century, it is unacceptable for a worker to be fatally injured during the implementation of his work. Safety challenges are particularly significant for new and often low-skilled workers due to a lack of training. Injuries and accidents occur because workers are not properly trained in occupational safety [3, 4]. Every construction site is different, so it is necessary to train technicians, workers and engineers on the potential risks that can arise from each new environment [5, 6]. In order to prevent the emergence of safety risks on construction sites, it is not possible to rely only on traditional, current measures for their prevention [7].

There is a solution. The construction industry complies with the concept of Industry 4.0 and provides significant space for the application of the latest trends, knowledge and technologies in the field of Smart&Safe solutions. One of the possible ways of applying this idea is the field of digitization and automation of construction related to the design of an intelligent construction site and the monitoring, identification and elimination of safety risks. It is necessary to solve it already in the educational process by using current innovative elements and approaches. Educational project “Construction Safety with Education and Training using Immersive Reality” (CSETIR) dealt with the development of interactive educational tool for the design of a safe construction site using a universally interoperable virtual environment.

2. CONSTRUCTION SAFETY WITH EDUCATION AND TRAINING USING IMMERSIVE REALITY (CSETIR)

The education project CSETIR was developed as part of an educational project supported by the Erasmus+ program. The civil engineering faculties of universities from Slovakia, Croatia, Portugal and Greece was involved as project partners. The opinions and experience of construction practice were implemented in the project through the representative of a construction company from Croatia. The following chapter provides information about the given project, its goals and outputs.

2.1. Project CSETIR – project goals

The CSETIR project was based on the synergy between higher education institutions and representatives of construction practice. The goal was to introduce the use of intelligent technologies in the proper training process for the elimination of safety risks in the construction industry. The effort is the implementation of digital tools that enable the creation of a virtual environment that simulates construction scenarios and enables teachers, instructors, technicians and engineers to identify and prevent safety risks.

The aim of the project was also to improve the exchange of knowledge between representatives of the three sectors with the aim of innovating approaches to accident prevention through effective cooperation between researchers in the field of virtual reality and construction companies. The CSETIR partnership has developed innovative and interactive VR/AR (virtual and augmented reality) solutions for the prevention of construction site accidents. CSETIR has created a useful tool for teachers, technicians and engineers that can be used in any construction project. The created digital tool with study materials is accessible online on the web site. The project solution supports the horizontal priorities of the Erasmus+ program: (i) supporting individuals in acquiring and developing basic skills and key competences, (ii) tackling skills gaps and mismatches; (iii) promoting and rewarding excellence in teaching and skills development. Project is aimed on three topics: ICT - new technologies - digital competences; new innovative curricula/educational methods/development of training courses; health and wellbeing.

2.2. Project CSETIR – project outputs

The CSETIR project was focused on the creation of a digital education tool for the elimination of safety risks on the construction site. To create the tool, it was necessary to process the following partial outputs:

- needs analysis,
- safety risks scenarios,
- development of interactive educational tool,

- training manuals.

2.2.1. Needs analysis

An analytical part provided input information for the solution of the project. It was focused on choosing a suitable VR/AR environment and finding training methods at all levels of qualifications.
Based on systematic and literature reviews done by project participants, on involvement in several international meetings and conferences focused on H&S, in construction sector contributions, several conclusions and guidelines became clear. The research analyzes were mainly focused on tools of BIM-based augmented reality/virtual reality (AR/VR) which can be used as a working environment for development of the interactive educational tool. The selection criteria were set as:

- is the tool available for use,
- is the tool proprietary or freely available, and if proprietary is it affordable,
- what are the hardware requirements (for computing power),
- is any additional special hardware needed (i.e. special hardware elements, not including Head Mounted Displays (HMD)),
- does the tool have a desktop version in addition to a full virtual environment,
- does the tool have a smartphone version (i.e. for Samsung Gear) in addition to a full virtual environment,
- does the tool support multiple platforms (supports more HMD’s such as HTC Vive, Oculus Rift, etc.),
- does the tool require additional supporting software, and if yes, is it available to use,
- how detailed and realistic can the virtual environment be,
- how simple is the tool to install and to use,
- does the tool support multiple users in VR at the same time,
- how simple would it be to replicate the research results outside the project partners’ institutions,
- is the tool appropriate to teach Health and Safety related topics,
- what hazards/scenarios are available in the tool,
- does the tool support the import of user generated BIM models,
- does the tool support creating additional scenarios,
- does the tool have open source, enabling modifications to suit the user’s needs.

Tab. 1: Summary analyzed tools of BIM-based augmented reality/virtual reality [8-17]

TOOL	CRITERIA							
	A	B	C	D	E	F	G	H
1. 3M	YES	YES	NO	NO[1]	NO	YES	NO	YES[2]
2. CAT	YES	YES	NO	NO[1]	NO	NO	NO	YES[2]
3. SRI	YES	NO	NO	NO[1]	NO	NO	NO	YES[2]
4. SAFETY COMPASS	YES	NO	NO	YES	NO	NO	YES	YES[2]
5. LANDMARK VR	YES	YES	NO	YES	NO	YES	NO	YES[2]
6. FULMAX CUBE	YES	YES	YES	YES	NO	N/A	NO	YES[2]
7. VISUALIZATION TECHNOLOGIES IN SAFETY PLANNING AND MANAGEMENT	YES	YES	YES	NO[1]	NO	YES	NO	YES[2]
8. SMVS	YES	YES	YES	NO[1]	NO	YES	NO	YES[2]
9. OSHA PIXO	YES	YES	NO	NO[1]	NO	YES	NO	YES[2]
10. LIRKIS G-CVE	YES	YES	YES	YES	YES	YES	YES	YES

Criteria: A - The tool is available; B - The tool is suitable to teach health & safety (H&S) topics; C - Ability to create and customize scenarios; D - Possibility to have multiple users in VR, E - Has open source; F - Supports various HMD’s; G - Has mobile and desktop versions; H - Possible to use and to replicate in outside the project partners’ institutions
Notes: 1 Only one user in VR, however others can watch on a separate screen; 2 Possible, but the intended user needs to buy the software and/or special hardware

Ten tools of BIM-based AR/VR were analyzed considering the selected evaluation criteria (Tab. 1). The result of the evaluation analysis was the selection of a suitable tool for solving the project. The development of interactive educational tool for the design of a safe construction site using a universally interoperable virtual environment was implemented in LIRKIS G-CVE environment which present web-based collaborative virtual environments. This VR collaborative virtual environment allows interaction in virtual space among more participants that may be spread over large distances. Globally, multi-user groups can participate together in one completely immersive virtual environment to achieve goals. Distributed virtual environments can be purposely used as training tools for real-time 3D simulations or scenarios. The main benefits of G-CVE tool are: (i) multi user, (ii) no expensive SW/HW needed, (iii) web based (only web browser needed), without installation of any software, (iv) work on any operation system and any device (also with Oculus, HTC, MS Hololens products), (v) switch to VR mode (with VR headset), (vi) open source. VR environment LIRKIS G-CVE was developed by researcher at Faculty of Electrical Engineering and Informatics, Technical university of Košice. LIRKIS G-CVE tool can combine the requirements of the construction site layout and construction smart management with the VR collaborative environment. This compatible virtual environment based on web-based VR technology for the design, monitoring, updating and change of construction conditions will not require the installation of any software. It will work on any of the currently available hardware solutions for working with VR. An indisputable benefit of the proposed application (VR based on web based VR technology) is the possibility of its use in the design of Smart&Safe construction site already in the project construction phase (as part of the site organization project processing) and also in the construction phase (as part of the site equipment project) with respect for all necessary aspects of the construction design, in term of the investor, designer or contractor.

Training was provided for levels 1 to 7 of the European Qualification Framework (EQF) [18]. In terms of training methodologies the partnership is mostly composed by higher education institutions that are experienced in training levels 5 to 7. Concerning levels 1 to 4, generally designated as Vocational Education and Training (VET) the partnership was employ the approaches suggested by European Centre for the Development of Vocational Training (CEDEFOP) and used by VET providers like European Association of Institutes for Vocational Training (EVBB) or European Vocational Training Association (EVTA). The training was based on the outcome based method proposed by Tuning Academy. All modules and training activities was designed and prepared taking into account the knowledge, skills and attitudes required. The competences required was defined to face the several risks and preventive measures adequate for the respective level of qualifications. This outcome based training will allow to prepare everyone from basic level (1) to master level (7), as follow:

- Level 1 – basic general knowledge,
- Level 2 – basic factual knowledge of a field of work or study
- Level 3 – knowledge of facts, principles, processes and general concepts, in a field of work or study
- Level 4 – factual and theoretical knowledge in broad contexts within a field of work or study
- Level 5 – comprehensive, specialised, factual and theoretical knowledge within a field of work or study and an awareness of the boundaries of that knowledge
- Level 6 – advanced knowledge of a field of work or study, involving a critical understanding of theories and principles
- Level 1 – highly specialised knowledge, some of which is at the forefront of knowledge in a field of work or study, as the basis for original thinking and/or research [18].

2.2.2. Safety risk scenarios

Construction workers face numerous hazards every day, but some are however more frequent and have more serious consequences. Due to the limitations of the final training module, not all hazard scenarios designed to teach safe work practices can be presented to the users in a reasonable amount of time. Therefore, a prioritizing of hazards was needed as an initial step in the BIM model creation and construction hazard scenario building process.

Construction injury statistics are often unreliable due to injury underreporting. Most injuries which do not require immediate assistance of a medical professional and more than a few lost work days are seldom reported. This is due to contractor's cost with regards to government penalties, health & safety (H&S) injury rating, worker compensations, higher insurance premiums and others. Injuries that are always reported are those with serious consequences, which might skew the total injury type statistics. For example, all falls from height are reported, while some less severe accidents which happen quite often, are most likely underreported. Both types of hazards are significant in their own way and both should be included in safety training tools.

Injury statistics for severe injuries are reliable as they are reported to the authorities. Most frequent severe injuries are from falls, struck-by accidents, electrocutions and caught in-between accidents, also called fatal four by the US Occupational Safety and Health Administration. Lower severity injuries are not often reported to the authorities, but there is however a way to quantify and rank them using tacit knowledge contained in either H&S experts' personal experience or in the contractor's private databases.

To structure the presentation of those more significant hazards, it was necessary to group them by type of construction workers who were exposed to the hazards, while the hazards to which all workers can be exposed to were grouped by injury type and severity rate (Tab. 2).

Tab. 2: List of safety risks scenarios

HAZARD TYPE	SCENARIO	SEVERITY RATE
1.FALL HAZARD	fall from height when working on roof structures	high
	falling from a mobile scaffold	medium to high
	fall from ladders	low to medium
	fall from an unprotected edge	medium to high
2.TRIPPING HAZARD	tripping on slab rebar	low to medium
	tripping when walking through the construction site	low
3.STRUCK BY	angle grinder accidents	high
	hazards when concreting with a pump	medium to high
	objects flying in the worker's eyes	low to medium
	fall of objects from height	high
	fall of object from a crane	high
	worker struck by construction machinery	medium to high
	collision with a vehicle	medium to high
	trench cave in	medium to high
4.CUTS AND AMPUTATIONS	table saw accidents	medium
5.OBJECT FALLING ON A WORKER	formwork collapsing on a worker	medium
	wall and column formwork overturning and falling on a worker	medium
6.ELECTROCUTION	electrocution due to faulty wires or tools	medium

2.2.3. Interactive educational tool and training manuals

The proposed digital tool for the elimination of safety risks at the construction site in a collaborative virtual environment enabling interaction in the virtual space between multiple participants; and a description of the visualization of security risk scenarios. The tool enables a training process for students (not only) in the field of occupational safety and health on the construction site. Developed tool consists of 3 inputs (BIM model and construction site, hazard scenario and safety requirements and measures) embedded and cooperating in a virtual environment LIRKIS G-CVE (Fig. 1).

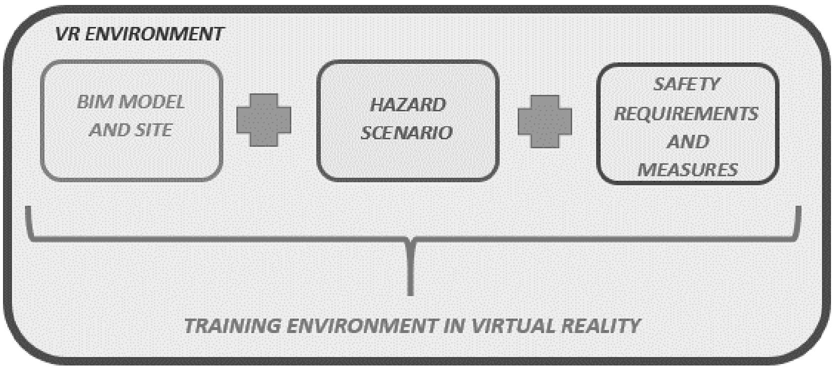

Fig. 1: Elements of the training environment in VR

Training tool allows to identify the safety risks during the implementation of construction works and propose measures for their elimination in virtual reality. The training strategy is based on visual display of the safety hazard situations, of preventive measures and simulation of the consequences of adopting the preventive measure. The particular scenario with safety hazard uses a BIM model in web-based collaborative virtual environments and preventive measures adequate for each risk using BIM. The trainee´s avatar, who has completed interactive training, stands on the construction site. VR environment enables the selection of suitable solutions for a specific safety hazard situation (Fig. 2) [19].

A significant benefit of developed tool is the processing of the dynamic environment which enables the creation of specific construction sites by instructors/teachers who do not have to use a static environment of BIM models of construction and its sites. The design, validation, feedback and subsequent improvement of the tool environment, identification of critical safety construction processes and the design of preventive measures were carried out within the framework of meetings of the international working group, which was made up of experts from the academic environment and construction practice. Scientific methods, analysis and synthesis of knowledge focused on the VR/AR environment, construction safety risks and education were used. Validation of the designed educational tool was carried out through meetings of experts, structured interviews and questionnaire surveys. Questionnaire surveys were aimed at verifying the choice of safety risks scenario, interactive environment and ways of evaluating the training process. The initial survey was attended by 46 respondents from universities and construction practice (OHS coordinators, site managers, construction workers, etc.). The representatives of the International Safety and Health Construction Coordinators Organization (ISHCCO) and International Association of Civil Engineering Faculties (IACEF) were involved to the validation process.

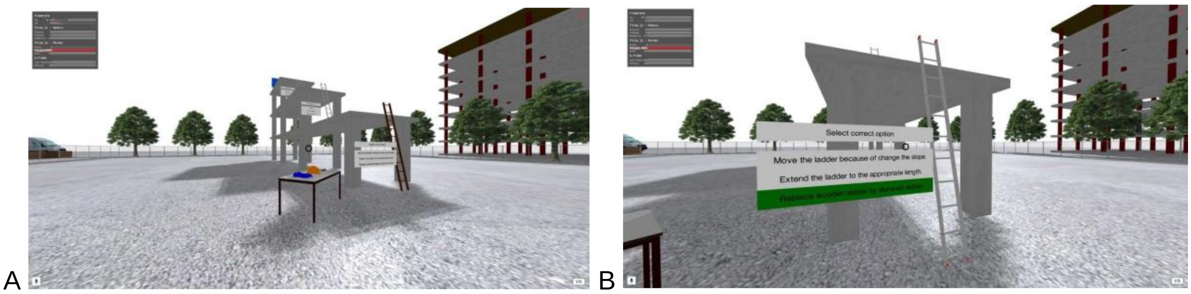

Fig. 2: A: Safety features of construction site equipment (ladder); B: Selection of preventive measure

The processing of training manuals was also an integral part of the developed tool. It presents instructions (manuals) for the use of a web-based interoperable virtual environment, where it is possible to create construction sites or upload modeled construction sites with safety hazards. Two types of training manuals were created - for instructors (teachers) and students (workers, learners), supplemented with links to video manuals. Manuals were created for both groups, which provide information about the software and hardware environment of the developed VR tool, the text and figure guide. The content, scope, arrangement of the training manuals was designed based on cooperation (meetings) with representatives of academic institutions and construction practice in Croatia, Slovakia, Portugal and Greece. Their functionality was subsequently verified by employees of selected construction companies (OHS coordinators, site managers, etc.) and construction workers. Their comments were incorporated into the final design of the training manuals. Verification was carried out through structured interviews.

3. CONCLUSIONS

Virtual simulation techniques are not often used in the construction industry for risk analysis and subsequently in the educational process of students, workers, engineers or technicians. Based on the discussions and research from the table, it became clear that the implementation of VR/AR tools for the elimination of safety risks on construction sites can also benefit construction practice. In fact, digital education and training technologies can be used in the field of health and safety. However, a condition is the close cooperation of the academic community and construction companies. These facts were an indication of the involvement of new technologies in the daily operation of the industry with regard to construction safety. VR/AR have shown potential in the field of research and have subsequently been implemented as promising tools for education and training.

The solution of the CSETIR project and its results are proof of this. This project offered innovative and different education and training techniques. VR/AR, BIM and other digital tools have been on the market for some time and can be used as part of a construction safety solution. The synergy of using practical experiences and digital platforms based on BIM and VR/AR simulations represents an innovative way of transferring competence enhancement in the field of health and safety in the construction industry to various target groups, which makes it possible to prevent risks and support the identification of dangerous situations.

CSETIR aims to implement a methodology for collaboration and practice, integrating a broad vision of the project, where all disciplines create a very close and interconnected communication. The developed tool supports improved communication, experiential training, a more practical and innovative approach to learning in an environment that reproduces the future practical challenges and situations. The transnational character of the project affected the reality of the labor market more globally, different cultures enabling the universality of results and outputs. In addition, the use of e-learning tools and digital platforms enabled the development of autonomous learning and training and the exchange of solutions and case studies between participants.

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IMPROVING CONSTRUCTION APPRENTICES' HEALTH AND SAFETY THROUGH SUPPORTIVE COMMUNICATION: A DIGITAL ROLE-PLAY GAME

Rita Peihua Zhang[1], Helen Lingard[2], Jack Clarke[3], Stefan Greuter[4], Lyndall Strazdins[5], Christine LaBond[6], Tinh Doan[7]

[123]*RMIT University (Australia)*
[4]*Deakin University (Australia)*
[567]*The Australian National University (Australia)*

Abstract

Research shows that supportive communication in the workplace is critical to construction apprentices' physical and psychological health and safety. This paper describes the process of developing a digital role-play game (RPG) to improve the communication between construction apprentices and their supervisors and co-workers. A participatory design approach was used for developing the RPG. Interviews were first conducted with apprentices and supervisors to explore characteristics of effective and supportive workplace communication, which then became the focus of the RPG's learning objectives. Three scenarios were developed for the RPG. A unique series of situations were designed, and specific characters were created for each scenario. When playing the game, players would be asked to decide how the characters should respond to an unfolding situation. An advisory committee, comprising apprentices and supervisors, was regularly consulted to seek input for refining the scenarios during the design process. Scripts were developed for the scenarios, which were subsequently filmed and digitalised with motion capture technology. Example situations from one of the three scenarios are introduced in this paper to illustrate the process of developing the digital RPG. The effectiveness of the digital RPG in improving workplace communication is being evaluated using a before-and-after study design among construction apprentices.

Keywords: apprentices, construction, communication, role play game, health and safety.

1 INTRODUCTION

1.1 Poor health and safety experiences of young construction workers

Young workers (frequently defined as workers under the age of 25) experience disproportionately high rates of workplace injuries and accidents compared to older workers [1, 2], especially among young male workers [3, 4]. Young workers constitute 17% of the Australian workforce in Australia but account for 20% of all workplace injuries [5]. The risk of workplace injuries for young workers is further elevated by working in the construction industry. Young construction workers also experience a higher risk of workplace fatalities than their counterparts in other industries. In Europe, the highest number of occupational fatalities involving young workers (aged up to 24 years) is recorded in construction [6]. In Australia, young workers accounted for 8% of fatalities across all industries but 13% of fatalities in the construction industry during 2016-2020 [7].

Young workers are also susceptible to psychological and mental ill-health when transitioning into full-time work, especially when employed in poor-quality jobs with high demands and complexity, low levels of control and low job security [8]. The working conditions in the construction industry are highly demanding and stressful, making construction a high-risk industry for mental ill-health [9]. Research shows that young construction workers experience substantially higher psychological distress levels than their counterparts in the general population [10]. Additionally, young male workers (15-24 years) in Australia accounted for 14.6% of suicides in construction, compared with 10% in non-construction industries during 2001-2019 [11].

1.2 Supportive communication and apprentices' health and safety

Research suggests that the social environment of the workplace shapes the health and safety (H&S) practices and experiences of young workers [12]. It is through social processes and interactions that young workers 'make sense' of the risk culture of their workplace and adapt to what is considered as 'normal' or acceptable work health and safety-related behaviour [13].

Supervisors and co-workers are important social influences for young workers, and supportive communication and positive interactions with supervisors and co-workers are determinants of young workers' H&S [14]. Pek, et al. [15] report that supervisors and co-workers influence young workers' risk-taking behaviour and experiences of workplace injuries through injunctive H&S norms, i.e., supervisors and co-workers' H&S behavioural expectations that young workers perceive through interacting and communicating with them. Tucker and Turner [16] found that young workers' responses to workplace H&S hazards are influenced by their communication with supervisors and co-workers. Specifically, young workers are more likely to bring H&S concerns to their supervisors if they gain co-workers' validation and support. However, young workers display reluctance to report H&S issues if their supervisors are not receptive to hearing about safety concerns. Similarly, Breslin, et al. [17] report that young workers' willingness to talk about H&S is affected by supervisors' willingness to listen. Supportive communication from supervisors is critical in encouraging young workers to speak openly and ask questions about H&S at work [18].

The workplace social environment is also critical to young workers' mental health and well-being [19]. A work environment characterised by supportive communication and positive interactions can help young workers to thrive, i.e., experience positive meaning and a sense of well-being at work [20]. Through examining Australian apprenticeships, Buchanan, et al. [19] identified that effective workplace structures of support for apprentices comprised both formal support (e.g., mentoring programs) and informal support (i.e., embedded in daily interactions between apprentices, supervisors, and co-workers). Informal support was found to be even more important than formal support for the health, well-being and satisfaction of apprentices [19]. Conversely, an unsupportive work environment can be detrimental to young workers' health and well-being. Einboden, et al. [21] report that apprentices at the bottom of the workplace hierarchy often experience overt and covert forms of abuse and aggression from supervisors and co-workers. This abusive and aggressive communication in the workplace contributes to apprentices' mental ill-health and attrition [21]. Gow, et al. [22] consistently report that apprentices' relationships with their supervisors and co-workers are the most significant predictor of intention to quit.

1.3 Calls for effective interventions to improve communication

Effective communication has been identified as a core H&S competence [23]. Many interventions have been designed to provide information and encourage young workers to identify and raise workplace H&S concerns. One such example is marketing campaigns in the form of web-based, print, and television advertising, which make an emotional appeal to young workers to speak up about workplace H&S by showing the consequences of workplace incidents [16]. However, such intervention programs do not consider workplace social structures and power relations, which can hinder young workers' ability to advocate for H&S rights, even when encouraged [24]. Interventions should involve other stakeholders such as employers and supervisors, who need to understand the structural and psychological barriers preventing young workers from participating in H&S communication.

Developing confidence and communication skills for self-advocacy has been a trend within training for young workers [25]. For example, the 'Safety Voice for Ergonomics' program in the USA was designed to help apprentices develop a 'safety voice' by integrating the soft skills of self-direction, self-control, accountability, responsibility, communication strategies, and leadership [26]. The 'Attitude to Work' program in Finland seeks to provide young workers with readiness and confidence to advocate for their H&S in unfamiliar work environments [27]. These programs also employ various active learning methods such as group discussion, problem-solving and role-play.

To our knowledge, interventions focused on young workers' H&S in the construction industry have not fully addressed the features highlighted above, including reflecting the workplace social context, developing communication competency and self-advocacy, using engaging delivery approaches and empowering young workers to speak up about H&S. There are calls for developing effective and novel interventions to better protect the physical and psychological H&S of young workers [28].

1.4 Research aim

Given the importance of communication for young workers' H&S, a research project is being undertaken to develop an innovative digital role-playing game (RPG) to foster supportive communication in the workplace and protect young workers' physical and psychological H&S. This paper uses examples from one of the RPG's scenarios to demonstrate the development process. The following section introduces the premise of RPGs and the participatory approach adopted to developing the project's RPG.

2 DIGITAL ROLE-PLAY GAMES

Role play is a well-established approach to developing soft skills, such as responding to particular situations and developing empathy between roles. It has been widely used in training medical professionals [29] and has also been used to teach engineering students about the social aspects of engineering practice [30]. The role played by a participant can reflect a participant's position, or the role of another person, thus promoting perspective-taking. Role-playing enhances learning because the roles are played in a safe environment, allowing participants to experiment and learn without the risk of irreversible consequences [31]. A role-playing game (RPG) has been defined as "*A game where each player takes on the role of a character. The character's story takes shape and evolves depending on the player's decisions and choices. Role play implies a complex interaction among the players (social interaction) or among a player and computer-controlled characters*" [32]. Digital RPGs are increasingly used to help users improve interpersonal skills, such as communication skills, negotiation skills, leadership skills and assertiveness training [33].

Digital game-based training presents benefits over traditional training approaches. Oblinger [34] argues that digital games provide powerful learning environments for young, digitally savvy learners accustomed to digital media-rich communication and information-processing environment. Through digital game-facilitated learning, learners will likely be motivated when stories and meaningful contexts are provided [34]. Digital game-based learning also creates stronger emotional, cognitive and behavioural connections between users and learning materials, which increases engagement attention, immersion, involvement, and feeling of presence [35]. So far there has been limited application of digital game-based training in construction, and applying this approach to training may improve learning outcomes relating to communication and H&S in the construction industry.

3 PARTICIPATORY DEVELOPMENT APPROACH

The value of involving participants in the design of H&S-related interventions has been recognised (see for example [36]; [37]). A participatory approach has also been advocated in the development of health interventions targeting young people [38]. A participatory approach keeps the needs, experiences, and knowledge of young people at the centre of intervention development and uses knowledge collected from end-users to design interventions that are relevant, effective, and appealing to young people [38].

Participatory design is user-centric and engages participants as co-designers of the intervention [39]. Spinuzzi [40] describes that participatory design: 1) seeks to understand tacit aspects of human activity; 2) assumes these aspects can be ethically examined through design partnerships formed with user participants, in which researcher-designers and participants co-design artefacts, systems, and prototypes; and 3) the partnership is iterative so researcher-designers and participants can verify and refine interpretations of relevant human activity represented in the intervention.

Spinuzzi [40] suggests that different research methods, such as interviews and focus groups, can be used in participatory design to develop an initial evidence base and iteratively shape the emerging design. The resulting intervention reflects content that has been co-interpreted by researcher-designers and user participants [40]. Thus, the participatory design combines end-users' tacit knowledge with researchers' analytical knowledge as inputs into intervention design [40].

Hagen, et al. [38] proposed a framework for the participatory design of health interventions for young people, which was adopted in developing the digital RPG in the present study (Fig. 1).

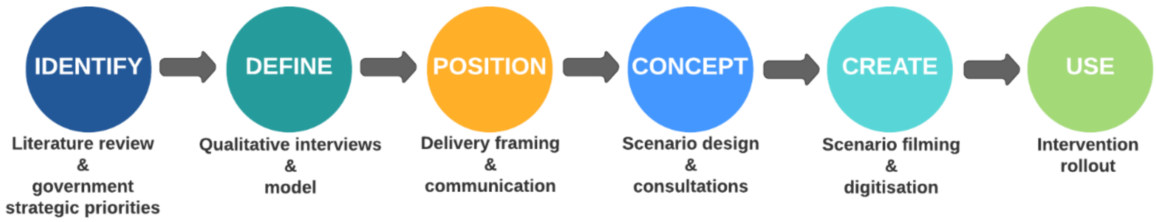

Fig. 1. The participatory design process (adapted from Hagen et al., 2012)

A literature review highlighted supportive communication as an important determinant of young workers' H&S. The problem definition, framing of the intervention, concept development and creation of the intervention are described in the remainder of this paper.

4 DESIGN OF THE DIGITAL INTERVENTION

4.1 Problem definition

A literature review identified communication as a contributing factor to young workers' H&S. To further investigate this phenomenon, semi-structured interviews were conducted with 30 apprentices and 11 supervisors in the construction industry of New South Wales (NSW), Australia. The interviews explored: (i) ways that apprentices, supervisors and co-workers talk about H&S; and (ii) characteristics of supportive communication and positive interactions. Exploratory and open-ended interview questions were used to elicit participants' opinions and personal experiences. Due to Covid-19-related travel restrictions, interviews were conducted over the phone, or via video, depending on participants' preferences, and were audio recorded.

Interview data was transcribed and thematically analysed using an inductive approach [41]. This consisted of conducting a thorough, detailed reading of interview transcripts, and assigning small, successive samples of text throughout the transcript to a code according to a concept or idea. The coding of the interview data was iterative and developed as the authors worked their way through the interviews. The thematic analysis identified communication characteristics and interaction styles that support positive H&S outcomes. The characteristics and interaction styles are shown in Fig. 2.

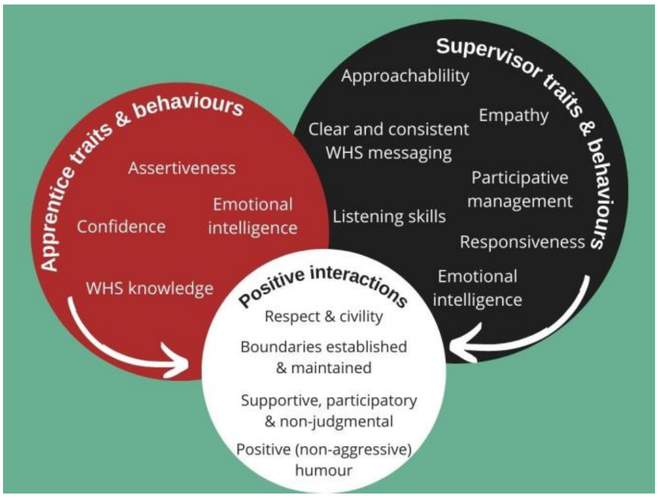

Fig. 2. Characteristics of effective and supportive communication

4.2 Intervention positioning

A digital role-playing game (RPG) format was conceived for the intervention. The communication characteristics and interaction styles identified in Fig. 2. became the key learning objectives of the RPG. Three scenarios were constructed for the RPG to support the learning objectives. Stories shared by apprentices during the interviews were used to build the RPG scenarios, ensuring the content reflected realistic events drawn from lived experiences of end-user representatives.

Each scenario depicted challenging situations to be navigated by characters (including a supervisor and up to three apprentices). Players are asked to decide how the characters should respond to each unfolding situation. Players' selected responses determine what happens next in each scenario. Scenarios run between five and eight minutes and involve multiple sequential and inter-related communication decisions. When players complete a scenario, they obtain an outcome as the product of their communication decisions, which can be positive or undesirable. Players are advised of the communication characteristics covered in the scenario and provided with an explanation of how their communication decisions contributed to the outcome. Players are then encouraged to replay the scenario to experiment with different choices.

Example situations from one of the three scenarios are described in the following section to describe the development process of the RPG.

4.3 Construction of the scenarios – An example: Non-judgemental and supportive interaction

4.3.1 Step 1: Content design based on interview results

Being non-judgemental and supportive were frequently mentioned in the interviews as important interaction characteristics that enable effective communication. Many apprentices considered a non-judgemental or psychologically safe communication environment as important for them to be able to speak up about H&S concerns or seek help. Apprentices recognised the roles of both supervisors and co-workers in creating a non-judgemental environment.

"[My supervisor is] absolutely really good with it. There's no real judgement if I can't do this work if that makes sense. If it's something I can't – I just can't do because I'm not strong or I'm not as sure. There's no actual judgement towards me about it. You know he's very understanding and he usually gets on top of it very quickly." (Natalie, female carpentry and joinery apprentice)

"… *like being comfortable with – with the people I work with onsite. Like, being very comfortable enough to kind of just openly speak, and not like worry that they're going to be like judging or anything like that. Kind of – I guess you could say it gives me the confidence*...." (Caleb, male carpentry apprentice)

Apprentices are more likely to open up and trust their supervisors if they raise H&S needs and supervisors support these needs. Supervisory support is particularly important when apprentices are new to an environment and feel uncertain about how others will see them if they raise H&S concerns. This is reflected in the story shared by Alexis, a 22-year-old female plumbing apprentice. Alexis was injured while carrying large heavy blocks in the rain when working for her previous employer. She was unable to work for three months due to the injury. Later she moved to her current training employer. One day when she was faced with carrying materials down steep timber stairs, she experienced a panic attack. She did not feel comfortable telling other trade workers because she was new to the site and worried that she would be judged unfavourably by them:

"…*at the time I felt like I couldn't talk to the tradies about it 'cause - like, I just started working with them - I felt like they would just go, "well, toughen up, sweetheart" or "have some concrete" sort of thing and get on with the job and, like, I don't know how I would have handled it if I got that response*." (Alexis, female plumbing apprentice)

However, Alexis discussed her concerns with her supervisor, whom she perceived to be supportive of workers' H&S. Her supervisor was supportive and suggested that she seek professional advice.

"*But I brought it up to my boss and I let him know, and he suggested that if it's a serious issue, maybe I should get some therapy to discuss with that, 'cause they - he knows that he can say something, but it might be wrong, so he tried to suggest, you know, professional help rather than give the wrong advice. So - but I said that it shouldn't really be a problem and, like, a few weeks later we did another job on even steeper wooden stairs and I carried, like, some really heavy stuff down it and I was all good and I didn't have a problem. So I told him about that and I told him how much I improved and, like, that was a one-off thing 'cause I, like, just started working on timber stairs again*."

Supportive interactions between apprentices and their supervisors and co-workers enable apprentices to develop confidence and achieve positive learning outcomes. An apprentice shared how the workplace support he received had helped him to overcome his fear of heights, which he considered to be an important step in learning and becoming a fully qualified tradesperson:

"…*sometimes they give you the push, which was good for me when I was first starting off…because I was pretty scared of heights, as a kid. So I still am a little bit, but like getting onto the roofs and stuff like that, and walking on the roof, and you're like, 'whoa.' You know, at the start, I got up on the roof and, like, 'oh, my legs aren't going to move, eh?' Like, 'this is not going to happen.' But eventually, they helped me walk on the roof, and you've just got to tell yourself, 'well, I'm going to have to do this by myself one day, or when you're a bit older,' so you've just got to do it. And it kind of helps for a lot of other things, I suppose. You do that one hard thing and you kind of slowly – like now I can walk on the roof fine*." (Paul, carpentry apprentice)

Based on the interview findings, a scenario titled "*This time it's personal*" was developed to address non-judgemental and supportive communication characteristics. The situation and associated decisions are depicted in Fig. 3.

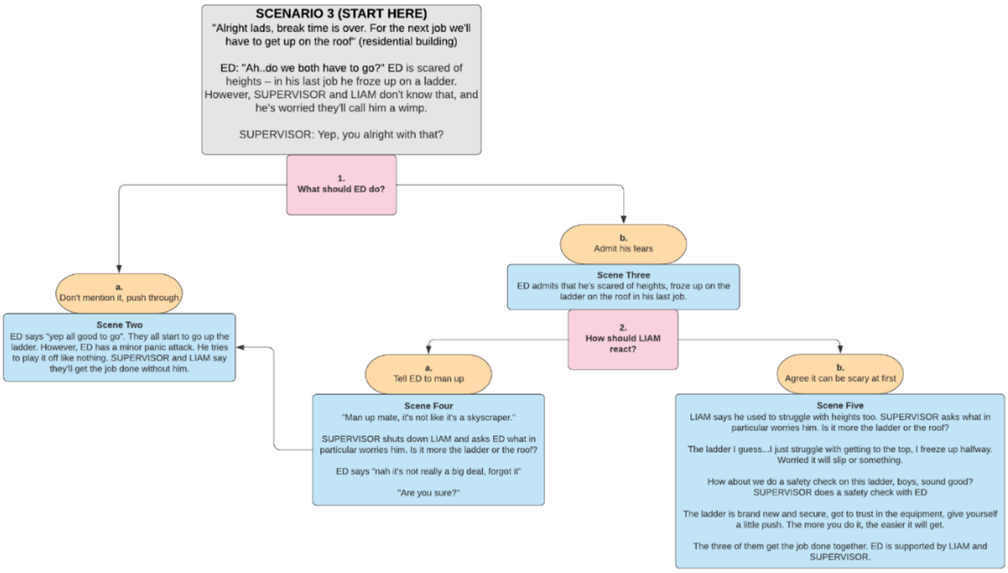

Fig.3. Scenario "This time it's personal" decision flowchart.

The context of the situation is that after taking a work break, the supervisor asks two apprentices to get up on the roof with him to do some work. However, the apprentice Ed has a fear of heights. He is unsure whether he should let his supervisor (Phil) and the other apprentice (Liam) know, as he worries that he may be ridiculed. The player is asked to decide for Ed whether to disclose his fear or try to continue working without mentioning it.

If the player opts for sharing his fear, Ed will tell his supervisor and Liam that he is scared of heights and 'froze' up on a ladder in a previous job. Next the player is asked to make another decision about the reaction of the apprentice Liam, who either tells Ed to "*man up*", or shows empathy by saying that getting on a ladder can be scary at first. In both options, the supervisor tries to provide support to Ed. However, Liam's reaction will lead Ed to respond to the supervisor's support differently, ultimately producing different well-being outcomes for Ed. Specifically, if the player selects the first choice, the supervisor will intervene by shutting down Liam and trying to help Ed. However, due to Liam's negative, judgemental response, Ed is embarrassed, pretends that his fear is not a big deal, and attempts to get on the roof. This time Ed's legs freeze again, and he experiences a panic attack. The supervisor and Liam end up getting up on the roof without Ed.

In contrast, if the player selects the empathetic and supportive response for Liam, the outcome is different. In this situation, Liam tells Ed that he has also struggled with heights before. The supervisor will propose doing a safety check on the ladder with Ed to reassure him that the equipment is of good quality and positioned correctly. The supervisor will also encourage Ed by telling him that he will get better at dealing with working at heights if he keeps trying. As a result, Ed feels supported by his supervisor and co-worker and is able to climb the ladder to work with them on the roof.

Positive relationships between apprentices and their supervisors/co-workers entail trustworthy personal connections that help to create a non-threatening context in which young people feel safe to express their thoughts and concerns. This example demonstrates the critical roles of both supervisors and co-workers in creating a non-judgmental and supportive communication environment. This also highlights the important role of supervisors in cultivating a supportive workplace culture.

4.3.2 Step 2: Consultation

The research project included an advisory group comprising four apprentices and two supervisors. The advisory group has voluntarily contributed to the project by providing feedback and advising on the development of the RPG scenarios. The content of this scenario was also reviewed by the advisory group members who provided input on the realism and relatability of the decision points, characters, language and outcomes. The first decision regarding Ed's fear of heights (shown above) was challenging for some apprentices as the option to "push through" seemed to align more with default behaviour than openly talking about being uncomfortable or afraid. Whilst pushing through appeared to be the more likely option for a young apprentice, the apprentices in the advisory group understood that it was the riskier choice and were not surprised when it led to Ed experiencing a panic attack.

Apprentices in the advisory group also pointed out that the presence of Liam, a more confident apprentice, serves to exacerbate the situation and that Ed would probably be more comfortable talking about his fear if Liam was not present, or was more supportive. This feedback influenced the scripting, staging and the performance of the scene in the next stage.

4.3.3 Step 3: Scripting the scenario

The decision flowchart for scenario “This time it’s personal” was modified and finalised based on the feedback received from the consultation process. The scenario was then scripted for subsequent filming.

4.4 Scenario filming and digitalisation

After consulting with the apprentices and supervisors for feedback on the three scenarios, they were further revised and then motion captured in which professional actors’ who provided the movement and facial expressions and voices for the digital characters. The motion capture process is shown in Fig. 4.

Fig. 4. Scenario filming with motion capture technology

The animation team created virtual sets and digital characters using Unreal MetaHuman and transferred the motion-captured animation to the virtual characters. The resulting animation was rendered in Unreal Engine 5. The animation was then edited into clips and uploaded to an interactive online video platform where they were encoded into a choose your own adventure style interactive narrative. An example of the digitised output is provided in Fig. 5

Fig. 5. Example digital images developed following filming

5 EVALUATION OF THE RPG INTERVENTION

With the three scenarios now fully workshopped, revised, digitised and in playable form, the digital RPG intervention is being evaluated using a before-and-after study design. The RPG intervention is being delivered to construction apprentices registered with training institutions in New South Wales and Victoria. Apprentices who have participated in the study were requested to complete a baseline survey first, and then invited to play the RPG. About four weeks after the delivery of the RPG, the apprentices were asked to complete a follow-up survey. Upon the completion of intervention delivery and data collection, responses from the baseline and follow-up surveys will be analysed to determine whether exposure to the intervention has produced any improvement in apprentices’ confidence in communication, willingness to voice safety concerns, perceived communication ability and sense of health, safety, and wellbeing in the workplace. Apart from the two surveys, each participant who plays the RPG is prompted to answer three questions after each scenario, including: 1) Have similar situations ever happened to you (or a mate)?; 2) Did you learn anything new about handling situations like this?;

and 3) Would you use what you learned from this? Google Analytics captured responses to these questions. Data from the first 181 participants shows that an average of 49.7% of players said they had experienced similar situations, perhaps reflecting their inexperience as young apprentices. However, an average of 71.0% answered that they learned something new and 82.7% said the game was useful.

6 DISCUSSION AND CONCLUSION

In light of the importance of supportive workplace communication and the critical role played by communication competence in shaping health, safety, and well-being outcomes, providing training to supervisors and workers to develop their communication skills is imperative. However, communication skills are difficult to teach in a traditional classroom situation. Research in other disciplines such as health education has demonstrated the promising opportunities of using experiential learning and role-playing as effective educational delivery methods to teach communication skills [42]. The digital role-playing game (RPG) developed in this study provides a novel training approach for supervisors and workers to learn communication skills in an interactive and engaging way.

Vocational education provided to young construction workers typically focuses on learning technical knowledge and skills. Relatively little attention is paid to the learning and teaching of 'soft skills' such as communication. This presents a significant capability gap in the vocational training of the construction workforce. The digital RPG in the present study was designed to support the learning of communication skills by construction apprentices and their supervisors. The digital RPG has excellent potential to be integrated into the vocational training curriculum to fill the capability gap.

Research shows that the effectiveness of learning through role-playing partially depends on the extent to which training involves taking roles that are realistic and relatable [43]. The participatory approach used to develop the RPG in the present study was critical to ensuring that the scenarios were realistic. The scenarios constructed were drawn from lived experiences of construction apprentices who participated in interviews and were further refined by applying feedback from an advisory group comprising of apprentices and supervisors.

The digital RPG is being evaluated with a before-and-after study design in New South Wales and Victoria. The evaluation will determine the extent to which apprentices' communication competence is improved by exposure to the digital RPG. A qualitative evaluation of the RPG's effect on supervisors' communication competence is also being undertaken.

7 ACKNOWLEDGEMENT

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HOW CONSTRUCTION SAFETY ACADEMICS ARE RESEARCHING WEARABLES FOR SAFETY, AND WHY IT MATTERS

Fred Sherratt[1], Peter Wong[2] and Simon Sherratt[3]

[1]*Construction Safety Research Alliance, University of Colorado at Boulder, USA*
[2]*School of Property, Construction and Project Management, RMIT, Australia*
[3] *Independent Researcher*

Abstract

Occupational safety, health and wellbeing management has fully embraced the Construction 4.0 revolution. Technology now offers myriad solutions to worker OSH, with a notable interest in the adoption of personal wearable technologies. There is a rapidly growing body of work focused on wearables for construction safety, however the technological optimism surrounding this particular 'digital transformation' of safety in practice is perhaps misplaced. Following a purposive literature review of this body of knowledge, analysis reveals some areas of concern, including research funding, methodology and methods used, and the overall aims and intentions for the findings. Yet this body of work is not only being used to justify the adoption of wearables on sites, but also sets a precedent for future research as it directs the narrative and agenda. This review is, therefore, both timely and necessary. It seeks to remind academics of the tenets of our work: to ask robust research questions in ethical ways that ensure valid, reliable, and robust findings able to contribute meaningfully to the body of knowledge in this field.

Keywords: construction 4.0, safety, wearables, wearable technologies, workers.

1 INTRODUCTION

Construction 4.0 has resulted in myriad new technologies and interconnected technological processes able to support and enhance the construction industry worldwide [1]. Construction 4.0 is often propounded as the solution to the industry's longstanding problems of poor productivity and predictability; through the increased use of robots, sensors and digital platforms linked through 5G capabilities and the Internet of Things (IoT), generating big data for Machine Learning (ML) and Artificial Intelligence (AI), all of construction's problems are to seemingly be solved by this latest technological revolution (see [2] for a more detailed discussion of this discourse).

Unsurprisingly, the field of construction occupational health, safety, and wellbeing (OSHW) has also aligned itself to this new wave of technological optimism, not least because of the recent plateau in severe injuries and fatality (SIF) rates [3] suggests a paradigm shift is needed in how we manage OSHW on sites to reduce them any further. Indeed, the strapline for this CIB conference is the 'Digital Transformation of Health and Safety in Construction' and a technological flavor can now be found in most OSHW events. For example, the recent industry-focused 'Future of EHS' conference held by the National Safety Council of America had a 'Safety Technology Pavilion' embedded within the program [4]. Enthusiasm for technology as the solution to the construction industry OSHW issues is also prominent within academia. One obvious motivator for this mirrors that of construction firms and safety professionals; that we clearly need to do something different to overcome the plateau in SIFs.

Yet to champion technology as the optimum remedy for the current situation is perhaps not quite so simple, not least because the '…history of the construction sector is littered with supposed panaceas derived from the application of modern technology' [5]. There is the possibility that technology in the case of worker OSHW may not be the magic potion it is heralded to be, yet it is arguable that the current body of academic research – which is used to make policy decisions, to influence and justify industry practice and to direct future avenues of enquiry – makes no such acknowledgement. Instead, technocratic optimism and a fundamental presumption in favor of technology abound, and construction management research appears to be more focused on overcoming any barriers to adoption [6] than asking whether a certain technology is the optimal thing to adopt in the first place [7].

In order to further unpack this situation and to provide some valid and reliable findings to underpin more critical discussion, a purposive literature review was undertaken of wearables for construction OSHW. The findings of this review were interrogated to explicitly unpack the funders of this body of work, the research questions being asked, the methodologies employed therein, and the potential claims that can be made of the findings generated. The aim of this work was to evaluate how construction safety academics are researching wearables for safety and to unpack the potential consequences of this body of work for the wider OSHW agenda.

2 WHY WORRY ABOUT WEARABLES?

This study focuses on wearable technologies for construction workers' OSHW. Wearables are here defined as sensor technologies worn by the worker. They can be integrated into hard hats or clothing or worn on the wrist like commercial smart watches and fitness monitoring devices [8] and can provide various forms of real-time data [9]. They have excited the interest of many researchers seeking to transfer potential benefits of this new source of data into practical improvements for OSHW in the field and have been noted as a 'trending technology' within the wider use of technologies for safety [10].

Wearables for safety tend to fall into one of four categories that generate different types of data about the worker, as set out by [11]:

1. **Physiological** sensor monitoring of workers, able to generate data on worker pulse and blood pressure, Electro-cardiogram (ECG) heart data, Electro-encephalogram (EEG) brain activity rates, Electro-myography (EMG) muscle activity rates, glucose levels and calorie use, perspiration, temperature [8] as well as skin photoplectometry to monitor stress levels [9] and eye-tracking able to monitor where workers are looking [12]
2. **Motion** sensor monitoring of workers, able to record their posture, speed, and acceleration [13]
3. **Location** sensor monitoring of workers can be integrated with the project BIM model and able to record worker's precise location on site and issue warnings when they are close to hazards or dangerous areas [9]
4. **Environmental** sensor monitoring of worker surroundings, able to facilitate the automated detection of hazardous materials and dangerous weather in real time, such as dust [9, p256], noise, and light intensity [8], as well as alerting workers to other hazards such as gas leaks, electrical discharge changes in humidity and temperature [13, 14].

Data collected from the above approaches are described as valuable, with the general presumption that the more data that can be collected, the better [15].

The selection of wearable technologies for this study is deliberate, as they are also among the most intrusive and ethically challenging to implement in practice and can result in serious negative consequences for workers. As the UK Government recently concluded: 'Pervasive monitoring…[is] associated with pronounced negative impacts on mental and physical wellbeing as workers experience the extreme pressure of constant, real time micro-management and automated assessment' [16, p6]. There is therefore the possibility for unintended consequences should wearables be introduced to the construction site space without due care and attention, and thus they should be carefully and robustly evaluated before they are championed as the panacea for construction OSHW.

3 METHOD

In order to unpack the current body of literature on wearables for construction safety in more depth, a purposive literature review was undertaken. There have already been a number of systematic literature reviews (e.g. [13], [17]) and bibliometric analyses (e.g. [10]) undertaken to examine safety technologies for construction which provide valuable resources to the field. Therefore, to avoid duplication of efforts for this study and keeping the aim of a critical evaluation of technological determinism and optimism within the field, a smaller and more purposive sample of literature was obtained for analysis. This review therefore differs in both its intent and the way the papers were reviewed which focused more on the methods used and by whom, rather than the claims made in the conclusions.

Initially, a search was performed in the electronic *Science Direct* database. The search process was guided by the presence of three keywords: [wearables] AND [construction] AND [Safety], which generated a total of 78,811 results. The top 250 of these papers (to set an appropriate scope for this study) were then reviewed using the basic inclusion criteria of: (i) Publication in a double-blind peer-reviewed journal, (ii) Written in the English language, (iii) The full-text article can be accessed, (iv) The paper included novel empirical work focused on wearables for safety management.

Exclusion criteria were subsequently applied to this sample of 250 papers to remove those irrelevant to this specific study. This included papers researching wearables for medical monitoring unlinked to safety or occupational health and its management, experiments using wearables within training environments rather than during work itself, and those researching wearables in factories, on production lines, or other fixed-industrial workplace environments. Papers that also did not use the wearable technology to collect data from the worker explicitly for subsequent use within OHSW management, such as using Augmented Reality through Google Glass for hazard recognition, were also excluded as no data was explicitly collected from the worker via the wearable technology, although of course the inevitable 'digital exhaust' remains [18]. This resulted in a total of 53 papers for review from the publications as shown in Fig 1.

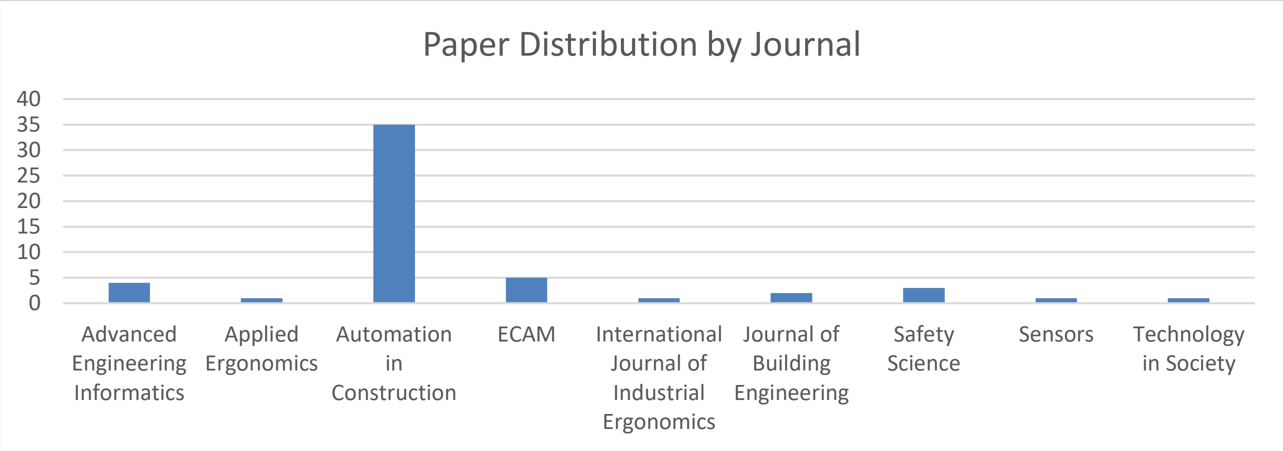

Fig 1: Paper distribution by journal

Each paper was then analyzed from a number of different perspectives. Basic data such as geographical location, methodology and funder was aggregated, whilst a discursive approach [19] was undertaken to the content of the papers themselves, focused on their discussions and positioning of 'wearables for safety' within their introductions, literature reviews and conclusions. This latter analysis sought to determine how the authoring academics used language to construct wearables for safety within the context of their papers, unpacking the discourse they mobilized in their narratives. Given the limited sample and approach to the data, no claims of generalizability are made here, and this work has been undertaken to show general trends and patterns within what could be considered the most impactful and high-quality papers currently available on this specific topic.

4 FINDINGS AND DISCUSSION

4.1 Who is doing the research?

Fig 2 shows how the activity of researchers roughly geographically correlates to the locations of dominant companies and markets in the wearable technology space [20]. Asia and North America contain the Top 6 companies in the global wearable technology markets and are the dominant locations where research of construction safety wearable technologies is also carried out. A notable number of the papers were collaborations across continents, however, within these collaborations, Asia and North America still dominated, and indeed there were several collaborations between the two.

4.2 Who is funding the research?

The vast majority of the research, where funded, was supported by National or Governmental research grants, and in many cases smaller grants from both had been combined to fund the research as a whole. This reflects the comments of [5] in that research funding itself is biased towards innovation and new technologies – including research on wearables for safety.

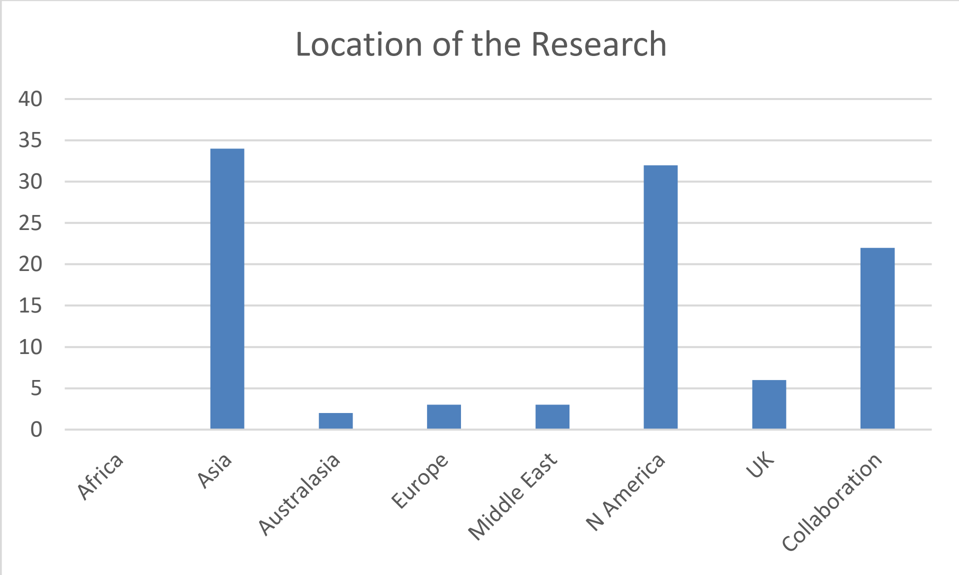

Fig 2 Location of the Research

In only 3 papers was a corporate partner/collaborator noted. Interestingly, [21] received in-kind support from '…two technology providers (Topcon and Selectronic-Funk Sicherheitstechnik GmbH), which enabled the extension of existing systems rather than creating them from scratch'. This study explored the potential for a cloud-based autonomous system to monitor workers to avoid struck-by incidents, and this argument therefore seems reasonable under the circumstances. However, this collaboration was not noted in the paper's acknowledgements but rather in the methodology, which instead reported two government funders.

Unfortunately, the dominance of public sector funding for wearables for safety research can seemingly be charged with continuing the long tradition of public funds being used to enhance the products and services of private companies, who can then mobilize such findings for future profit [22].

4.3 How are we doing the research?

Details of the location and samples for the studies can be seen in Table 1.

Table 1: Locations and sample compositions for the body of research

	Lab Study	**Site Study**	**Lab & Site Study**	**Survey**
Students	13	1		
Workers	4	18	1	
Subjects	10	2		3
Unknown			1	
TOTALS:	**27**	**21**	**2**	**3**

As shown in Table 1, 51% of the studies were undertaken in a laboratory environment, 40% being undertaken in the field on jobsites. There are likely several reasons for this, not least problems of access to live, working, and high-hazard environments. As [23, p64] explained in their study: 'to deploy and test the [RTLS] system within a construction environment is dangerous, and the main contractor of the construction project was aware of the potential accidents that may be caused to or caused by the research team during the test'. Therefore, the '…performance of the system was evaluated in a construction environment and testing environment similar to that of previous research'.

Yet it does not necessarily follow that how technology behaves in the lab will equate to performance out on site. Construction sites are not welcoming environments. Poor working conditions are commonplace, as they are constantly challenged by dust, noise, and the weather. Such conditions can affect the use of technology in the field and go some way to explain the continued popularity of that high-tech tool – the pencil – over all other ways to make your mark or collect data. Indeed, in their site-based study, [24] note that the participants in their study of sensor vests seeking to warn workers of hazards '…had difficulty in identifying signals due to loss of attention during field trials, and they were unable to perceive parts of the transmitted information correctly.' This highlights the importance of field trials for wearables for safety, as participant reactions in a safe and secure laboratory simply do not accurately reflect the construction site environment, and conclusions for effectiveness should be drawn appropriately, however, not all the papers of acknowledged the reported research methods or approaches as limitations. Given the nascent stage of wearables for construction safety, it may be that the technology has simply not yet been fully developed for the construction field and is awaiting confirmation from the labs that such an investment would be worthwhile. However, this should limit claims to effectiveness accordingly.

It was also noticeable that the sample sizes for the research of wearables for safety are relatively small. A total of 303 samples were used in the 27 lab-based studies, giving an average sample size of only 11 individuals per study. Two site-based studies report sizeable samples of 79 and 100 workers; however, these were outliers within the research as a whole. Removing these two studies from the data resulted in an average of only 6 participants per site-based study. In four cases no sample sizes could be determined from the published research.

Such small sample sizes are concerning when their findings are then used to verify success of application and to make the case for more widespread adoption. This is particularly worrisome when there is the possibility for unintended consequences, such as potential negative impacts on worker mental health and wellbeing. If wearables for safety were instead a new drug aiming to cure a disease (a not unreasonable analogy), such sample sizes would be considered both unethical and unscientific, and much more sizeable and rigorous trials would be required before the drug was prescribed to patients. We should perhaps hold this analogy a little closer as we move forwards with the research of wearables to ensure any benefits are scientifically proven and, thus, the benefits outweigh the risks before we use such research to urge and argue for their increased use in practice.

Furthermore, the composition of many samples would also likely have consequences for the validity of this body of research. As shown in Table 1, students or 'subjects' are often used for experiments rather than construction workers. The substitution of students for laboratory studies is perfectly acceptable but must be clearly acknowledged as a limitation for translating the research into practice. In many cases, the term 'subject' was used for the lab-based studies, yet the average ages of the participants often fell into the student body age range. The commonplace use of this term obfuscates the participants and is therefore problematic when the reliability of the study is considered. It can also create a potential problem when the findings are considered for application in the field, as to again draw on a medical analogy, pharmaceutical trials ensure their participants are appropriate for the study being undertaken. For example, with regards to Musculoskeletal Disorder (MSD) motion sensors, the study participants should be required to undertake construction tasks as they are done professionally in the field, something students are not likely to be able to replicate. To presume manual skills and tasks are something anyone can do is not only naïve, but also more than a little condescending.

A final point of note is that using students and laboratory studies does not fully replicate the intended use of wearables for safety. To use something for a limited period in a warm and dry laboratory is not equivalent to a worker wearing it for 8hrs+ per day in the field, again challenging research quality by negating ecological validity. In the vast majority of this research, it was the technology being tested rather than its use in the field, however, should the same type of studies be replicated or enhanced to explore user experience, then further problems will arise as there is a world of difference in being monitored for a few hours to help out your professor, and being monitored constantly throughout your working day.

Indeed, academics seem content to carry out research to develop products and systems, keeping them on the leading edge of research (which in turn enhances citations, h-indices and consultancy potential, all of which are a grim necessity of academe) rather than more challenging research to robustly test existing products in the field to determine their actual effectiveness in keeping workers safer and healthier on jobsites.

With regards to the survey data, again, methodology matters. For example, in introducing their survey work examining the impact of safety technologies (including wearables for safety) [25] state that it is '…crucial to establish safety management using technologies based on big data for the construction industry.' They also note that 'construction is one of the least digitized industries…which makes it difficult to solve the problems experienced by the sector.' Why digitization is the only solution able to solve such problems is not further justified, and this introduction is a familiar narrative to many studies that draw on a discourse of technological optimism and determinism as they then go on to claim that '…the construction industry can benefit from such technologies to a great extent in terms of improving safety performance.' It would seem technology is simply going to solve all our OSHW problems by default. Their subsequent survey seeks opinion data from a sample of senior management-level construction professionals (notably not site-based supervisors or workers, who are often much harder to access) to 'evaluate their performance in terms of practicing emerging technologies in relation to construction safety'. Using structural equation modelling of this opinion data sought from those a long way away from any actual construction site, they eventually conclude that 'The analysis of the structural model proves that there is a positive and significant relationship between emerging technologies and construction safety performance' with 'wearable devices…detected to be [among] the most significant technologies in terms of impacting safety performance.' This provides a welcome citation for those seeking to justify the use of wearables for safety in practice, despite its foundations in opinion data generated some distance from the field. Whilst such surveys can and indeed are both insightful and useful, they should perhaps not be used to prove 'success' in practice.

Indeed, when considered amongst the very limited experimental work carried out to date in this space, the body of evidence of the benefits of wearables for safety reveals itself to be rather thin. Yet this would not matter if the inherent limitations of laboratory studies, opinion data, small samples, and the use of students were appropriately noted when such research is subsequently cited by others, and comment is made of the 'general' state of safety technologies, including wearables. But all too often it is not, and instead this body of research is frequently referred to as scientific 'evidence' and 'proof' that wearables for safety are effective, appropriate, and demonstrably beneficial for practice.

4.4 What is being researched and why?

4.4.1 Wearables for what?

The research focus of the body of wearables for safety research and the categories of wearables found therein can be seen in Table 2. Please note the 3 survey papers are not included in Table 2.

The majority of studies focused on the reduction of MSDs within the construction workforce. These studies sought to develop systems able to monitor and warn workers of poor posture and unhealthy activities as they go about their working day. Various technologies are tested, including Inertial Measurement Unit Sensors (IMU) (n=6), insoles (n=3), and even smartphones and Apps (n=2).

The use of physiological sensors, including EEGs and heart-rate devices, were mobilised in a variety of applications to measure and monitor a number of different factors and were the most prominent use of wearables for safety within the sample of papers. The states of distraction, fatigue, stress, general mental condition and even hazard awareness of workers could all be determined through the use of physiological sensors.

An interesting body of work focused on the use of wearables to effectively turn the workers themselves into site surveillance devices. For example, loss of balance monitoring using insoles or IMUs was applied to both the assessment of workers' vulnerabilities to slips trips and falls, and to provide management feedback on the locations of working conditions that may cause slip, trip, and fall injuries. This approach was also applied to hazard identification, through the use of insoles (n=3), and IMUs (n=1) to again identify and inform management of the location of unsafe conditions.

It should also be here noted that although only 44% of the papers monitored worker location, this has only been recorded for the studies that explicitly noted this element of data capture. In many cases, location monitoring was not mentioned, even with technologies connected to the IoT and wider AI/ML systems. In many cases, location data cannot not be collected by default, and thus the potential for the original intentions of such surveillance to be vulnerable to exploitation for productivity or other non-safety monitoring inevitably remains [2].

Table 2: Areas of focus and sensor categorization for the body of research

		Sensor Categorization			
Focus	**No Papers**	**Physiological**	**Motion**	**Location**	**Environ**
MSDs	11	1	11	1	
Fatigue	7	7	1	1	
Hazard Identification	5	1	4	4	
Distraction/Vigilance	4	4		1	
Slips/Trips/Falls	5	1	4	4	
Struck By Accidents	4			4	
Physical Demand	3	3	1		
Heat stress	2	2			
Risk Perception	2	2		2	
Activity Recognition	1		1	1	
Hazard Awareness	1	1			
Location	1			1	
PPE Compliance	1			1	
Worker mental state	1	1		1	
Stress	1	1			
Total Worker Health	1	1		1	
TOTALS:	**50**	**25**	**22**	**22**	**0**

4.4.2 A worrying sense of purpose

The justification and rationale for much of this monitoring are of course to improve the construction industry OSHW. However, the subsequent processes through which the data generated is analysed into meaningful ways to bring about that change are far less well articulated within this body of literature – if they are articulated at all. In many cases, the research stops at the point where technological success has been 'proved', with little consideration of how the findings will then be used in practice.

For example, [26], in their study aiming to 'identify workers with poor postural controls' in their quest to reduce falls on jobsites, generate data for '…managers/foremen for onsite balance monitoring of the construction workers using the 20-second test at different times of the day and establishing their corresponding balance performance profiles.' To share such personal worker data is fundamentally problematic, but to think that construction managers and site foremen have time in their day to monitor/test workers is perhaps more than a little unrealistic. Furthermore, this study becomes even more worrisome as the goal appears to be to 'assist early identification of fall prone workers, plan mitigation schemes before a fall accident happens and ultimately help reduce falls in the construction industry' [26]. When the most straightforward mitigation scheme is to get rid of that particular worker, we have simply returned to the punitive 'Bad Apple' theory of safety management from decades ago, and this wearable for safety can all too easily be used to identify and fire workers based only on data from a random test and an AI judging whether their wobbles are too extreme.

Another set of studies that have a worrying sense of purpose are those directed at determining worker fatigue. Construction work inevitably creates fatigue – it involves manual labor, long hours and often punishing shift systems, thus, improvements for OSHW should arguably focus on how to reduce work activities/shifts to ensure workers do not become fatigued. However, some wearables for safety, using EEG monitoring, instead seek to determine whether workers are or become fatigued during the working day [27], or are even too fatigued to be put to work in the first place [28]. In both instances, this is a laudable motivation, as both physical and mental fatigue can easily result in accidents, however, the consequences could be considerable for workers deemed unable to work or continue to work, as they are likely to be sent home unpaid. Unless such monitoring also includes those who put people to work (the management and supervisors), this is inequitable, unfair, and again resurrects the 'Bad Apple' theory of safety – by simply punishing those who do not meet technologically-determined benchmarks.

A further problem, as noted above, is in sharing personal data with management or supervisors. The lament is made by [21] that 'General Data Protection Regulation (GDPR) requirements raise data recording and storage complexity…[and] may affect a system like the one proposed negatively.' Yet these EU regulations were put in place precisely to protect individuals from the use and misuse of their data and should not be undone lightly.

Much more extensive research outside of the construction industry has already proven that constant monitoring of workers is bad for their health [16], and so to combine this with archaic approaches to OSHW management in the field is a serious concern. Despite good intentions, the lack of consideration of how the vast amounts of data generated by wearables can and will be used is itself highly problematic.

4.4.3 A worrying lack of purpose

A counter position was also found within the data, where research had been undertaken with no greater purpose than 'monitoring' workers. For example, in their study of activity recognition via smartphone technology, [19] only offer a vague justification that 'Effective and timely analysis and tracking of workforce activities are essential to overall productivity measurement, progress evaluation, labor training programs, and safety and health management.' Such vagaries are also found in wearables simply seeking to locate workers on jobsites. Whilst [23] justify their study as necessary because 'There is an imminent need for the development of a tool to assist in the real-time monitoring of workers, in order to reduce the number of construction accidents.' Their system aims to '…provide alerts when 'any worker violates pre-defined hazard proximity rules' and provide data on the 'automatic positional monitoring of site workers', which is therefore of '…considerable assistance to site safety management teams.' Yet simply knowing where workers are on a jobsite and the ability for such dynamic workplaces to have fixed 'hazard proximity rules' seems vague with regards to practical application. How such monitoring will be carried out and by whom is also unclear.

5 CONCLUSIONS

Wearables for safety form a distinct and sizeable subcategory of the wider safety technology industry. They are able to monitor, measure and generate a wide variety of data on construction workers through various and different wearable devices, from personal EEG monitoring of physiological factors to Real Time Location Systems (RTLS). Notably, no studies within this sample sought to research wearables for immediate environmental monitoring to support workers in the field despite this suggested application from wider literature. Instead, the studies in this sample focused entirely on wearables that generated data from the workers themselves for use by others.

The analysis undertaken here shows that academic research of wearables for safety could generously be considered 'limited'. Small samples and lab-based work with students indicate this is a nascent field of research, nowhere near able to make claims of effectiveness in the field. That many studies are published in the journal *Automation in Construction* further indicates that these are first steps in the field, yet also is perhaps unhelpful when the myriad equations, calculations and 'hard data' analyses perhaps reassure more than they should of the 'science' behind these studies. Research must first shift into social science spaces better able to test their implementation reliably and their validity in practice, incorporating management practices, worker experiences and, most importantly, ethical issues into the studies. Indeed, the lack of discussion or even consideration of ethics and privacy within this body of literature as a whole is worrisome, despite this being a common worker concern [30], yet this is perhaps to be expected given the current technological focus of wearables for safety research. There is some progress in this area, for example, the research of blockchain to 'balance privacy and OSH' by [31] is welcomed but is also more than a little ironic; proposing a technological solution to problems caused by technology use in the first place.

Yet this raises another point. Technocratic determinism that wearables for safety will inevitably improve OSHW safety management on sites means we are perhaps failing to consider any other options for improved safety management – things that do not involve technology at all. We know many construction activities cause MSDs in workers, so is it not better to put our efforts into researching new ways to construct and thus eliminate or mitigate problems at their source rather than use insole sensors to monitor workers as they continue to struggle in the field? Such wearables can become just another form of PPE, albeit one that can tell you when you're 'doing it wrong', but that is not exactly aiming high at the hierarchy of control.

Most importantly, this study demonstrates that whilst wearables for construction safety are already a prominent and growing commercial industry in and of themselves, we should as academics be mindful of what science is actually able to prove. The current body of academic research of wearables for safety cannot (yet) demonstrate that they do make a positive difference on construction jobsites. We should therefore be much more cautious in championing this tool of Construction 4.0 as the panacea for OSHW management – and start to develop valid, reliable and generalizable studies that examine wearables for safety entirely objectively, mindful of our ethical obligations. Our first responsibility should always be to the construction workers who risk their health, safety and wellbeing when they go to work each day, rather than to governments fixated on demonstrating 'technological progress' or firms seeking to maximise profits from invasions of worker privacy.

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SAFETY MANAGEMENT IN CONSTRUCTION SITE BASED ON AGENT-BASED MODELING: AN ANALYSIS OF SOCIAL THEORIES

Vanessa Cruz Pacheco[1], Márcio Costa Barros Júnior[1], Guilherme dos Santos Bonfim[1], Elaine Pinto Varela Alberte[1] and Dayana Bastos Costa[1]

[1]*Federal University of Bahia (BRAZIL)*

Abstract

The construction sector is one of the segments that most register work accidents in Brazil. Safety management is a fundamental activity at the construction site because it identifies, controls, and assesses hazards in the work environment. There is a need for tools to support safety management at the construction site that considers human behavior and cultural issues in the region to identify management strategies that promote the reduction of unsafe behavior of workers. Recent work has developed agent-based computational models to analyze the theme based on social theories such as risk theory and the theory of planned behaviour. Agent-based modeling (ABM) is a computational methodology with solid potential for the simplified representation and analysis of complex systems such as construction sites. This article paper analyzes social theories applied to agent-based models focused on construction safety management and identify the most appropriate theory(s) to represent a Brazilian construction site. To this end, the study conducts a literature review and a structured analysis of the data collected about the safety management of construction sites in Brazil, ABM applied to the subject, and related social theories. As a result, (1) the social theories used to analyze the safety behavior of construction workers are identified, and (2) social theories are selected to propose a conceptual framework to support the development of an ABM focused on the Brazilian context. From the analysis of sixteen articles found in the literature review, it was possible to identify eleven social theories used to investigate the safe behavior of civil construction workers. The study proposed a decision-making framework for Brazilian construction workers' cognitive process of unsafe behavior based on risk theory, organizational support theory, and social identity theory.

Keywords: Agent-based modelling, safety, construction site, social theories, human behavior.

1 INTRODUCTION

The construction industry has great relevance in the country's economic structure, being responsible for a considerable part of the generation of jobs in Brazil. [1]. According to the Digital Observatory of Occupational Health and Safety [2], there were about 446.9 thousand work accidents in the country in 2020, with more than 10 thousand occurring only within the construction sector. The mortality rate in the Brazilian construction industry reaches 11.76 cases for each group of 100,000 full-time workers per year [3]. In the Middle East, the mortality rate is 18.6 per 100,000 [4], while in established economies, the rate is 4.2 per 100,000 [5].

Ensuring the safety of people in construction is a comprehensive and challenging task due to the sector's dynamic and complex working conditions. Accidents and fatalities remain a worldwide problem despite existing regulatory reforms, legislation, and research [6]. Several authors associate human behavior as one of the main factors related to the occurrence of occupational injuries and accidents, highlighting that work safety programs focus on individual behavior and risk management ([7], [8]).

The creation of tools to support construction safety management is an action that should be encouraged. Agent-based modeling (ABM) stands out as a suitable approach for analyzing this environment [9]. ABM is a computer simulation method that analyzes a complex social system using virtual agents to reproduce the behavior and interactions between individuals in the system [10]. The accuracy of this modeling type allows the analysis of a heterogeneous set of agents from a single system of resources [9]. From the development of an ABM, it is possible to define and analyze the interactions between the personnel related to the safety of the construction site, their properties, and individual behaviors. Their interaction rules can be represented respectively at the beginning, forming a system at the macro level. However, social theories need to be used to base the simulation of the construction worker's behavior as close to reality as possible.

Through an integrative literature review, this interdisciplinary research aims to map the main social theories used in literature to understand the safe behavior of construction workers. The study aims to develop a theoretical proposal of the cognitive behavioral process of Brazilian construction workers and identify social theories that can support this proposal. We expected that the results of this study will contribute to the development of agent-based models that support the search for safer Brazilian construction sites.

The remainder of this paper is organized as follows: Section 2 presents the literature review, and Section 3 describes the methodology adopted. Section 4 presents the results of the integrative literature. Section 5 presents the selected theories, discusses their validity for the Brazilian scenario, and presents and discusses a cognitive process framework proposal to support the development of an ABM focused on the Brazilian context. Finally, Section 6 presents the conclusions.

2 LITERATURE REVIEW

In recent years, the unsafe behavior of workers has received attention in investigations of accidents in the construction industry, as deviation from safety procedures by employees has been identified as the leading cause of accidents in the sector [11]. Worker behavior is considered one of the four main contributors to safety incidents [12]. However, the industry cannot always control the risks in construction, given the multitude and instability of factors involved in the production stage of construction (materials, equipment, and workers) [13]. Therefore, safety management should increase awareness of risks and provide safe working conditions to minimize risks.

Management strategies can reduce workers' unsafe behavior on a construction site [14]. The safety culture can affect the safety relationship in the construction work environment, associated with management commitment and employee participation [15]. Employee perception of the organization's safety climate is manifested according to how safety is rewarded and supported by the organization [16]. A positive safety climate induces safer worker behavior and fewer accidents and injuries [17].

By measuring the safety climate, it is possible to predict the occurrence of future accidents or injuries in the work environment, as it represents an external or instant reflection of the safety culture [18], which can highlight areas for overall improvement in the work environment's safety [19]. Given the direct relationship between safety climate and human behavior, social theories such as risk theory and planned behavior theory are used by different authors ([10], [11], [14]) to understand how management strategies can impact workers' safe behavior, both within the construction industry and other industries.

In literature, studies that analyze aspects of safety from the base of production (workers) to the top (management) are based on behavioral and social theories to justify the agent's decision-making ([11], [12], [14]). The most analyzed organizational factors were the influence of feedback from managers, followed by training and safety inspections. However, the main focus of the studies was to investigate co-workers' impact on employees' behavior. There is a lack of technology integration in real projects at construction sites. This integration is fundamental to enable the effective use of technology, such as agent-based modeling, to assist managers in decision-making.

3 RESEARCH METHOD

Three stages composed the present research. The first stage consisted of bibliographic research on the topic, analyzing the panorama of Brazil's construction safety sector and the context related to the application of computational technologies to analyze the safe behavior of construction workers. The second stage performed a structured analysis of research that applied social theories to investigate the safety behavior of construction employees. This stage consisted of an integrative literature review [20]. The study conducted a structured analysis of 16 research selected in the literature to map and analyze the main social theories used by the authors. The study chose Scopus and Science Direct as databases due to their representativeness and relevance within the knowledge of construction, testing different research strings until reaching the one that provided the best results with the larger sample size according to the research objective (Table 1).

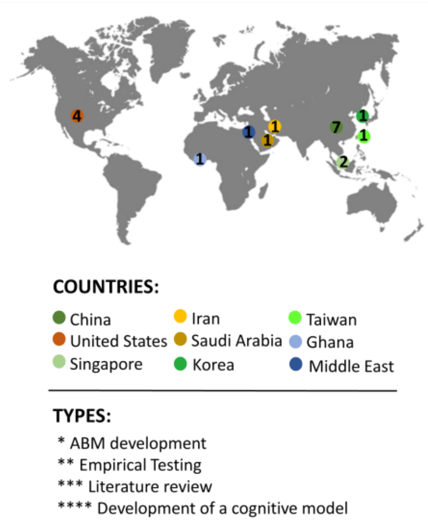
Fig. 1 presents the analyzed studies, relating the authors, year of the research, type of research, countries, and study objective to an identification code. Each study has a specific purpose, but all analyze the safety behavior of construction workers from the perspective of social theories.

The third stage involved the development of a proposal for a cognitive-behavioral structure of Brazilian workers based on social theories identified in the previous step and considered applicable to the

Brazilian context. The proposed framework aims to support the development of an ABM focused on the Brazilian context that plans to simulate the influence of safety management strategies on workers' safe behavior. The study used three Brazilian national studies to identify the relationship between selected social theories and the Brazilian context and to validate the proposed framework. It selected these bibliographies because they are national studies presenting essential data on Brazilian workers' safety behavior.

Table 1. String definition

Database	Search Terms	Results
Scopus and Science Direct	TITLE-ABS-KEY (("agent-based" AND (model* OR simulation)) AND (construction OR build*) AND safety))	10
Snowball sampling	-	6



Country	COD	REF/Type	Year	Purpose
	SR1	[21]*	2022	To explore differences in safe behavior change among construction workers with different personality traits.
	SR2	[22]*	2022	To compare the influence of traditional management actions with management practices using technologies to analyze the safe behavior among construction workers.
	SR3	[23]*	2022	To study the influence of seven factors (safety, organization, psychology, and individual) on the dynamic performance of safe behavior by construction workers.
	SR4	[24]***	2021	To conduct a literature review on the construction safety climate and provide a theoretical framework.
	SR5	[25]**	2021	To investigate psychological ownership as a mediator in the relationship between safety climate and occupational safety behaviors among construction professionals in Ghana.
	SR6	[14]*	2020	To explore the causes of cognitive impairment in construction workers and the influence of social groups and social organization factors on the safe behavior of construction workers.
	SR7	[18]**	2020	To investigate how organizational support can cultivate a multilevel safety climate in the construction industry.
	SR8	[26]*	2019	To investigate the effects of two different actions to support employees on three levels of severity of safety performance in a construction project.
	SR9	[10]*	2019	To analyze interpersonal interactions on construction sites between workers and management teams to study the effect of these interactions on construction safety performance.
	SR10	[11]*	2018	To investigate the social influence on the safe behavior of construction workers and interaction with different safety management interventions and different site risk conditions.
	SR11	[27]*	2018	To analyze the influence of different management strategies on the safe behavior of construction workers in different locations with different levels of risk.
	SR12	[28]*	2016	To assess security performance and network resilience to risks for communication and security management.
	SR13	[29]*	2016	To analyze safety behaviors when planning a construction activity.
	SR14	[30]****	2016	To develop a cognitive model of construction workers' unsafe behaviors.
	SR15	[19]**	2015	To investigate the systematic influence of three types of institutional pressure (namely, coercive, mimetic, and normative pressures) on the safety climate of construction projects.
	SR16	[31]**	2013	To investigate the factors behind why scaffolders opted not to use safety harnesses.

Fig. 1. Selected Research (SR)

4 RESULTS

The studies were from nine different countries. No publications related to the Brazilian context were found (Fig. 1). Several studies point to the influence of cultural differences on safety [32]. Therefore, these studies do not represent the reality of safety in Brazil.

The analysis of the studies allowed identifying social theories used to understand the safety behavior of construction workers. In agent-based modeling, it can guide decision-making by employees and the rules of interactions between agents.

The Theory of Planned Behavior and the Risk Homeostasis Theory are the prevailing theories. The first appears in eight of the sixteen selected surveys. The second appears in four. Studies can use these theories in isolation or combination. Both have great potential to understand the causes of individuals' unsafe behaviors.

Table 2 presents the conceptual definition of the theories and an analysis of how the authors used them in their respective studies.

Some studies (SR1; SR2; SR6; SR9) created "frameworks" to understand the factors that influence the behavior of construction workers. The cognitive process structure proposed by SR6 for construction workers considers the influence of individual, social, organizational, and group social cognitive factors in each of the three stages of the cognitive process. In contrast, the model proposed by SR9 considers five stages of the workers' cognitive process and relates it only to individual cognitive factors.

SR2 presents a similar conceptual structure to that of SR9, adding the influence of typical manager behaviors, like the social and organizational factors proposed by SR6. At the same time, the structure of SR1 related the three stages of the cognitive process to different risk perceptions and tolerances, according to the different personalities of construction collaborators.

Notably, none considered the safety climate's influence on workers' behavior.

Table 2: Relationship between social theories and selected research

Social theory	Definition	Selected research	Analysis
Risk homeostasis theory	Risk perception and risk tolerance are the main dimensions determining individuals' risk behavior [33].	SR1, SR8, SR10 and SR11	SR1 analyzes, through ABM, the relationship between the risk theory and the Big Five personality traits, by associating different perceptions and acceptance of risk with the personality traits of construction workers. According to SR8, alerting co-workers to leave the risk area and to use personal protective equipment can reduce risk exposure. SR10 based the proposed ABM on risk perception and assessment concepts by considering that people's risk attitude guides their perception. SR11 considers the tolerable level of danger as one of the ABM variables related to management strategies and perceived production pressure.
Theory of Planned Behavior	All individuals are rational [23]. This theory presents five primary constructs: attitude, subject norm, perceived behavioral control, behavioral intention, and behavior [34].	SR2, SR3, SR4, SR9, SR11, SR13, SR14 and SR16	SR2 associates the subject norm with “Demonstrative role” and “Behavior feedback,” the safety attitude with “Demonstrative role,” “Behavior feedback,” “safety inspection,” and “intelligent video surveillance,” and the perceived behavioral control with “Taking action.” ABM developed by SR3 considered attitude, subject norm, and perceived behavioral control as responsible for construction worker safety behaviors. These constructs can be affected by individual characteristics, organizational traits, and psychological abilities. The SR4 literature review presents a conceptual framework of the relationship between construction safety climate (CSC) and construction worker safe behavior (CWSB). This framework was based on previous CSC research and the Theory of Planned Behavior (TPB). SR9 associates the subject norm with “perceived responses,” the safety attitude with “decide a safe response,” and perceived behavioral control with “execute the safe response.” SR11 used the theory as justification to analyze the effects of contagion probability and safety-productivity tradeoff. SR13 considered in the ABM the effect of the subject norm through the influence on the truck drivers' safety attitude to analyze the truck drivers' safety behavior during the earthmoving operation. SR14 is based on theory reflecting the various factors influencing workers to perform unsafe behavior. SR16 used TPB to investigate why the scaffolders decided not to utilize safety harnesses.
Theory of Organizational Support	Employees develop beliefs about the degree of appreciation that the organization attaches to their contributions, as well as the company's concern for the well-being of its members [35].	SR7	SR7, in the research, sought to investigate how organizational support (OS) in cascade can cultivate a group-level safety climate (GSC), by relating the safety climate (SC) with supervisory safety-specific transformational leadership (SSTL) and co-worker support (CS). SR7 results indicate that OS does not have a direct effect on SCG. Instead, OS acts as an indirect factor that contributes to the increase in SCG through the mediation of Organization-level safety climate (OSC) and SSTL, in addition to moderating the relationship between CS and GSC.

Table 2: Relationship between social theories and selected research (Continuation)

Social theory	Definition	Selected research	Analysis
Social exchange theory	Two interacting parties do a cost-benefit analysis to assess risks and benefits [36].	SR5, SR7	SR5 presents a model of safety climate and safety behavior mediated by employee psychological ownership, based on this theory. SR7 uses this theory to help visualize the association between organizational support and the safety climate.
Social identity theory	People are aware that they belong to social groups with emotional meaning and value [37].	SR3 and SR10	SR3 considers, through this theory, the influence of the safety climate and the leader-member exchange (LMX) on the workers' subjective norm. SR10 uses this theory in the proposed ABM to substantiate the social influence mechanism between agents.
Social comparison theory	People define their social and personal worth by comparing themselves to others [38].	SR10	SR10, based on this theory, considers that agents adjust their behavior based on interaction with other agents (observation and communication).
Social network theory	The theory highlights the role of social relationships in changing an individual's attitude or behavior [39].	SR12	Based on the theory, SR12 analyzed and compared three designs and simulated a network model to see how it reacts to security alerts.
Institutional theory	Organizations tend to adhere to norms and behaviors that are socially accepted to maintain structural congruence with their specific institutional environment [40].	SR15	SR15, building on the theory, developed and tested a model to explain how coercive, mimetic, and normative pressures systematically influence the safety climate of construction projects in China.
Information processing theory	Three stages compose the cognitive process: obtaining information, understanding information, and responding and acting [41].	SR6	Based on the theory, SR6 developed a framework for the cognitive process of construction workers. The authors considered the influence of the individual, the organization, and some group factors in each of the three stages of the cognitive process.
Bounded rationality theory	The limitation of an individual's cognitive process can lead to underestimation or overestimation of the risk [42].	SR6 and SR13	SR6 considers in the cognitive stage of understanding the agents' information that the worker calculates the risk and income level brought by the behavior. SR13 uses the dynamic system (DS) model of mental fatigue to model truck drivers' mental fatigue during work.
Social learning theory	Individual behavior results from interacting with cognition, action, and environment [43].	SR6	The results obtained in SR6 indicate that the social learning category should include behavioral feedback and the demonstration role.

Some theories have a social influence bias used in studies to model human behavior. However, not only social exchanges and influences determine workers' behavior. It is essential to analyze the internal process that drives employees' actions [11]. When deciding, it is necessary to consider what individuals understand and perceive as risk [11]. This process includes workers' awareness and knowledge of safety.

Some studies have considered unsafe behavior failures in workers' cognitive processes (SR1; SR2; SR3; SR6; SR9; SR14). In other words, failures may occur in understanding and processing information, selecting which response to perform, and executing the action. Unsafe behaviors result from errors in risk observation/perception, the level of risk judgment, and subsequent inadequate decision-making [30]. In contrast, SR10 did not relate errors to the cognitive process. Therefore, errors do not necessarily result from judgment or bad decision-making in the cognitive process but rather from mistaken actions during the action-taking phase. Hence, an error may occur without the cognitive process being unsafe, and it may also happen without errors in the cognitive process under an unsafe condition, as it relates to individuals' risk perception [11].

5 CONSTRUCTION WORKERS IN BRAZIL: A COGNITIVE PROCESS FRAMEWORK PROPOSAL

This section presents a proposed structure for the cognitive decision-making process of Brazilian construction workers. The proposed framework aims to model the behavior of these agents, simulating the influence of safety management strategies (training, communication, and safety climate) on workers' safe behavior.

There are two approaches to modeling human behavior using artificial intelligence: mathematical and cognitive, which can be adopted separately or together. SR1, SR2, SR3, SR6, SR9, and SR14 analyze the cognitive factors of workers and how they influence the unsafe behavior of employees, which is responsible for increasing the number of accidents and injuries on construction sites. Despite the similarities between workers' cognitive decision-making processes, each author presented their specific cognitive process, indicating the individual, organizational, and social factors influencing the worker's unsafe behavior. They all emphasize the worker's risk perception, assessment, and decision-making.

Considering the analyses of the identified theories in the literature, the proposed framework adopts the following social theories to define the structure of the cognitive process of decision-making by construction workers: the Theory of Risk Homeostasis, the Theory of Organizational Support, and the Theory of Social Identity. The study chose these theories based on their relationship with existing safety aspects in Brazilian construction. Table 3 presents the connection of these theories with three field surveys carried out on construction sites in Brazil ([45], [46], [47]). The study selected these studies for their relevant content on the safety behavior of construction workers in Brazil. Cultural elements are responsible for differentiating workers' risk perceptions and the impact of management strategies on agents' safe behavior [32]. Social theories must be chosen according to their relationship to the local culture.

The proposed framework, presented in Fig. 2, is based, first and foremost, on the structure proposed by SR1, which relates the three stages of the cognitive process of employees (Information processing theory) with the **Theory of Risk** (Table 3).

However, unlike SR1, which associates the perception of risk and tolerance with the different personalities of workers, this structure associates the perception of risk with managerial actions, such as safety communication, safety training, and safety inspection, as proposed by the RS6. Although, RS6 does not associate workers' cognitive processes with risk theory. Based on the literature review, the proposed conceptual framework considers the impact of management strategies on the safety behavior of construction workers. Safety training and communication are managerial actions that teach workers to recognize and avoid risks in the work environment. Therefore, these were considered influential factors in workers' perception of risk.

Table 3: Relationship between social theories and the Brazilian context

Social theory	Aspects of social theories	Analysis of safety aspects in Brazilian construction
Risk homeostasis theory	This theory states that each individual has their perception and tolerance for risk. It is understood that each construction worker will present their risk perception, even if they are exposed to the same real risk. The factors that influence risk tolerance are personal characteristics, expected consequences, and safety culture [44].	The excessive trust of managers and workers and the lack of formal procedures lead to practices incompatible with legislation and good practices in the construction sector [45]. Even knowing the possible consequences, the worker feels confident to take unnecessary risks due to the low rate of accidents he has witnessed or experienced throughout his professional life [46]. Employee awareness and collaboration are among the main difficulties in complying with safety legislation. The improvement in management actions and practices needs to focus on the participation, training, and awareness of the workforce at the construction site [47]. When analyzing some risk situations, it is necessary immediate training to construction workers so that they "perceive" the risks in their workstations [46].

Table 3: Relationship between social theories and the Brazilian context (Continuation)

Social theory	Aspects of social theories	Analysis of safety aspects in Brazilian construction
Social identity theory	According to SR10, this theory has been used by organizations to understand the behavior of their employees. This is because organizational identification acts as a mechanism that regulates motivation, behavior, and job satisfaction. SR3 assumes that construction workers will be impacted by other social groups, such as managers, supervisors, and coworkers when they implement safety behaviors.	The deficient safety culture is evidenced by the lack of information among workers about the importance of using Personal Protective Equipment (PPE) and the lack of adequate supervision by managers [45]. Instructions on safety at work were only followed in the presence of the construction engineer or inspector of the contracting company [46].
Organizational support theory	Through this theory, SR7 asserts that an organization that values safety will develop effective policies and procedures to maintain high safety standards. In addition, it will require frontline management to effectively enforce these safety policies and procedures to create a safe work environment.	The results of a case study about accidents at construction sites show that the causes of accidents were strongly associated with organizational factors [45]. Research carried out at construction sites showed that regardless of the strength of the safety culture, organizational failures - and not individual factors - played a decisive role among the factors that caused problems [45]. According to workers, receiving safety information during planned training and with specific instructions has a more significant impact than receiving safety advice just a few minutes before the start of the task [46].

Given the relationship presented by the authors between safety climate and safety culture, it is possible to affirm the influence of safety climate on employee risk tolerance (SR3; SR4; SR7). In addition, Rundmo [44] proposes a relationship between the individual risk tolerance level and the organizational climate.

SR6 related organizational factors in its model with individual cognitive factors, such as safety awareness and knowledge, experience, attitude, and subject norm. Safety communication, inspection, and training influence safety awareness and knowledge, increasing the employee's perception of risk. According to the **Theory of Organizational Support**, these managerial actions impact according to the level of priority given to safety by members of the organization. According to the **Social Identity Theory**, employees exhibit safe behavior based on the actions and behaviors performed by their coworkers and managers (Table 3). To cover the complexity of the variables to be analyzed by an ABM, the model must be composed of agents with different risk perceptions and tolerance levels.

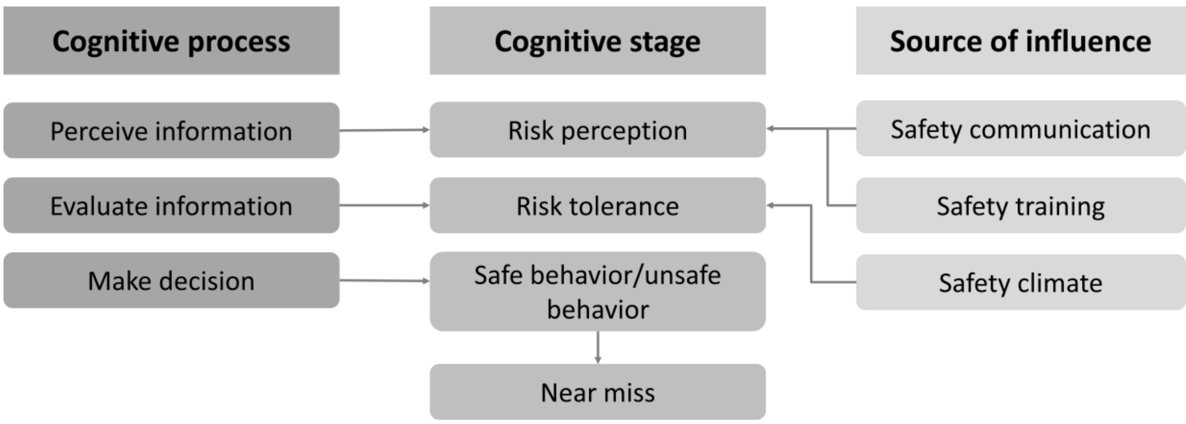


Fig. 2. Framework of the cognitive process of unsafe behavior of construction workers.

6 CONCLUSIONS

From the results obtained in the proposed literature review, it was possible to outline a current panorama of social theories used to understand and model workers' safety behavior on construction sites. It is essential to understand the influence of the cognitive process of construction workers on the process of risk perception and decision-making that may or may not result in an accident. The study identified the Risk Theory, the Organizational Support Theory, and the Social Identity Theory as adequate social theories to model the cognitive decision-making process of the behavior of Brazilian civil construction workers. The proposed framework aims to reproduce this behavior based on the influence of safety management strategies (training, inspection, communication, and safety climate) on agents' safe and unsafe behavior. This research expected that this conceptual framework could direct the development of models based on agents that evaluate the impact of safety management strategies on construction sites. Such models aim to support security managers in their decision-making. The results of this paper are limited to the scope of the sample obtained by the search string and databases used. Several organizational, individual, and social factors are related to workers' safety behavior, but this study was limited to three management strategies. Finally, this research suggests validating the proposed conceptual structure through field data collection and developing an agent-based model for application in the Brazilian scenario to advance the presented knowledge.

7 ACKNOWLEDGMENTS

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ONTOLOGY-BASED WORKFLOW AND CONCEPT FOR SAFETY INSPECTION OF SCAFFOLDING

Sebastian Seiß[1], Jürgen Melzner[1]

[1]Bauhaus-Universität Weimar (Germany)

Abstract

The construction industry presents a high-risk work environment where the frequency of accidents is about twice as high as in other workplaces. To address this issue, ontologies, specifically Digital Construction Ontologies (DiCon) and Ontology-based Conjunctive Query Answering (OCQA), can play a crucial role in improving occupational safety standards on construction sites. These ontologies allow mapping of different knowledge areas, such as bills of quantities, schedules, equipment, site personnel, and inspection planning, among others. This study aims to extend the contents of these ontologies to include inspections in the area of occupational health and safety.

The use of ontologies can help in organizing and structuring the knowledge base and ensuring that all relevant information is included in the process. This leads to a more comprehensive approach to occupational safety and minimizes the likelihood of accidents on construction sites. Scaffolding inspection is given as an example to demonstrate the importance of including health and safety inspections in the construction process.

The extension of DiCon and OCQA ontologies to include inspections in the field of occupational health and safety is a crucial step towards a safer and more organized construction site. The use of ontologies allows a systematic and structured approach to occupational safety, thereby reducing the risks and consequences of accidents. The aim of this study is to promote the importance of including health and safety inspections in the construction process and the benefits of using ontologies to achieve that goal.

The proposed framework includes inspections in the field of scaffolding contributes to safety on construction sites, thus minimizing the likelihood of accidents and making construction sites a safer place for workers. This paper demonstrates and validates a technique for automating the scheduling of quality inspections by using semantic web technologies. An evaluation is carried out on specimens of construction sites.

Keywords: BIM, code compliance, workflow automation, ontology, linked data, scaffolding, construction management

1 INTRODUCTION

Despite significant efforts that have been made over the past decade towards adapting and developing modern information and communication technologies in the construction industry, its worldwide occupational safety and health (OSH) performance remains extremely poor. Statistical data indicate that in many countries, the construction sector has one of the highest accident rates. Falling from heights in particular, still accounts for a large proportion of accidents on construction sites.

Through an analysis of these hazards and through their systematical assessment, the number of accidents can be reduced further. To act preventively, an attempt will be made to integrate safety regulations and scheduling rules into an object-oriented building model. Earlier, many approaches showed that the overall framework of planning could be checked for compliance with safety standards, and could be changed and adjusted accordingly in the first phase of the project and, at the same time, it would be possible to plan an effective workflow [1, 2]. In recent years, a significant amount of research has been dedicated to the analysis of job hazards (JHA) based on Building Information Modelling (BIM). This approach involves scrutinizing 3D models by using rule interrogation techniques to pinpoint potential hazard locations [3]. An overview of the approaches can be found in [4].

The use of ontologies for knowledge representation in occupational safety is not new. For example, Wang and Boukamp have developed a concept with the help of an ontology-based approach to allocate the knowledge available in the company about hazards to construction methods, processes and sub-processes [5, 6].

All of this research relates to the identification and assessment of hazard sites. Our approach focuses on creating a safe working environment for the scaffolding trade by automatically generating quality-relevant checks through a knowledge base.

In the planning phase, the order of priority of the protective measures in accordance with the German Occupational Health and Safety Act (§ 4 ArbSchG) must be considered for the use of the scaffold (see Figure1).

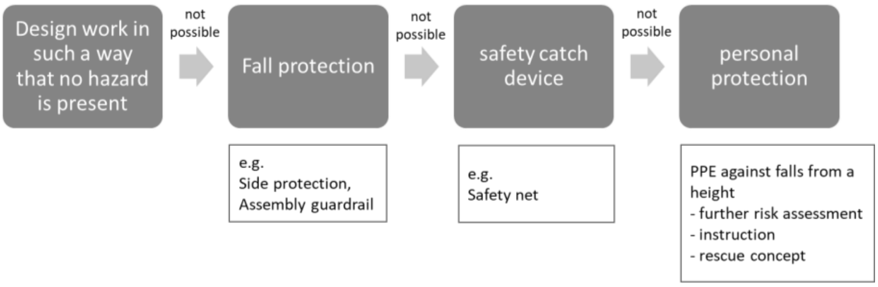


Figure 1. Priority of protective measures when using scaffolding

To ensure the effectiveness of safety equipment, it is crucial that the equipment is installed and operated correctly. Employing ontologies can aid in organizing and structuring the knowledge base, ensuring that all pertinent information is incorporated into the process. This results in a more comprehensive approach to occupational safety, reducing the probability of accidents at construction sites. For instance, scaffolding inspection is cited as an example to emphasize the significance of integrating health and safety inspections into the construction process.

2 BACKGROUND

2.1 Quality and quality assurance

Generally, an individual subjectively evaluates quality which is difficult to measure as it is not based on a technical evaluation or agreement and, therefore, lacks transparency. According to DIN EN ISO 9000:2005, quality is defined as “the degree to which a set of inherent characteristics meets requirements”. Thus, it is essential to define qualities precisely before creating the product or service. Quality requirements can be defined on a project-specific basis by project participants and across projects by standards, norms, guidelines, and laws [7]. According to DIN ISO EN 9000 3.3.5-3.3.8, quality assurance is understood to be “a part of quality management directed towards the creation of trust that quality requirements will be fulfilled”.

Quality inspections serve to verify whether the construction work provided meets the required specifications, including those agreed upon in the contract or regulated by rules. Quality inspections refer to “determining conformity with quality requirements” [8]. The execution and results of quality inspections must be recorded in protocols and documentation. According to DIN 55350, test planning refers to the “planning of one or more tests”. A test plan describes the “specification of one or more tests” [8]. Therefore, the test plan contains the overall plan for carrying out the inspections. The test plan must be developed before the start of the inspections and in accordance with the requirements to be tested [9].

In this paper, the quality assurance of scaffolding work is considered. In order for the scaffolding to fulfil its intended use, it must be assembled properly in accordance with the general rules and regulations. In this context, the requirements for proper construction are “a set of inherent characteristics” which need to be verified.

2.2 Quality assurance for scaffolding

The use of working, protective and assembly scaffolds includes any activity with them. It includes the erection, modification and dismantling (assembly), the inspection of the scaffold, the transport of scaffold parts and the use (utilization) of the scaffold by users [10]. Scaffolding is divided into different types depending on its use: facade scaffolding, room scaffolding, suspended scaffolding, mobile scaffolding, safety as well as roof safety scaffolding, and assembly scaffolding. This article is limited to facade scaffolding due to the frequency of its use.

In connection with scaffolding work, there are different actors who have different tasks and responsibilities. For example, **scaffold erectors are** entrepreneurs (employers) who erect and convert or dismantle scaffolds themselves with their employees.

The **competent persons** of the scaffold erector are commissioned by the contractor, for example, scaffolding foreman or scaffolding assembly foreman. The scope of duties includes, among other things, the preparation and updating of the assembly instructions, the preparation and updating of the plan for the use of the scaffold by the scaffold user and supervising the erection, modification and dismantling work.

Skilled employees of the scaffold erector may erect, modify or dismantle scaffolds. They are employees with a completed vocational training in the scaffolding or the construction trade.

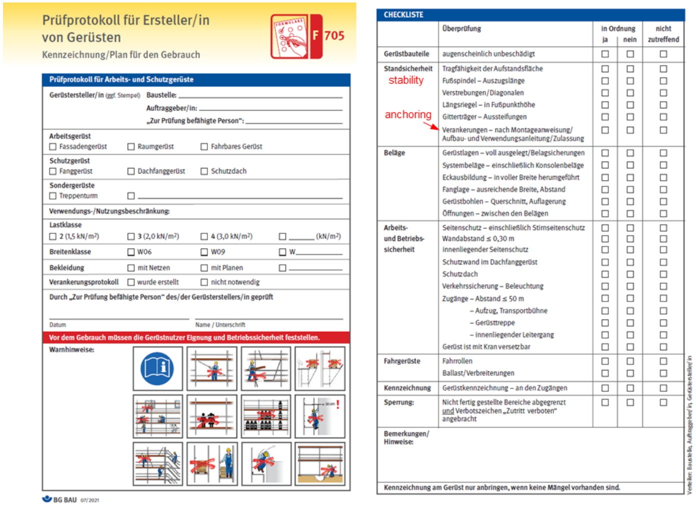
A **qualified person for the testing** is commissioned to inspect that the condition of scaffolding complies with the regulations before he/she approves it for use. The group of persons qualified for the examination includes, for example, scaffolding erection supervisors, scaffolding foremen, certified scaffolding supervisors and certified scaffolding team leaders.

A **scaffold user** is an entrepreneur who uses scaffolds himself and they are also used by his employees.

Qualified person is a person whom a contractor commissions to inspect the scaffold before or during the use of it by employees.

The above actors are defined as entities in the following ontology.

Usually, inspection reports for scaffolding work are carried out manually and on paper (Fig. 2). This method is very superficial and is not project-specific or site-specific and is very error-prone. The quality of the test results depends heavily on the qualifications of the inspector.



Prüfprotokoll für Ersteller/in von Gerüsten
Kennzeichnung/Plan für den Gebrauch
F 705

Prüfprotokoll für Arbeits- und Schutzgerüste

Gerüstersteller/in (ggf. Stempel) Baustelle: ____
Auftraggeber/in: ____
„Zur Prüfung befähigte Person“: ____

Arbeitsgerüst
☐ Fassadengerüst ☐ Raumgerüst ☐ Fahrbares Gerüst

Schutzgerüst
☐ Fanggerüst ☐ Dachfanggerüst ☐ Schutzdach

Sondergerüste
☐ Treppenturm ☐ ____

Verwendungs-/Nutzungsbeschränkung:

Lastklasse
☐ 2 (1,5 kN/m²) ☐ 3 (2,0 kN/m²) ☐ 4 (3,0 kN/m²) ☐ ____ (kN/m²)

Breitenklasse ☐ W06 ☐ W09 ☐ W____

Bekleidung ☐ mit Netzen ☐ mit Planen ☐ ____

Verankerungsprotokoll ☐ wurde erstellt ☐ nicht notwendig

Durch „Zur Prüfung befähigte Person“ des/der Gerüststellers/in geprüft

Datum Name / Unterschrift

Vor dem Gebrauch müssen die Gerüstnutzer Eignung und Betriebssicherheit feststellen.

Warnhinweise:

BG BAU

CHECKLISTE

	Überprüfung	in Ordnung ja	in Ordnung nein	nicht zutreffend
Gerüstbauteile	augenscheinlich unbeschädigt	☐	☐	☐
Standsicherheit stability	Tragfähigkeit der Aufstandsfläche	☐	☐	☐
	Fußspindel – Auszugslänge	☐	☐	☐
	Verstrebungen/Diagonalen	☐	☐	☐
	Längsriegel – in Fußpunkthöhe	☐	☐	☐
anchoring	Gitterträger – Aussteifungen	☐	☐	☐
	Verankerungen – nach Montageanweisung/ Aufbau- und Verwendungsanleitung/Zulassung	☐	☐	☐
Beläge	Gerüstlagen – voll ausgelegt/Belagsicherungen	☐	☐	☐
	Systembeläge – einschließlich Konsolenbeläge	☐	☐	☐
	Eckausbildung – in voller Breite herumgeführt	☐	☐	☐
	Fanglage – ausreichende Breite, Abstand	☐	☐	☐
	Gerüstbohlen – Querschnitt, Auflagerung	☐	☐	☐
	Öffnungen – zwischen den Belägen	☐	☐	☐
Arbeits- und Betriebssicherheit	Seitenschutz – einschließlich Stirnseitenschutz	☐	☐	☐
	Wandabstand ≤ 0,30 m	☐	☐	☐
	innenliegender Seitenschutz	☐	☐	☐
	Schutzwand im Dachfanggerüst	☐	☐	☐
	Schutzdach	☐	☐	☐
	Verkehrssicherung – Beleuchtung	☐	☐	☐
	Zugänge – Abstand ≤ 50 m	☐	☐	☐
	– Aufzug, Transportbühne	☐	☐	☐
	– Gerüsttreppe	☐	☐	☐
	– innenliegender Leitergang	☐	☐	☐
	Gerüst ist mit Kran versetzbar	☐	☐	☐
Fahrgerüste	Fahrrollen	☐	☐	☐
	Ballast/Verbreiterungen	☐	☐	☐
Kennzeichnung	Gerüstkennzeichnung – an den Zugängen	☐	☐	☐
Sperrung:	Nicht fertig gestellte Bereiche abgegrenzt und Verbotszeichen „Zutritt verboten“ angebracht	☐	☐	☐
Bemerkungen/ Hinweise:				
Kennzeichnung am Gerüst nur anbringen, wenn keine Mängel vorhanden sind.				

Verteiler: Baustelle, Auftraggeber/in, Gerüstersteller/in

Figure 2. Manual checklist for scaffold erectors

2.3 Rule-based inspection planning by using semantic web technologies

The semantic web provides open standards that allow interoperability, flexibility, and extensibility. The World Wide Web Consortium (W3C) has introduced standardized specification languages such as RDF, RDFS, and OWL. RDFS and OWL are languages used for describing an ontology while RDF describes the entities of the real world [11]. An ontology is a systematic representation of the knowledge of a particular domain based on its concepts. Ontologies represent knowledge based on information and their relationships and enable the inference of new knowledge by using rules [12]. This implies that an ontology aims to capture domain-specific semantics and describe them through a concept; it also relates the concept to other domain-related ontologies. In this context, the term ontology refers to a knowledge base or a data model.

Rules can be understood as conditional relationships, where if condition A is true then condition B is also true. Rules consist of a premise that defines a condition and a conclusion that represents the inference. Established rules can either be valid or be shorn of validity because of exceptions [13]. In this application, rules map explicit knowledge of inspections from regulations, technical manuals, or corporate processes in a machine-readable way.

The implementation of rule languages is accomplished with the help of the schemas described by Zhang and Pauwels (see Figure 3). In this context, the terminology box (T-box) represents a schema extended by the rules of the rule box (R-box). The assertion box (A-box) represents instances that follow the T-box and are processed by the R-box. Subsequently, an inference machine accesses the A-, T-, and R-box to draw new knowledge based on the rules stored in the R-box.

The closed knowledge generated by the inference engine is communicated to the application through API calls or SPARQL queries and made accessible to the user through a user interface [14] (Pauwels & Zhang, 2015). The validation language SHACL, which is used as a rule language in this paper, was published by the W3C organization on 8 September 2015 as Recommendation. In summary, SHACL is a language that allows RDF data to be validated or new knowledge to be inferred [14].

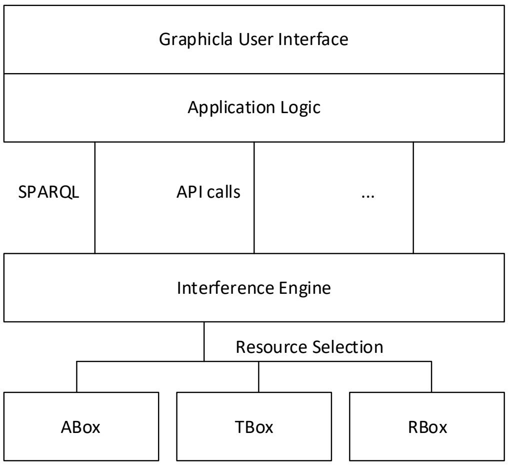


Figure 3. Overview of implementation path for any rule-checking application that relies on a dedicated rule language. [14]

3 METHODOLOGY

In ontology research, multiple methodologies have been developed for defining ontologies, such as the ones formulated by Grüninger and Fox and by Uschold and Gruninger, besides Ontology Development Guideline 101, and OnTo-Knowledge Methodology [16]. In this study, a hybrid model combining the LOT methodology with Uschold and Gruninger's methodology and Grüninger and Fox's approach is followed to compensate for the limitations of each methodology. The LOT methodology divides the ontology engineering process into four phases: specification, implementation, publication, and maintenance [17]. The ontology development and engineering process is shown in Figure 4. The specification phase is used to determine the scope, purpose, use-cases, users, and requirements of the inspection cost ontology. It is worth noting that knowledge acquisition is an iterative process that occurs throughout the entire ontology engineering process, starting from step 1.3 [18]. Based on the specification, a conceptualization process that includes existing ontologies and encoding is developed. The implementation is completed by evaluating the developed ontology using different evaluation methods. Finally, the ontology is documented on an HTML sheet and published on GitHub to enable access by a wide range of users and developers. GitHub facilitates proper ontology maintenance through collaboration and version control based on the repository [19].

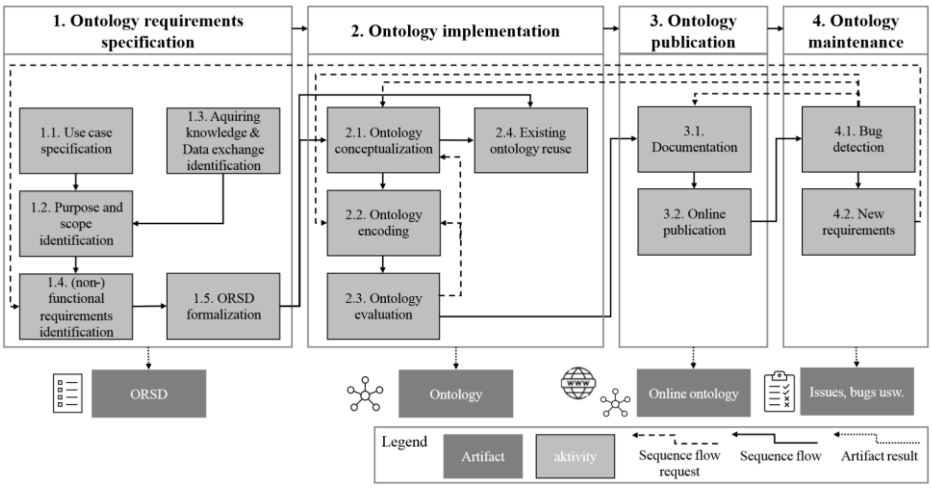


Figure 4. Ontology development/engineering methodology [17]

4 SPECIFICATION

The purpose of specification is to develop a formal document that describes the ontology of planning inspections for scaffolding in natural language, using competency questions (CQs) as requirements [18]. These CQs are derived from previously defined use-cases that are based on the purpose and scope of the corresponding ontology. The specification document will be provided on GitHub. In the following, different specification steps are formalized.

Purpose: The ontology will focus on planning inspections for scaffolding in construction execution to provide a structured representation of inspection planning information that can be utilized by construction project management, including construction managers, inspectors, and planners. The proposed ontology should, in detail:

1. Define the types of scaffolding systems that require inspection planning
2. Strengthen the quality awareness of employees
3. Support decision making in inspection planning for scaffolding

Scope: The proposed ontology will only cover the inspection planning process for facade scaffolding systems and will not address other inspection-related tasks or cost-related information.

Use-cases:

1. Description of inspections for scaffolding
2. Automated planning of inspections for scaffolding

End-users: The ontology is primarily intended for use by construction project management, including person qualified to inspect, scaffold erectors, construction managers, and planners. The ontology will not be used by construction workers or other stakeholders who are not involved in the management of construction sites.

Non-functional requirements (NFRs): NFRs are a type of requirement that defines how a system should perform, behave, and operate rather than what the system should do. Various studies have already defined NFRs for ontologies in the field of construction which can be summarized as follows: 1) Coverage/sufficiency; 2) Consistency; 3) Usability; 4) Extendibility/reusability; 5) Clarity and conciseness [16, 20, 21, 22]. The defined NFRs are used as evaluation criteria and covered by different evaluation methods.

Functional requirements: The functional requirements are described as competency questions (CQs) according to the previously defined use-cases. Fig. 5 lists the CQs to be answered by the proposed ontology.

Description of inspections for scaffolding	Automated planning of inspections for scaffolding
1. What are the related entities of an inspection for scaffolding?	3. How can reasoning support inspection assignment for scaffolding?
2. What are the relationships between the assembly process and the inspection process?	

Figure 5.competency questions (CQs)

5 CONCEPTUALIZATION AND IMPLEMENTATION

The purpose of this project is to develop an ontology system consisting of two modules: (1) overall OCQA and (2) OCQA-SCAFFOLDING

5.1 Overall OCQA

The proposed ontology system for the project is divided into three modules in accordance with the project aim: (1) overall OCQA, (2) OCQA-SCAFFOLDING and (3) catalogue. The OCQA-SCAFFOLDING ontology is an extension of the OCQA ontology and is specifically designed to provide information on quality inspections in construction and to support inspection planning. OCQA also includes automated inspection planning rules, thus making it an ideal reference for the development of OCQA-SCAFFOLDING. Moreover, OCQA itself is an extension of the DiCon ontology that offers fundamental concepts for construction workflows, such as agents, processes, and equipment. Also, DiCon itself aligns different ontologies, such as ifcOWL, to represent a BIM. The alignment of the different ontologies can be observed in Figure 6. The implementation of other ontologies is achieved as a hard reuse via owl:imports, which reuses the imported ontology as it is and as a whole. Only the alignment between DiCon and ifcOWL is realized by owl:equivalent relationships. Trade-specific modules of the OCQA ontology cover task-specific inspection planning. For example, the OCQA-SCAFFOLDING extension covers all inspections concerning trade scaffolding [16, 17].

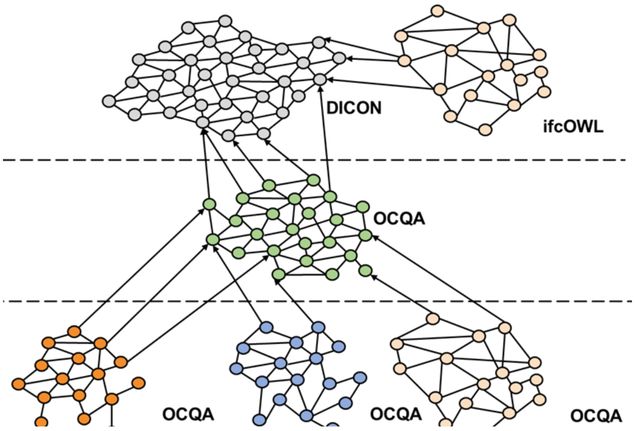


Figure 6. Alignment of OCQA to DiCon and extension of OCQA by trade specific extensions.

5.2 Ontology for scaffolding inspections (OCQA-SCAFFOLDING)

Quality control in the scaffolding trade is divided into three time units. We differentiate between the work preparation phase before the scaffolding work begins, followed secondly by the phase of erecting or dismantling scaffolding, and thirdly by the operation of the scaffolding during use point.

In the work preparation phase, the main focus is on planning the work, which includes risk assessment, instruction for the employees and the determination of the specifications for the scaffolding construction. In this paper, the ontology for knowledge representation for quality assurance measures in the second phase (erecting phase) is presented.

Once the scaffold has been assembled, the contractor who erected the scaffold must have it inspected for proper assembly and safe functioning. The inspection may only be carried out by a person qualified to do so. That is, he can be a competent person (see 2.2.) if he has the required knowledge and skills.

In general, the audit refers to the following three categories: Components used, stability, and occupational and operational safety (Fig. 7).

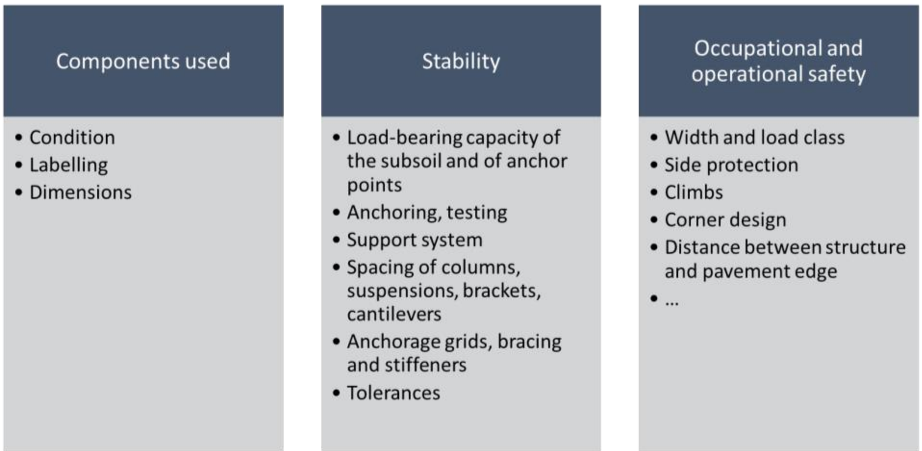


Figure 7. Example for the inspection of scaffolds

After completion of the scaffolding construction work and before handing it over to the user, the contractor responsible for erecting the scaffolding must ensure that the scaffolding components are in perfect condition and that they comply with the instructions for assembly and use. It includes checking the scaffolding for stability as well as occupational and operational safety.

The structure of the ontology is illustrated below by using the example of stability and, in particular, when checking the anchoring. In order to fill in the knowledge database, the W-questions have to be answered:

Question	Description
How often?	Inspection frequency
How much?	Scope of inspection
How is the inspection carried out?	Type of inspection (inspection based on qualitative or quantitative characteristics)
How is the inspection to be carried out?	Test method
With what?	Test equipment
When?	Inspection time and classification of the test in the production process
By whom?	Inspector
Where?	Test location
How?	Test instruction

Table 1. W-questions to fill in the knowledge database

The load-bearing capacity of the fasteners between the scaffold bracket and the anchorage base must be verified for the anchorage forces. The proof is to be provided by a) the design approval of the DeutschesInstitutfürBautechnik b) static calculation or c) test loads.

Based on the described requirements, the OCQA was extended with the OCQA Scaffolding (see Figure). Each *ocqa:inspection* is modelled as the subclass of the class *dice:activity* of the DiCon ontology. Therefore, the class ocqa:inspection inherits all relations of dice:activity like start- , end date and duration. The OCQA Scaffolding is presented as a separate module which is added to the OCQA via owl:import. The classes of the OCQA Scaffolding are modelled as subclasses of the OCQA. Thus, the OCQA Scaffolding represents a specification of the OCQA for inspections in the field of scaffold construction. Figure 8 exemplarily shows the extension for a scaffolding anchor inspection by the class *ocqa-scaffolding:scaffolding Anchor Inspection*. The inspection procedure is modelled as the *ocqa-scaffolding:*Anchor Pull Procedure, which is carried out by using an *ocqa-scaffolding:pull-out_device*. The inspection can only be executed by certified *ocqa-scaffolding:scaffolding_erection_supervisors.* The inspection is based on DIN XY and is represented through the *ocqa-scaffolding*:*Scaffolding Regulation* class.

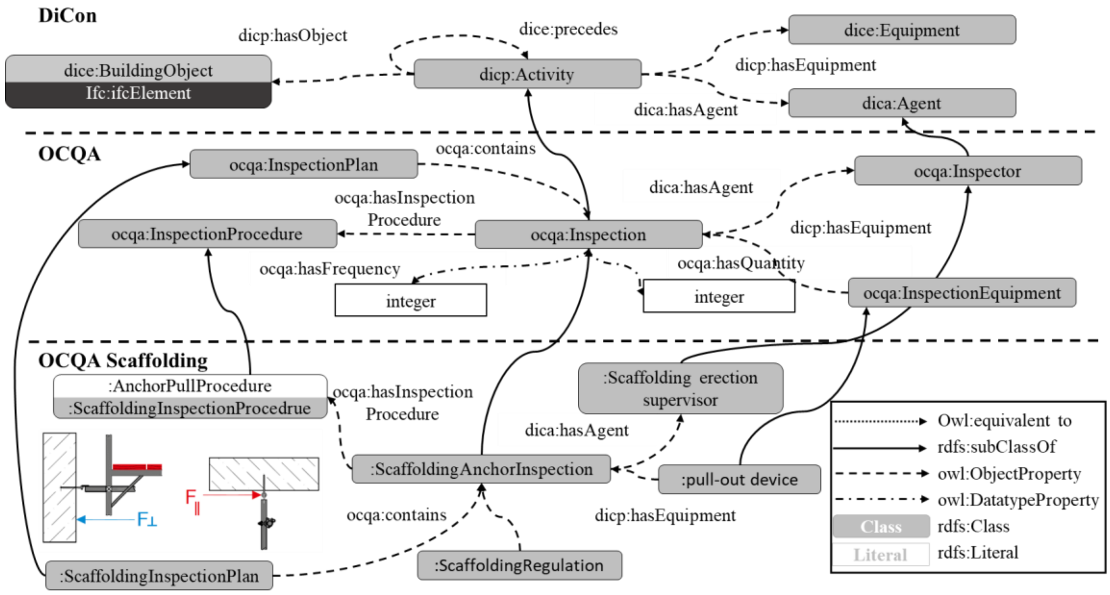


Figure 8. Extension of OCQA to OCQA-Scaffolding

5.3 OCQA Scaffolding inspection planning

The proposed ontology, OCQA-Scaffolding, has been designed to enable automated reasoning of scaffolding inspection. To achieve it, the ontology must be able to infer new knowledge based on the requirement proposed before. Therefore, the inference process has been divided into multiple distinct steps. The inference process using SHACL is illustrated in Listing 1. In the first step, the rule assigns the ifcowl:ElementProxy for the anchors and scaffolding as *dice:scaffolding_anchor* and *dice:scaffdoling*. In the second step, the rule checks if the scaffolding has been installed via anchors. If anchors are used in the scaffold, an inspection for the anchor pull-out test is generated. Because information about who, when, how and why are static for this kind of inspection, all queries are inferences based on static rules. The quantity of inspection is calculated based on the rule *ocqa_rules:CalculateNumberOfInspections*. This rule involves selecting all anchors of the model and applying a multiplication factor of 0.1 to determine the appropriate number of anchors that need to be inspected.

```
ocqa_rules:ClassifyScaffoldingElements
a sh:NodeShape;
sh:targetClass ifc:IfcBuildingElementProxy;
sh:order 1;
[Classify objects named anchor as dice:scaffolding_anchor and scaffolding as dice:scaffolding].
ocqa_rules:InferScaffoldingAnchorInspections
a sh:NodeShape;
sh:targetClass dice:scaffolding;
sh:order 2;
sh:condition [Check if scaffolding has anchors]
sh:rule [
   a sh:TripleRule ;
   sh:subject sh:this ;
   sh:predicate ocqa:hasInspection;
   sh:object [Generate new ocqa_scaffolding:ScaffoldingAnchorInspection];].
ocqa_rules:AssignGerneralParameters
a sh:NodeShape;
sh:targetClass ocqa_scaffolding:ScaffoldingAnchorInspection;
sh:order 3;
sh:rule [
   a sh:SPARQLRule ;
   sh:construct """[Prefixes]
   CONSTRUCT {
    $this  dica:hasAgent ?agent;
            ocqa:hasInspectionProcedure ocqa-scaffolding:AnchorPullingProcedure
            dica:hasStart ?EndDateScaffoldingConsturction
            dica:hasEnd ?StartDateInsulationConstruction}
   WHERE {[Subquery to get variables]}"""].
ocqa_rules:CalculateNumberOfInspections
a sh:NodeShape;
sh:targetClass ocqa_scaffolding:ScaffoldingAnchorInspection;
sh:order 4;
sh:rule [
   a sh:SPARQLRule ;
   sh:construct """[Prefixes]
   CONSTRUCT {$this ocqa:hasQuantity ?NumerOfInspections}
   WHERE {[Subquery to get the sum over all anchors multiplied by 0.1 as ?NumerOfInspections]}
"""].
```

Listing 1. SHACL-rule for appraisal cost inferencing

6 CASE STUDY AND FUTURE WORK

The case study is based on a 15-floor building as shown in Figures 9 and 10. The scaffolding provides temporary access to the upper levels of the building for workers to complete the necessary tasks like insulation, painting or installation of windows.

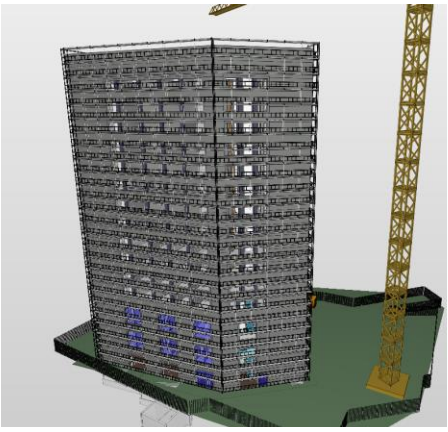


Figure 9. Overview of building

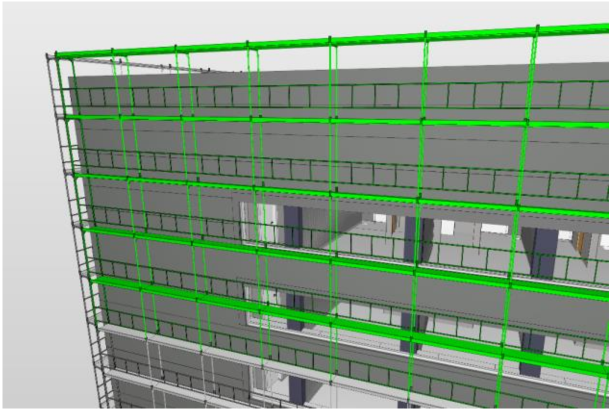


Figure 10. Detailed illustration of scaffolding

The rules described in section 5.2.3 are applied to the BIM, the schedule provided, and the organizational data of the prject. The inferred inspection, *ex:Inspection_246,* for the scaffolding anchors is illustrated in Figure 11. In total, 300 anchors are found on the scaffolding and, therefore, 30 inspections of the same in groups of 10 have to be done in this example project. The scaffolding object is represented as *ex:1Kdjj60BjCrg9QEI_zGO_7* and is linked to the inspection via the relation *dicp:hasObject*. Furthermore, the start and end dates of the inspection are reasoned by using the end date of the scaffolding construction and the start date of the following insulation task.

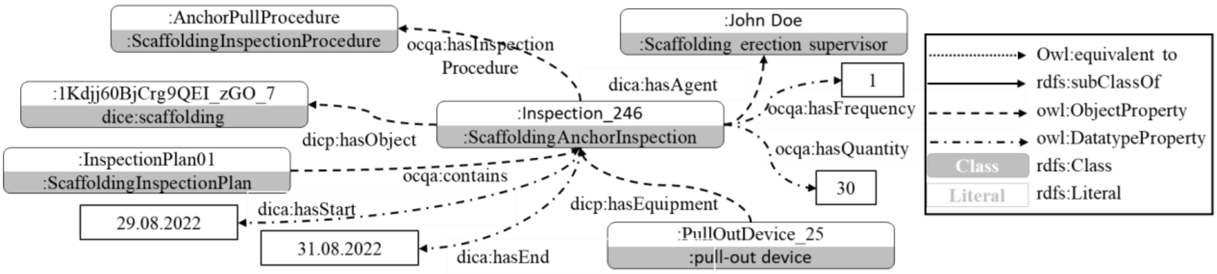


Figure 11. Representation of the inferred inspection for inspection scaffold anchors based on the model and the illustrated rule.

7 CONCLUSION

The presented approach shows a concept for the ontology-based knowledge representation in the quality assurance of scaffolding processes. This paper demonstrated and validated a technique for automating the scheduling of quality inspections by using semantic web technologies. The implementation uses the predefined OCQA ontology and SHACL rules containing norms and standards for quality inspections of scaffolding works. Automating the planning of quality inspections allows quality managers to schedule inspections more efficiently and without errors. The developed inspection plans contain localization, responsibilities, costs, start and end dates, equipment, and inspection instructions based on the ifc-objects in da 3D-BIM model. Also, inspection plans can be updated against changes in the construction schedule, method or plan.

Automated planning of quality inspections is achieved through the formalization of rules in SHACL, which are implemented by using SPARQL. SHACL, as a semantic web standard, provides high flexibility, modularity, and extendibility, thus enabling rules implemented in SHACL to be shared, reused, and adapted across projects and companies. The reasoning process relies on well-structured information inputs that include data on the construction, construction process, and company-specific information. To ensure that the ontology and rules have the necessary input information, exchange information requirements must be defined.

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A BIBLIOGRAPHIC ANALYSIS OF THE PUBLICATIONS OF SWA DEKKER: MAPPING ITS USE IN CONSTRUCTION SAFETY RESEARCH

Eric Asa[1], Fidelis Emuze[2], Bright Awuku[3] and Amma Agyekum[4]

[134] *Department of Civil, Construction and Environmental Engineering, North Dakota State University, Fargo, (United States of America)*

[2] *Department of Built Environment, Central University of Technology, Free State, Bloemfontein, (South Africa)*

Abstract

Safety science, aimed at the best practice of health, safety, and wellbeing (HSW) promotion, is a significant multi-inter-trans- disciplinary (MIT) research endeavour pursued by multiple scholars in social sciences, engineering, psychology, law, business, medicine, and other disciplines. Resolving HSW issues involves drawing insights from human life, endeavour, and industries. In past decades, scholars have propagated two schools of thought in occupational safety research (OSR) - one was propagated by the late Jens Rasmussen and the other by Sidney Dekker. Like Rasmussen, Dekker is a pre-eminent scientist who has authored several books, journals, and conference publications in OSR. In this paper, keyword analysis and bibliographic coupling were employed to measure the contributions of Dekker to OSR and HSW efforts of construction management scholars. The paper, inter-alia, shows the international coverage of OSR research and the topical nature of the problems its tackles. The use of publications by Dekker in construction research is confirmed in this paper, and topical issues addressed include safety climate, human factors, situation awareness, resilience engineering, and human reliability organisations. The paper provides a platform for reflections on areas requiring further engagement in the community of practice.

Keywords: Accident, Construction, Health, Safety, Wellbeing

1. INTRODUCTION

Safety science, which is aimed at the best practice of health, safety, and wellbeing (HSW) promotion, is a significant multi-inter-trans- disciplinary (MIT) research endeavor pursued by multiple scholars in social sciences, engineering, psychology, law, business, medicine, and other disciplines [1], [2]. Resolving HSW issues involves drawing insights from human life endeavors and industries. Occupational health and safety (OHS) research has decreased workplace accidents across several industries. According to [3], work-related deaths decreased by about 90% between 1933 and 1997. Today's workplace is much safer, yet accidents have not been eliminated. The challenge is that gains in safety performance have plateaued, coupled with the unexpected occurrence of significant fatal incidents, which are difficult to predict and forecast.

In this work, co-authorship (author, organizations, and countries) and co-occurrence (all keywords, author keywords and keywords plus) analyses were employed to study the evolution and contribution of Dekker to OHS research. The reported research addressed Dekker's work's direction, propagation, and evolution over the years and its relationship to the construction industry.

2. RESEARCH METHOD

There has been a considerable increase in publications and electronic compilation of published works. A systematic literature review does not capture all the intricacies of a research area of interest. It may introduce bias and errors due to the subjectivity of the decisions made in an SLR. For instance, Scopus (launched in 2004) has 85.4 million records, and Web of Science(WoS), (launched in 1997) has 79 million in core collections and 171 million on its platform. The growth in knowledge hidden in large quantities of published literature (mostly journal and conference publications) has increased interest in synthesising publications to discover or extend knowledge, unearth research gaps, ascertain research trends or directions, and provide evidence-based knowledge and processes for field applications. This is especially true in the medical professions, where such literature-based studies have become a major source of experience and knowledge for medical practitioners. According to [4], this has resulted in better professional judgment and knowledge in several areas of human endeavor.

Of the methods employed in literature studies/research, bibliometric analysis has emerged as the preferred methodology for analyzing scientific publications across disciplines [5]. Bibliometric analysis is described as the application of quantitative methods to electronic publication data [5], [6], [7] and a robust statistical approach to reach conclusions. Bibliometric analysis has recently seen considerable growth [5]. It is apparent from its wide application in every facet of research that it has become a mainstream research methodology for analysing published works and discovering/answering several questions about past research in a subject area. The methodology can be used to analyze patterns of citations, discover top research topics, portray research directions, identify research gaps, review journals, aid research decision making and others [8]. This research aims to use bibliometric analysis to document the nature of Dekker's research in occupational health and safety.

Figure 1 represents the methodology employed in this research work. The methodological approach commenced with a statement regarding the purpose of the research and the use of bibliometric methods (in the context of VOS viewer software and processes) to study Dekker's research publications on OHS (Fig. 1). Dekker is one of the pre-eminent researchers in this vital area of research, and his work could be considered a significant force in the field. A search was performed in the Web of Science electronic database to compile Dekker's publications. The World Wide Web houses several electronic databases on various research topics.

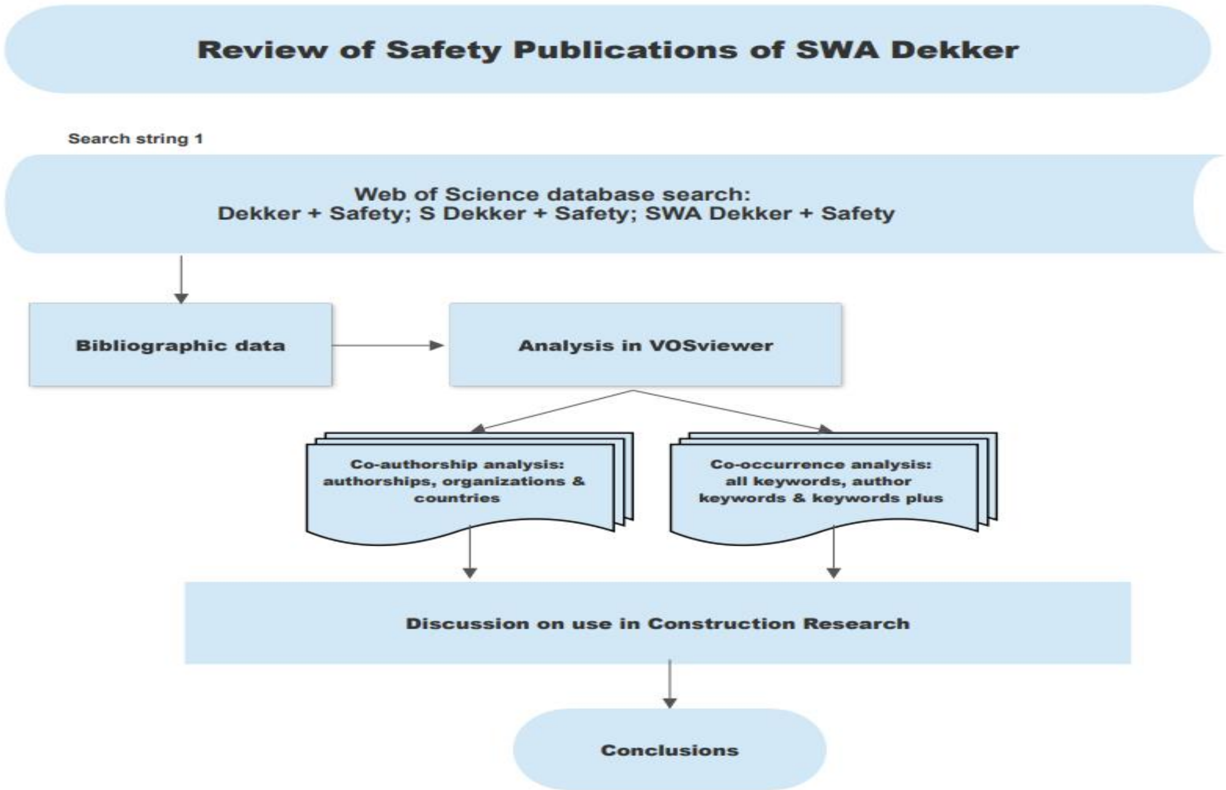

Figure 1: Research process

WoS is a mix of research areas related to technology, sciences, arts, social sciences, and humanities. The authors used the WoS database as it is well-organized, highly regarded, and might be the most frequently used electronic database globally [9]. The following are the results of various search strings used in this work to extract the research publications of Dekker from about 171 million records with about 1.9 billion cited references housed by the WoS. Dekker and safety resulted in 403 publications; S

Dekker and safety resulted in 245 publications; SWA Dekker and safety resulted in 50 publications; and SWA Dekker and safety or S Dekker and safety or Dekker and safety resulted in 403 publications.

The report module in WoS was used to perform a preliminary analysis of the search results and citations. It showed that Dekker's research publications encompassed industrial engineering, ergonomics, operations research, health care sciences, health policy sciences, environmental science, applied psychology, social sciences, transportation, and civil engineering. Industrial engineering has enjoyed the highest number (about 35) of publications compared to about four publications in civil engineering. The vast research reach of Dekker's research is indicative of his influence and knowledge in workplace safety research.

2.1. Publications and Citations

Dekker's publications date back to 2002, when he published about three papers. His most productive year was 2011, where he published 12 papers, followed by 2014 (11 papers) and 2020 (10 papers). The citation of the work of Dekker grew slowly between 2002 and 2010. However, there has been exponential growth in the number of citations in recent years as his work has gained considerable recognition in safety research (since 2011).

Three different productivity trends can be deduced from Dekker's research publication history. Research period 1 depicts the beginning of Dekker's work from 2002 to 2008. Research production was low over the period. 2010 to 2013 represented his second research period when his research productivity increased. Dekker published the most research papers in 2011 (period 2). Dekker's third research period he covered from 2014 to the present. His average productivity was higher than in the two previous periods. According to Google Scholar, Dekker's work has attracted 16728 citations, with an h-index of 56 and an i10-index of 166.

Several bibliographic software has been invented recently, but the most outstanding one has been VOS viewer, the brainchild of Van Eck and Waltman [10]. VOS viewer is a distance-based, bibliometric visualization software that employs the VOS technique as an alternate multidimensional technique [11], [12]. The software can be used for bibliographic mapping, scientometrics, and the mapping and visualization of research results [5], [11]. This research used VOS viewer software and methodologies to perform keyword and bibliographic analyses.

2.1.1 Co-authorship Analysis

Co-authorship analysis encompasses authors, organizations and countries and results from two authors documenting or acknowledging their involvement in the same publication. Co-authorship can be used to study research collaboration across countries and institutions, author-to-author relationships, decentralisation or centralization in research [5]. The units of analysis are authorship, organizations, and countries. These three data points are used to quantify the research productivity and influence.

2.1.2 Authorship Analysis

In bibliometric analysis, authorship analysis is used to depict the productivity of authors on the subject matter or research area [13]. In performing authorship analysis in VOS viewer, a threshold of 25 with two documents and five citations was used for authorship and countries, whereas 25 with five documents was used for institutions. Fig. 2 is the authorship overlay map. Dekker had the two highest publications and citations under Dekker, Sidney W.A (45 publications, 797 citations and 45 total link strength) and Dekker, Sidney (34 publications, 430 citations and 20 total link strength). The next author on the list, Rae, Andrew, had eight publications, 38 citations,

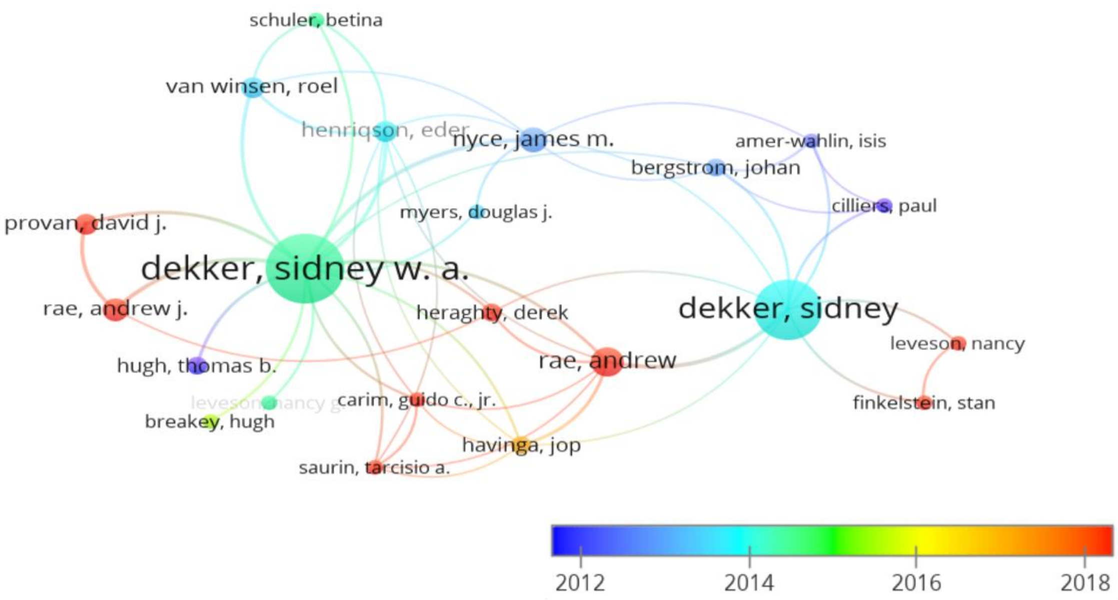

Figure 2: Variation of Authorship Overlay with Years.

and 18 links strengths. Dekker S., considerably lower on the list of prominent authors, had only four publications but has attracted 205 citations and four total links strengths. Dekker S.'s citations are third in line as it is the third name Dekker has published under. Thus, Dekker holds the top three most cited publications under his three pen names, a unique feature of his research work and publications.

In the earlier part of his research (in the 2000s), Dekker started his publications as Dekker S and Dekker SWA. From 2010 to 2018, when the bulk of Dekker's research publications occurred, he used the name Dekker, Sidney and Dekker, Sidney W.A. From about 2010 to recent times, Dekker has become recognized in OHS research and has published several papers and books on the subject matter. A greater proportion of his publications were with others in the same field. The top two on the list were SWA Dekker and Sidney Dekker. SWA Dekker has 45 published documents with 797 citations.

2.1.3 Organizations

This is used to understand the contributions of organizations to an area of research. There were very few countries involved as this was mostly limited to the work of a single author (Dekker). Dekker started his work in Lund University in Sweden, but he later moved to Griffiths University in Brisbane, Australia. Griffith University (the home university of Dekker) has 54 publications with 819 citations compared to the distant second university – the University of Queensland, which has 15 publications and 276 citations. Lund University had 16 publications with 450 citations. However, the total link strength of Griffith University, University of Queensland and Lund University are 38, 24 and 14, respectively. Interestingly, the Linkoping Institute of Technology had six publications with 418 citations but 0 total link strength. The co-authorship and organization map is shown in Fig. 3.

Figure 3. Co-authorship and Organization Map.

2.1.4 Countries

Fig. 4 depicts countries involved in this research. The countries with the highest number of publications were Australia (59 publications), USA (15 publications), Sweden (22 publications), Germany (2 publications), Netherlands (9 publications), Brazil (5 publications), South Africa (2 publications), and Canada (2 publications). It is apparent that Australia is the foremost country – the home of Dekker's research enterprise at Griffith's University and is followed by Sweden. Dekker's research is intercontinental as his work is linked with the USA, Brazil, and other countries across the globe.

It is evident that the research started in Sweden in 2000's, but Australia is now the seat of Dekker's research. Dekker also has a strong link to Netherlands as he did his initial studies in University of Nijmegen and Leiden University prior to pursuing his Ph.D. at Ohio State University.

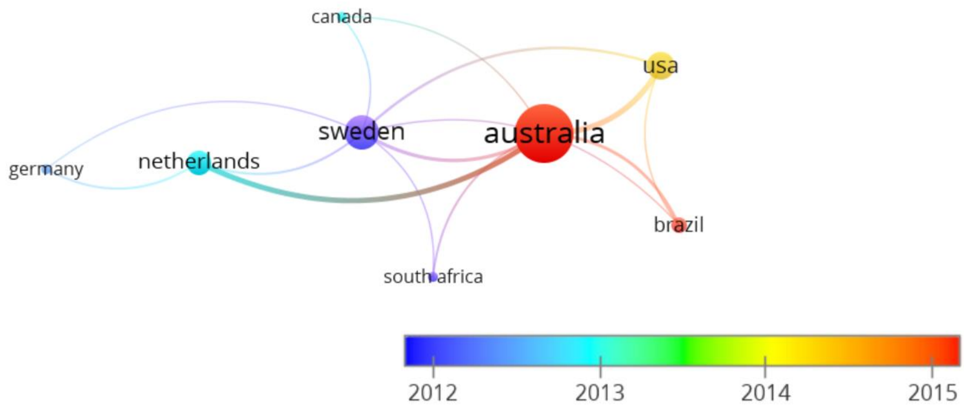

Figure 4: Co-authorship and Countries.

2.1.5. Co-occurrence Analysis

Co-occurrence analysis is used to show disciplinary distribution of the research area, depict the research frontier and detect which direction the research in the discipline is heading towards or evolving into [14], [15]. Keywords analysis can detect past studies' direction and research hotspots [16]. In this research, the units of analysis employed in the software are all keywords, author keywords and keyword plus in the context of full counting.

All Keywords

Under co-occurrence analysis and all keywords, the threshold for the minimum number of occurrences for a keyword to make the list was 5 top five keywords, and their associated occurrences were management (14 with a link strength of 108), safety (16 with a link strength of 107), human error (15 with a link strength of 93), organizations (11 with a link strength of 82), and accountability (10 with a link strength of 77). Fig. 5 is a map of the keyword co-occurrence analysis results. The various clusters of keywords (differentiated by the various types of color) cover the various areas in that Dekker conducted research in the past.

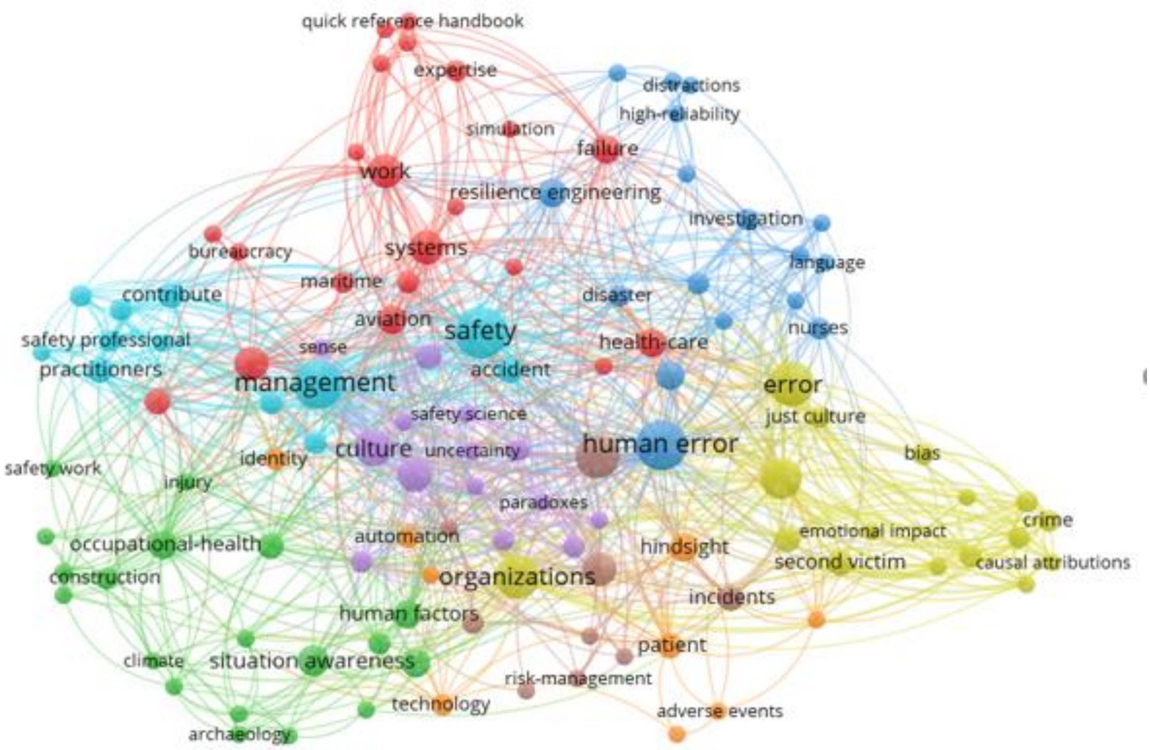

Figure 5: Keyword Co-occurrence Analysis.

In the area of occupational health research (green color), include keywords directly related to the construction, such as climate, human factors, safety work, injury, construction, archaeology, situation awareness, accident, and management, which are all directed to construction. Thus, it could be said that part of Dekker's work and publications was related to OHS in the construction industry.

With regards to author keywords, the main keywords and total link strength are human error (15 occurrences with a link strength of 44), safety (15 occurrences with a link strength of 44), accident investigation (8 occurrences with a link strength of 20), criminalization (3 occurrences with a link strength of 12), and human factors (5 occurrences with a link strength of 12). The green cluster is related to construction and is centered around safety. The remaining keywords in the green cluster are safety work, safety differently, and subcontractor with links to the complexity and human factors.

Author Keywords

In the author's keywords map, safety management, subcontractors, safety work, and safety could be related to the construction industry. This conjecture is proposed because construction is the only industry globally that heavily employs subcontractors as part of business practice.

Keyword Plus

Keyword plus consists of keywords extracted from titles of cited references from the WoS database. It is a computer algorithm-generated set of phrases and words commonly present in the titles of a paper's references but may not occur in the author keyword or the title of the paper itself [17], [18]. In the context of keyword plus the five top keywords and their associated total link strength are as follows: management with 14 occurrences and a total link strength of 66; an organization with 11 occurrences and a total link strength of 55; error with 12 occurrences and a total link strength of 44; culture with seven occurrences and a total link strength of 30; and accountability with six occurrences and a total link strength of 28.

3. DISCUSSION

Figure 4 provides incontrovertible evidence that the safe science endeavors of Dekker are influential with the ranks of scholars with a keen interest in health, safety, and wellbeing (i.e., CIB W099) and all that affect people in construction (PiC) (i.e., W123). Beyond the papers of these two CIB working commissions indexed in the ICONDA Library on [19], the influence of Dekker’s books, book chapters and articles is evident in papers presented in central construction management or education conferences such as the annual Association of Researchers in Construction Management (ARCOM) and Associated Schools of Construction (ASC) conferences in the UK and USA, respectively. From Fig. 5, topics that align with conference and article themes and focus include human error, resilience engineering, just culture, human factors, and risk management [20].

Two examples from both ARCOM and ASC conferences support this view. For instance, the ARCOM paper of [21] combined concepts such as high reliability organizing (HRO), human factor, and social capital to highlight the relational aspects of managing project safety in Hong Kong with analytic potentials for other regions. With a theoretical foundation that drew from other notable scholars in construction safety, the authors of this work put forward a conceptual framework and methodological suggestions for advancing knowledge. The paper shows that Dekker’s work is increasingly used to map concepts and ideas to resolve nutty construction safety issues that lead to accidents, injuries, and fatalities. Applying HRO and resilience engineering to construction drew ideas from Dekker's book chapters and two journal articles [22]. The article that is already cited over 70 times used the construction industry to explore how to apply HRO and RE in a project-based work environment with a transient workforce. The article aimed to flesh out how to manage safety without sacrificing production performance using HRO and RE concepts. Using principles of HRO and RE, such as management commitment, sensitivity to the frontline, prioritisation of safety, empowerment of employees, and just culture, the authors opined that progress could be made on-site with work-level initiatives. Aspects of mindfulness and cultivation of resilience could help reshape safety positively.

Citing a report that was influenced by Dekker’s work is relevant here. The report is a master thesis on Eastern European construction workers’ safety behavior, climate, and culture [23]. The quality study among the workers shows that management commitment favours production more than safety in Norway, with migrant workers not faring well compared to Norwegians in communication. The author thus contends that such practices strongly relate to the national belonging of workers and inadequate safety climate among migrants who perceived discrimination, language barrier, separation, and trust as very low on the project work site. The migrant construction workers believed that ‘injustice is high’ on the project work site. This result contrasts Dekker’s call for a ‘just culture’. In addition, the Norwegian thesis says that a safety climate leads to a low level of organizational commitment and participative behavior from workers. In effect, project sites in the study context may witness many silent deviations in the mode of ‘drift to failure’, forming the focus of Dekker’s two books. The study concluded that the safety culture among leased Eastern Europeans was neither informed, learning, reporting, flexible, or just. The culture observed in the qualitative construction work study was not balancing production and protection. Such imbalance is a problem in construction in both developing and developed countries [24].

This concise discussion on the influence of Dekker’s publications on construction safety will be incomplete without recognizing the impact of human error research projects in the sector. Most cited work on human error, failure, or human factors in construction management research either directly or indirectly refer to the books of Dekker on the topic. A well-cited article in the construction domain attempted to predict safety behavior using an integrative model [25]. The model assessed the safety of construction workers through safety climate and individual aspects. The article put forward notable findings. The results shared in the article show that management safety commitment was related to social support and production pressure. Production pressure was identified as a significant factor affecting safety motivation, knowledge, participation, and compliance among construction workers for the umpteen times.

4. CONCLUSIONS

OHS is a primary societal concern, and several entities and researchers in engineering, social sciences, psychology, law, business, medicine, and other disciplines across the globe undertake research in this area. S.W.A. Dekker is one of the outstanding researchers in this endeavor. As shown by Figs. 3 and 4, his work is widely accepted within the safety science research community with the co-authorship of publications spanning multiple territories and institutions. More importantly, Fig. 5 shows that the areas of research interests in the construction site community align with the extant work of Dekker with concepts such as human factors, human errors, HRO, and RE. Examples of how scholars in construction management have used his publications cover safety climate, safety culture, and just culture, apart from the behavior of construction workers. In broad terms, scholars in construction safety research build upon the safety science concepts of Dekker to proffer solutions to problems or areas of new safety debates.

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LESSONS FROM ILLUSTRATIVE CASE STUDIES OF COST IMPACTS OF CONSTRUCTION ACCIDENTS

Wakisa Simukonda[1], Fidelis Emuze[2]

[1]Department of Construction Management, Nelson Mandela University (South Africa)

[2]Department of Built Environment, Central University of Technology – Free State (South Africa)

Abstract

The high numbers of fatal and non-fatal accidents in the architecture, engineering and construction (AEC) industry continue to dominate the international Occupational Health and Safety (OHS) agenda. This paper aims to critically review the cost implications of construction accidents to engender control systems. Two illustrative case studies were reviewed and formed the basis for analysis. Case studies research approach was deemed necessary to illustrate the correlation between accidents and their cost implications. The study confirmed that accidents have substantial cost implications for enterprises and society, arising through direct costs (DCs) and indirect costs (IDCs). Higher percentages of DCs incurred by construction enterprises arise from wage and medical expenses. At the same time, IDCs actualize through production disturbance costs (i.e., overtime costs), additional medical, consumables and funeral costs and administrative costs (i.e., incident investigation). The study affirmed that IDCs are substantially more than DCs, i.e., two times greater in most cases. Falling from height was the leading cause of fatal and nonfatal injuries and, consequently, the highest contributor to both DCs and IDCs and hence, the total cost of accidents (CoA). To obviate the irreparable consequences of CoA on contractors' profitability and workers' OHS, construction enterprises should address operational challenges with modern construction methods, such as off-site construction (OSC) supportive of no harm to people.

Keywords: Accidents, construction, cost of accidents, the direct cost of accidents, indirect cost of accidents.

1. INTRODUCTION

The high numbers of fatal and non-fatal accidents in the architecture, engineering and construction (AEC) industry continue to dominate the international Occupational Health and Safety (OHS) agenda. Over the past decade, the review of OHS data reveals that construction is a frontline hazardous industry. In 2019, about 20% (1,061) of all worker fatalities (5,333) in the United States of America (USA) were recorded in the construction industry, representing one in five deaths [1]. In Hong Kong (HK), the construction industry recorded 3,902, 3,541 and 2,947 accidents in 2017, 2018 and 2019, respectively [2]. In United Kingdom (UK), 6% of construction workers either sustain injuries or suffer from construction work-related illnesses [3]. The fatality and accident rates for sub-Saharan Africa (SSA) are pegged at 21.0 and 16,012 per 100,000 workers, respectively [4]. These figures enthuse construction workers' vulnerability to various safety hazards of construction operations.

Among the uncommon accident types causing the most severe injuries and fatalities in the construction sector are falls, struck-by, caught-in between and electrocution [5] [6] [7] [8] [9]. According to [10], falls, trips and slips accounted for 338 fatalities in USA construction sector, while contact with objects was responsible for 169 of all 1,008 fatalities registered in 2018, representing 33% and 17%, respectively. In the UK construction industry, falls from a height are a leading cause of fatalities at 47%, followed by caught-in between objects (16%), struck by objects (12%), struck by moving vehicles (10%) and electrocution (4%) [8]. Slips, trips and falls on the same level are front liners in causing non-fatal injuries at 26%, followed by injured while handling, lifting or carrying objects at 19%, falls from a height at 19% and struck by objects at 12% [8]. These accident types are attributable to various kinds of safety hazards prevalent in the construction industry. These include working from an elevated work platform (EWP), slippery surfaces and failure of support systems, improper use of personal protective equipment (PPEs), the collapse of scaffolds, flying or falling objects, stepping on live electric wires, mental stress, organizational pressure, excessive workloads, misjudgment, lack of experience, poor communication and visualization and failure to comply with standard working procedures, among others [11] [12] [13] [14] [15] [16].

1.1. Defining the cost of accidents

Costs of construction accidents (CoA) could impose a significant economic burden on contracting firms and could be the difference between making a profit or incurring a loss. [17] define CoA as “the sum of the costs of losses generated by each victim individually, plus the costs of loss and damage of work equipment, costs of consumption of consumables, fines and penalties, if necessary, the funeral benefits and not least cost necessary for taking work safety measures”. The preceding definition appears to define CoA by stating the actual cost items experienced by the victims. According to [18], the parameters that reflect possible total CoA include direct costs (DCs), indirect costs (IDC), payment costs and immensurable costs. The seminal literature on CoA classifies CoA into DCs and IDCs [19]. Other classifications of CoA depending on specific characteristics of the accident costs are found in the literature. These include insured and uninsured costs; insurance-related costs, work-related costs and perturbation-related costs based on health and safety (H&S) costs [20]; and time, material and components, external services and other costs, reflecting classification in accounting systems [21]. Other authors have preserved the traditional classification and added one or two categories, i.e., H&S costs and quality of life costs [22] [23]. Irrespective of the various classifications of CoA, the traditional categorization into DCs and IDCs as proposed by [19] has remained common among researchers [24] [25]. Pursuing the trajectory of CoA as one of the primary foci of the illustrative case studies reviewed in this study, it is imperative to provide a description DCs and IDCs.

1.1.1. Direct cost of accidents

DCs are described as actual cash expenses a business incurs from accidents resulting in worker injuries and fatalities. They are direct cash flows associated with treatment and compensation to accident victims. Such cost items include insurance premiums, wages and medical bills [9] [24], indemnity payments offered to injured workers and medical bills to accident victims [9], workers’ compensational payments, medical expenses and legal costs [26], workers’ compensation premiums paid from workers’ compensation jurisdiction for injured or incapacitated workers [27]. All other accidents costs that are not covered by workers’ compensation insurance are described as IDCs.

1.1.2 Indirect cost of accidents

[25] describe IDCs as uninsured, non-billable and thus, unrecoverable costs. Cost items under IDCs among various authors demonstrate strong similarities, and based on the comprehensive literature review, IDCs comprise inter alia production and productivity losses due interruptions in production process [9] [24]; cost of work or process delays [9]; the cost of overtime payments and salary costs for replacement of workers [9]; cost of continuing payments to injured workers, retraining or workers orientation costs [24] [27]; costs of replenishing damaged buildings, equipment, tools and materials [9]; costs of repair work, administrative costs; cost of consumables, increased supervision and overtime work to make up for the lost time [9] [24]; stand-by costs of idle plant and equipment, costs of rescheduling of the work, fines and legal fees, funeral and compensation due to fatalities [24]; loss of current and future earnings, cost of social welfare to the victims, reputation damage, increased insurance premiums, decreased efficiency and loss of morale among workers, and cost of transporting the injured [9] [27]. Since IDCs are multiple and invariably infinite, the cost components have been aggregated into broader groups for ease of identification and measuring. Such groups include production disturbance, administrative, damaged property, and human capital costs [28]. Production disturbance costs are associated with reduced efficiency in the production process due to 15 cost items. Such cost items include lost productivity due to disruption in the production process; additional medical care; inspection; lost efficiency of the workers; discussing and watching the incident; loss of income; cost of temporary staff; inefficiencies of the backup staff; recruiting and training new workers; overtime costs; reduced morale; and lost time while assisting the workers [9] [25] [28] [29]. Administrative costs may be expressed as short, medium or long-term and include 16 components some of which are investigations, transportation, legal, funeral, insurance and supervision costs; travel concessions; damaged corporate image; first aid and administrative costs; time lost expended with project stakeholders, regulatory inspectors and completion of police and medical reports; as well as loss of function and operation income due to slowness in operation [3] [9] [25] [31]. Damaged property costs are costs associated with losses to materials and equipment (6 cost items). Such costs include cost of standby plant and equipment; replacement of damaged equipment; repair to damaged buildings and materials; loss in product quality; productivity loss due to damaged equipment and materials; and cost of damage to buildings, materials, equipment and products [3] [9] [25] [31]. Human capital costs are costs related to long-run loss of output or potential of workers after they return to work and has 4 cost

components, including loss of expertise and experience, future earnings, government revenue and social welfare payments for lost income and earnings capacity [3] [9] [25] [31].

1.2 Implication of costs of accidents

Accidents involve additional costs to employer, employees and the society at large. Understanding the proportion of costs borne by each of these economic agents is an important facet in understanding the true cost impact of accidents. Employers incur production disturbance costs, administrative costs and costs related to insurance premiums. Productivity of workers is of special importance to business performance. Productivity is achieved in construction if the resources are put to optimal use during the production process, characterized by a smooth and uninterrupted flow. Sadly, the occurrence of accidents disrupts the production process. If a worker suffers from a work-related injury or illness, their current work is left incomplete. If the injury is severe, the worker may not be able to attend pre-scheduled shifts [17]. Further, if the injured person had specialised skills or many years of experience, the production process is stopped until a new recruit is found or trained. Additionally, the company may experience low efficiencies in the immediate aftermaths of the accidents due to reduced morale of the workers as well as inefficiencies of the backup staff [17]. Certainly, inefficiencies in the production process result in inter alia, productivity losses as a result of the business enterprise failing to execute its primary value proposition. Administrative costs include costs of worker's compensation schemes, the administrative burden for inspections, investigations and reports, costs associated with funerals, legal fines and penalties as well as travel concessions for permanently disabled workers [30]. The administrative costs may be unexpected, and such eat into profit margins of the enterprise. The enterprise may be forced into a long-term financial commitment to the victim, i.e., by paying salaries to non-productive employees thereby increasing its wage bill. The insurance costs, such as compensation payments and insurance premiums may also increase thereby increasing the operational costs of the enterprise. On the other hand, cost items attributable to employees include medical and rehabilitation costs, loss of future earnings, out of pocket funeral, travel, prescription and home expenses, monetized value of non-financial human costs, private health insurance payments and payments to carers [26] [30]. Costs items borne by the society include inter alia, tax losses, carer costs, social payments, investigation costs, loss of human capital, medical subsidies, legal costs and compensation and welfare costs [26] [30].

Expressed as a percentage of the completed construction work, [24] reported that CoA in South Africa was around 5% of a completed construction project. In Australia, the construction industry is ranked third as the highest contributor to CoA, at 11% of the total CoA [2]. CoA as a percentage of completed construction projects could be high due to the nature of the construction industry - significantly more employees, more layers of jobsite management and stakeholders involved in the project and the OHS risks inherent in crowded workplaces. CoA have profound consequences on financial performance and the very existence of business enterprises, as profit margins get eaten up. With these economic repercussions in mind, reducing CoA should be a company's strategic objective and a motivating factor for improving OHS management to attain and increase profitability [31]. Understanding the cost impacts of construction accidents could be a motivating factor for engendering accident control systems to protect people and finance. However, in order to mitigate costs of accidents, enterprises must be made aware of the source of accidents and their impacts. Various studies report causes of accidents and their impacts without highlighting specific accidents types and major cost items to which attention must be paid. Consequently, the study reviews the cost implications of construction accidents through a review of case studies in order to bring to the fore the major accidents' types and their associated cost items to endanger control systems.

2 RESEARCH METHOD

A qualitative case study research was adopted for this study. Case studies involve in-depth analysis of a phenomenon in its natural context [32]. Specifically, multiple illustrative case studies approach was deemed necessary to adequately illustrate and depict the correlation between the occurrence of accidents and the implication on cost. Illustrative case studies are descriptive studies aimed at depicting the circumstances of an event to explain a phenomenon. According to [33], illustrative case studies are an example of a plausibility probe, researchers use to sharpen a hypothesis or theory. Even though case studies yield narrow results [34], illustrative case studies are used to demonstrating in depth the empirical relevance of a theoretical proposition [33]. Illustrative case studies are common in international relations and social sciences [33].

The choice to adopt case studies research approach was influenced by the need to use information from previously documented case studies without necessarily engaging in additional studies. Given that data on CoA is sensitive and may not be easily accessible, and that when data is available the review may take a considerable amount of time to re-organize and analyze [9], it was necessary to use archival case studies for the purposes of reviewing the cost implications of construction accidents to engender control systems. The selected case studies were those that discussed the direct and indirect costs of accidents in the construction industry. To ensure that this paper adds value to the previously documented case studies selected for this review, the data on CoA appended in the case studies were further analyzed to give a different perspective and understanding of the results. The focus of analysis was on IDCs and DCs, and specific cost items contributing higher percentages of costs to the total CoA. This approach ensured that cost impacts of accidents were clearly demonstrated in this paper. However, due to limited case studies on CoA in the extant literature, two case studies selected on basis of their content in depicting true CoA were reviewed, i.e., [9] and [17]. Case study one was based on [9] comprehensive review of construction-related accidents using accident database of a large utility company domiciled in Southern Africa to determine the true CoA. The utility company was involved on major capital expansion project worth $15 billion over five years. The review was conducted on 100 incidents sampled from a total 872 accidents and included fatalities, first aid, medical and lost time. The case was selected in order to comprehensively illustrate the actual amounts allocated to each cost components of DCs and IDCs, suggestive of their contribution to total CoA and hence, their implication. Case study two was based on initial case study conducted by [17]. It involved the collapse of the earth of the bank that needed to be adequately supported while installing a water supply and sewerage system for a rural community project. Since IDCs recorded a higher percentage of total CoA in case study one, it was imperative to focus on IDCs on case study number two in order depict how such costs are realised. As such, case study two was selected with the aim of depicting disruptions in the production process that lead to inefficiencies and eventually loss of thousands of productive working hours. Production disturbance costs are a cost item with highest percentage of costs within IDCs.

3 FINDINGS AND DISCUSSION

3.1 Case study one

This case study narrates the true CoA reported by [9] on construction related accidents in an energy utility company in Southern Africa. The case study analysed 100 cases sampled from 872 accidents namely, fatalities, first aid, medical and lost time accidents. The aim of the case study is to highlight the true costs of construction accidents, caused by injuries and fatalities.

3.1.1 Costs of accidents, including fatalities

As already highlighted, true CoA are divided into direct and indirect costs. The case study revealed that DCs made up R10,087,350 ($511,694) while IDCs amounted to R22,893,850 ($1,160,665) of the total costs of 100 accidents on the project. DCs represented 30.59 percent while IDCs were 69.41 percent of the total costs of 100 accidents. Thus, IDCs were 56% higher or 2.27 times greater than DCs on this particular project.

Within the DCs, wages for injured persons represented the highest share of DCs at 93.04 percent followed by medical costs at 6.96 percent. Among the causes of accidents under review, accidents caused by falls had the highest total and average wage and medical costs per accident. A combined total amount of R4,733,550 ($239,949) was spent on wages (i.e., R4,412,800) ($223,717) and medical bills (i.e., R320,750) ($16,261). The average wage and medical cost per accident caused by falls were R119,265 ($6,047) and R8,669 ($439), respectively. The second highest contributor to DCs of accidents were accidents caused by electrocution. The total DCs expended on wages (i.e., R3,587,508) ($181,902) and medical bills (i.e., R241,700) ($12,255) for accidents caused by electrocution amounted to R3,829,208 ($194,157). Average wage and medical costs per accident were R99,306 ($5,035.51) and R13,428 ($680), respectively. Other accident types such as burns, cuts/caught-by, struck-by and exertion/ergonomic had relatively lower total and average DCs on both wages to injured workers and medical bills. The analysis of the cost components shows that wages represent the highest cost of DCs followed by medical costs. A total of R8,000,308 ($405,673) was spent on wages paid to injured workers as a result of accidents caused by falls and electrocution. On the other hand, only R562,450 ($28,520) was expended on medical bills for the same causes of accidents. Thus, accidents caused by falls are almost 14 times more expensive than accidents caused by electrocution in terms of DCs.

Cost components within IDCs included overtime costs; time lost by injured employee and co-workers; injured employees productivity lost costs; supervision and management lost time; incident investigation costs; training of replacement employees; damage to equipment; idle plant and equipment; and other costs (additional medical, consumables and funeral costs). Of these cost components, the category of 'other costs' represented the highest share of IDCs at 77.9 percent (i.e., R17,839,200) ($904,572), followed by incident investigation costs at 10.3 percent (i.e., R2,356,600) ($119,496), and overtime costs at 6.4 percent (i.e., R1,476,100) ($74,848). 'Other costs' category represented the highest average costs of IDCs with electrical and falling accidents contributing the highest costs at ZAR369,078 ($20,450) and ZAR255,011 ($14,130) respectively. Similarly, incident investigation costs represented the second largest contributor to IDCs with falling and electrical accidents accounting for the highest costs at ZAR 28,149 ($1,560) and ZAR41,294 ($2,288), respectively. Overtime costs occupied a third slot with falling and electrical accidents contributing highest average overtime costs, i.e., R17,366 and R28,900, respectively. Accident types accounting for higher costs in other cost components of IDCs are shown in Fig. 1.

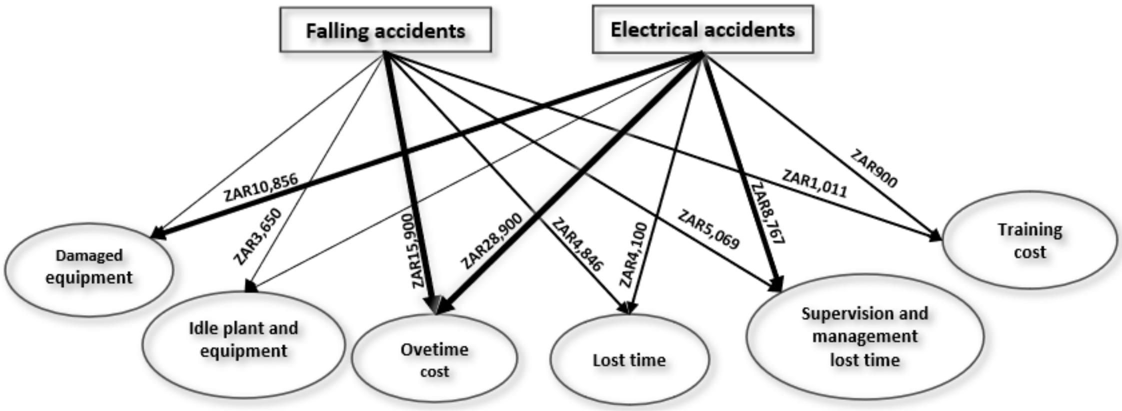

Fig. 1: Accident types and other IDCs

It is evident from the findings that falling and electrical accidents were the most prevalent causative agents of accidents accounting for the higher costs in various cost components of IDCs. Taken together, falling and electrical accidents accounted for the largest IDCs emanating from other costs category at 81 percent each. Cuts and caught-by accidents represented the highest IDCs of investigations at 40 percent and overtime costs at 25 percent. The findings show that falling and electrical accidents account for higher costs of IDCs just as was the case with DCs. Consequently, falling and electrical accidents accounted for a higher percentage of total CoA on the project.

The case study has shown that construction enterprises would potentially incur higher costs through accidents related to falls and electrocution. These accident types account for higher IDCs and DCs through medical and wage expenses. IDCs and DCs eat into construction enterprises' profits and would be the difference between making and incurring a loss on a project. One way in which falls and electrocution could be minimized is through the adoption of modern methods of production. Since falling accidents could be caused by slips, trips, improper use of PPE, absence of safeguards, poor judgment and visualisation, working from elevated work platforms (EWPs), as well as other environmental conditions and human behaviours, adoption of construction methods that evidently minimize these safety hazards could make a big difference. Offsite construction (OSC) supports offsite manufacture of building components. According to [35], OSC environments lend themselves to reduction of hazardous operations such as working from EWPs which is the main causative agent of falling and fatal accidents. Further, falling accidents could be minimized through a clean and orderly environment that provides less risk of contamination, falls, trips and slips [38]. Electrical accidents could be minimized through the orderliness of the workplace that could avoid improper connections of cables and stepping on live wires. Further, the factory setting of OSC lends itself to better construction processes and safety risk management that could minimize safety risks to a greater extent. Reduction of construction accidents, i.e., falling and electrocution, through OSC, would minimize accidents costs, both DCs and IDCs, resulting into costs savings and improved profitability margins.

3.2 Case study two

Case study two is an illustration of productivity losses which contracting firms' experience when accidents occur. The primary case study was reported by [17] and involved collapse of the bank of the earth that was not adequately supported at a construction site of a water supply and sewerage system. The accident resulted into two fatalities and several injuries.

The first victim who performed digging died on the spot as a result of the crumbling bank of the earth. Immediately, the company hired a replacement and paid overtime to complete the work within the allotted schedule. Losses were experienced through lost working time, overtime pay, and inefficiencies caused by the new worker in the period in which the worker was executing the new job. The second victim, a welder, died two days after the accident. The company took seven days to replace the welder as other welders were engaged in other activities. The productivity losses were experienced through the loss of expertise in the welder, seven working days while waiting for the replacement and losses due to inefficiencies caused by the new welders in the period in which the welders were executing the new job. The third victim sustained minor injuries and was on temporary disability for five days. The company hired a replacement, but the victim lost time was never recovered. Productivity losses included five working days and losses due to inefficiencies of the victim returning to work. The fourth victim suffered a leg fracture and stayed on temporary disability for 120 days. The victim's lost working days were not recovered by colleagues' overtime work. Productivity losses included 120 working days. Other costs incurred by the enterprise included costs due to damaged fixed assets, i.e., electrofusion welding machine that required repairing, fines for breaching OHS requirements as well as costs for purchasing work equipment and PPE, costs related to restoration of the area where the accident had occurred, funeral expenses and hiring of third parties to complete the project within the contractual deadline to avoid liquidated damages.

It can be deduced from the case study that the occurrence of the accident led to the company incurring both DCs and IDCs. DCs manifested through medical costs realised through medical expenses for the first, second, third and fourth victims. Other DCs were incurred through wages paid to the injured victims during the period they were unproductive. IDCs were realised through disruptions in the production process. Production inefficiencies manifested through the loss of thousands of working hours through loss of working time of the injured workers and the time the injured workers were recuperating at home; loss of working time of the crew of the injured workers while assisting the victim; loss of working time of the workers in the vicinity of the accidents; loss of productivity time due to cleaning the site of the accident and inspecting the OHS protocols around the job site; loss of time as investigations were being undertaken to establish the cause of the incident; loss of working time as management staff focus shifted from traditional duties to the incident; time lost during restoration work; lost time through inefficiencies caused by the new workers; and loss of working time due to idle or damaged equipment. Further, production inefficiencies were recorded when the injured worker's current work was left incomplete, and failed to attend to pre-scheduled shifts; the production process was stopped until a replacement was found; the morale of the workers, as well as the backup staff, was reduced in the immediate aftermaths of the accident; welding equipment and products were damaged and needed replacement or rework; and when investigations were conducted to ascertain the cause of the accident. Apart from production disturbance costs, other IDCs were experienced through administrative costs (i.e., costs of funeral and fines sanctioned on the firm) and damaged property costs (i.e., damaged electrofusion welding machine).

[37] define productivity as "the output over input that indicates the efficiency of a productive system". In the construction industry, productivity implies the productivity of several resources employed during project construction. It includes workers' productivity, equipment, technology, energy, capital, logistics support and supply chain [37]. Thus, productivity is achieved in construction if these resources are put to optimal use in the production process, characterized by a smooth and uninterrupted flow.

Accidents on construction sites may result in reduced productivity levels, especially with traditional onsite construction methods that rely on the workforce to execute the work. Accidents lead to fatal and non-fatal injuries or illnesses. Non-fatal injuries or illnesses lead to temporary or permanent impairment with non-lasting or lasting functional limitations. If a worker suffers from work-related injury or illness, their current work will be left incomplete, and if the injury is severe, the worker may not be able to attend pre-scheduled shifts. Further, if the injured person had specialised skills or many years of experience, the production process might have to stop until a recruit is found or until someone is trained. Additionally, the company may experience reduced or low efficiencies in the immediate aftermaths of the accidents due to reduced morale of the workers as well as inefficiencies of the backup staff. Productivity losses are also experienced as the work gets stopped or suspended, especially in the immediate hours of the accident, to provide care to the victims, take stock of the OHS protocols, and investigate the accident. Works may also experience prolonged stoppage if stop work orders (SWO) are issued. Other administrative and clerical duties kick in, i.e., arranging transport of the victims to the medical facilities and establishing investigations to document the incident. All these activities cause production disturbances and production losses. Accidents also result in damaged products, materials and equipment, which may require the company to rework or replace. The idle time of construction equipment due to accidents also contributes to productivity losses. The case study by [17], therefore, provides a comprehensive example of how accidents minimize productivity levels, resulting in low output and increased operations costs, with a consequential impact on profitability margins.

However, OSC operations have been recognised as critical to construction sector productivity. Most of the factors causing production inefficiencies when accidents occur, as highlighted above, could be eliminated by adopting the OSC. In the main, accident prevention on construction sites would guarantee production efficiency as the sequence of non-productive activities triggered by accidents would be non-existent. For the accident of this nature, i.e., collapse of the bank of the earth that was adequately supported, OSC would prevent injuries to persons through minimized operations and number of workers onsite as well as mechanization of the most of construction operations. This would minimize exposure of workers to hazardous environments and working conditions thereby enhancing their safety.

4 CONCLUSIONS

The two case studies have demonstrated the magnitude of CoA that could impact a construction enterprise's profitability. DCs of accidents are mainly made up of medical expenses and wages. IDCs consist of additional medical, consumables and funeral costs, investigation costs, and production disturbance costs, i.e., overtime costs. Irrespective of the nature of the accidents, including causative agents and severity, IDCs of accidents are significantly higher compared to DCs, namely at least two times greater. To minimise CoA, construction enterprises must minimize and eradicate falling accidents which are the primary causative agents of both fatal and non-fatal accidents, accounting for the largest IDCs of accidents. Falling accidents also account for the largest DCs through wages paid to injured workers. Although it is cumbersome to ascertain the actual CoA, the estimation and cost analysis of the IDCs and DCs of accidents revealed in the case studies is an indication of their awareness and the impact they potentially have on construction enterprises' bottom line that would necessitate construction enterprises to adopt specific measures to prevent accidents from occurring to protect people and finance. Among others, constructing enterprises are transiting towards the adoption of OSC as a modern construction method that potentially minimizes the exposure to falling and electrical accidents and improve production efficiencies in the construction industry, through transferring of construction activities to an offsite factory-controlled environment, where OHS management is enhanced. The study brings to the fore the major cost items associated with DCs and IDCs. As the implication of the review study, the paper highlights the major causative agents of accidents and associated cost items to allow enterprises refocus their OHS management strategies. The scarcity of case studies on cost of accidents is a sign of limited research on the subject area globally. Researchers need to conduct more research that would attempt to determine true cost of construction accidents and establish their impact on enterprise economic performance. The findings of this study may not be generalised as the two case studies may not represent a wide array of accidents occurring in the global construction industry.

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DEVELOPING AN AUDIT CHECKLIST TO ASSESS CONSTRUCTION SITE HEALTH AND SAFETY PRACTICE

Sabrina Shahid Saba[1], Noel Painting[2], Mahmood Alam[3], Hannah Wood[4]

[1,2,3,4] University of Brighton, United Kingdom

Abstract

Bangladesh is a fast-growing nation with a 7.9% GDP growth rate, and the construction industry is one of the main contributors to the economic growth in Bangladesh. This growth of the construction industry has become possible because of the affordable skilled and unskilled labour availability. However, the health and safety practice in this construction industry is still quite inadequate, resulting in many injuries and fatalities. For this research, three case studies have been conducted in Bangladesh. As part of the case studies, a comprehensive audit checklist has been developed. This audit checklist helped in data collection concerning all the health and safety aspects of a construction site. However, there needs to be more literature regarding developing an audit checklist of health and safety in the construction industry of developing countries. Several researchers have used audit checklists to measure or assess the health and safety of construction sites in Bangladesh. The audit checklist used in this research consists of multiple items under the following aspects of construction site health and safety such as; site set-up, site management, competence check, risk assessment, permit to work, first aid facilities, site safety rules, site safety signs, provisions of PPE, provisions of working at height, plant and equipment used on the site, maintenance of the equipment, working in confined space, working with explosive materials, traffic management, worker's welfare, protection of the public, emergency fire procedure, hazard awareness, handling of hazardous substance, prevention of pollution, waste separation, handling of asbestos containing materials, internal/external audit and so forth. This audit checklist can assist the Construction Managers, Designers, Clients or Researchers in assessing the health and safety of construction sites.

Keywords: Construction health and safety, Workers' welfare, Case study, Audit checklist, Site risk, Safety management

1 INTRODUCTION

Construction industry is one of the most hazardous industries worldwide. In the developing countries the number of construction accidents/incidents, fatalities and injuries is much higher than developed countries. Bangladesh is a fast-growing developing nation, with GDP growth of 7.9%. Bangladeshi construction industry is a major contributor to the nation's GDP in 2016 [1]. This growth of the construction industry has become possible because of the availability of affordable skilled and unskilled labour. The labour force survey by Bangladesh Bureau Statistics (BBS) demonstrated that approximately 2.4 million workers are now employed in the development business [2]. However, this is the only number of registered workers, but the actual number of workers is unknown. Whereas the construction industry plays a vital role in the economic growth of this country, it is one of the worst performing in the occupational health and safety of its workers. According to the statistics of Occupational Safety, Health and Environment (OSHE), there were 147 fatalities in 2016 due to accidents on construction sites. Another report by the Bangladesh Institute of Labour Studies (BILS) shows that from 2005 to 2016, there was a total of 1,196 deaths in the construction industry (averaging at least 100 deaths per year). A report of BILS demonstrated that approximately 100 injuries occur in a year [2]. Compared to the total population, construction-related deaths are disproportionately low. From this number, it is comprehensible that the statistics are not accurate because of under-reporting and under-recording. The actual number of construction-related accidents, incidents and injuries is still unknown. There is few research have been conducted to find out the main causes of construction site accidents [1, 3-9]. According to these authors, the main causes of construction accidents are; lack of safety awareness, lack of education and training, reckless action of authority and workers, poor equipment and their maintenance, lack of emergency measures, lack of information flow, lack of technical guide, lack of personal protective measures, type and nature of construction [1]; shortage of enforcement of safety regulations, errors in scaffolding fixing, shortage of safety sign, errors in equipment, errors in inspection, lack of emergency steps [4, 5]; falling during steel erection, falling from unprotected edges, lifts and staircases, falling during slab concreting, unmindful falling, falling during plastering/ painting of exterior walls, all falling (sum of above), electric shock, collapse of structure/ scaffold, removing formwork, gas exploration [6]; lack of personal protective equipment, lack of safety elimination/ avoiding designs, unfit equipment, lack of knowledge and training on equipment [3]; fall from heights, electrocution, suffocation, wall collapse, fall of material, formwork/shuttering failure, roof collapse, earth collapse, scaffold failure [9]. However, the number of items covered in these checklists are insufficient and they excluded the wide range of risks involved in the construction activities. There are few studies already which have developed construction workplace health and safety audit tool and explored limitation of other studies [10-12]. However, there is still gap of an audit tool which is developed based on Bangladeshi construction industry' requirements. Hence, the author developed a comprehensive audit checklist for the Bangladeshi construction sites which can be implemented both in academic research and industrial safety practice. This audit checklist has been developed to collect data for construction case studies as part of the author's PhD research project.

2 METHODOLOGY

This section describes the approach of the development of this audit checklist. This audit checklist development followed a six stage process in Fig.1. These stages are; reviewing the existing audit checklist guideline in literature, reviewing the existing audit checklist studies to get idea, making the first draft of the audit checklist, implementing this audit in the pilot study, amending the audit checklist according to the feedback, finalising and implementing this final audit checklist for data collection,

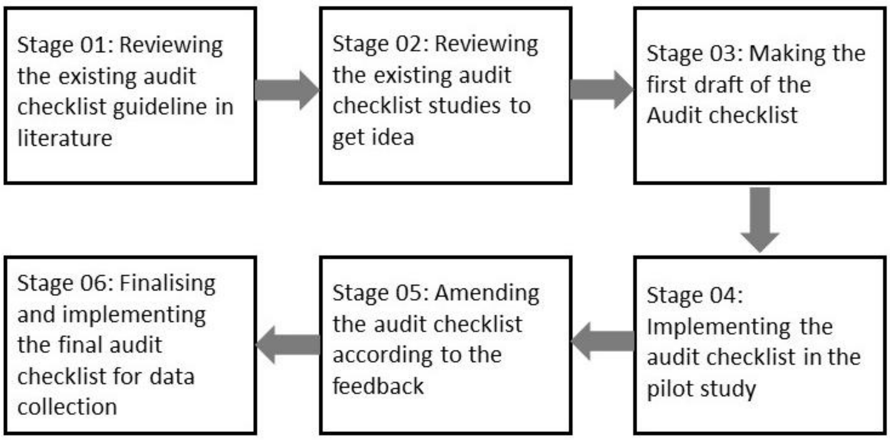

Figure 01: Flowchart of the stages of this audit checklist development

Stage 01: There are different categories of the audit checklists. The type of checklists should be selected based on the objective of the case study. According to Seoane [13], the audit checklists can be divided into six categories which are;

1) Optional: Where there are three possible choices of answer. Usually they are 'affirmative', 'negative' and 'not applicable'.
2) Alternative: A choice of two answers that are generally opposite or complementary are requested.
3) Graded: In this type of checklist, the response is graded and a score or scale is established. This type of checklists can be used for quantitative research.
4) Multiple choice: Several possible answers are given in this type of checklist and also an option called 'other' is included.
5) Interrogative: This kind of checklists require brief lengthier answers. This kind of checklists are used for mostly qualitative research.
6) Branched or interlinked: In this type of checklists, based on choosing one answer the other options are provided in the form of branches or links. This kind of checklists are sequential in terms of the response.

There are many guidelines available for developing an audit checklist or audit tool. For example, Stufflebeam [14] provided a checklists development checklist (CDC), Gagliardi *et al.* [15] developed a guideline of implementation planning checklist for medical sector. Boritz *et al.* [16] mentioned that for designing a checklist the following factors should be considered; customization, diagnosticity and the structure of the checklists. The audit checklist in this case studies was developed based on the optional type of response which includes three options; affirmative (yes), negative (no) and not applicable. Because, the audit checklists are constructed in a way to find out the current health and safety practice on the construction sites. Hence, the audit checklists give the opportunity to choose if the listed items are practiced on site. Also, there is a comment box added at the bottom of the audit checklist for any further information. There is also literature available to regarding the content criteria and validity of an audit tool related to occupational health and safety [17, 18]. The author's audit checklist was developed as part of her PhD thesis. The author conducted interviews and case studies to evaluate safety culture of the Bangladeshi construction industry. Hence, this audit checklist was developed based on the legal framework of Bangladeshi construction industry. A less binary with more flexible option (such as; Likert scale) could be chosen for the audit checklist. However, the photographic evidence gives comprehensive idea of the health and safety practice on the cite which was not possible from only using questionnaire or audit checklist.

Stage 02: There are studies been conducted on the development and use of audit checklist/checklist in health care or medical sector [19-28]. Curl *et al.* [25] developed an audit checklist to assess the outdoor falls risk for the older people. This audit checklist was also developed for qualitative purpose. As part of the study they conducted interviews of the older people and took photographs of the items listed on the audit checklist to understand how these items affect the fall risk of the older people. Checklist is also used as a data collection and validation tool in other sectors such as; education [20, 21], food industry [29] and so on.

Stage 03: The purpose of the audit checklist is to evaluate the health and safety practice on the construction sites in Bangladesh. Because, photographs of the items listed on the audit checklists also have been collected from the construction site in support of the response of the checklist. Hence, the purpose of the case study is qualitative. Photographic content analysis has been used to analyse the photos. However, the author intends to publish another consequential paper regarding the result of the case studies. Heavy literature review has been carried out to develop the audit checklists. Hence, the researcher created this comprehensive audit checklist based on the following resources;

Regulatory framework: The items of the audit checklist were initially identified from the basic requirements of Bangladesh National Building Code (Volume 3; part 7 and part 10). In addition to that, few items under risk assessments and competence check were adapted from the UK regulations (such as; The Management of Health and Safety at Work, 1999).

Online sources: Some online construction audit checklists are available which were used as starting point. The construction site health and safety self-audit form [30] and design & construction auditor checklist [31] are some of the checklists which inspired the author on the development of the audit checklists.

Professional qualification: The author has completed few professional qualifications of construction health and safety management. These are; 1) NEBOSH Health and Safety Management for Construction Certificate (UK), 2) Managing Safely (from IOSH-Institute of Occupational Safety and Health), 3) Safety, Health and Environment for Construction Site Manager (from IOSH), 4) CDM-managing health and safety (from CIOB Academy). These qualifications helped her to understand the mandatory health and safety aspects of the construction site safety practice. The audit checklist consists of three main broad sections which are; description of the project, health & safety practice and a comment box at the end of it for the participants to provide information regarding the items. The middle section consists of 24 items (health and safety).

Stage 04: This audit checklist was distributed to a medium sized residential under construction project as pilot study in Bangladesh. As the data collection was conducted during lockdown in 2021 in Bangladesh hence the inclusion criteria of case studies are; 1) Construction sites having Covid-19 safety measures according to the latest Bangladeshi Covid-19 safety and health guideline, 2) Funding type: any, 3) Occupancy type: any, 4) Construction phase: Under construction phase, 5) Procurement route: any, 6) Contract type: any, 7) Size of the project: medium or large. The specification of the project size is given in table 01.

Table 01: The size of the projects chosen for the case studies.

	Extra small	**Small**	**Medium**	**Large**
Area	0-4,999 sft	5000 -19,999 sft	20,000 sft- 79,999 sft	80,000 sft- above

Budget	0-14,999,999 Taka/ 127,499.9915 GBP (approx.)	15,000,000 Taka/127,500 GBP -39,999,999Taka/ 339,999.99 GBP (approx.)	40,000,000 Taka/ 340,000 GBP - 159,999,999 Taka/ 1,359,999.99 GBP (approx.)	160,000,000 Taka / 1,360,000 GBP (approx.) - above

During the data collection process face to face data collection was prohibited according to University of Brighton's guideline. Hence, the inclusion criteria for participants who collected data are;

1) Site Manager/Site Supervisor/Site Engineer of that construction site

2) Willing to collect data voluntarily

Ethics approval has been sought from ethics approval committee of University of Brighton before starting data collection. In this pilot study, at first permission was sought from the Project Manager of the project. Then participant information sheet was sent to the Site Manager/Site Supervisor/Site Engineer of that construction site and signed consent form was sought from them. The Site Manager/Site Supervisor/Site Engineer filled up the audit checklist and also captured the relevant photographs. An instruction document was also provided to the Site Manager/Site Supervisor/Site Engineer to comply with the ethics guideline of University of Brighton.

Stage 05: After pilot study, according to the feedback some phrasing of the questions was amended. However, there was no change of the items in the audit checklist.

Stage 06: The final version was distributed among two more large sized projects which met the inclusion criteria. Photos were collected for the items listed in the audit checklist wherever possible to support the response.

3 THE SITE HEALTH AND SAFETY AUDIT CHECKLIST

The audit checklist starts with the description of the construction project which include; type of the project, procurement route, gross floor area, value of the project, project sponsor type, Type of the organisation managing the site, Job title of the respondent, Type of the organisation of the respondent and so on.

The second part 'health and safety practice on site' is developed based on; site set-up; site management, competence, risk assessment, permit to work, first aid, safety rules, safety signs, provision of PPE, working at height, plant and equipment used on the site, maintenance of the equipment, working in confined space, working with explosive materials, traffic management, worker's welfare, protection of the public, emergency fire procedure, hazard awareness, handling of hazardous substance, prevention of pollution, waste separation, handling of asbestos containing materials, internal/external audit.

The last part consists of a comment box for further information which can be altered as per the purpose of the audit checklist.

Table 02: Construction site health and safety audit checklist

Name of the research topic	Site health and safety practice in Bangladesh construction industry
Type of this construction project	Commercial/ Retail/ Residential/Industrial/Infra-structure
Procurement route	Traditional/ Design and build/Construction management/Contractor led/ Custom led/Fast track construction
Project Gross Floor Area	0 -19,999 sft/20,000 sft- 79,999 sft/80,000 sft- above
Value of the project	0-39,998,000 tk/40,000,000 tk - 159,998,000 tk/16 crore- above
Project sponsor type	Government/ Private/ Local Authority/International Private Funder/ International Public Funder/ Other (………………..)
Type of the organisation Managing the site	Architectural firm/ Real Estate firm/ Structural engineering company/ Project management firm
Job title of the respondent	The Site Engineer/ Site Supervisor/ Site Manager
Type of the organisation of the respondent (your employer)	Consultant/ Contractor/ Client/ Sub-contractor/ Government/ Local Government/Other (…………………………)
Date of data collection	
Distributed by	

Safety and health management practice on site	Yes	No	Not applicable
Which of these do you have as part of your site set-up?			
1. Safety officer for the site			
2. Safety briefing			
3. Induction of the site			
4. Fire License from Fire department			
5. Lay out Plan of the project			
6. Factory license from Inspector's Office. (for factories)			
Which of these do you use part of your site management?			
7. Method statements for construction work			
8. Construction phase plan			
9. H&S file or site document			
10. Risk assessment for the existing site			
Which of the following do you collect on site to demonstrate competence?			
11. Qualification cards for the construction workers			
12. Training on manual handling			
13. Training on lifting operations			
14. Training on safety and health (more details required)			
15. Training on work equipment (more details required)			
16. Training on fire emergency			
17. Training on first aid			
18. Drug test of the workers			
Which of these activities would be included in your risk assessment?			
19. For working in confined space			
20. For working at height			
21. For falling objects			
22. For working with chemical substances			
23. For harmful chemicals (asbestos/lead)			
24. For high voltage work			
25. For Coronavirus Covid-19			
26. For plant operatives slip, trip and falls			
27. For stability of adjoining structures/trenches/fences			
28. For lone working			
29. For hot work			
30. For noise exposure			
31. For vibration			
32. For air pollution			
For which of these would you require a permit to work?			
33. Hot work permit			
34. Confined space work permit			
35. High voltage work permit			
36. Work at height permit			
Which of these would you have on site as part of your first aid provision?			
37. **First aid box**			
38. Designated first aider			
39. Incident & accident reporting book			
How do you communicate the site safety rules to operative?			
40. Site rules issued to the site workers (printed copies)			
41. Toolbox talk			
42. Whistle blowing			
43. Designated smoking area			
Which of the following safety signs do you use?			
44. Red signs (prohibition sings)			
45. Blue signs (mandatory signs)			
46. Yellow signs (hazard signs)			
47. Green signs (safe condition signs e.g. fire escape, first aid sign)			
Which of the following Personal protective equipment item is mandatory?			
48. Hard helmet			
49. Facemask			
50. Safety boots			
51. Safety gloves			
52. Safety clothing			
53. Eye goggles			
54. Hearing protection (ear defender)			
55. High visibility clothing			
Which of these provisions is provided for working at height?			
56. Safety net			
57. Safety harness			
58. Caution signs for voids			
59. Safety measure to use ladder E.g. securing, step ladders, stabilizers			
60. Safety certification to use fixed scaffold			
61. Safety measure to use mobile tower			
62. Safety licence to use Mobile Elevated Working Platforms (MEWPs)			

Which of the following plant and equipment is used on your site?			
Ride on plant: 63. Roller			
64. Excavators			
65. Road planers			
66. Dumpers			
Pedestrian controlled plant: 67. Vibrating plate compactors			
68. Surface grinder			
Lifting equipment: 69. Mobile Cranes			
70. Forklift truck			
71. Lorry loaders			
What maintenance records do you keep for equipment checking?			
72. Daily check			
73. Weekly check			
74. Monthly check			
75. Six monthly check			
Which of the following is mandatory when working in confined space?			
76. Adequate lighting			
77. Adequate ventilation			
78. Special training/ instruction for the workers			
79. Permit to work			
80. Emergency support for the workers			
81. Respiratory protective equipment			
82. Safety signs for excavations			
Which of the following is mandatory when working with explosive materials?			
83. Caution signs			
84. Enforcement of exclusion zone			
85. Permit to work			
86. Instruction to the workers			
Do you have following to aid traffic management?			
87. Separate pedestrian route			
88. Separate vehicular route			
89. Banksman to guide vehicles			
90. Designated area for loading/ unloading			
Do you provide the following for workers' welfare?			
91. Resting place for the workers			
92. Drinkable water supply			
93. Eating place			
94. Toilet facilities			
95. Washing facilities			
96. Enough lighting			
97. Drying facilities			
98. Personal possession storage			
Which of the following do you use to protect the public?			
99. Secured perimeters of the site			
100. Protected public walkways			
101. Safe alternative route for the passers by			
102. Tunnels (protection for the falling objects)			
103. Safety signs for the passers by			
104. Secured entry points of the site			
105. CCTV at the entrances			
106. Adequate lighting at night time			
Which of the following do you include for emergency fire procedures?			
107. Fire Drill			
108. Fire alarms			
109. Inspection to ensure clear fire routes/exits			
110. Designated fire escape route			
111. Fire assembly point			
112. Fire-fighting equipment			
Which of the following do you use to increase hazard awareness?			
113. Reporting procedure for workers who observe hazards			
114. Incentive scheme for reporting hazards			
115. Incentive schemes for near misses			
116. Instruction to stop work procedure			
Which of the following do you organise when you have hazardous substances on site?			
117. Appropriate storage			
118. Appropriate handling			
119. Appropriate use			

Which of the following prevention of pollution measures do you employ?			
120. Identification of potential sources of pollution			
121. Dust suppression measure			
122. Prevention of air pollution			
123. Noise prevention measure			
124. Prevention of ground water contamination			
125. Other			
Which materials do you waste separate on site?			
126. Timber			
127. Dry wall/ plaster board (Gypsum)			
128. Concrete, ceramic, tiles bricks			
129. Glass			
130. Plastic			
131. Bituminous mixtures			
132. Metallic waste (including cable)			
133. Contaminated soil and stone			
134. Cement			
135. Paint and varnishes			
136. Adhesives and sealants			
137. Packaging			
138. Asbestos containing materials			
Do you engage in any of the following with asbestos and asbestos containing materials?			
139. Identification			
140. Removal			
141. Handling			
142. Storage			
143. Disposal			
Do you employ the following safety and health on site audit/inspection?			
144. Internal audit			
145. External audit			

Serial No	Additional notes

Aforementioned photographs have been collected under the items where ever possible. Few examples have been illustrated below in “Fig. 2, 3, 4 and 5”. “Fig.2” was provided in support of the provisions of PPE and “Fig.2” was provided to show the provisions provided for working at height. From the photos it is evident that these construction sites don’t have adequate health and safety measures.

Figure 02: Provisions of PPE

Figure 03: Provisions provided for at working at height

The answers in the audit checklist are ambiguous quite often. Such as, “Fig.4” and “Fig.5” were provided in support of the provisions for working at height. According to Bangladesh National Building Code, *“every open sided floor or platform 1.2m or more above adjacent floor or ground level shall be guarded by a railing on all open sides, except where there is entrance to ramp, stairway or fixed ladder”* (Vol 3, part 7, chapter 3, section 3.6.5). However, there is lack of safety net, guard railing and toe board in all sides of the floor. Furthermore, there is also lack of the minimum safety measures in each floor. Therefore, only ‘yes’ and ‘no’ option isn’t adequate and needs extension of the answer of the audit checklist.

Figure 04: Provisions of working at height

Figure 05: Safety measures for working at height

Many discrepancies have been found from the audit checklist and the photographs. Although being quantitative in nature, this audit checklist has been used qualitatively. This audit checklist can be altered depending on the nature and purpose of the study.

4 CONCLUSION

There are currently few comprehensive audit checklist is present in the construction health and safety literature. However, there is still gap of an audit tool which is developed based on Bangladeshi construction industry' requirements. This audit checklist can be used as a starting point and can be altered and elaborated based on the type of research/construction project/location/legislative requirements. This audit checklist can be used for setting up a construction project or auditing. The health and safety compliance requirements can be very lengthy and confusing. In this case, this type of audit checklist can give a basic guideline. However, this audit checklist does not include the environmental aspects of a construction project. This paper only revealed the methodological developments of this audit checklist. However, the analysis of the photos in support of this audit checklist is complex and the intention is to publish a subsequent paper exploring the finding from the photo analysis.

5 RECOMMENDATION

In this research the simplest category of audit checklist has been developed using only three options. In addition to this, photos have been collected to evaluate the degrees of health and safety measures which are absent or implemented on a construction site. However, this audit checklist can be developed for quantitative purpose using grade type (Likert scale) or multiple choice type questions to measure the degrees of health and safety practice.

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ADDRESSING UNIVERSITY FACILITY PERSONNEL SAFETY CONCERNS DURING OPERATIONS, MAINTENANCE, AND REPAIR ACTIVITIES

Nicholas Tymvios[1], Jake Smithwick[2]

[1]*Bucknell University (USA)*
[2]*University of North Carolina at Charlotte (USA)*

Abstract

Facility managers (FM) are in charge and responsible for the operations, maintenance, and repair (OM&R) phase of a structure. During this time, FM personnel and technicians, along with subcontractors, perform a variety of tasks related to building upkeep, maintenance, renovations, and refreshes. FMs employed in higher educational institutions are no exception, but they have an additional complexity of managing OM&R activities for a diverse portfolio of structures such as academic, civic, residential, athletic, commercial, healthcare, and others. Furthermore, these types of facilities require upgrades and additional work in order to address dynamic and evolving safety requirements.

At the moment no comprehensive investigation has been conducted in the USA regarding safety concerns and mitigation strategies for constructed facilities, post-structure delivery. To spearhead this trajectory of research, the researchers surveyed FM personnel employed in higher educational institutions in the US with the aim to: 1) identify FMs' involvement in design decisions for the facilities in preparation, 2) identify the building systems for which FMs generally provide input during design, 3) determine the hazards that concern FMs the most for OM&R activities, and 4) determine whether FMs make modifications to existing structures in order to address safety concerns.

A total of 171 responses were collected, from 1,947 identified contacts belonging to public and private U.S. institutions, with a student population greater than 2,000 students. The researchers found that the majority of FMs are asked to provide input during the design phase, the building systems that they mostly provide input are HVAC, Lighting, and Plumbing, electrical hazards and hazards relating to falls are the ones that FMs are mostly concerned about during their OM&R operations.

Keywords: Safety, maintenance, repair, design for safe maintenance.

1 INTRODUCTION

A building's lifecycle consists of two relatively brief phases for "conception/design", and "construction", followed by a lengthier phase, dedicated to its function; the "occupancy" phase which accounts for 95% of the lifecycle [1]. During occupancy, a building is exposed to daily operations which in turn leads to the need for scheduled (or emergency) maintenance and repair activities. The combined set of activities required from facility managers for operations, maintenance, and repair are grouped in this publication as OM&R [2, 3].

In addition to OM&R, often facility managers are asked to make changes or improvements to their facilities to address the installation of new equipment not planned during design [4], or to address safety concerns related to maintenance [5]. Modifications to the structures are undertaken by facility management technicians, or by subcontracting work to third-party entities [6]. During OM&R activities, maintenance personnel or third-party contractors can be exposed to several hazards that vary depending on the type of facility but they have not been extensively researched in the US, while in other countries, the investigation was limited to characteristics that link OM&R operations to types of injuries [7].

As suggested by Szymberski [8], early interventions have the greatest ability to influence safety performance, and these efforts should occur during design, which is one of the principles in the Prevention through Design (PtD) (also known as Design for Safety) concept proposed by Lorent [9]. The authors of this manuscript aim to eventually extend the concept of PtD, which was developed for the construction industry, to maintenance operations in the US industry, and the research described here represents the initial investigation and efforts toward that goal.

2 BACKGROUND

Facilities management is a term that encompasses all activities required to manage a structure after its construction phase, and functioning as intended [10]. Activities included during this post-construction phase include maintenance and monitoring of various building systems, the repair and renovation of various building elements, as well as making minor or major modifications to internal walls and layouts of the structure [1].

At the moment there is limited scholarly work performed on investigating safety concerns affecting the work performed by facility management personnel or their subcontractors. Thus, there is a need to investigate, and identify concerns that facility management personnel may have during OM&R activities. There are gaps in knowledge that need to be identified in order to improve facility management safety performance, and these include identifying the building elements/systems that pose the greatest concerns during OM&R operations, as well as identifying, quantifying, and assessing the financial impact of these post-construction safety-related modifications.

The researchers through a survey of facility management personnel employed in higher educational institutions in the US with the aim to:

- identify FMs involvement in design decisions for the facilities in preparation,
- identify the building systems for which FMs generally provide input during design,
- determine the hazards that most concern FMs during OM&R activities, and
- determine whether FMs make modifications to existing structures to address safety concerns.

The researchers chose to investigate educational institutions in the US because university facilities and campuses encompass diverse environments with a variety of structures, including academic, civic, residential, athletic, commercial, healthcare, and others. Additionally, these types of facilities require upgrades and additional work to address dynamic and evolving safety requirements.

3 METHODOLOGY

To gather this information, an online survey was distributed to facility management administrators employed at universities in the US in the fall of 2021. Contact information was collected by conducting online searches of each university's directory, and the researchers decided to limit the population to individuals employed in 4-year institutions with a student population of at least 2,000. A university of that size would in general have complex enough facility management operations and have the need for frequent (every few years) capital projects.

Using the Carnegie classification for universities [11], a total of 1,947 US universities were identified. After eliminating “For Profit” universities (n = 195), and universities with student population of less than 2,000 students (n=322), 1,430 universities remained. Several of the remaining institutions (n=538) did not have a searchable website or directory where the researchers could identify individuals to be targeted for the survey, and as a result, contact information for individuals was obtained for 892 institutions.

Regarding the role of the individuals contacted, the researchers aimed to identify individuals with roles and responsibilities relating to the management of maintenance operations on their respective campuses, such as “Director of Maintenance”, “Director of Physical Plant”, etc., and in the survey, they were asked to respond to 4 categories of questions:

- Their departments' participation in design/constructability reviews for major (capital) projects and minor (renovation) projects, their method of participation, and the building systems on which they provide input.
- The hazards that concern them the most when their crews perform their typical work tasks and any other safety concerns they have.
- Whether there have been modifications to the structures in their facilities to address safety concerns, and the nature of these modifications.
- Demographic questions regarding the gross square footage (building area) of their campus, their years of experience in design, construction, and facility maintenance, their level of education, and any credentials they may have

The potential participants were emailed invitations to complete the study survey. A reminder email was sent two weeks after the initial contact. Out of the 892 individuals that were contacted, 171 completed the survey resulting in a response rate of 19.2%.

4 RESULTS

4.1 Demographics

The study participants were geographically diverse, with responses from 43 of the 50 states and one response from DC that is not shown on the map in Fig. 1. In regards to University ownership, 107 of the responses came from public institutions, while 64 came from private ones. Further distribution of the responses is shown in Fig. 2 according to the size of the university in terms of its student population. The Carnegie Classification of institutions of higher education [11] categorizes tertiary institutions according to various metrics, including student population, and they categorize small institutions as having a population of less than 3,000 students, a medium institution between 3,000 and 9,999, and large institution with a student population greater than 10,000 students. As observed, the majority of the universities with a small student population were private universities, while the majority of the universities with a large student population were public.

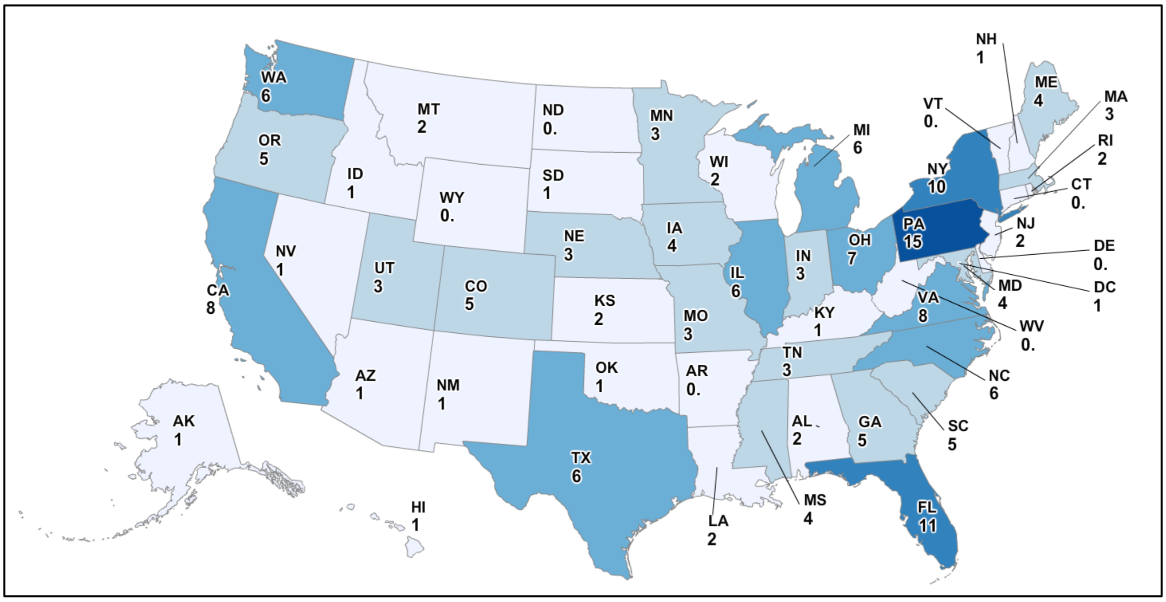

Figure 1: Geographic distribution of responses

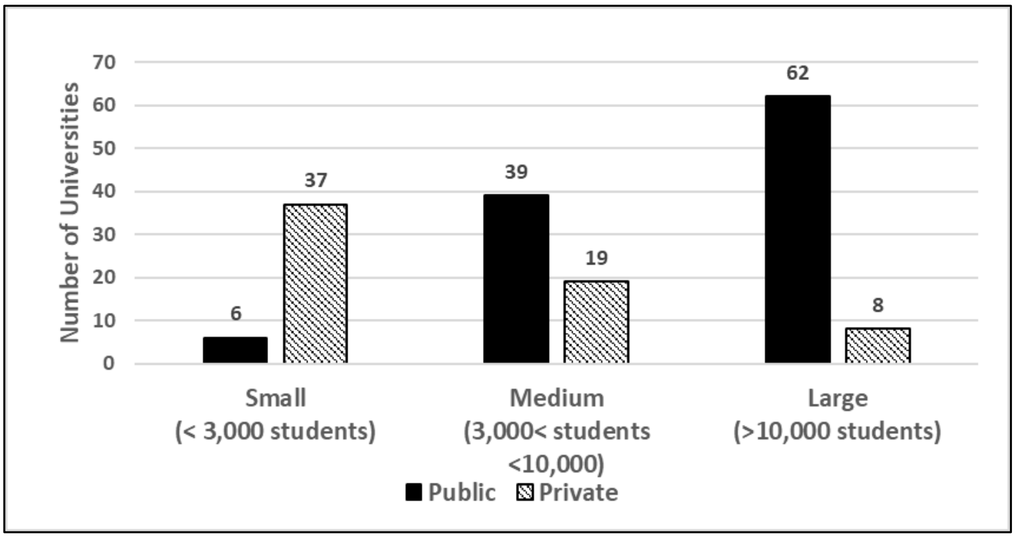

Figure 2: Distribution of responses according to university ownership and student population

Regarding work experience in the relevant sectors of the industry, the participants appeared to have extensive experience, with an average greater than 14 years in Design, Construction, and Facilities Management. Their knowledge in the three related fields indicates that their input would be valuable and beneficial for the scope of this investigation. Specifically, the range of experience is shown below:

- Design: Average (years) = 14.5; range from 0 to 40 years
- Construction: Average (years) = 19.7; range from 0.5 to 45 years
- Facilities Operations and Management: Average (years) = 22.5; range from 3.5 to 45 years

The average gross square footage of space that the participants' departments maintained was 4,895,270 ft^2 (454,785 m^2), with a range from 200,000 – 28,000,000 ft^2.This extensive area suggests that the campuses represented by the participants have multiple buildings of various ages, each with its own varying maintenance needs.

4.2 Participation in design reviews

A key aspect of facility management's role in planning for safe OM&R activities, is their early involvement during planning of new facilities. To identify the extent that this happens at the various universities we asked the following two questions:

"Do representatives from YOUR university's Facility management participate in design or constructability reviews input during the "Design" phase:

- *For "Major" projects/renovations (Capital Projects)*
- *For "Minor" projects/renovations"*

The results indicated that the plurality of the participants' departments participate in such reviews as shown in Table 1. These numbers are encouraging since they suggest that facility management needs are discussed in these meetings.

Table 1: Facility Management participation during constructability reviews

Project Type	Never	Sometimes	About half the times	Most of the times	Always
Major Projects (n=160)	2 (1.3%)	8 (5.0%)	3 (1.9%)	40 (25.0%)	107 (66.9%)
Minor Projects (n=156)	1 (0.6%)	12 (7.5%)	11 (6.9%)	63 (39.4%)	69 (43.1%)

Participants were also asked to identify the systems on which they provide input during the constructability meetings. One hundred forty-nine (149) individuals provided responses to this question, and they are summarized in Table 2. As observed, the majority of the systems are of concern to facility managers, with a few exceptions such as parking garages, and the location and height of windows. Universities generally employ their own personnel to manage and maintain all building systems, and as a result, facility managers employed in university settings might feel more responsible to their own co-workers. In a similar investigation of facility managers in the general industry [3], only "electrical systems" was identified to be of major concern for day-to-day operations with a value of 57.1%, while concern for all other systems ranged from 6.7% (Central Control Systems) to 31.3% (HVAC).

Table 2: Building systems discussed during constructability meetings

System	%	System	%
Mechanical systems / HVAC	98.0%	Building vehicle access (e.g., loading docks)	75.2%
Plumbing	89.9%	Lift and Escalators	71.1%
Building and general maintenance (walls, doors, ceilings, finishes, flooring, etc.)	87.3%	Signage / wayfinding	57.0%
Lighting	87.2%	Water / wastewater treatment and processing systems	55.7%
Electrical (not lighting)	86.6%	Snow-removal and De-Icing	53.0%
Roofing	85.9%	Curtain Wall	47.0%
Fire / life-safety systems	84.6%	Location and height of windows	33.6%
Landscaping / grounds	81.9%	Parking Garage	28.2%

4.3 Hazards

Participants were also asked to identify the hazards that concern them the most when their maintenance/repair crews perform their typical work tasks. In this question participants were asked to select their top five (5) hazards, and 141 individuals provided responses. The categories of the hazards were developed from a literature search [12, 13], and were used in a similar investigation that surveyed facility management individuals employed in other industries [3]. As observed in Table 3, the top three hazards identified by facility managers who participated in the study are "Fall from heights and ladders", "MEP hazards", and "Electrical hazards".

Table 3: Hazards identified to have the greatest concern

Hazard	%	Hazard	%
Falls from heights and ladders	66.9%	Exposure to high pressures (liquids/gases)	16.9%
Mechanical-Electrical-Plumbing (MEP) hazards	66.9%	Ergonomics hazards when performing tasks	16.2%
Electrical Hazards (electrical arc, electrocution, etc.)	67.6%	Pinch/cuts	16.2%
Slips and trips	49.3%	Interactions with occupants	14.2%
Working in confined spaces	39.9%	Exposure to hazardous weather environment	11.5%
Chemical/Biological contaminant: exposure, handling/storage, asbestos, spills/releases, etc.	35.8%	Falling objects	8.1%
Interactions with moving objects and equipment	29.7%	Noise Exposure	8.1%
Sprains and Strains	26.4%		

4.4 Building modifications to address safety

Participants were also asked to identify whether any modifications have been made to their facilities, beyond normal day-to-day maintenance, to address health / safety needs. This question aimed to identify the types of changes, and categorize these according to the hierarchy of safety controls. One hundred forty-three (143) individuals responded to this question, and 17 (11.9%) indicated that there were no modifications made to their facilities, while the remaining 126 (88.1%) indicated that modifications occurred.

The tiers for the hierarchy of controls used in this manuscript were obtained from the National Safety Council's hierarchy descriptions [14], and it include the following: 1) Elimination, 2) Substitution, 3) Engineering Controls, 4) Warnings, 5) Administrative controls, and 6) Personal Protective Equipment (PPE). For this publication, the lower levels in the hierarchy of controls—warnings, administration, and PPE—were combined into one category, and that was referred as "administrative controls", since administrators need to be involved in effectively implementing warnings and ensuring the availability and proper use of PPE. Participants provided their modifications as a narrative response, and the authors categorized them according to the hierarchy of controls described previously.

Many of the participants (37.3%, n=47) described modifications that would be categorized as administrative controls and resemble controls practiced in the construction industry. Examples of such measures included the following:

- *"Developed and implemented a training schedule to address the most common concerns"*
- *"Fire alarm upgrades, CO detector installation"*
- *"Modify maintenance schedules to address COVID related issues"*

More than half (65.9%, n=83) of participants described modifications that fall under the category of engineering controls. Examples of which are the following:

- *"Completed and furnished equipment for tag out lockout"*
- *"Recent renovation to a lab building. Fall protection missed on the roof around HVAC equipment. Added 260k for FP after the fact."*
- *"Enhanced accessibility to equipment, ie., catwalk improvements, handrails"*

- *"Added catwalks in large attic spaces to allow better access to equipment. Added safety platforms at heights to prevent falls."*

Participants provided fewer examples of substitution and elimination levels of control. Thirteen (10.32%) of the participants described modifications that can be categorized as substitutions, such as:

- *"The pandemic has informed us of choosing materials that are easily cleaned"*
- *"Lowered equipment to allow better maintenance access"*
- *"Exterior elevated walking surfaces were reviewed and provided with a non-slip coating"*

Three (2.4%) participants provided examples that could be categorized as elimination controls, and these were:

- *"HVAC split systems do not have the condenser located on the roof of a building"*
- *"Change out doors with an asbestos core."*
- *"Elimination of Asbestos Containing Building Materials."*

When compared to a survey of participants from the general industry [3], facility managers in universities implement a greater number of engineering control improvements. As observed in Table 4, more of the facility managers employed in universities described improvements that can be categorized at all of the higher levels of control (engineering/substitution/elimination), while they described fewer controls that can be categorized as administrative, compared to those employed in the general industry. These two investigations were conducted in relatively close time frame to each other. The survey described in this paper was conducted in the fall of 2021, while the survey for the general industry was conducted in the fall of 2019.

Table 4: Comparison of the types of controls implemented between facility manager groups

Control Type	University Facility Managers	General Industry Facility Managers [3]
Administrative	37.3%	52.1%
Engineering	65.9%	22.5%
Elimination	10.32%	4.6%
Substitution	2.4%	0.8%

5 CONCLUSIONS

As observed in this investigation, many facility managers (88.1%) at educational institutions modify their facilities after occupancy to address safety concerns. This number is greater compared to a similar investigation of general industry facility managers, where 65.8% of the participants performed such work [3]. The three main categories of hazards that concern this group of facility managers the most are: "Falls from heights and ladders" (66.9%), "Mechanical-Electrical-Plumbing (MEP) hazards" (66.9%), and "Electrical Hazards (electrical arc, electrocution, etc.)" (67.6%).

5.1 Hazards

The survey results indicate that facility managers (FMs) are primarily concerned about various hazards during OM&R activities. These hazards include "falls from heights and ladders", "MEP" hazards, and "electrical" hazards. This emphasizes the importance of addressing these specific hazards through appropriate safety measures and early intervention, preferably during the design phase, using Prevention through Design. Furthermore, since the occupancy phase of a structure spans several decades, it is imperative to eliminate the constant exposure of OM&R crews to such hazards. By incorporating safety considerations into the design phase, significant safety improvements can be achieved.

5.2 Types of controls

More participants in this investigation described improvements that can be attributed to higher levels of controls, while they reported fewer measures categorized as administrative, compared to a similar population of participants in the general industry. This difference can be attributed to several factors. Firstly, this investigation was conducted during the COVID-19 pandemic, which necessitated additional improvements to address the spread of the virus, such as the installation of barriers and enhanced building ventilation. However, the impact of COVID-19 may explain the difference in engineering controls but not the difference in elimination and substitution controls, as university facility managers still reported more controls in those categories.

The universities included in the survey were either public or not for profit universities, and they might have a bigger budget (in comparison) that can be used for facility improvements to address safety concerns. The majority of facility managers surveyed in the general industry worked for private entities, where facility management departments are considered “business cost centres” since OM&R activities do not generate income for private organizations [3, 15]. It is also possible that the general industry is employing measures and controls that are more of the “low hanging fruit” variety (administrative), since the lack of a significant budget for extensive renovations required for higher controls is not available. While university facility departments seem to be more proactive since they probably have already implemented all the administrative control measures possible and are moving higher in the hierarchy of controls in order to improve their safety performance.

5.3 Involvement in the design phase

One method to address OM&R hazards is to tackle them early, and preferably during the design phase [16]. Facility managers are the best qualified individuals to communicate these concerns, since they encounter these hazards on a daily basis. As observed in this investigation, the majority of the facility managers participating stated that they are involved during the constructability review process of their facilities for both major “capital” projects, and for minor projects, thus allowing them to provide feedback and suggestions for safe future OM&R activities. This finding suggests that FMs have a great capacity to play a role in influencing design decisions, highlighting the need for greater collaboration between design professionals and FMs to address safety concerns and optimize OM&R activities, in all industries.

5.4 Future Work

This investigation is still in its preliminary stages, but the authors established a baseline that shows that university facility managers are involved, and included in conversations for new construction and renovation of the facilities that they will eventually manage. Future research will investigate the taxonomy of facilities management safety and the methodology to incorporate facility management input during OM&R operations. This research aims to provide guidelines and/or checklists for safety considerations during design reviews.

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INFLUENCING SITE TEAM COLLABORATION & ENGAGEMENT USING VIRTUAL REALITY DURING ON-SITE SAFETY PLANNING: AN EXPLORATORY CASE STUDY

Mark Swallow[1], Sam Zulu[2]
[1] Sheffield Hallam University (UNITED KINGDOM)
[2] Leeds Beckett University (UNITED KINGDOM)

Abstract

For construction managers, effective collaboration, communication and engagement during safety planning is essential to improve efficiency and reduce risks during on-site execution. Whilst the use of Virtual Reality (VR) has gained increased global attention in academic research, very few have documented its practical application during active on-site construction safety processes from a site team perspective. This study aims to bridge this gap by observing the use of VR during live safety planning workshops, capturing practical examples where the use of VR influences the site teams engagement and collaboration. Working with a UK based construction contractor this study adopted an exploratory case study approach. Qualitative data was collected over a series of safety workshops during a live project with 15 active site team members involved in activity planning, site installation and supervision. Data collection included direct observations and focus groups, with the qualitative data analysed using a hybrid thematic analysis method. The results provide working examples of site team collaboration when producing safety logistics plans. Analysis of this data indicated that VR influenced the project teams engagement, namely in the inclusion of operatives, effective information communication, information retention and encouraged knowledge transfer which led to improved confidence when planning.

Keywords: Virtual reality, construction, safety, engagement, collaboration, hybrid thematic analysis

1 INTRODUCTION

Planning site activities requires coordination with project stakeholders, often involving numerous organisations with varied levels of knowledge, experience and awareness of the specific project design and site constraints. From a construction management perspective, collaboration and engagement within the planning process is crucial to the efficiency and safe execution of construction activities [1]. However, for many organisations on-site planning practices have relied on 2D information and siloed processes that do not involve key members of the site team.

As an industry, construction has seen an increased uptake in digital technologies, used for a variety of safety applications. For example the use of 3D / 4D models have been shown to have benefits in safety planning, specifically in improving visualisation, communication and collaboration [2], [3]. Furthermore, the use of immersive technologies (ImTs) including virtual reality (VR) is also receiving growing attention [4]. Within academia, many have begun to explore the effects when utilising VR, for example in engagement within safety training (Sacks et al., 2013; Vasilevski & Birt, 2020) and project collaboration (Sacks et al., 2015). However despite this, the adoption of VR within the industry remains low [8]–[10]. Moreover, the practical industry application in this field is underdeveloped and research lacks real project examples. This has resulted in researchers calling for further exploration to investigate the effectiveness of VR within active, real-time site environments [11], [12], involving on-site construction management and operatives [13]. Therefore this paper aims to provide a fresh insight documenting practical accounts using VR within a real-life case project, assessing its influences on team collaboration and engagement.

Working with a UK based construction contractor and their subcontractor, qualitative data was collected through direct observations of safety planning workshops and focus group discussions. Through applying hybrid thematic analysis, the results provide practical examples of the use of VR during safety planning, furthering the research into how VR can influence site team collaboration and engagement.

This research paper forms part of a wider investigation into the integration of immersive technologies within the UK construction industry, specifically within the context of on-site safety processes.

2 VIRTUAL REALITY WITHIN CONSTRUCTION SAFETY PROCESSES

Virtual Reality has taken significant strides forward in recent decades, particularly within the gaming industry. This development has resulted in high specification VR headsets becoming available within the mainstream market. Typically, VR uses a head mounted display (HMD) and hand controller devices, allowing the user to immerse and interact within a fully computer generated virtual environment. Many researchers have concluded that VR improves engagement [14] and communication [15], providing an effective medium to visualise and explore detailed designs or sequences in advance to the build process. The use of VR also removes risks to personal safety [16], [17] eliminating the need to enter the real life situation which offers a potential solution for the construction industry, particularly for high-risk training scenarios. This said, the use of VR within the construction industry has only recently become an option that is realistic and feasible, mainly due to advancements in technology providing affordable and compatible applications.

Whilst the benefits of VR within academia are acknowledged, practical site based research using VR from a safety planning context is under-represented in the UK, with limited examples within wider global literature [12]. In Cyprus, Muhammad et al. [18] collected data through questionnaire surveys to compare the use of VR to traditional 2D forms of planning, finding a VR approach more effective in collision detection. Rolim et al. [19] explored the use of VR for developing risk assessments within a Brazilian airport development by conducting an exploratory case study. Through collecting interview data with airport staff, their results indicated improvements in the identification and evaluation of risk from an operation teams perspective. Zaker & Coloma [20] investigated the application of VR for mechanical and electrical design reviews and adopted a case study approach using real models on a project in Barcelona, Spain. They identified that whilst investment and resistance are key challenges to the adoption of VR, there were practical benefits in clash detection applications. Also using a case study method, Afzal & Shafiq [21] investigated the use of 4D VR on a project in United Arab Emirates to simulate construction activities. Their research assessed the impact on communication and risk assessment where project members did not share a common language, concluding that VR simulations increased hazard identification among operatives.

There is limited research available that involves applying VR in active construction projects that focus specifically on safety planning from an on-site team working perspective. This paper seeks to address this and investigates the potential influences of VR, specifically related to engagement and collaboration.

3 METHODOLOGY

Case studies are a common research approach [22] and according to Zainal [23] they allow the researcher to examine the data within a specific context to "*investigate contemporary real-life phenomenon through detailed contextual analysis of a limited number of events or conditions*". Exploratory case studies are suited to this research aim as they explore data in real-life and natural settings, including the complexities of these real situations. This is also a suitable approach where there is limited pre-existing knowledge in the specific field to develop theory [24].

3.1 The Case Study

For this study the researchers selected a single case to produce in-depth data to understand this specific phenomenon in detail [24]. The researchers collaborated with a UK based construction contractor, selected due to their prior experience using VR (for marketing purposes) and were looking to test its application within a more practical on-site context. The contractors chosen project was the design and construction of a 3 storey new build extension to an existing (live) school located in Yorkshire, England. For this paper, only the data collected during safety planning workshops related to the steel frame and ground floor concrete installation are included.

3.1.1 Site Team Participants

The participants for this study were chosen due to their direct involvement with the case project and site activity selected for data collection. A total of 15 site members were involved in the planning workshops, consisting of 1 senior director, 4 project / site managers, 1 commercial manager, 3 quantity surveyors, 1 safety manager and 5 steel erection (subcontractor) operatives. The site management and commercial management were familiar with the project, however the operatives had not been involved with the project to this point. Table 1 identifies the participants, their ID, role, age range and industry experience. Whilst the contractor had prior experience with VR, this was limited from a site perspective. From the 15 participants in this study, 2 had prior experience and the remaining 13 had no experience using VR (including all of the project / site managers, quantity surveyors and site operatives).

Table 1 Site Safety Planning Workshop Participant Information

No	Participant ID	Role	Age Range	Years in Industry	Employment
1	CS MD1	Managing Director	31-49	21-30	Contractor A
2	CS SM1	Site Manager	31-49	21-30	Contractor A
3	CS SM2	Site Manager	31-49	11-20	Contractor A
4	CS SM3	Site Manager	18-30	0-10	Contractor A
5	CS PM1	Project Manager	31-49	21-30	Contractor A
6	CS QS1	Quantity Surveyor	31-49	11-20	Contractor A
7	CS QS2	Quantity Surveyor	18-30	0-10	Contractor A
8	CS QS3	Quantity Surveyor	18-30	0-10	Contractor A
9	CS SO1	Safety Officer	31-49	21-30	Contractor A
10	CS CM1	Commercial Manager	18-30	0-10	Contractor A
11	CS O1	Operative (steel frame)	50+	31-40	Contractor B
12	CS O2	Operative (steel frame)	50+	31-40	Contractor B
13	CS O3	Operative (steel frame)	50+	31-40	Contractor B
14	CS O4	Operative (steel frame)	31-49	11-20	Contractor B
15	CS O5	Operative (steel frame)	31-49	11-20	Contractor B

3.2 Overview of Data Collection

Fig. 1 overviews the data collection methodology. Following the recruitment of the case organisations and collection of project information needed to create the VR environment (see 3.3.1), qualitative data was collected during on-site workshops through observations and focus groups, analysed using hybrid thematic analysis (see 3.5).

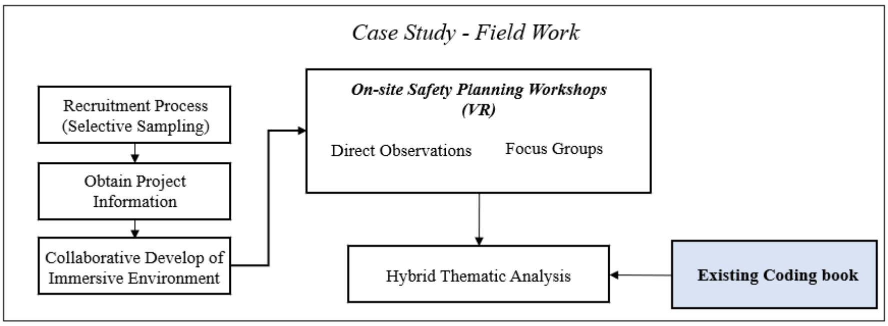

Figure 1 Overview of Data Collection Process

3.3 Safety Planning Workshops

The safety workshops used VR headsets to explore methods of safe installation, construction plant positioning / movement and segregation zones specifically related to the steel frame and concrete floor installation.

3.3.1 Preparing the Environment

Prior to conducting the practical workshops, researchers consulted with the case construction contractor to evaluate the hardware / software requirements and project information needed to construct the VR environments. During the time of the study the Meta Quest headsets and hand controllers had been introduced in the market, which were an affordable and easily accessible devise. It was decided these were to be used as the headsets required no tripod sensor set up and so the most suitable for on-site use. To run the VR models, laptop devices with Intel Core i7 processors were utilized with Autodesk Revit 2022 and Enscape software installed. In order to create the VR environments, 2D and 3D project information was shared by the case construction contractor and information integrated into central Revit models by the researchers. Firstly, the surrounding site and existing structures were modeled from survey data. Next the 3D steel superstructure model (received in IFC) was integrated into the Revit model and the general on-site arrangements (such as welfare and perimeter fencing) located using the initial 2D plans. Lastly initial phasing markups were used as reference for the proposed sequencing of the frame. Typical plant and safety equipment were also loaded into the Revit model ready for use during the workshops. The information collected and created is illustrated in Fig. 2.

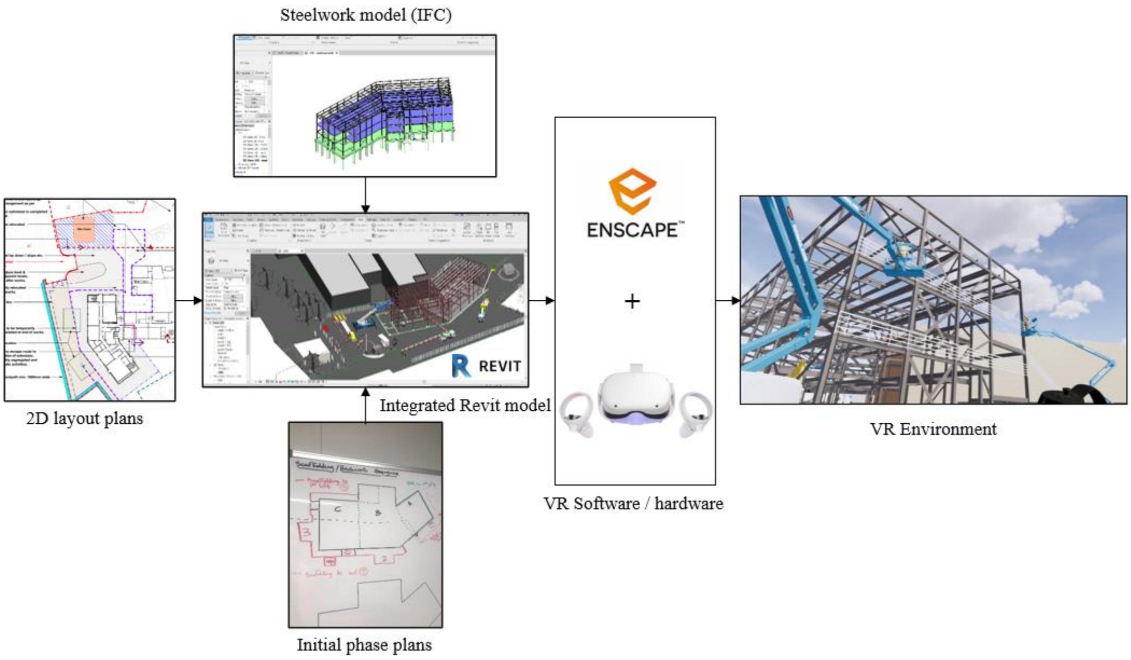

Figure 2 Creating the VR Environment for Site Safety Planning Workshops

To conduct the workshops, the VR equipment was set up within the on-site office arrangements (additional COVID safety precautions were also in place). VR headsets and hand controllers were provided to the site team and used by various participants. Headset visuals were also projected onto the wall screen and recorded (as shown in fig. 3).

Figure 3 Site Safety Planning Workshop Example

3.3.2 Non-Participation Observations

A total of 3 workshops that related to the planning of the steel frame and concrete floor installation were observed in this study. Data collection took place from December 2021 to January 2022 and as the project was live, timescales for these interactions were influenced by the on-site programme and contractor procurement. The researchers each had over 20 years' experience within the construction industry, with expertise in site management, health and safety and building information modelling. For this study the researchers did not participate in the workshops however made notes during the observations [22], [24]. The safety planning workshops were led by the project manager [CS PM1] and site manager [CS SM1] and throughout the workshops verbal discussions were captured through Microsoft Teams.

3.4 Focus Group Discussions

Following each workshop the researchers facilitated focus groups, a common method used for data collection in exploratory research [25]. The purpose of the focus groups was to capture the site teams views on the use of VR, specifically when used within safety planning. This also included questions around how this could contribute to improvements in collaboration and engagement. Focus groups were recorded for accurate records and transcribed prior to analysis. Due to the live environment, the participants involvement was dependent on their availability at the time of the workshops. Table 2 identifies the participants within each focus group session.

Table 2 Focus Group Participants

Safety planning workshop	ID of participant within focus group	Total number in focus group
1	CS SM1, CS SM2, CS PM1, CS QS1, CS QS2, CS QS3, CS SO1, CS CM1, CS O1, CS O2, CS O3, CS O4, CS O5.	13
2	CS SM1, CS SM2, CS SM3, CS PM1.	4
3	CS SM1, CS SM2, CS SM3, CS PM1, CS QS1, CS QS2, CS MD1	7

3.5 Hybrid Thematic Analysis

Hybrid thematic analysis involves both deductive (theory driven) and inductive (data driven) approaches [26]. The analysis process began with familiarisation of the transcripts and researchers observations. Using NVivo12 software, key text or phrases within the transcripts were allocated into pre-existing codes, (a priori codes) which were developed by the researchers in a prior study. This existing coding book contained a total of 142 codes, categorised into 17 themes, however this paper only includes the results from theme 15 - *engagement and collaboration*. As the analysis was hybrid, the researchers also created new codes (a posteriori codes) if they were not present in the coding book [26]. Once the coding was complete, theme maps where created that assisted the researcher in the refinement of codes. Fig. 4 provides an example of the analysis process.

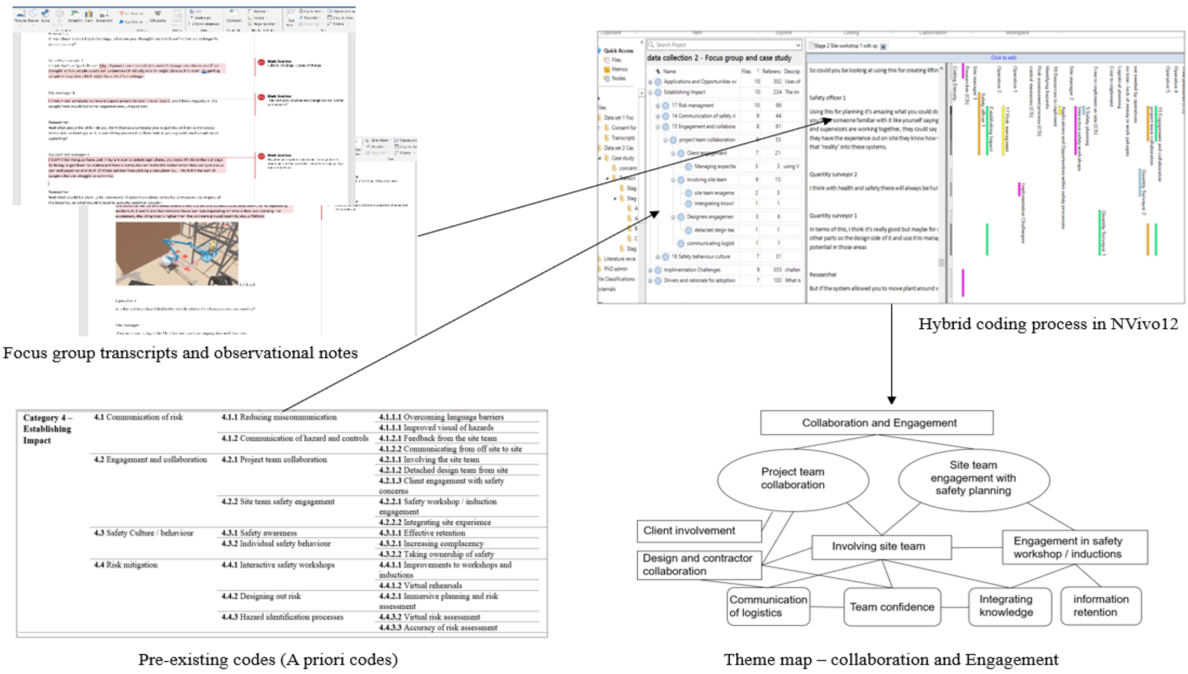

Figure 4 Hybrid Coding Process using Pre-existing Codes and Case Study Data

4 RESULTS

The theme *collaboration and engagement* was referenced on 61 occasions within the data sets. The existing code book initially contained 6 codes, the analysis process created an additional 3 as illustrated in table 3.

Table 3 Engagement and Collaboration – Example of Themes and Codes

Theme	**Code (tier 1)**	**Code (tier 2)**
A priori codes and *A posteriori codes (in italics)*		
Engagement and collaboration (61 instances)	Project team collaboration	Involving the site operatives with Planning
		Client engagement with safety planning
		Site team confidence in planning
		Communication of hazards in VR
	Site team safety engagement	Safety workshop engagement
		Integrating site experience
		Information retention

The results are structured by first discussing the researchers observations, followed by a narrative with example extracts from the focus groups. Finally, examples from the planning workshops are presented that highlight team collaboration and engagement using VR.

4.1 Researchers Observations

The researchers directly observed each of the safety workshops and took notes of the site team's interactions using the VR headsets, and how they communicated and collaborated with others. Researchers observed that the site operatives and site management very quickly engaged with using the VR headsets. In particular, it was observed that whilst the operatives had no prior knowledge of the site and the constraints, within minutes they could orientate themselves which allow them to participate in the workshop. The site team were openly discussing their ideas and tested them within the virtual world. In further workshops, previous plans were also discussed, the researcher noted an impressive retention of information. Fig. 5 shows an example of an observational note made by one of the researchers during the first workshop in relation to engagement and collaboration.

> "I quickly noticed that the use of VR encouraged the site team to work together and engage with the planning process. Particularly the operatives who had not had any knowledge of the project to this point. Whilst the operatives had no experience using VR, they were quick to test it, picking up the equipment and controls and instantly beginning to communicate with the site management, pointing out potential logistical issues they could foresee. This appeared to facilitate discussion and allowed the team to direct questions to each other and test different ideas effectively. All participants were getting involved, and as a result proposed plant positioning and segregation areas were developed very quickly. The workshops were interactive and it was clear by the verbal discussions within the site team that there was an improvement in collaboration. They would often compare this with other traditional forms of information they typically would use to plan".

Figure 5 Example of Researchers Observational Notes

4.2 Theme - Engagement and Collaboration

During the focus group discussions, the site team were asked whether they thought using VR could impact team collaboration and engagement within safety planning. From a site operative perspective, they expressed that the immersive virtual environment was significantly more engaging than the traditional 2D plans they were familiar with. Operatives also explained that involving them during discussions around site planning were welcomed, as one operative noted "*we are used to management telling us how it is… for us we are more or less told what's happening, where it's all going*" [CS O1]. For site operatives, they claimed that the VR workshops assisted in their engagement into the planning process. Some operatives also identified the workshops impacted their awareness of project specific hazards, for example CS O2 commented *"involving us* [operatives] *is helping us understand the hazards… and that will have a positive impact, there is no question*". For the site managers they linked the closer collaboration to the improved visuals and communication, allowing the team to share ideas. For example CS SM2 commented:

> "*well just look at this project, when we have used this* [VR] *just look at what we managed to find, how effective it was. It was so easy to discuss that amongst ourselves and to communicate with the operatives too. That's a huge benefit to us as a site team…bringing everyone together to talk about safety is the point, this added to the communication and engagement*"

The site team were asked to describe what features of the VR could be useful in assisting collaboration during safety planning. Most of the responses were provided by management and linked to the clearer project visuals and the ability to test logistical arrangements and see them in real scale. For them, being able to quickly move the location of a crane and see the operational radius was a particular advantage during these workshops. In many examples this allowed the team (including operatives and management) to almost immediately provide feedback on the feasibility of the location and discuss possible solutions. This included segregation in the form of exclusion zones and signage positions. One site manager suggested that the VR environment provided the medium to explore these options more effectively than their traditional planning processes, and stated "*for project collaboration it's definitely a positive… I think for me this helped facilitate a conversation*" [CS SM1]. From a safety management perspective they focused on the importance of engagement with safety, allowing the team to explore possible solutions with clearer visuals as highlighted in the statement below:

> "*it's kept everyone engaged all the time*… *looking at how we are going to do that but virtually, it's a great planning tool to allow the team to work together and for a project manager and site manager to get some up front ideas*… *For me it's my job to get these guys together… logistic planning wise*" [CS SO1].

According to the senior management, the value added during the planning process was linked to the reduction of risk through collaboration, sharing of team knowledge and information. For instance CS MD1 noted:

> "*it's had a positive impact in a preconstruction environment. From a planning point of view, it had real potential to convey and translate the plan to the workforce who are delivering*. *Certainly from a safety planning and from a logistics side this had real value…If we can access the environment in a more accurate and visual way to interpret the various pieces of information and bring it together – that can de-risk a project*"

4.3 Practical Examples using VR for Safety Planning

During the analysis process, practical examples from the workshops which captured engagement and collaboration where coded within the theme. Two examples are provided below.

Example 1: Arranging Crane Set Up Locations

In planning workshop 1, the site team were discussing crane locations to install the steel frame. For the 4^{th} crane location it had been identified that the radius area would encroach on the site car park and pedestrian entrance, initially intended as a 'no PPE zone' area. The extract below details interdisciplinary collaboration between the site team during the planning workshop.

> CS O1: "*If it's going to move there I would say that the fencing needs to move towards the welfare area, we need more room to operate the crane*"
>
> CS SM2: "*The radius is now in our offloading area on this lift*"
>
> CS SM1: "*We might have to use the overflow car park as there is not enough space here now, we also need to maintain segregation for the main pedestrian access*"

> CS SM2: "*Those areas will need fencing off so we can back in the steel deliveries and secure them whilst they are being offloaded. That whole area to the left and from the gates will now need to be a PPE zone*"

Noticeably, this exchange highlights collaboration amongst the site team when exploring logistics for the proposed crane location, including the site operatives who were new to the project. During this discussion the model was updated within the VR environment, allowing the teams to check the feasibility of the proposed arrangements. In this example, the team discussed and agreed: pedestrian entrance segregation, vehicle locations for offloading, inclusion of PPE zones and additional banks person. Fig. 6 shows the on-site workshop and use of the VR headsets, the updated VR model and also a progress photo taken during the execution on-site which shows a match to the agreed plan.

Figure 6 VR Planning - Crane Locations & On-site Crane Arrangements

Example 2: Co-ordination of Traffic Arrangements - Concrete Pour & Steel Erection

During planning workshop 2, the site managers were exploring the traffic arrangements for activities due to take place simultaneously. This included pouring of the ground floor concrete slab, the final phase steel frame erection and installing the perimeter handrail to the upper floors. The below extract is taken from the planning workshop.

> CS PM1: "*I think the concrete pump could go in that corner of the build, we have room to set up there*"

> CS SM1: "*We would come in through this entrance as the crane is still in operation using the other, then reverse up to the pump by turning there*"

> CS PM1: "*Yes I think that's best, if we minimise reversing by turning there, they can reverse up to the pump, that would be the best way. Segregation can be in place along that line and back through the midpoint of the build, gate entrance over here with PPE point*".

As with the previous example, the model was updated within the VR environment. For this example, the team discussed and agreed: site plant / concrete vehicle movement, activity / vehicle segregation, separate offloading areas, pedestrian entrance and PPE zone. Fig. 7 illustrates the updated VR model and progress photo taken during the execution on-site which shows a match to the agreed plan.

Figure 7 VR Traffic Arrangements & Pedestrian Segregation

5 CONCLUSIONS & RECOMMENDATIONS

This paper aimed to document practical accounts using VR within a real-life case project, assessing its influence on team collaboration and engagement during safety workshops. This study used active project information and collected qualitative data through observing interactions and conducting focus groups with active site team members. The results provided a unique user insight from a site team perspective and indicate that the use of VR had a positive influence on collaboration, specifically the promotion of communication and inclusion when compared to more traditional approaches. The researchers noted that irrespective of participants knowledge of the project, they were able to effectively contribute with minimal time to familiarise themselves with the site and were able to effectively retain the information. Moreover, the practical examples presented in this paper show that safety planning using immersive environments can actively encouraged multidisciplinary collaboration and influence team engagement, which allowed for effective knowledge transfer. In this case study the on-site team welcomed the integration of VR as part of the planning process. They recognised it has the potential to help reduce project risk by accurately identifying and mitigating potential hazards and allow for more accurate communication and testing of logistics. The practical examples also show that the use of VR can assist in the efficient creation of detailed logistics plans in real life scenarios. The on-site progress provided confirmation that the plans created in the immersive planning workshops were accurately implemented during the physical on-site construction stage, resulting in confidence using VR during the planning process moving forward.

This study provides an on-site perspective into the benefits and opportunities to improve project team engagement and collaboration. Whilst this study provides results from short term use of VR within these site processes, the researchers acknowledge the studies limitations and recommend that longitudinal studies be carried out to further investigate the potential influences on collaboration and engagement. Further investigation into the practical integration of VR for project specific safety planning that includes the wider project team is also encouraged.

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DIGITAL TWIN FOR CONTROL OF NOISE EMISSIONS FROM HEAVY EQUIPMENT ON CONSTRUCTION SITES

Nasim Babazadeh[1], Jochen Teizer[2], Hans-Joachim Bargstädt[1], Jürgen Melzner[1]

[1]*Bauhaus-Universität Weimar (Germany)*
[2]*Technical University of Denmark (Denmark)*

Abstract

Noise originating from construction sites has been found to cause psychological and social distress for the public, as well as hearing loss for construction workers. Although it is important to focus on construction noise during the pre-construction phase of planning for proactive avoidance, noise propagation models are rarely used to assess its impact on the health of workers and those living nearby. The primary reason for this is that information about noise sources is difficult to obtain from conventional construction schedules for preparing noise prediction models, so-called "noise maps". Building Information Modeling (BIM) is already widely used to achieve project management goals such as time and cost control. Likewise, the Internet of Things (IoT) can add reliable runtime noise data capture functionality as part of a Digital Twin (DT) and utilize remote sensing technology to record precise on- and off-construction site noise data sets. Although noise maps are widely used for large-scale noise forecasting, such as traffic noise in cities, their potential for supporting health and safety in the construction industry has not yet been recognized. This research aims to define an approach for creating stepwise noise maps using noise source data exported from a BIM model and real-time captured data from the construction site. Construction noise maps will not only assist in the task of assigning work packages for minimizing noise coming from construction equipment and, accordingly, a proper site layout plan and schedule for the project, but they will also provide the project manager with precise knowledge that gives control over the exposure of construction workers and the surrounding community to higher sound pressure levels.

Keywords**:** Building Information Modeling, Construction site layout planning, Emissions monitoring, Internet of Things, Noise map, Remote sensing, Construction task scheduling, Simulation

1. INTRODUCTION

The construction industry contributes significantly to environmental pollution with excessive noise, air pollution, emissions of particulate matter, and energy usage. One main source of pollution is the use of heavy machinery in the construction process. Due to the growing awareness of the environmental impact of the construction process, designers and planners are trying to produce more environmentally friendly designs and process plans. Moreover, researchers are seeking to take advantage of digitalization in the construction sector, such as the application of Building Information Modeling (BIM) and Digital Twin (DT), to define the potential methods that monitor and reduce emissions.

Noise is a type of environmental pollution that puts people's health at risk by compromising their hearing and perception, affecting their physical and psychological well-being and work performance, and reducing the ambiance of their surroundings in terms of comfort and calm. When compared to other forms of pollution, noise pollution, also referred as acoustic pollution, has increased significantly in today's modern world [1]. The propagation of noise from construction activity is one of the most significant environmental concerns in urban areas because of the increase in construction and renovation projects involving heavy machinery and equipment [2]. Although construction sites are temporary, dynamic work environments, the loud noise they emit can harm workers' hearing and cause significant disturbances up to several hundred meters away from the site. In response to this annoyance, residents in surrounding areas may complain and sue construction companies, which would cause unexpected problems such as process disruption, compensation costs, or even project suspension [3]. Moreover, in certain countries, like Germany, construction noise causes tension between tenants and landlords over rent reductions [4]. To minimize construction noise-related nuisances, city councils and governmental organizations have stipulated restrictions on the duration of construction work and permissible noise levels during working hours on weekdays.

Despite the importance of construction noise, as mentioned above, it is mostly overlooked during the construction process and also during the design and planning phase. The main reason for that is that the construction noise prediction is not mandatory in the design and planning process. There is often a disconnect in the information flow between the designer or planner and the acoustic consultant. Firstly, the evaluation of the noise control measures is always requested from the project owner (as the person responsible), usually after the time plan is fixed. Moreover, exporting the noise sources from the conventional process plans is not an easy task. Therefore, there is mostly a need for a third person as an interpreter , who can help the acoustic consultant understand the construction process and define noise sources for noise prediction. Thus, rather than the pre-construction phase, which offers more flexibility for changes in the process plan, the noise consideration is basically done in the execution phase.

Moving toward the implementation of BIM in the project has benefits on both sides. Transparency in the design and process plan offered by BIM helps with noise source detection for noise prediction models. And later, within the BIM Collaboration Format (BCF), the acoustic expert can also be included in the process of planning and design, which can omit the need for a third person as a translator. Having a stepwise construction noise propagation model is also useful for resolving any future disputes over noise between construction companies and residents of nearby buildings [5]. One step further, in recent years, the implementation of DT and remote sensing technologies on construction sites has presented a new approach for emission prediction and control. The goal of this project is to create a framework in which sensor data is transformed into noise prediction models and noise source data is exported via BIM models. It will also check whether the DT implementation can also concentrate on noise propagation.

2. BACKGROUND

Some researchers have been focused on minimizing the nuisance and harm caused by construction noise within the framework of modeling it by Monte Carlo methods [2] or case-based reasoning approaches [6]. Moreover, some survey-based research has been conducted to define the stages of construction that generate the most annoyance [7]. Recently, the construction industry has been more interested in the use of smart sensors. In some research, data collected by sensing devices installed at construction sites or worn by workers was sent through the Internet of Things (IoT) to a processor to assure resource location tracking [8-13] or to monitor ambient noise for occupational health and safety purposes [14].

In a study by Wei et al. [15], wearable sensors were used to gather noise data and prevent Noise-Induced Hearing Loss (NIHL) among construction workers during a school classroom renovation project. The collected data was then imported into Vectorworks and mainly focused on indoor noise propagation. Another study by Aguilar-Aguilera et al. [16] involved interpolating the monitored noise data using a script in Dynamo and Python to visualize noise in the Revit model. However, the case study for this research only involved data from a concrete plant, which did not fully capture the intricacies of the construction process. Although previous research on BIM has concentrated on enhancing indoor acoustics, the use of BIM models to detect and define noise sources has not yet been thoroughly explored.

In the last decade, Digital Twin has emerged as a data-driven management and control tool for physical systems in the manufacturing, production, and operations fields [17]. Although it has been utilized in industries like aerospace and automotive, its implementation in the construction sector is still new and limited [18]. For example, Teizer et al. [19] have introduced the concept of Digital Twin for Construction Safety (DTCS) aimed at improving safety performance on construction sites. Also, Bokde et al. [20] have developed a methodology for using Digital Twin to track the emission data from building sites to promote green construction practices. The implementation of DT to track and monitor construction noise is still unfocused.

The approach suggested in this study will first use the noise mapping method to develop a stepwise noise propagation model, integrating data from the BIM model and pictures captured from the construction site. Later, the noise data monitored by sensors will be used to validate the model, and the resulting noise emission values will be imported into the DT model of the project for documentation, tracking, and ongoing monitoring of noise emissions.

3. METHODOLOGY

This paper introduces a noise mapping approach supported by BIM/DT, consisting of two main parts. The first part, explained in detail in Section 3.1, is the noise mapping process. The second part, explained in Section 3.2, involves data extraction from the BIM model and DT preparation. To model construction noise propagation, this study uses data extracted from the BIM and pictures captured from the construction site. Finally, recorded values from sensors in real time are used for validation progress.

3.1. Noise mapping process

The proper form of environmental noise prediction is through noise mapping methods, which comprise estimations of the expected sound pressure levels at various locations, including the neighboring building facades, which are depicted using colors [21]. There are many well-known software for mapping noise, including Soundplan, Lima, CadnaA (Computer Aided Noise Abatement), Noise3D, and IMMI. CadnaA software was chosen for use in the current study to put the proposed approach into practice. The reason is that the software has the ability to import different file formats and connect the model with an open-source database, which will later be beneficial for connecting the sensor data to the model. In addition to producing accurate calculation results, it is also user-friendly. Three different data sets are required in order to generate noise maps for the construction process: 1) noise sources, 2) the project's site plan, and 3) permissible noise values in the guidelines

3.1.1. Noise sources

The quantity, duration, and allocated equipment of the noisy process are among the data associated with noise sources. This information must be exported from the camera images captured during construction or process plan of the project. Data such as the sound pressure level of construction equipment or construction phases can be found by reviewing prior research and construction equipment information catalogues [22, 23].

3.1.2. Site plan of the construction

The noise mapping software can import a geometry model of the site plan in the .dwg format or files from web map services in the .xml, .osm, and .gml formats. For this digital ground model to be imported into the noise mapping software, it must be at least at LOD 1 (Level of Detail), where the height and elevation data for the area are also captured. Sensitive receptors can be identified once the site plan has been put into the noise mapping program together with the elevation data of the nearby buildings. Schools, hospitals, sanatoriums, rehab facilities, and residential buildings close to the construction site are referred to as sensitive receptors that can be highly affected by the noise. These buildings' facades have been designated as the noise receiving locations. In addition, the specific placement of sensors and noise monitoring points can be determined as a recipient in the digital model.

3.1.3. Permissible sound pressure levels

Various organizations, such as OSHA (Occupational Safety and Health Administration) [24] and equivalent administrations in other countries, have set rules and restrictions for construction noise in order to protect the well-being of workers and communities near construction sites. Certain countries, like Germany, have specific regulations for construction noise [3], while other countries include it in their general environmental noise laws. The permissible sound pressure levels for construction noise during working hours (usually from 07:00–20:00; this may vary by country) depend on the location of the construction project (residential, industrial, or mixed use areas) and should not exceed the values offered by guidelines in the neighborhood. For instance, in Germany, the Allgemeine Verwaltungsvorschrift zum Schutz gegen Baulärm- Geräuschimmissionen (AVV) Baulärm (engl.General Administrative Regulation for Protection against Noise Emissions from Construction Work) sets the permissible sound pressure level for construction noise from 50 (A) dB to 55 dB (A) in residential areas during working hours (07:00–20:00), while noisy activities are strictly prohibited on Sundays. The noise mapping process requires the definition of the permissible sound pressure levels, the duration of day, evening, and night based on guidelines, and the categorization of the land use of the area for detailed calculations.

3.2. Building information modelling and digital twin

BIM is widely used in the construction industry to achieve project management objectives such as time and cost control. A BIM model is a digital representation of a construction project that contains geometric and semantic data. The semantic (non-physical) data can be described as timelines, zones, materials, and component relations that are included in a BIM model. The BIM working technique can be used at any stage of the design process, from early conceptual design to detailed design, construction, and even the extended phase of operation. The project would greatly benefit from switching from conventional procedures to BIM-based working methods. Since it lessens inaccuracies in the building design and process plan while increasing transparency in the construction process [25]. Emission sources in the construction work, such as construction noise, can be exported from BIM models, in contrast to conventional process plans. Moreover, in the era of construction 4.0, digitization of construction sites is focused not only on the design and execution phases but also on operation and maintenance. As a result, building sites now include sensors that keep track of emissions data, including noise, greenhouse gases, and particles. The monitored real-time data must be preserved in a virtual model, or "digital twin," and then utilized to produce simulations for prediction, estimation, and control [20]. The monitored data from sensors can also be used to validate the prediction models, and specifically for this research construction noise. This research will first export the noise source data from the BIM model and captured data from the sensors and cameras on the construction site. These data will then be processed and used as noise sources in the noise mapping procedure to create a stepwise noise prediction model. Later, the values derived from the prediction model will be controlled with the data being tracked in real-time with sensors. In the end, the noise emission values will be imported into the Digital Twin Platform (DTP) to prepare the emission model for the project [26].

4. IMPLEMENTATION IN CASE STUDY

To implement the following approach, a construction project located in the city of Aarhus (Denmark), in Harbor, has been chosen. The project is a high-rise building with some parts remaining from the older building. Fig. 1 shows the satellite image of the location of the project and a picture from the construction side. As indicated in Fig. 1 (right), the design of the project consists of two parts: a new high rise building in the middle and the part of the existing building that will be renovated.

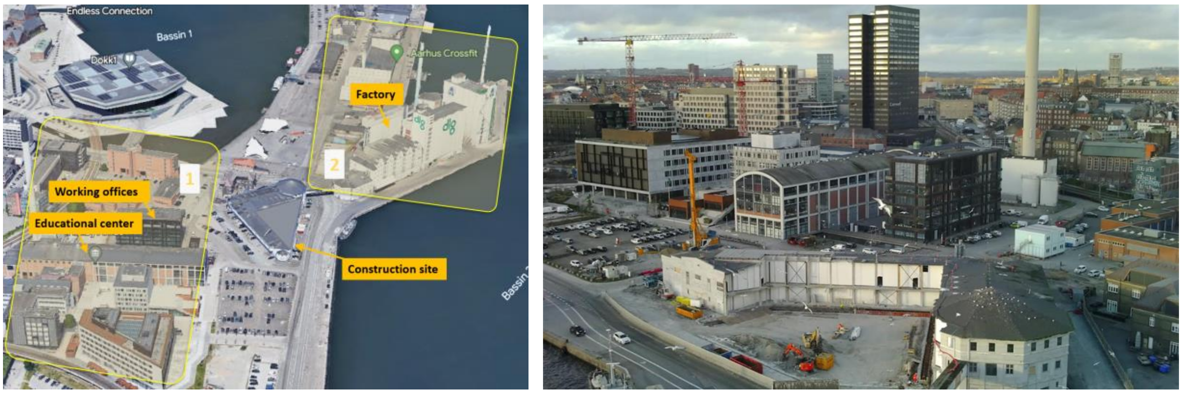

Figure 1: Satellite image (Google Earth, January 2020) showing the neighborhood of the construction site (left image) and during final preparation of the construction site (early October 2022) (right image).

Following the identification of sensitive receptors, the area was divided into two zones, as indicated in Fig. 1 (left). The surrounding neighborhood consists of working offices and a film school, which are represented by Zone 1 in Fig. 1 (left), and the factory on the other side, which is represented by Zone 2 in the same figure. Based on the nature of the area, the final focus of these noise maps would be to track the noise-related nuisances in Zone 1, which contains educational schools and working offices.

4.1. Sensor installation

Several Airnode sensors [27] have been installed in the project to track the emissions and noise from the construction project. Four out of eighteen sensors installed in the construction project can record and monitor noise data, in addition to emission data and particulars. Fig. 2 (right) shows the mentioned sensors, and Fig. 2 (left) shows the general location of sensors. Noise measurements by sensors are done using an A-weighting one second measurement, slow measurement, method.

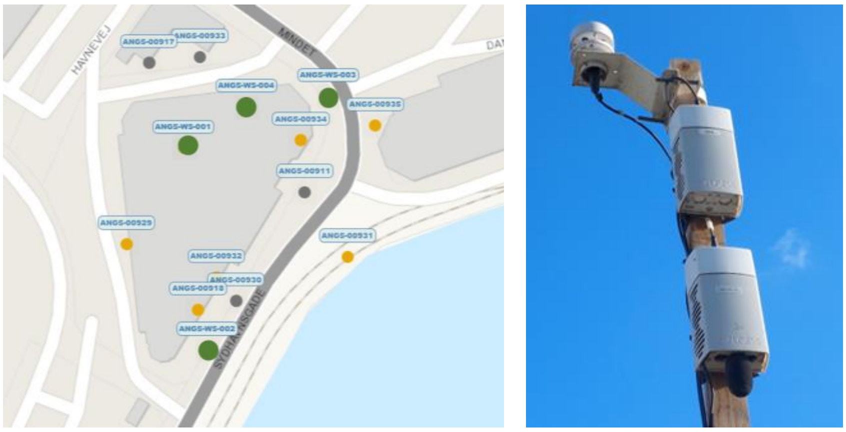

Figure 2: Location of all of installed sensors at the project, incl. the noise sensors that are indicated with green circles (left image) and close view of the Airnode sensors installed in the project to monitor noise and emission values (right image).

The BIM model of the earthwork and secant pile wall were modeled in the BIM-based platform, Revit, as well as the time plan of the processes have been analyzed. Two drilling rigs from the BAUER company with the model numbers "BG55" and "BG35" and a sound power level (LWA) of 112 dB (A) have been chosen for the following task. The movement paths of this equipment are detected, and they will be defined as noise sources in the CadnaA software for preparing the noise prediction model. Fig. 3 shows the movement path of the equipment, detected from the pictures captured from the construction site. It is important to note that each number in Fig. 3 represents the time at which the movement took place. Number one is 8:39, number two is 10:09, number three is 11:54, number four is 13:54, and number five is 14:24.

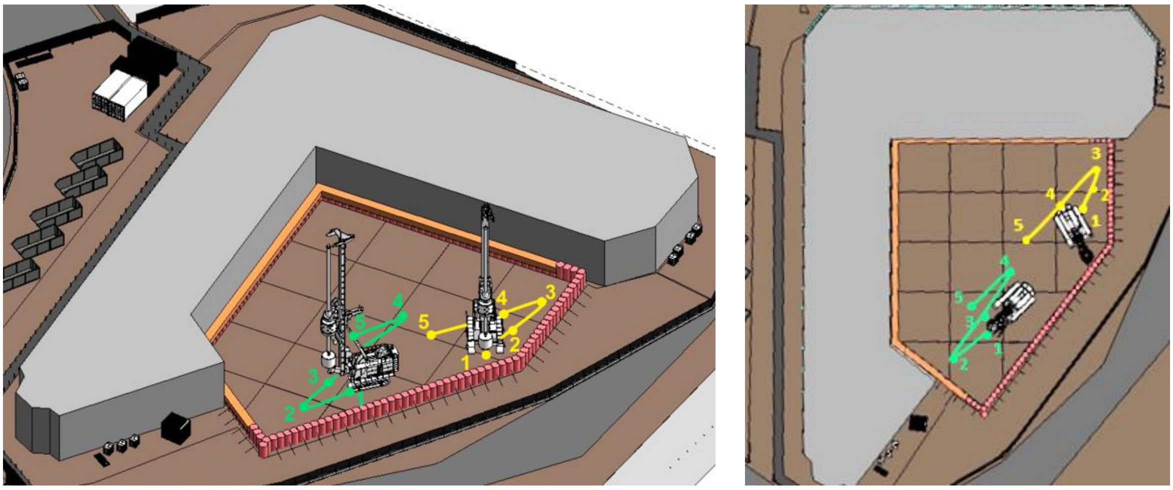

Figure 3: Movement path of the drilling rig shown in a digital construction site layout plan (isometric and plan views, left and right image, respectively).

4.2. Noise map preparation

To prepare noise maps, firstly, the site location, including elevation data for the surrounding buildings, is imported from the OpenStreetMap, a geographic database [28]. The duration of the working day has been set to 08:00–17:00, based on the reports from the construction project. The Danish Environmental Protection Agency [29] has stipulated noise regulations for environmental noise. Despite other countries like Germany, the rules are generally for environmental and industrial noise, and construction noise is not specified in the guidelines. Although the area consists of industrial buildings like factories, there are some working offices and educational centers in the surrounding area; therefore, the area has been categorized as a "business and industry area with restrictions". According to the environmental noise regulation in Denmark [29], the permissible noise values are set at 60 dB (A). The following calculations and set-ups will also follow these values. According to the suggestions of the ISO 1996 [30] and Gilchrist et al. [2], air attenuation can be neglected for distances less than 250 m. The effect of wind speed on sound propagation also becomes more significant over longer distances [2]. Therefore, the attenuation effect of the wind and meteorological factors has been neglected in the calculation.

The drilling rig has been defined as a noise source that follows the paths mentioned in Fig. 3 (yellow and green trajectories). According to Fig. 1 (left), the aim is to attempt to predict the potential noise propagation in the area and to take into account the safety of the nearby residence, including a film school and working offices, as well as the site workers. Lastly, the DTP has been used to create the noise emission model using the monitored data from the sensors (shown in Fig. 2). The final results and calculated values will be compared and thoroughly explained in the following sections.

5. PROCESSING THE MONITORED DATA FOR FURTHER VALIDATIONS

The recorded data from the sensors must be used to evaluate and verify the result of the noise simulation model. The recorded sensor data for October 24, 2022, has been exported as the date when detailed information about the construction process is available. To be able to use the monitored data for validation, it is needed to filter and control the recorded noise values. Section 5.1, discusses how these data will be processed.

5.1. Processing the monitored data

As mentioned in Section 4, the data collected from the sensors has been transferred via IOT to a dashboard for documentation. Firstly, the monitored data needed to be analyzed for the calculation of ambient noise. The noise levels that were recorded are a combination of different noises, such as a passing car, background noise, or a momentary accident. It is necessary to determine whether construction noise dominates the neighborhood and is louder than ambient noise. As a result, background noise or ambient noise must be computed using monitored data, which will be covered in more detail in Section 5.1.1.

5.1.1. Definition of background noise

As shown in Fig. 4, the monitored data are the sum of background (ambient) noise and construction noise altogether. Since there is no access for the first measurements of the ambient or city noise in that area, background noise needed to be calculated from the monitored data outside of the construction's working hours. According to the definition of ISO 1996-1 (the primary standard on environmental noise measurements) [30], as illustrated in Fig. 4, the total sound is all noise, including noise from other sources at a particular time or place. When a specific noise is removed from the overall sound spectrum, residual noise remains as the background noise. Specific noises A, B, and C are created by various noise sources.

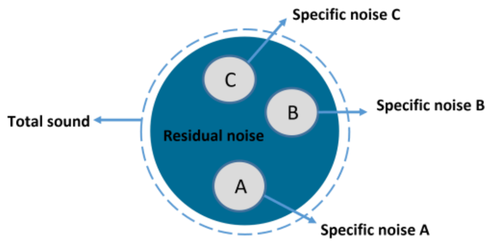

Figure 4: Definition of noise in the environment based on ISO 1996-1 [30].

According to the summation and subtraction of noise values using logarithmic equations, when noise values are added together, a maximum of 3 decibels will be added if two equal noises are mixed. If the difference between the two values is greater than 10 decibels, the highest noise level takes precedence. As a conclusion, after the calculation of possible background noise, if the difference between the background noise and the recorded value is greater than 3 decibels, the dominant noise will be defined as construction noise [1]. Equation 1 shows the details of the mentioned rule.

$$L_{N+S} - L_N = \Delta L \qquad (\Delta L: Difference) \qquad \text{(Equation 1)}$$

$$If\ 0 < \Delta L < 1\ dB(A);\ L_{\ total} = L_{N+S} + 3,\ \ If\ 2 < \Delta L < 3\ dB(A); L_{\ total} = \ L_{N+S} + 2$$

$$If\ 3 < \Delta L < 7\ dB(A);\ L_{total} = \ L_{N+S} + 1, If\ 7 < \Delta L < 9\ dB(A) = \ L_{total} = L_{N+s} + 0.5;$$

$$If\ \Delta L > 10\ dB(A);\ \ L_{N+S} = \ L_N$$

L_{N+S} is the overall measured noise, which consists of background noise and source noise, and L_N is calculated background noise.

5.1.2. *Filtering the background noise from the monitored values from sensors*

Although the working hours are set to 07:00–18:00 from Monday to Friday in Denmark, the pictures taken from the construction side on 10.24.2022, show that the work started at 8:00 and finished by 17:00. Therefore, for that specific day, the recorded data for out of construction working hours has been used to calculate L_{eq} (equivalent continuous sound level) as ambient noise. This is the preferable approach to describing sound levels that change over time because it provides a single decibel value that accounts for the overall sound energy across the time period that is of concern [1, 30]. Therefore, as shown in Fig. 5, the values highlighted in green have been chosen for the background noise calculation.

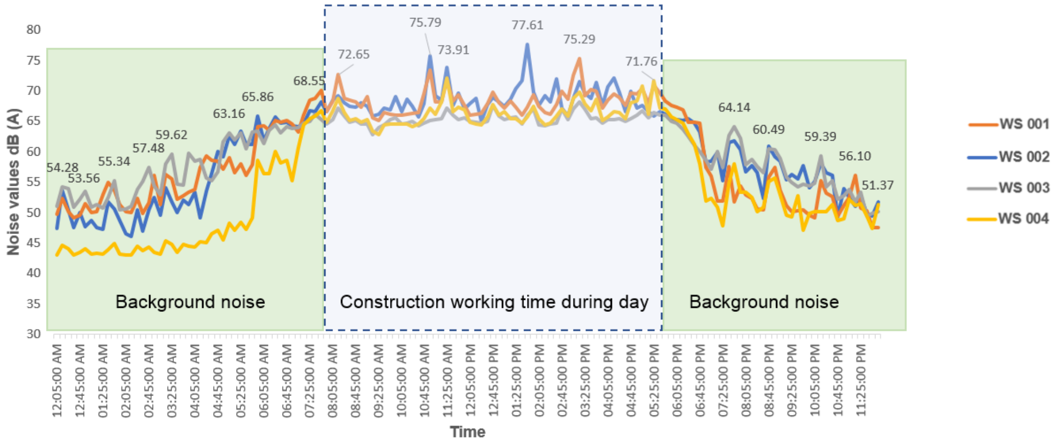

Figure 5: Four noise sensor recordings on 24.10.2022; selected data for background noise calculation.

The calculation shows that the background noise is 54 dB(A). When these values are compared to the monitored noise values via sensors, it is possible to conclude that the construction noise is greater than the ambient noise that dominates the area. Therefore, the background noise can be neglected in future calculations and comparisons.

6. RESULTS AND DISCUSSION

The noise maps for the explained movement path in Section 2.1 are prepared and shown in Fig. 6. In each noise map, the exact location of sensors installed at the construction site has been defined as a receiver point. The calculated values and real data values will be compared in Section 6.1.

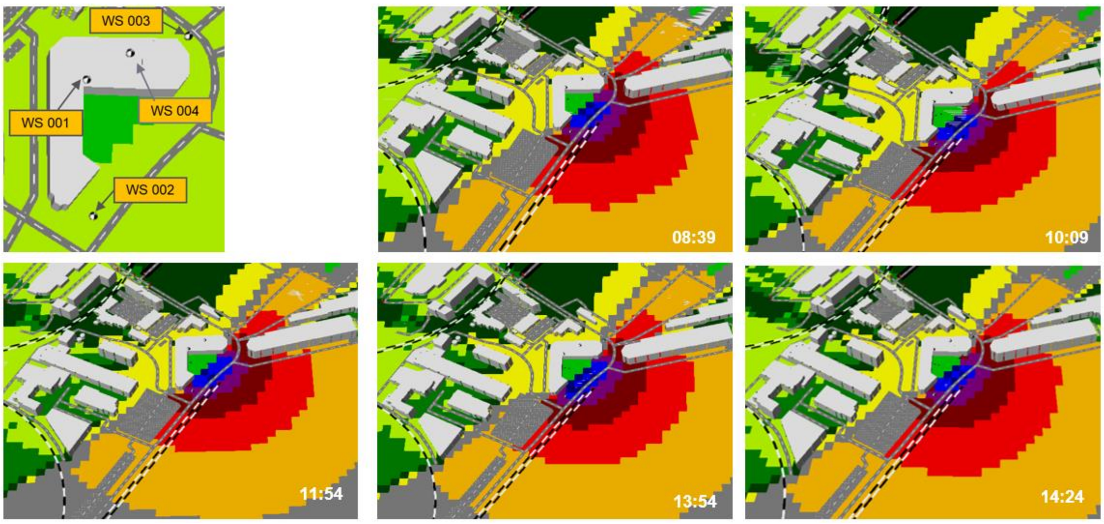

Figure 6: 3D views: Sensor locations in the noise map (top left image); noise maps for the five earlier defined drilling rig locations (corresponding timestamps shown at the right bottom of the each picture).

6.1. Comparison of the simulation data

The receiver points inside the noise mapping model have been defined at the exact location of the sensor in order to compare the noise map values with the actual monitored data from sensors. These receiver points in the noise maps are labelled with the orange indicator, as shown in in Fig. 6. A noise map has been prepared for the points 1 to 5 shown in Fig. 3. The calculated values in the receiver points of noise maps have been exported and compared with the values recorded by sensors on 10.24.2022, at the exact time of the movement. The results of the comparison are shown in Fig. 7.

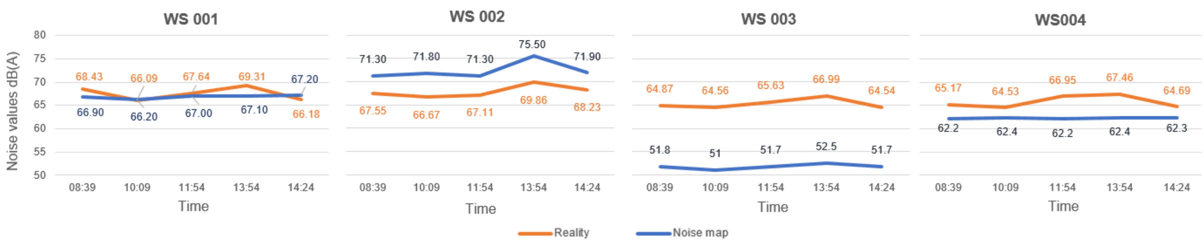

Figure 7: Comparison of sensor data and calculated data from the noise maps, Sensor WS001 (upper left), Sensor WS002 (up-right), WS 003 (bottom-left), WS 004 (bottom-right).

As it is shown in Fig. 7, for the sensor WS001, the simulation result at 10:09 is exactly the same as the monitored data, as well as at 11:45 with a very slight difference. In general, the difference between the simulation values and the recorded ones is approximately ± 2 dB(A), which can show a good fit. For sensor WS 002, the simulated data are a bit higher than the monitored data, as well as for sensor WS 003. The reason for this difference could be that there is an unforeseen noise from the environment, such as generated noise from the harbor port, which would affect a portion of the values that the sensors get from each noise source. As is also clear from Fig. 2, these two sensors are installed on the border of the construction site, close to the street. Any sudden noisy activity can also affect the amount of noise that these sensors are detecting. For the sensor WS004, the differences in the values are higher at 11:45 and 13:54. The reason again could be an unforeseen higher noise accident in the area, since the area is harbor side and the environment is so dynamic in terms of noise pollution.

6.2. Comparison of noise values with noise limits

Based on ISO 1996 [30], to compare the recorded and calculated noise values with the permitted sound level of 60 dB(A), as noted in Section 4.1, these values first have to be compared to the background noise to determine whether or not there is a noise problem caused by construction noise. This indicates that there should be a 3 to 5 decibel difference between the measured values and background noise, proving that construction noise is the cause of the majority of the noise in the area. Afterward, these results can be compared to the Danish standards' permissible noise values of 60 dB(A). In Section 5.1.2, a comparison between the noise source and the background noise had already been made. Now the recorded data can be compared to the 60 dB(A), indicating a 5 to 15-decibel overshoot. For example, the sensor WS002 showed construction noise exceeding the limits at 13:54 by 15 dB (A), which could have been detected beforehand within the predicted values by noise maps. To prevent such a noise problem, the number of heavy equipment operators at the construction site could have been limited at that time, or a mobile noise barrier could have been installed within the construction boundaries.

In the final step, the DT model for the noise emission values has been generated in the DTP using Autodesk Platform Services [26, 31]. As shown in Fig. 8 the DT model has shown the emission values from the heavy construction equipment. For the preparation of this model, it is assumed that there is just one drilling rig in the construction site.

As there is a data flow between the real world and the digital model, this will help to monitor and track the noise emissions of the construction project at various stages. Also, it could assist the user, in this case, the project manager, in keeping track of the noise to protect the health and safety of the workers by preventing them from being exposed to levels of noise that exceed guideline values or for extended periods. Therefore, having access to prediction models and DT for the construction project has a great benefit for the project as well as for controlling and tracking the noise emissions of the project.

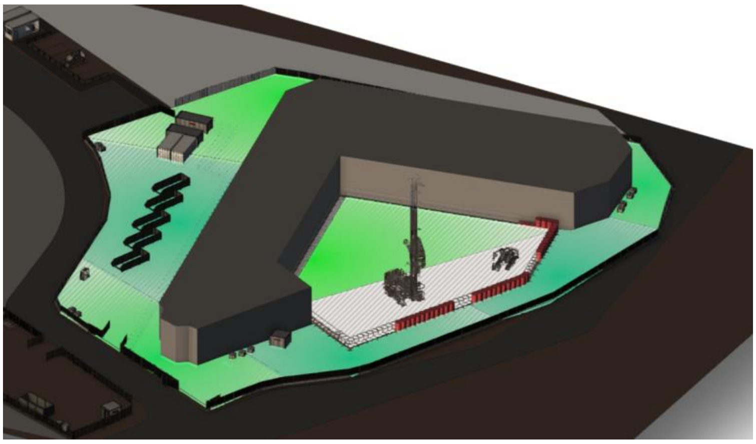

Figure 8: Visual in DT dashboard for end user consumption (green colors indicate low noise levels).

7. CONCLUSIONS AND LIMITATIONS

Construction project pollution, particularly acoustical pollution, can now be controlled in a new way owing to the adoption of emerging DT in the construction industry [32]. Access to noise propagation models, which foretell potential pollution and then integrate such results in the DT model, will aid construction companies by protecting them from unexpected setbacks (e.g., compliance claims) and also achieving the lowest possible risk of discomfort for nearby working or living people. Both the construction site planning and execution phase benefit from having access to such noise propagation models that include real data. The results of this case study show that the wise choice by the architectural engineering office, keeping a part of the old structure to shield construction noise, had a significant positive effect on the reduction in noise-related nuisance for the neighboring buildings. This study hints that the suggested approach can assist practitioners in developing environmentally conscious designs or even planning the task sequences of the demolition phase in higher level of detail. Moreover, it is expected that noise maps will also assist the project manager in controlling the health of the workers during this noisy task.

The limits of this study and improvement suggestions are:

(1) Recent challenges for direct data export and import between DT/BIM and noise mapping applications are that the noise mapping software does not accept IFC file formats. Therefore, the information needed to be saved and imported into other file formats, such as Excel,.dxf, or .dwg, with a lower Level of Detail (LOD).
(2) The exact location of the construction equipment can also be tracked using more accurate methods, such as Real-time Kinematic-Global Navigation Satellite Systems (RTK-GNSS) data collection, like in [33]. Alternatively, additional and live machine data recording is suggested to compensate for any of the technology limitations.
(3) The live image feed received from the construction site is not synchronized with the recorded noise values. Therefore, the validation is not done at the exact moment but rather with a 4-minute delay. For a higher level of accuracy in the work, it is suggested that, at each time of recording noise, a picture of the construction site be taken immediately.
(4) Moreover, the detailed measurement to record ambient noise is also suggested since there is a factory located near a construction project where sometimes noisy activities take place.

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DRIVERS OF SAFETY VIOLATIONS ON SMALL CONSTRUCTION SITES

Fidelis Emuze[1]

[1]Central University of Technology, Free State (South Africa)

Abstract

The construction safety literature confirms that on-site errors and violations are detrimental to work completion and operatives in projects. This paper aims to revisit the drivers that normalise safety violations on sites with specific attention to small construction works. The study sought responses to 'what are the drivers of safety violations in construction'? On-site interviews and observations were used to collect textual data from personnel physically present on live projects supervised by three contractors. The observations were conducted to verify the information obtained from the interviewees. Notably, the drivers of safety violations tend to normalise it to the extent that such deviations become accepted practice. Although it serves only illustrative purposes, the data suggests that situational awareness should be improved to tackle the drivers of routine safety violations among the operatives that work for small contractors.

Keywords: construction site, safety knowledge, safety violation, South Africa

INTRODUCTION

Safety is a long-term issue in construction operations. Despite legislative efforts to eliminate or reduce harm in the workplace, a high rate of injuries and accidents still occur on construction projects, especially in some developing countries such as Ghana and South Africa with small contracting firms. For instance, construction is one of the most hazardous sectors in Ghana, where the number of accidents is relatively high [1]. For example, from 2010 to 2016, 558 accidents were recorded on construction sites in Accra and Kumasi. In these countries, operatives in construction work under different hazardous conditions, leading to injuries, accidents, and fatalities [2]. The reality in developing countries contrasts with construction safety in developed countries that have reported improvement [3]. Despite several causes (such as inadequate education and training) of poor construction safety in developing countries, on-site safety violations cannot be ignored [4]. As an illustration, in Namibia, a neighbouring country to South Africa, many construction workers are reluctant to use personal protective equipment (PPE) while performing on-site tasks [5].

Often the outcome of safety violation is detrimental to work completion and project operatives [6]. In South Africa, which is the study context of this paper, Emuze argued for countermeasures for construction to safety violations [7]. His conceptual argument was premised on reported routine violations, including deviation from safe work procedures on construction sites. The study foregrounds the idea that there is a major case to address the violation of safety rules found on construction sites because of they occur at both organisational and individual levels. For example, such problems render induction and toolbox talks on-site ineffective in construction operations.

The frequency of safety violations in the 2018 study by Emuze necessitates examining if such actions have become routines through normalisation on construction sites [7]. This is because safety violations can increase the risk of accidents on construction sites [8]. These violations are common on construction sites operated by small construction firms because of inadequate health and safety (H&S) awareness and compliance [9]. So, the study sought responses to 'what are the drivers of safety violations on small construction sites'? In the context of this paper, the term small construction sites refer to projects registered on the CIDB (Construction Industry Development Board) database with a value of less than R10m ($524000.00). The next section of the paper unpacks the research method before the salient results are presented. Thereafter the results are discussed concerning the extant safety science literature to tie the concluding remarks to that larger safety management corpus.

RESEARCH METHOD

The study adopted a phenomenology (qualitative) research design. Interpretivists use phenomenology to study lived experiences from the first-person (interviewer or observer) point of view [10]. The phenomenon of interest ranges from experiences involving perceptions, thoughts, memories, and social interactions [10]. In this study instance, the phenomenon of interest is from experiences of safety violations by operatives on construction sites controlled by small contractors in the central region of South Africa. Phenomenology is utilized to directly investigate participants' lived experiences [11]. In line with the traditions of qualitative phenomenological studies [11], the primary data for the reported research were collated through semi-structured interviews and observation from three construction sites in Free State, South Africa. The scope of the study did not include design – and site constraints related factors. The interview techniques reveal how people, in this case, construction operatives, interpret their experiences. The investigative study was carried out to explain safety violations based on the participants' lived experiences in the construction site environment. In the main, the study sought responses to "'what are the drivers of safety violations in construction"?

The same instrument was employed for all the semi-structured interviews to improve confidence in the analysed data, in line with Huberman and Miles [12]. The study adopted a purposive sampling method to select the construction sites and engaged participants. Physical work on-site and lived work experience in construction activities were among the criteria for selecting participants. Two students registered for postgraduate diplomas in construction qualification collected the data from the sites. The students were knowledgeable about the subject, taking construction management and safety courses. They were provided training before the exercise of data collection. The training includes research methodology classes, ethical norms to observe, and data collection procedures. Ethical norms include informed consent, privacy, and voluntary contribution to the study. The data collection exercises were audio-recorded, and the collected data were transcribed. After transcription, the textual data (words, phrases, and sentences) were analysed to enrich the development of the study's concepts in line with the stated aim. Thus, an open coding system of coding was adopted in the transcription of interview data. The study used narrative coding techniques in line with Corbin and Strauss [13]. The generated codes were re-organised based on frequency, occurrence, and reference. From the re-organised codes, the sub-themes were developed.

As previously reported, the data were collected from the interviewees on project sites in Free State, South Africa. The 15 participants (P1 – P15) were selected from three sites within Free State, South Africa. The study's design was exploratory instead of descriptive or explanatory, so the fieldwork stopped once data saturation was achieved. The participants held positions as site agents, engineers, general workers, site managers, general foremen, artisans, safety officers, and project managers. Notably, most interviewees had years of industry engagement and could be considered experienced in construction operations. Table 1 shows that of the 15 participants, 33% have matric, 29% have post-matric certificates, and 46% have degrees. This indicates that most participants were educated and could reflect and comment on their lived experiences. Also, the table shows that 28% have 11-15 years of work experience, 6% have 6-10 years of work experience, and 66% have 0-5 years of work experience. The extent of site experience of the interview gives confidence to their perceptions on the subject matter. However, in line with the norm in South African construction sites, the interviewees are mostly male at 66%.

Table 1: Background information of the interviewees

Profile	Frequency	Percentage
Experience (Years)		
0 to 5	10	60
6 to 10	1	6
11 to 15	4	26
Total	15	100
Gender		
Male	11	66

Female	4	34
Total	15	100
Education		
Matric	5	33
Certificate/Diploma	3	29
University degree	7	46
Total	15	100

As part of the qualitative study, on-site observations were expedited to refute or reinforce the interview data. Observation studies involve going to a workplace to collect data by looking at workers performing their tasks [14]. Such research is usually conducted to determine how people interact and behave in the work environment. A study can either expedite direct observation or participant observation. The former is done when the field workers (data collectors) observe without interference in work proceedings. At the same time, the latter is conducted when the field worker participates in an activity and then takes notes. In a nutshell, this study's direct observation mode was expedited by completing field notes because it is unobtrusive as much as possible [15]. The two field workers (students) visited the three construction sites mentioned earlier to observe operations without interfering in work processes. The observation took less than 60 minutes daily, while note-taking was done concurrently as pictures were not allowed.

RESULTS AND INTERPRETATION

The responses to the semi-structured questions asked in the face-to-face interviews and observation are presented in this section. The textual data suggest that the five main drivers of safety violations predominate. One driver (work pressure) relates to the unsafe working environment, widely cited as a cause of accidents in industrial workplaces. Another driver, demotivation, is a psychological factor, while the third factor, fatigue, is health-related. Table 2 shows that fatigue, demotivation, and work pressure play varying roles that lead to the manifestation of safety violations on small construction project sites. In effect, the quotes in the table suggest that tiredness impacts the attention span of operatives while work pressure may lead to short cut to ensure early exit from the site. "The management wants to hit targets," participant 4 said. He further said, “management off-site often would try to push work even into the weekend when we received materials after hours”. Another interviewee (Participant 6) comment that if they have a project that takes nine months, the workers must push it to at least six months in the view of site management. According to the interviews, these views attest to the nature of work on small construction sites. Such a nature provides fertile grounds for safety violations. One can conclude from the comments that the management on such sites prioritizes meeting production targets higher than the safety precautions. The quote from participants 13 and 14 I Table 2 means workers may be demotivated to work for varying reasons. If they work in such a state of mind, the likelihood of violation exists.

Table 2: Work-related drivers of safety violations

Driver	**Direct Interview Quotes**
Fatigue Work pressure	Participant 2&3“When we are tired, we cannot focus well; we just want to work and go home.” Participate 9 “” We work under pressure to finish in time.”
Demotivation	Participant 13&14 “workers must just focus on being at work and do the work; we cannot force them to work when it is time to work; they should do that.”

Table 3 shows that the interviews highlighted two additional drivers of safety violations on small construction sites. The first driver pertains to indifference or lack of concern for H&S. According to the interviewees, many site workers still need to follow the rules and procedures of site safety because of gaps in management dispositions toward people and work. The interviewees contend that concerns about personal protective equipment (PPE) and the inadequate emphasis on H&S by site operatives and their managers fuel the normalization of safety violations on site. Indifference and negligence related to H&S on-site are not good news for safe work operations on construction sites.

Table 3: Organisation-related drivers of safety violations

Driver	**Direct Interview Quotes**
Indifference	Participant 10 “We discuss this matter at our safety meetings, but the discussed policy is not maintained by management because they focus more on completing the job.”
Negligence	Participant 12 “There was this one time when one of the workers accidentally hurt himself because he was not wearing his safety boots when he was compacting when he was compacting the trench so that they could lay the sewage pipe.” Participant 11 “PPE does run out for workers, and it can take a while before it is delivered. Which makes it difficult for workers to wear their full PPE when they come to work.”

Negligence is an antithesis of awareness, which helps to maintain required levels of H&S compliance on site. When negligence abounds, the tendency to deviate from the rules intentionally (violations) is present. Perhaps, this is why construction operatives injure themselves at work when the correct PPE is not used, as cited by Participant P12 in Table 3. The availability of PPEs is also a concern as it may indirectly influence operatives to violate safety rules, as mentioned by Participant 11.” The remedies to these two drivers should come from site management and operatives, although the former has complete control of the work and the environment in which it is expedited.

A comprehension of the aggregated interview data further suggests that the role of H&S policy and procedure is underestimated on the visited sites. This assumption stems from comments indicating that policy and procedure are not followed. More than half of the interviewees say that workers on small construction projects frequently lack knowledge about PPE and behave carelessly, which can sadly lead to deadly incidents that cost lives. The reflective account of the interview data feeds into the observational study’s outcome, as summarised in Table 4. Notably, the interview data collaborated with the observations on the three construction project sites. As shown in Table 4, the two observers noted violations related to PPE, housekeeping and communication.

Table 4: Observed safety violation issues on the construction sites

H&S practice	**Aspect observed**	**Observation**
Personal protective equipment (PPE)	Safety goggles Safety boots	Not wearing safety goggles when they were cutting manholes. Not wearing safety boots when working with machines.

Communication	Information sharing	Does not properly communicate when people are operating incorrectly
Housekeeping	Conditions of the work area on site	Workers often fail to remove waste before, during and after several tasks.

Discussion

The presented results in the previous section reaffirm that the decision not to abide by the rules and procedures in the worksite was shaped by organisational (Table 2) and psychosocial factors [16]. The five drivers unpacked in the paper appear to form part of a construction worker's repertoire of skilled or habitual actions. The drivers always involve cutting corners, that is, following the path of the least effort to complete a task, as referenced in Table 2. According to Reason [16, pp.51],

> "such routine violations are promoted by inelegant procedures and a relatively indifferent environment. That is, one that rarely punishes violations or reward compliance."

The above direct quote from Reason [16] is re-enacted in the three small construction sites visited during the reported study. Through interviews and observations, one can conclude that the drivers highlighted in this paper may follow the path illustrated in Figure 1. The pathway mirrors previous empirical studies, which show that when workers assume different roles on a project site based on their H&S tendencies influenced by time and work pressures, level of experience, risk perceptions, and safety culture [17] [18], violations may occur in a variety of forms. The interview data from a 2018 South African paper show that toolbox talks once a week and inductions for workers and site visitors are ways of tackling safety violations. However, these two measures could not yield desired outcome (i.e., lowering the frequency of violations). The study, inter-alia, concludes that the South African construction industry requires credible countermeasures to reduce workplace safety violations. The countermeasure may begin with workplace policies and actions that motivate workers by reducing fatigue and work pressure. Indifference and negligence should also not be tolerated on construction sites, either from management or workers, in large or small-size projects.

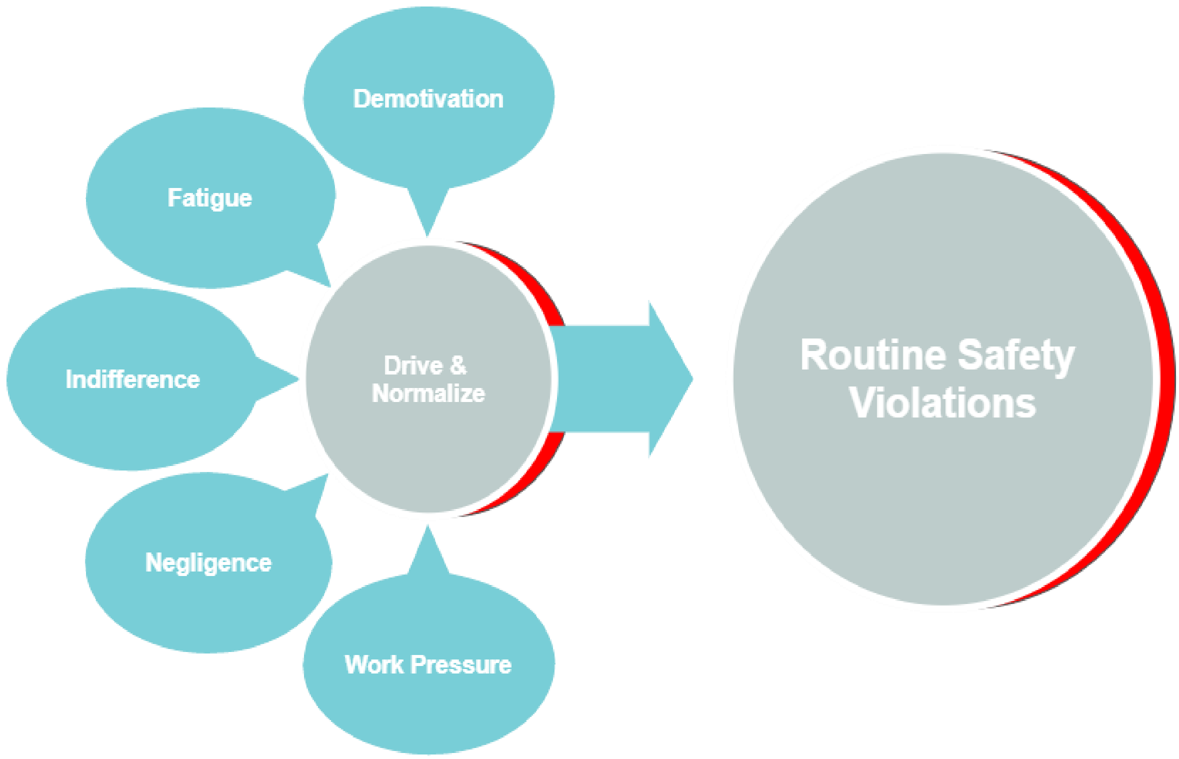

Figure 1: Potential pathway of the drivers of routine safety violations

CONCLUDING REMARKS

This paper revisited the drivers that normalize safety violations on sites with specific attention to small construction works. The study sought responses to 'What are the drivers of safety violations in construction'? To obtain the responses to the central question, a phenomenology study involving 15 on-site interviews and observations was used to collect textual data from personnel physically present on live projects supervised by three contractors. The observations were conducted to verify the information obtained from the interviewees.

The results highlight five drivers of routine safety violations: demotivation, fatigue, indifference, negligence, and work pressure. These drivers are not new as causal factors of accidents in the industrial work environment. They represent antecedents of routine violations, as Reason [16] described. Their emergence in this study shows their endurance and pervasiveness in the worksite – large or small. These drivers could collectively normalize safety violations so that intentional deviations from rules become accepted work practices. Such a turn of events or school of thought should not be allowed unchallenged if construction operatives are to feel safe and healthy on any site. Although it serves only illustrative purposes, the data suggests that situation awareness should be enhanced among the operatives that work for small contractors.

In closing, it is vital to note that the results reported in this paper are products of an exploratory research design rooted in the qualitative traditions of phenomenology. Like other phenomenological studies, the reported data cannot be statistically generalised. But it can be transferred to similar contexts (small construction sites or firms in a developing country). The observation data are limited to field notes. They would be more credible if photography evidence collection were allowed on the sites. Further studies thus have major scope for extending the results shared here by using multiple techniques for data collection.

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COPING AS A MEDIATOR BETWEEN COMMON MENTAL DISORDERS AND MENTAL WELL-BEING AMONG THE CONSTRUCTION WORKFORCE IN SOUTH AFRICA

Mohlomi Terah Raliile[1]*, Theo C. Haupt[2] , Kahilu Kajimo-Shakantu[3]

[1,3]Department of Quantity Surveying and Construction Management, University of the Free State, 205 Nelson Mandela Drive, Park West, Bloemfontein, Free State, South Africa.

*mohlomiraliile@gmail.com**

[2]School of Build Environment and Engineering, Nelson Mandela University, Department of Construction Management, Gqeberha, South Africa

ABSTRACT

This cross-sectional study examined direct relationships between coping, common mental disorders and wellbeing. Further, the study examined if coping mediates the relationship between CMDs and wellbeing of the construction workforce in South Africa. Data were collected from a conveniently sampled population of general contractors in South Africa. A total of 201 participants were obtained. A quantitative research approach was used, and data were analysed using IBM SPSS v28 for descriptive statistics and exploratory factor analysis (EFA). The WHO-5 Wellbeing Index Measure was used to assess subjective wellbeing. The instruments for CMDs and coping were designed by the author based on the occupational stress theories, therefore, EFA was be conducted prior to the analysis to identify dimensions which measure factors of concern. Reliability and validity of the constructs were measured and met the minimum thresholds. IBM Amos V28 was further used for confirmatory factor analysis (CFA) and structural equation modelling (SEM) to test the hypothesised relationships. The findings of the study revealed that overall wellbeing was good indicated by 77.97, although not optimum. Contrary to expectation there were no significant relationships for the hypothesised relationships. Therefore, important issues emerging from the study are (1) the need to develop a multifaceted and validated psychological wellbeing scale for the construction industry to address wellbeing and coping holistically; and, (2) study the perception of the workers towards the use of substances as this did not seem to have an impact on wellbeing. The study only examined the mediation relationship between common mental disorders and subjective wellbeing on a conveniently sampled population using self-report questionnaire. The study may also suffer from limitations associated with self-reporting questionnaires. This study contributes to the knowledge gap about coping and its effects on mental wellbeing of the South African construction workforce. Further, the findings provide insight onto specific areas of focus and how CMDs can be managed.

Keywords: Construction Industry, Construction Workforce, Mental Well-being, Coping, WHO-5.

1.0. INTRODUCTION

The relationship between work and health is an intricate one, as for many, work is a source of self-realisation, social contacts and financial security which contribute positively to an individual's mental health and overall wellbeing [1],[2]. Mental health is one of the most significant spheres of public health [3] and the socioeconomic consequences attributed to poor mental health are considerable. Poor mental health is increasingly becoming the most challenging issue in occupational health and safety [4]. Mental ill-health negatively impacts on productivity, job satisfaction and results in serious economic and social burdens [4],[5],[6],[7].

Mental ill-health among the construction workforce is a major concern and its pervasiveness is a result of the industry's reluctance to change its culture, structures, work processes, and practices inherent to construction product delivery [8],[9]. In construction, poor mental health issues result in most injuries and accidents, lost working days, absenteeism, low employee morale, high staff turnover rates, increasing medical expenses and high suicide rate of all industries [10],[11],[12],[13]. Construction work is very stressful because of psychologically and physiologically demanding tasks performed in hazardous work environments [14]. This demands subsequently lead to common mental disorders such as depression, stress (acute, chronic, PTSD), anxiety and substance abuse disorders [15]. When workers perceive unsafe working conditions, they worry about their wellbeing and become increasingly anxious where they believe exposure to work hazards may result in diseases or injury.

In order to cope with the demands emanating from physically and mentally demanding tasks, construction workers resort to either maladaptive (negative) or adaptive (positive) coping strategies. Coping is known to be a mediating/moderating effect for stress and mental health. It is closely related to the concept of cognitive appraisal and, to the stress relevant person-environment transactions [16],[17]. "Coping is constantly changing cognitive and behavioural efforts to manage specific external and/or internal demands that are appraised as taxing or exceeding the resources of the person [16:141]. Adaptive coping operates as a mental health protective factor which is effective in combating life stressors. These protective factors such as marital status; high job control; high job support; low job demand; low workplace discrimination; family-friendly job opportunities; workplace justice; better welfare and positive socioeconomic measures make it easy for construction workers to positively manage stress at work and outside work. On the contrary, increased job demand, reduced work support, and reduced job control have been linked with maladaptive coping strategies among the construction workforce such as alcohol, drugs, avoidance behaviour and substance abuse (ADSA) [18]. Construction workers are at risk of resorting to maladaptive coping strategies because of their job characteristics which do not encourage openness about mental health issues, the macho culture, physically demanding tasks coupled with long working hours making it hard for active coping strategies and the high illiteracy rate which is also linked to unhealthy lifestyle habits.

Mental health studies have mostly been conducted in developed countries such as the EU countries, UK, USA, Hong Kong, Australia, and New Zealand. In developing countries, these issues are characterized by social problems and economic hardships, such as inequality and crime [19]. In South Africa for example, work-life balance as well as maintaining balanced mental health is increasingly becoming difficult for employees [20]. South African companies are known to be culturally diverse and heavily integrated into the global economy and this comes with a burden to create a sustainable, international, and competitive advantage through human capital [20],[21],[22],[23]. Also, there is a shortage of skilled workforce, and the remaining skilled workers carry a heavy burden of work [24]. Mental health issues in South Africa and more so in the construction industry have not been contextualised. and the magnitude of these issues remains unclear.

There is a lack of development in the field of cross-cultural research in relation to mental health issues in South African countries since focus has been on the western approach to addressing psychological issues. South Africa consists of a different demographic population mainly consisting of people of similar ethnicities with different cultures, beliefs, and values. Although mental ill-health emanating from construction activities can be manageable and treated like any other occupational health and safety risk, when addressed at an organisational level, the challenge lies with identifying how workers cope given the diversity of the population. Therefore, it is imperative to address mental health and well-being issues in relation to specific mediators to gain an in-depth understanding of how workers cope with common mental health emanating from the workplace. It is hoped that the focus on specific cross-cultural studies investigating the dearth of coping mechanism and their prevalence will assist in the development of effective stress management tools and subsequently assist clinicians to improve diagnostic and psycho-therapeutical processes. Therefore, this study investigated the *adaptive coping and maladaptive coping as mediators for the relationship between CMDs and wellbeing*.

2.0. METHODOLOGY

In this quantitative cross-sectional study, data were collected from construction companies in South Africa. Convenience sampling was the preferred sampling technique based on proximity and familiarity of the sample population to the researcher. This sampling technique maximised the response rate because the study was conducted within a limited period. Some respondents were recommended by other participants – a variant of snowballing sampling technique. After receiving the questionnaire, data were cleaned by excluding questionnaires with missing data, disengaged responses, extreme values and outliers. A total of 201 questionnaires were suitable for analysis and a response rate of 56% was achieved. The questionnaire included the coping strategies, common mental disorders (CMDs), and WHO-5 Wellbeing Index Measure. The WHO-5 measure for wellness was used because it is easy to interpret and understand and also because it is a validated measure used across all disciplines to measure the subjective wellbeing of the general population. CMD and coping questionnaires were designed by the author and Exploratory Factor Analysis (EFA) was conducted to identify the number of components necessary to explain the interrelationships among the variables and to assess whether the questions measured what the researcher intended to measure. Own questionnaires were developed based on existing literature and existing stress theories. The use of validated instruments may not necessarily apply in cross-cultural studies especially for coping and common mental disorders due to diverse cultural practices and the perceptions around mental problems. Once the underlying structure for the constructs was established in EFA, CFA and SEM were used to test the hypothesis. IBM Statistical Package for Social Sciences (SPSS) v28 was used for descriptive statistics and Exploratory Factor Analysis (EFA), and IBM Amos v28 for CFA and SEM.

For the WHO-5, descriptive statistics was used to analyse and to interpret using the prescribed scoring system. The WHO-5 comprises of five items (1) “I have felt cheerful and in good spirits.”, (2) “I have felt calm and relaxed.”, (3) “I have felt active and vigorous.”, (4) “I woke up feeling fresh and rested.”, (5) “My daily life has been filled with things that interest me.” The respondents were presented with a statement “Please indicate for each of the five statements which is the closest to how you have been feeling over the last two weeks”. Composite reliability, Average Variance Explained and Cronbach’s Alpha were further used to determine reliability and validity of the constructs. This study receive ethical clearance from the General Human Research Ethics Committee (GHREC) (Ethical Clearance Number: UFS-HSD2021/2006/22) at the University of the Free State. Informed consent was granted from the respondents before conducting the study and all research protocols were followed according to the requirements of the GHREC.

3.0. RESULTS

This section presents the analysis of the data collected and discusses the findings. Data were analysed using IBM Statistical Package for Social Sciences (SPSS) version 28. Tables were used to present data and key findings.

3.1. Respondents

The respondents of the study were the construction workforce working for general contractors in South Africa. Most of the respondents were black (88.1%) followed by white (7.0%) and coloured (5.0%). The sample were artisans, construction project professionals (CPP) and construction labourers. Table 1 presents the profile of the respondents of the study.

Table 1 Respondents Profile

	Frequency	Percen t
Gender		
Male	164	81.6
Female	37	18.4
Total	201	100.0
Age		
18 to 24	16	8.0
25 to 34	87	43.3
35 to 44	65	32.3
45 to 54	24	11.9
55 to 64	9	4.5
Total	201	100.0
Education Level		
Primary/Elementary School	24	11.9
Secondary/High School	119	59.2
Technical/Vocational Qualification	19	9.5
University Degree	35	17.4
No formal schooling	4	2.0
Architect	4	2.0
Construction Manager	7	3.5
Health and Safety Manager/Officer	10	5.0
Project Manager	5	2.5
Quantity Surveyor	11	5.5
Civil Engineer	6	3.0
Forman/Supervisor	15	7.5
Artisan	15	7.5
Construction Worker/Labourer	124	61.7
Other (site clerk and storage managers)	4	2.0
Architect	4	2.0
Total	201	100.0

The findings in Table 1, revealed there were more male respondents (81.6%) than female respondents (18.4%) from the sample. The results differ from those of the usual gender distribution of the construction workforce in South Africa which usually has less than 12% female workers. Majority of the respondents were between the ages of 25 to 34 years (43.3%). The second most prevalent age group were between 35 to 44 years (32.3%) of age followed by 45 to 54 years (11.9%), 18 to 24 years (8.0%) and lastly 55 to 64 years (4.5%). The construction workforce consists of older workers relative to other sectors as a result of the ageing workforce and lack of interest from the youth to seek employment in the sector. The average age of construction workers is 42.5 [25]. However, from Table 1, most respondents were between the ages 25 and 34 years. This can be attributed to recent changes because of Covid-19 as employment trends resulted in the youth experiencing the highest employment between February 2020 and March 2021 (32.5% to 35%), while older workers experienced a decrease from 45% to 41%. Therefore, the findings represent the current employment-to-population ratios in the industry. The responses were obtained from site personnel working for contractors and were representative of the construction workforce. Construction workers (labourers) and artisans make up about 55% to 70% of its workforce, while construction professional between 30% to 45%. When categorising the working groups into CPPs, and artisans/labourers, the percentage distribution is 29%:71%. Therefore, the sample represents the population of interest adequately.

3.2. Exploratory Factor Analysis

The measuring instruments for data collection of CMDs and coping were developed by the researcher based on literature and experience. In order to test for construct validity and to determine the number of factors necessary to explain the interrelationships among the set of variable mearing the constructs CMDs and coping, exploratory factor analysis (EFA) was used. Therefore, EFA assisted in the identification deemed suitable for measuring the factors of concern.

3.3. Data inspection for CMDs and Coping

To conduct EFA, data inspection technique was conducted to determine the sample adequacy required for EFA. The Kaiser-Meyer-Olkin test and Bartlett's Test for sphericity were used to test for sample adequacy. Based on the results in Table 2 and Table 3 the sample meets the size and variance requirements for conducting EFA based on the recommended thresholds for KMO (above 0.60) and Bartlett's Test for Sphericity ($p<0.05$) [26].

Table 2: KMO and Bartlett't Test CMDs

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0,804
Bartlett's Test of Sphericity	Approx. Chi-Square	421,066
	df	15
	Sig.	0,000

Table 3: KMO and Bartlett's Test Coping

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0,767
Bartlett's Test of Sphericity	Approx. Chi-Square	535,033
	df	36
	Sig.	0,000

3.4. Factor extraction and rotation

Principal Component Analysis (PCA) was the preferred factor extraction method because the research instrument of this study was designed by the author. PCA is data driven and provides an empirical summary of the data. In this study, no underlying theory about the factor structure was available precluding factor analysis (FA). Therefore, no prior assessment of the factor structure of the primary data existed. Only one solution was extracted for each of the constructs CMDs, maladaptive coping and adaptive coping .There was no need for factor rotation for this construction. The solutions were therefore, considered unidimensional and adequate evidence of convergent and discriminant validity was provided for the constructs.

For CMDs the correlation values of 6 components (depression, anxiety, stress, post-traumatic stress disorder and burnout) were above the recommended cut-off value of 0.30 and < 0.90. For coping, the correlation values for the 6 components (sport/exercising, spending time with friends, talking to someone, hobbies, sleeping and relaxing and walking in nature) measuring *adaptive coping* and the 3 components (alcohol consumption, cigarette smoking, cannabis smoking) for *maladaptive coping* were above the recommended cut-off value of 0.30 and less than 0.90. the other components were dropped and the retained components were deemed the most suitable for testing the hypothesised relationships.

3.5. WHO-5 Wellbeing Index

The WHO-5 was used to measure the subjective wellbeing of the individuals. It is a validated wellbeing measure and there was no need to conduct EFA. However, CFA and validity and reliability for the instrument were conducted along with other three constructs of the study. Table 4 presents the descriptive statistics for the overall score. WHO-5 measures wellbeing by calculating the raw score which is calculated by totalling the numerical values of the five answers - in this case the five means - where the raw scores range from 0 to 25, 0 representing the worst possible and 25 representing the optimum quality of life. The raw score is multiplied by 4 to obtain a percentage score ranging from 0 to 100 whereby, 0 represents the worst possible, whereas a score of 100 represents the optimum quality of life.

Table 4: WHO-5 Wellbeing Index Measure

	N	Mean	Std. Deviation
I have felt cheerful and in good spirits	201	4,04	1,296
My daily life has been filled with things that interest me	201	3,95	1,379
I woke up feeling fresh and rested	201	3,87	1,412
I have felt calm and relaxed	201	3,85	1,244
I have felt active and vigorous	201	3,77	1,341

For the result in Table 4, the total was determined by adding 4.04 + 3.95 + 3.87 + 3.85 + 3.77 which equated to 19.48. Furthermore, 19.48 x 4 = 77.92. Therefore, the WHO-5 score = 77.92. The score is above the cutoff score which is determined as ≤50. Scores < 50 are indicative of poor wellbeing. Therefore, it may be inferred that the workers had an overall good wellbeing but not optimum wellbeing.

3.6. Confirmatory Factor Analysis (CFA)

AMOS v28 was used to perform CFA. The model was assessed for convergent validity, and discriminant validity. Contrary to CFA, EFA is based on reasoning which is *a posteriori* in that it is data driven while CFA is based on reasoning which is *a priori* in that it is based on theoretical considerations. Therefore, assessing reliability and validity is a further check on how well the measurement items fit the theory *a priori*. The reliability and validity statistics are based on the factor loadings from the CFA and are shown in Table 5.

Table 5 Reliability and Validity

	Constructs	Item Correlation	Factor Loading	CR	AVE	Alpha
	Common Mental Disorders (CMDs)					
1	Depression	0,683	0,756	0,782	0,446	0,825
2	Stress	0,528	0,628			
3	Anxiety	0,653	0,735			
4	PTSD	0,588	0,644			
5	Burnout	0,621	0,677			
6	Suicidality	0,488	0,546			
	Maladaptive Coping					
1	CopingMLC1/MLDP	0,532	0,724	0,543	0,462	0,710
2	CopingMLC2/MLDP	0,559	0,69			
3	CopingMLC3/MLDP	0,525	0,622			
	Adaptive Coping					
1	CopingAC1	0,568	0,622	0,765	0,426	0,807
2	CopingAC2	0,630	0,728			
3	CopingAC3	0,611	0,728			
4	CopingAC4	0,689	0,761			
5	CopingAC5	0,465	0,539			
6	CopingAC6	0,448	0,491			
	WHO Wellbeing Index					
1	WHO1	0,683	0,804	0,805	0,747	0,863

2	WHO2	0,737	0,81
3	WHO3	0,686	0,666
4	WHO4	0,709	0,761
5	WHO5	0,597	0,813

The standardised factor loading of all items were > 0.40 which is fair. The recommended threshold values for the parameters are AVE ≥ 0.5. However, AVE = 0.40 can be accepted if the CR > 0.60 for the construct (Hair et al., 2019). The recommended threshold for CR between 0.60 and 0.70 is appropriate (ibid). Although 0.60 is sometimes used as a lower cut-off value, 0.50 is considered acceptable (ibid). The Cronbach alpha and composite reliability for all variables are > 0.70 so it shows that the variables had good reliability.

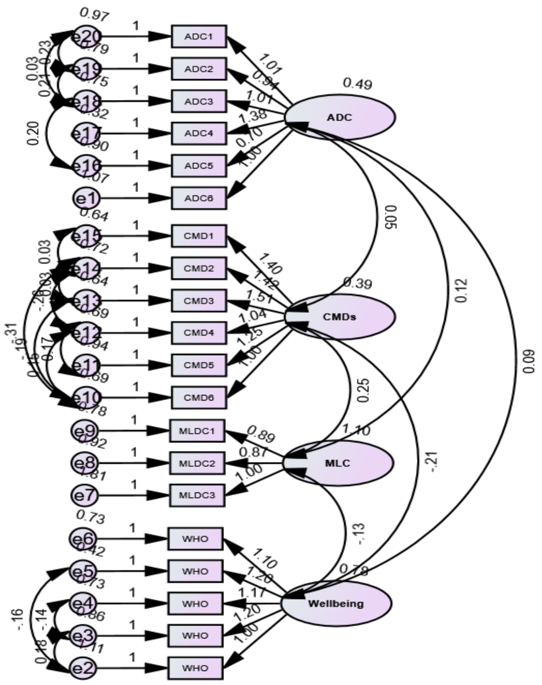

Figure 1 CFA Final Model

3.7. Testing the hypothesised relationships: Structural Equation Modeling

In order to test the hypothesised relationship *adaptive coping (ADC) and maladaptive coping (MLDP) mediate the relationship between CMDs and wellbeing (WB)*, structural equation modelling was used to test the relationships between the constructs indicated in Figure 2.

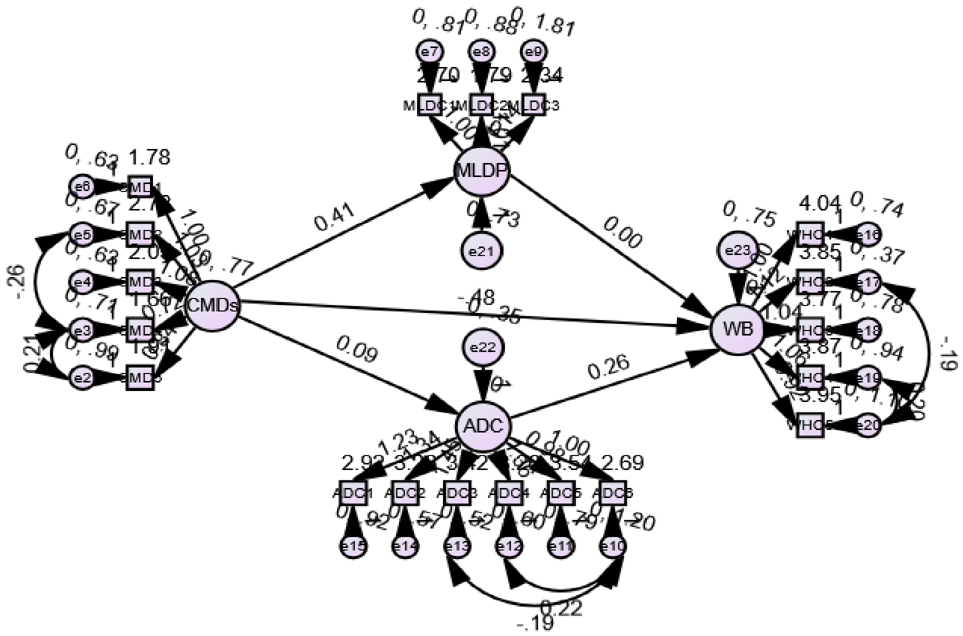

Figure 2 Structural Model

Table 5: Hypothesised Direct Relationships

H.No.	**Comments**	Paths	Regression Estimate	P	Remarks
H1	Positive Significant	Common Mental Disorders >Maladaptive Coping	0.41	***	H1 Supported
H2	Negative Significant	Common Mental Disorders >Adaptive Coping	0.091	0.123	H2 Rejected
H3	Negative Significant	Common Mental Disorders>Wellbeing	-0.477	***	H3 Supported
H4	Negative Significant	Maladaptive Coping>Wellbeing	0.003	0.978	H4 Rejected
H5	Positive Significant	Adaptive Coping>Wellbeing	0.259	0.049	H5 Supported
	Model Fitness: x2/df=1.752, CFI=0.924, RMSEA=0.061, NFI=0.843, RFI=0.810, IFI=0.926, TLI=0.908 and CN=201 (p<0.05)				

The hypothesed relationships based on path analysis show a positive and significant relationship between CMDs and maladaptive coping (β=0.44, P<0.000). The was no significant relationship between CMDs and adaptive coping (β=0.091, P<.05). CMDs were negatively and significantly associated with wellbeing (β=-0.477, P<0.000). The hypothesized relationship between maladaptive coping and wellbeing was not significant (β=0.003, P<0.978). Adaptive coping and wellbeing were positively and significantly associated (β=0.259, P<0.049). Based on these findings, the hypothesized relationships for H1, H3 and H5 were supported. However, H2 and H4 were rejected since p-value is not significant contrary to the hypothesized relationship.

3.8. Mediation Test

The mediation relationships were conducted by treating common mental disorders (CMDs) as an independent variable and wellbeing as dependent variable. Adaptive coping and maladaptive coping were treated as mediators. The mediation analysis is based on the analysis of indirect effects [27].

Mediation analysis was performed by using the standardized direct and indirect effects based on bootstrap procedures (500 samples) and bias-corrected bootstrap confidence interval (95%). The results are provided in Table 6:

Table 6: Mediation Analysis

H. No.	Path	Total Effects	Direct Effects	Indirect Effects	Remarks
H6	CMD>MLDP>WB	-0.420**	-0.429**	0.009(ns)	H6 Rejected since indirect effect is not statistically significant.
H7	CMD>ADC>WB	-0.422**	-0.436**	0.014(ns)	H7 Rejected since indirect effect is not statistically significant.

ns=non-significant, *<.05, **<.01, ***<.001

Result shows that based of the hypothesized relationship; coping as a mediator between common mental disorders and wellbeing, both maladaptive (β=0.009, P<0.716) and adaptive coping (β=0.014, P<0.191) did not have any significant relationship between CMDs and WB.

4.0. DISCUSSION

The data in Table 5 indicated that of the 5 hypothesised direct relationships, 3 hypothesis were supported and 2 rejected. H1 revealed that there was a positive and significant relationship between common mental disorders and maladaptive coping. This is line with most literature findings [28],[29],[30]. The three maladaptive coping strategies for the current study were linked with the use of alcohol, cigarette smoking and cannabis smoking. These drugs have been liked to several mental disorders such as depression and anxiety. They are may distort perception and affect the workers performance. In the construction industry, most workers resort to maladaptive coping as psychostimulants avert the effects of common mental disorders resulting from work stressors [23]. This is a challenge for the industry which relies heavily on manpower and a call for serious intervention to educate workers on how to cope with work demands.

From the findings, it was also evident that common mental disorders negatively impacted the wellbeing of the workers. Work stressors/demands lead to physiological, behavioural or psychological manifestations of stress or strain, and subsequently result in poor wellbeing [16]. The Job Demand Control Support Theory (JDC/S) assumes that strain which leads to CMDs results from an imbalance between job demands and decision latitude (control) in the workplace, where the lack of control is perceived as an environmental limitation on response capabilities and health outcomes [31]. It may be inferred that the findings are in line with the JDC model. Bowen et al. [23] conducted studies in South Africa which focused on compering the perceived relationships between job stress and job demand, control and support (JDC/S) issues among construction project professionals (CPPs) and the findings revealed that depression was still the most underrated mental disorder. While this study focused on several CMDs and the general workforce, it worth noting that not only depression is underrated but CMDs in general.

Adaptive coping had a significant and positive effect on the wellbeing of workers. Based on the psychological theory of stress [31], the systematic theory of stress [32], both coping and an individuals' desire to return to homeostasis after encountering a stressful situation contribute positively to an individuals' wellbeing. Therefore, it may be inferred that adaptive coping minimises the effects of occupational demands on individual workers.

Contrary to expectation, there was no significant relationship between CMDs and adaptive coping. it may be inferred that adaptive coping strategies investigated in the study were mainly attributed to social support (talking to friends/loved ones; talking to someone), active coping (sports/exercise; hobbies), religious coping (spending time in nature) and avoidance coping which may temporarily be adaptive in some instances. Further, Maladaptive coping did not have any significant effect on wellbeing. The opposite would have been expected based on literature. However, this may be attributed to temporary alleviation of job strain. Although it is widely accepted that maladaptive coping affects wellbeing, the findings of the study were based on subjective wellbeing. it is therefore unclear whether workers resorting to substances may constitute as a positive factor or whether this can be attributed to anecdotal evidence among the workforce regarding the use of substances as a feel good habit or to gain strength. for example, most workers who use cannabis claim it gives them strength [33] and is an natural herb. Therefore, further studies may be necessary to investigate the perceptions of workers towards substances and the effects of maladaptive coping using multi-faceted wellbeing measures [34] covering *eudaimonic wellness, hedonic wellness and quality of life.* The current study only focused on wellness with specific focus on subjective wellbeing which is attributed partly to hedonic wellness and wellness.

For the hypothesised relationships of the study: *adaptive coping and maladaptive coping mediate the relationship between CMDs and wellbeing*, there was no significant relationship suggesting neither adaptive coping nor maladaptive coping mediated the effects of common mental disorders and wellbeing. While coping strategies affect mental health and indirectly affect wellbeing, it is imperative to focus on strategies such as problem based coping and emotional based coping to buffer the effects of mental health on workers wellbeing. Furthermore, several studies have revealed that problem- focused coping (efforts to modify the source of the stress) is more effective than emotional focused coping (attempts to regulate the emotional distress caused by a stressor) in stress management, depression and anxiety among construction professionals [35],[36]. Emotion-focused coping may lead towards avoiding dealing with the source of stress, however, the current study did not focus on these strategies. Therefore, an important emerging issue is the need to investigate typologies of coping strategies among the construction workforce to better understand which ones are more effective. It was also surprising to note that maladaptive coping did not have any significant indirect relationship. this call for further investigation.

5.0. CONCLUSION

This study investigated coping as a mediating effect between common mental disorders and wellbeing. For adaptive coping, the study only focused on active coping, avoidance coping, social support and religious coping. Further studies should focus on emotional-focused coping and problem-focused coping strategies. Another limitation was the use of one scale to measure wellbeing. Future research should be done to investigate other wellbeing areas to include multiple facets of wellbeing such as eudaimonic wellbeing, hedonic wellbeing and quality of life. The current study only focused on wellness in relation to subjective wellbeing due to the ease of administering the WHO-5 Wellbeing Index. Future studies should also focus on the use of a mixed method approach and other psychological wellbeing health scales to gainer in-depth understanding about the workers mental health. Furthermore, the sampling method used in the study faces challenges associated with self-report questionnaires such as response bias, social desirability, introspective ability, understanding and limitations with rating scales. This study is important as it informs areas of concern regarding different coping strategies employed by the construction workforce and how they affect their wellbeing. Important emerging issues from the study are the lack of mediation between the hypothesised relationships. This may be attributed to the types of coping strategies investigated. Another issue is the insignificant relationship between maladaptive coping and wellbeing. Although it is widely accepted that maladaptive coping affects wellbeing, this was not the case. Therefore, it is imperative to investigate the perceptions of the workers towards substances since the study only focused on subjective wellbeing in relation to the WHO-5 Wellbeing index.

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MENTAL HEALTH AND WELLBEING EXPERIENCES OF HIGHER EDUCATION APPRENTICES

Nnedinma Umeokafor[1] and Chioma Okoro[2]

[1] *School of Engineering, University of Greenwich, London (UNITED KINGDOM)*

[2] *College of Business and Economics, University of Johannesburg (SOUTH AFRICA)*

Abstract

Improved mental health and wellbeing (MHW) of students has positive implications for their engagement, performance, and satisfaction. Consequently, the MHW of higher education students has been examined; however, the MHW of higher education apprentices, who are underrepresented students, has received little or no attention. Using a university in the UK as a case study, the reported study examines the MHW experiences of higher education apprentices and improvement strategies. A questionnaire survey was adopted. Mean and standard deviation scores as well as the Mann-Whitney U test were used to analyse the data using SPSS. The study found that stress from the academic programme, poor quality of life, and apprentices worrying about the programme's worthwhileness were the top experiences. Further findings revealed that a higher demonstration of institutional commitment, understanding of their diverse circumstances to accommodate them better, and the lecturer/tutor being approachable are critical improvement strategies. Significant differences in the MHW experiences of the apprentices based on their programmes of study (construction and non-construction) were found for three indicators including stress from the academic programme, level of programme worthwhileness (apprentices' feeling), and previous day level of happiness. While interviews and digital stories are recommended to gain a deeper understanding of these issues, higher education institutions (HEIs) and scholars could conduct similar research using the current study as a framework.

Keywords: Apprentices; Underrepresented students; Student engagement and performance; Diversity, equality, and inclusion; Male and female; Mental health and wellbeing.

1. INTRODUCTION

The historic inclusion of mental health and wellbeing (MHW) in the Sustainable Development Goals (SDGs) by the United Nations (UN) has placed it at the forefront of global and corporate agenda [1, 2]. This stems from the poor global MHW records. According to the World Health Organisation (WHO) [3], in 2019, 15 percent of working-age adults have a mental disorder, and annually, 12 billion working days are lost to depression and anxiety, costing 1 trillion dollars due to lost productivity. A similar case is reported in industries such as construction where in the United Kingdom (UK), male workers are three times more likely to die from suicide than the national average [4]. In 2022, a survey by Mates in Mind among 300 self-employed construction workers in the UK indicated that one-third experienced high levels of anxiety each day [4]. A survey of higher education students and staff in ten countries including France, Spain, Australia, Netherlands, the UK and the United States (US) in 2022 found that 73 percent of higher education students and staff, respectively, struggled to maintain their wellbeing [5]. A Healthy Minds Network and American College Health Association survey of colleges and universities in the US showed that mental issues have a negative impact on academic performance [6]. Further, Lipson et al. [7] analysed ten-year (2007 to 2017) mental health data of undergraduate and graduate students in the US. The study surveyed the participating institutions and found that the portion of students with lifetime diagnoses increased from 22 to 36 percent, just like depression (43.3 to 55.8 percent) and suicidal ideation (5.8 to 10.8 percent). However, the rate of treatment increased, and stigma reduced.

However, despite the plethora of studies on the MHW of higher education students, there are still significant gaps. For example, construction and built environment students fall into two industries/sectors with poor MHW record as demonstrated in the preceding paragraph. However, the MHW of apprentices has received limited attention [8]. Park et al. [9] examined the MHW lived experiences of university students in a large Mid-West University in the USA using semi-structured interviews. However, the students were not apprentices. Carette et al. [10] explored the factors that affect students' knowledge of psychological wellbeing using semi-structured interviews but not on construction students and apprentices. Using survey in Australia, Turner et al. [11] examined the resilience of built environment students regarding their wellbeing. The focus of Scott-Young et al. [8] was gender (male and female) inequality in the mental health of built environment students. Hernández-Torrano et al. [12] conducted a systematic review of literature on university students' MHW (from 1975 to 2020) while Smith et al. [13] examined the role of student peers in the MHW of higher education students with a focus on six UK universities. Mental health of international students was reported in Frampton et al. [14] and the mental and wellbeing lived experiences of university students were covered in Park et al. [9]. Other studies such Schettino et al. [15] and Okoro et al. [16] did not address the gaps stated above.

Further, students' MHW improvement strategies are still limited or non-existent in some HEIs. For example, Pollard et al. [17] reported the limitations in the MHW improvement strategies and efforts in HEIs in England. Only 52 percent of the HEIs surveyed had specific strategies for improving student mental health and/or wellbeing. Forty-three percent combined them while one and seven percent were dedicated to wellbeing and mental health strategies, respectively. By implication, examining MHW as separate concepts is challenging [17] and as high as 48 percent had no mental health and/or wellbeing strategy.

Therefore, the current study examines the MHW experiences of underrepresented students, apprentices. The nature of apprenticeship delivery presents unique challenges which result in or exacerbate MHW challenges. Unlike full-time candidates, apprentices spend longer time working (four days); 20 percent is supposed to be for studying and lecturers [18] and some travel long distances to the university/college. The success of their programme is dependent on their success at work and HEIs. Hence, they must balance work, domestic responsibilities and study. While this has implications for their MHW, the older ones among them may have a higher domestic responsibility; hence, at a higher risk of mental health issues. It also impacts the Teaching Excellence Framework and National Student Survey [19] and the performance and satisfaction of the apprentices. As a result, there are calls to develop strategies tailored to them to improve their experiences [19] of which MHW is inclusive. However, the MHW of apprentices is influenced or impacted by the delivery and model of the programme, which is underexamined [20].

Therefore, the current study examines the MHW experiences of apprentices using a university in the UK. The objectives were to 1) evaluate the MHW experiences of apprentices, 2) Identify MHW improvement strategies for apprentices and 3) Determine the differences in MHW experiences among apprentices based on gender and programme of study.

Higher education institutions and construction workplaces will be informed about the experiences of apprentices and develop strategies to support them and reduce the impacts on their MHW. The rest of the paper presents an overview of literature on MHW of apprentices and improvement strategies, followed by the methods employed to conduct the study.

2. LITERATURE REVIEW

2.2. Apprenticeship delivery model and MHW implications

In addition to the time limitations resulting from the apprenticeship programme, it operates a tripartite agreement system, involving the employer, HEIs and apprentices (Quality Assurance Agency (QAA) for Higher Education [21]. The role of employer representatives, professional, statutory, and regulatory bodies are also noted by the QAA [21]. These various systems present complexities in delivering, communicating and meeting the students' needs; sometimes, students are not assigned tasks that align with their learning at a given time [20]. Given that the programme is dependent on work-based learning [23], the apprentices' learning is impacted. This is exacerbated by the limited independent individual study time they have [20] and when HEIs struggle to connect learning with work-based activities, the learning stress increases [23]. Alsubaie et al. [24] found that the lack of social support impacts on the MHW of apprentices compared to the traditional ones. Therefore, there is a need for more attention on the MHW of apprentices in higher education.

2.3. Mental health and wellbeing indicators in higher education students

Pollard et al. [17] and Hughes and Spanner [25] recognise the challenges in measuring the MHW of higher education students. For example, there is a lack of data on the prevenance of MHW of students and the effectiveness of the common strategies adopted [25]. The extant data mainly focuses on one university, limiting generalisation (ibid.). Further, 'many interventions … available in universities are not evaluated in context or, where they are, the evaluations are not shared outside of the institution to support sector learning… All of which means that there is a lack of clarity about what constitutes good practice' [25:73]. Furthermore, many studies and surveys of students use different methods, measures, and samples to improve coverage and reliability, but they are flawed because of some points above and their inability to be compared to non-student population [17]. Another challenge to measuring MHW is the constant change in the MHW experience, especially those transitioning to adulthood (aged 10 to 29) [9]. Consequently, what constitutes good practice is unclear due to lack of reliable and robust data/information [17, 25]. However, Savarese et al. [26] proposed and tested indicators in three categories including psychological manifestations, family and social relations and quality-of-life indicators. Although not without limitation just like other above, it is incorporated in the framework for measuring MHW in the current study, as summarised in Table 1.

Table 1: Mental health and wellbeing indicators in higher education students

Indicators	**Sources**
Psychological manifestations	
Anxiety disorders	[27- 28]
Anxiety, depression	
Negative thoughts, images, memories, and feelings (revisiting)	[26, 29]
Reactivation of a previous trauma (post-traumatic stress disorder (PTSD)) and PTSD from Covid-19	
Repercussions on self-esteem and self-efficacy	[26]
Family and social relations	
Stress due to forced cohabitation with family	[26, 28]
Difficulties in long-distance relationships (loss of friendships, end of romantic relationships)	[26]
Difficulties related to social and relational limitations	[26,29]
Quality-of-life indicators	
Feeling fit, exercising, and consuming more alcohol	[26]
Declaration of having slept well Percent	[26, 30, 31]
Declaration of having had appetite changes	[26, 32]

2.4. Mental health and wellbeing inequality in higher education

Studies show the influences on MHW, for example, gender [8, 27] and background [33]. Poor MHW exacerbates inequality in higher education among students [33]. For example, Robertson et al. [33] found that underrepresented and/or disadvantaged groups (who have low attainment, progression to employment/postgraduate studies, and less likelihood of completing their studies) are at a higher risk of having or experiencing poor MHW in higher education. These are students from low-income backgrounds, consisting of the care-experienced ones, those from Black, Asian and Minority Ethnic groups, mature students and LGBTQ+ students. Similarly, Liu et al. [27] found a statistical difference between male and female students in HEIs in terms of distress manifestation, emotional panic and exposure to the risk of contagion. If this is the case, it can be argued that the same may apply to apprentices. Hence, the current study also investigates if there is a difference in the MHW strategies and experiences of male and female apprentices, and between construction and non-construction students.

2.4.1. Mental health and wellbeing improvement strategies for higher education students

Improvement strategies are proactive, preventive, and reactive [17]. The need for student involvement in the development of MHW strategies was stressed in the literature [10,34]. This enables a platform for them speak out, especially if the staff are approachable and discuss academic work and MHW challenges [9, 10, 34]. Given the diverse and changing nature of the students, this should be constant with adequate time dedicated for it [9]. This will depend on the availability, awareness and promotion of a range of services including counselling, academic skills development, advisory services and greater commitment from the institutions [17, 34].

Table 2 summaries the strategies from the literature, which are refined based on the features of higher education apprenticeship delivery. For the apprentices, some strategies in the table may be unique given the nature of the programmes including delivery environment. However, one main issue is the lack of adequate consideration of the difference in the delivery of the programmes in the development and implementation of these MHW strategies in HEIs. The students on the traditional pathways (non-apprenticeship routes), especially the full-timers received more attention, with strategies/policies skewed to them [18].

Table 2: Summary of MHW improvement strategies for Higher Education students

Improvement strategies	Sources
Ensuring lecturer/tutors are approachable to students	[9, 34]
Making clear staff/learning expectations of student	[34]
Building relationships between staff and students including through pastoral care	[9, 17, 34, 35]
Increasing individual learning support e.g. providing more feedback	[34]
Improving and monitoring student engagement in learning by using a variety of activities	[17,34]
Improving awareness and availability, range, and quality of services	[17, 34, 35]
HEIs demonstrating greater understanding of students' diverse circumstances and commitments and accommodating them	[10, 34]
Fostering inclusive and caring sense of community among the student body,	[17,34]
Involving students in co-creating activities, programme, and university policies	[10, 17, 35-38]
Seeking students' views on improving their wellbeing	[9,10,34, 35]
Allocating more time for independent study	[20]

3. METHODOLOGY

Given the research questions/objectives, the positivist paradigm was deemed the most appropriate for addressing them. Hence, a questionnaire survey was adopted. This is because quantitative methods such as surveys excel in addressing 'what' questions and assessing relationships [39]. Following a literature review, the data collection instrument was developed. The first section examined the background of the apprentices. The others focused on the apprentices' experience of MHW indicators including the stressors in ordinary scale (from 1 to 5) where 1 is the 'strongly disagree' and 5 'strongly agree'. The middle scale is 'neither agree nor disagree'. For the MHW improvement strategies, the importance was measured using a scale ranging from 1 'not important' to 5 'very important'. Ethical approval for the project was obtained from the university's Research Ethics Committee. Apprentices in all the departments in the institution were approached, a total of 294. These were in construction and non-construction fields including civil engineering, surveying, nursing environmental science, and business programmes, hence the availability of data for the inferential analysis. Studies have conducted inferential statistics with a smaller number of responses, 37 [40]. The study was advertised, and invitation sent to respondents. Convenience sampling was used to include those who were willing and available to participate. The participation information sheet covered key ethical considerations, the study's purpose, and participants' rights (voluntary participation, anonymity, confidentiality, and so on). Of the questionnaires distributed, 40 (33.6 percent) were received and used for the analysis.

The collected data were analysed using the Statistical Package for Social Sciences (SPSS) where descriptive statistics (frequency, mean score (MS), standard deviation (SD), and percentages) and inferential statistics (Mann-Whitney U Test) were conducted. The Mann-Whitney U Test was conducted to see if there are significant differences in gender (male and female) and programme of study (construction (civil engineering and surveying) and non-construction (environmental sciences and others). The Mann Whitney U test is used for ordinal or continuous data to check for significant differences between two independent groups. The test was conducted at a significance level (p-value) of 0.05. This means that for the null hypothesis (no significant difference) to be rejected, the p-value must be less than or equal to 0.05.

4. RESULTS AND DISCUSSION

4.1 Respondents' profile

Of the 40 respondents, 29 are employed by engineering organisations, five in environmental sciences, one in surveying, and the remaining in others (including nursing and business). However, their programmes of study are different: 26 are in Civil Engineering Level 6, one is in the Chartered Surveyor Level 6, 11 take the Environmental Practitioner route and the remaining are in others. The levels of study ranged from 4 to 6 and their age range from 18 to 20 (9), 21 to 24 (18) and 25 and above (13). There were 15 female, 23 were male and two selected the gender-neutral option. Their ethnicities are: White (29), mixed/multiple races (1), Asian (4), Black (4), and others (1), one respondent did not indicate the ethnicity. The respondents were diverse in the field of employment, qualification route, age and gender. Therefore, it was possible to compare the differences between the independent groups (based on gender and programme type).

4.2 Mental health and wellbeing of higher education apprentices

The indicators of higher education apprentices' MHW found in literature (Table 1) were analysed. The top ten are presented in Table 3. Academic programme-induced stress such as attending university ranked first (MS 3.90; SD 1.033) followed by quality-of-life indicators (MS 3.53; SD 1.012) and the value attached to the programmes (MS 3.50; SD 1.301).

These findings are consistent with Savarese et al.'s (2020) study, which identified the academic programme and quality of life (insufficient sleep) as key stressors, especially while transitioning to higher education. The findings also support concerns in literature on the features of apprenticeship delivery being a key stressor [20, 23, 24]. The first two highest ranking factors support this which may explain the value attached to the programmes (ranked 3rd) despite the financial benefits, apprentices being paid while they study, graduating with professional qualifications and no debts from students' loan [20]. This is revealing as the associated stress from the programmes has implications on the number of intake or recruitment of apprentices.

Regarding the low-ranking factors, the level of anxiety from the previous day ranked low, whereas in Polland et al. [17], there were high levels of stress and anxiety among non-apprenticeship students in several higher institutions. However, stress is also ranked the highest in Table 3. A possible explanation is the characteristics of apprenticeship delivery which are different from the traditional students. Nevertheless, the implication is the need to examine this in detail.

The top ten factors were subjected to inferential statistics. The Mann-Whitney U test results for gender and study programme are presented in Table 3. The results showed that for gender, the p-value for all the factors is not equal or less than 0.05. Hence, the null hypothesis for gender cannot be rejected. Therefore, there is evidence to conclude that there are no differences in the MHW experiences of male and female apprentices. For the programme of study, the null hypothesis is rejected for three indicators (Stress from academic programme; Level of programme worthwhileness: Apprentices' feeling; and previous day level of happiness) as the p-values are less or equal to 0.05. Hence, the evidence suggests statistically significant differences in three indicators.

Table 3: An assessment of the MHW indicators of higher education apprentices

Indicators				Gender			Programme of study		
	Mean	**SD**	**R**	**U**	**Sig**	**Z**	**U**	**Sig**	**Z**
Stress from academic programme	3.90	1.033	1	117.5	.085	-1.723	91.5	0.15*	-2.424
Quality-of-life — comfortable & affordable; sport, fitness	3.53	1.012	2	125	.139	-1.480	129	.215	-1.241
The feeling of apprenticeship worthwhileness	3.50	1.301	3	143	.361	-.914	85	.010*	-2.590
Consequences of self-esteem and self-efficacy	3.35	0.893	4	131.5	.194	-1.298	167	.950	-.063
Previous day level of happiness	3.05	1.260	5	120.5	.108	-1.606	85.5	.010*	-2.569
Involving apprentice in decision-making	3.05	1.108	6	165.00	.813	-.237	157.5	.716	-.364
Negative feelings, memories, and thoughts	3.05	1.339	7	134.5	.246	-1.160	153.5	.188	-.472
Extent of satisfaction recently	3.03	1.165	8	138.5	.284	-1.071	143	.415	-.815
Feeling of depression in the past two weeks: The extent	3.05	1.261	9	147	.434	-.783	125	.188	-1.318
Level of anxiety the previous day	2.98	1.4234	10	123	.123	-1.541	140.5	.377	-.883

Keys: Standard deviation (SD); Mann-Whitney U (U); Asymp. Sig 2-tailed (Sig); Relative importance index (R); Z-Score (Z); *significance at ⩽0.05

4.3 Mental health and wellbeing strategies for higher education apprentices

Table 4 contains the ten highest ranked MHW strategies based on the importance to the apprentices. It shows that the first three high-ranking factors are dependent on the educational institutions where they must ensure that lecturers are approachable to apprentices (MS 4.54; SD 0.913), seek to understand and accommodate the diverse circumstances of apprentices in curriculum development and delivery (MS 4.54; SD 1.022), and ensure that the lecturers improve the communication of their expectations of apprentices (MS 4.28; SD 1.099).

Further, Table 4 presents the results of the Mann-Whitney U Test on the MHW strategies to see if there are differences due to gender and programme of study. As no p-value is less than or equal to 0.05, the null hypothesis cannot be rejected for all. Hence there is no evidence to conclude that there are statistically significant differences on the level of importance of the MHW improvement strategies to apprentices.

MHW concerns are evidenced in the literature review section (for example, Liu et al. [27], Scott-Young et al. [8]; and Robertson et al. [33]) as a major concern. The apprentices viewed the inclusion of their circumstances in curriculum design and delivery to improve their MHW as the most important way to improve their MHW (MS 4.54; SD 1.022). This is supported by the findings of the Mann-Whitney U Test where three of the ten factors indicate differences in the experiences of the apprentices in terms of the programme of study (Table 3). In contrast, no differences in the MHW experiences of the apprentices were found in seven MHW indicators (Table 3) and all the strategies (Table 4). The lack of agreement between the finding of the current study and previous studies can be explained by the small sample size of the current study, and the characteristics of the apprenticeship programme delivery. However, as supported by Liu et al. [27], Scott-Young et al. [8] and Robertson et al. [33] any MHW policies and strategies in HEIs must be inclusive to be effective and efficient. Further, this is supported by 'HEIs accommodating the diverse circumstances of apprentices in curriculum design and delivery' (a high-ranking strategy based on apprentices' perception of importance). This suggests perceived discrimination in learning among the apprentices. However, it is unclear how effective and efficient the strategies in Table 4 will be until tested. Nevertheless, their views have implications for the MHW, learning experience and satisfaction [20, 23] hence should not be taken for granted. By implication, addressing equality, diversity and inclusion issues in curriculum design and delivery will likely improve apprentices' learning experience, satisfaction and MHW.

Table 4: An assessment of the importance of MHW improvement strategies for the higher education apprentices

Strategies				**Gender**			**Programme of study**		
	Mean	**SD**	**R**	**U**	**Sig**	**Z**	**U**	**Sig**	**Z**
Ensuring lecturers are approachable	4.54	0.913	1	167	.837	-.206	132	.169	-1.376
HEIs accommodating the diverse circumstances of apprentices in curriculum design & delivery	4.54	1.022	1	141.5	.214	-1.244	165	.872	-.162
Improved clarity on lecturers' expectations of apprentices	4.28	1.099	2	169.5	.919	-.102	145	.478	-.718
Increase apprentices independent study times	4.28	1.050	2	149.5	.433	-.784	139	.304	-1.027
Increase individual learning support for apprentices	4.15	1.065	3	151	-.691	.490	138	.318	-.988
Employers and HEIs establishing culture of speaking out for apprentices.	4.15	0.875	3	159.5	.677	-.416	159	.750	-.318
Employers and HEIs committing to apprentices' MHW	4.08	0.882	4	145.5	.606	.515	132	.424	-.799
Improvement is educational institutions services (range, availability and quality)	4.03	0.959	5	114.5	.068	-1.802	121.5	.135	-1.494
Improve apprentice engagement through various activities	3.92	0.900	9	115.5	.071	-1.802	124	.154	-1.424
Improving interactions between lecturer and line managers of the apprentices	3.90	1.095	10	145	.390	-.859	145	.463	-.734

Keys: Standard deviation (SD); Mann-Whitney U (U); Asymp. Sig 2-tailed (Sig); Relative importance index (R); Z-Score (Z); *significance at ⩽0.05

5. CONCLUSION AND RECOMMENDATIONS

The current study examined the MHW of underrepresented students using apprentices in a HEI in the UK. It found that 'stress from the apprenticeship programme' is the highest stressed followed by the 'poor quality-of-life' which can be explained by the structure of the programme. Despite the benefits and incentives for apprenticeship, the challenges encountered in the programme result in the apprentices questioning its worthwhileness which ranked third as a stressor. The implications of this on the intake/recruitment into the programmes is poorly understood; hence, further research is recommended. The study supports findings in the extant literature on the differences in MHW experiences regarding three indicators including stress from academic programme, level of programme worthwhileness (apprentices' feeling), and previous day level of happiness. No differences in the perceptions of the apprentices on the MHW strategies was found.

To improve the MHW experiences of the apprentices surveyed, more opportunities to communicate with the lectures/tutors should be provided. In addition, the inclusion of their diverse circumstances in curriculum design and delivery is recommended. Higher education institutions, construction stakeholders and researchers could use the current study as a framework to develop strategies to support apprentices and reduce the impacts on their MHW.

A major limitation of the study is the single source of data (one HEI), which limits generalisation. Further research using more universities is recommended. Qualitative research such as interviews and digital stories are recommended to gain a deeper understanding of these concerns and strategies and to explain the apparent inconclusive findings.

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A CRITICAL ASSESSMENT OF MENTAL HEALTH RESEARCH IN CONSTRUCTION INDUSTRY

Siddharth Bhandari[1], Fred Sherratt[2], and Evan Stoddard[3]

[1]Research Faculty and Associate Director of Construction Safety Research Alliance, Dept. ofCivil, Environmental, and Architectural Engineering, Univ. of Colorado Boulder, Boulder, CO.Email: siddharth.bhandari@colorado.edu
[2]Associate Director of Construction Safety Research Alliance, Dept. of Civil, Environmental, andArchitectural Engineering, Univ. of Colorado Boulder, Boulder, CO. Email: fred.sherratt@colorado.edu
[3]Graduate Research Assistant, Dept. of Civil, Environmental, and Architectural Engineering,Univ. of Colorado, Boulder, CO. Email: evan.stoddard@colorado.edu

Abstract

An issue as serious as mental health and suicide prevention demands the utmost scientific rigor in its investigation. Yet a structured review of research on mental health illness and suicides, antecedents of poor mental health, and proposed interventions in the construction industry have major limitations that may lead to ineffective and even potentially dangerous interventions. The review presented in this paper reveals much of the work undertaken in the construction domain is based only on correlations, pseudoscience, and positivistic explorations rooted in confirmation bias. Indeed, many solutions proposed by academics and so-called thought leaders have in some instances been labelled as potentially harmful by clinical psychologists in peer-reviewed publications. The resulting morass from research that is not firmly rooted in appropriate scientific methods has encouraged some construction practitioners to accept dogmas as unquestionable scientific axioms. The critical review presented here seeks to highlight key gaps in the body of knowledge, while providing guidance on how practitioners can begin to better understand the potential impacts of mental health interventions. The aim of this article is to open a dialogue and debate within the construction community on the role of organizations in combatting mental health-related issues, whilst encouraging the careful interrogation of any proposed solutions against preset standards of success and failure.

Keywords: work-related stressors, employee assistance programs, and performance metrics.

1 INTRODUCTION

Workers in the construction industry have suicide rates that are orders of magnitude higher than any other industry in the U.S. [1]. Studies have found that most construction workers reported experiences with serious mental health issue [2], a concern exacerbated by the poor culture surrounding mental health within the industry e.g., stigma, peer-pressure, alcohol and substance abuse etc. [3-5]. This is true for most developed nations from which reliable research is emerging to show construction workers are posting high rates of mental illness diagnosis, long-term disorders, addictions, and suicide rates [3,15- 18]. For the long-term sustainability of this critical global industry that is highly dependent on its human resources, there is a need to understand the what, why, and how of poor mental wellness among construction workers. In this study, the focus will be on construction workforces in North America, United Kingdom, and Australia because they have significant similarities in work methods, demographical makeup, and other demographic characteristics.

Foundationally, Fig. 1 illustrates the goals of the construction engineering and management (CEM) academic and professional community within this space. It is a highly simplified model that does not represent a medical position on treating mental health; however, for the purposes of this paper it demonstrates the three key areas in which mental health of construction workers is currently being studied [2-6]. Specifically, both research and practical efforts within the CEM domain have been focused on identifying which stressors (personal and work-related) are negatively impacting the mental health of employees and testing the efficacy of interventions touted to minimize the impact of stressors, to facilitate positive mental health outcomes.

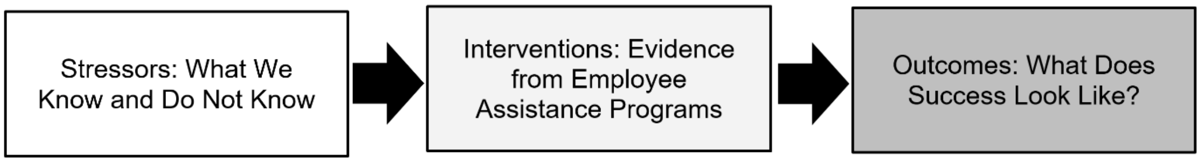

***Fig. 1*:** Foundational Framework

This paper tackles each of the constructs in Fig 1 individually and demonstrates that **some** of the research being conducted and the interventions being proposed are potentially ineffective and harmful. Given the burgeoning nature of research on mental health in the CEM domain, the authors intend to layout the basis for an argument that supports the creation of a better framework for reviewing mental health research and wellness research and practices. Based on interdisciplinary research grounded in scientific methods, this paper proposes some guidance for practitioners and future researchers on potential pathways to avoid biased, pseudo-scientific, or context-dependent evidence with limited validity.

A search was performed to capture key publications on this subject using a wide variety of individual or combined keywords. These key words included but were not limited to “construction,” “suicide,” “mental health diagnosis,” “stressors,” “Employee Assistance Programs (EAP),” and “work-related antecedents to poor mental health.” These keywords were searched in the following recognized databases and indexing tools: Google Scholar, Web of Science; Engineering Village; PubMed; PsychInfo; and the American Society of Civil Engineering. The literature reviewed was used to critically evaluate the research being performed and suggest pathways for future research.

2 STRESSORS IN CONSTRUCTION: WHAT WE KNOW AND DO NOT KNOW

A stressor is defined as stimuli within an individual’s environment that causes long lasting and measurable negative psychological or neurological change. Stressors can lead to different kinds of mental health issues ranging from negative affective mood states to suicide ideation. Unfortunately, a universal definition for a *clinically diagnosed* stressor is contentious and confounded by not only the inconsistencies in opinions among medical professionals [13, 24] but also a number of psycho-social facets [22- 23]. The authors adopted the aforementioned definition which is based on the seminal work published in peer-reviewed literature [19- 21] because it sets a high bar for what constitutes as a stressor which increases the relevancy of the discussion presented below. By classifying stressors as the agents that have been empirically proven to cause negative physiological impacts on critical organs and chronic neurological strains [25-31], the discussion presented below has high significance from an individual and organizational perspective. Indeed, the medical community itself is still debating definitions, diagnoses and treatments, and therefore strict adherence to a definition with objectively measurable outcomes in individuals will help reduce subjectivity and any implicit biases in this paper.

Table 1: Evidence on Work-related Stressors found in Construction Industry

Work-related Stressor	Definition	Evidence QualityMedical)
Sexual Harassment and Assault [32-35]	Although harassment and assault are not similar, the stressor here captures offensive sex-related acts in workplace.	Causal with high external validity
Bullying [36-37]	Repetitive negative and aggressive actions taken that canbe verbally or physically abusive in nature.	Causal with high external validity
Discrimination[38-39]	Systemic practice of treating any individual or group ofpeople less fairly than others.	Causal with high external validity
Job Demand[40, 42]	The physiological and psychological demands placed onthe individual by the work they are performing.	Correlational with high external validity
Social Isolation[48]	The weakening relationships that threaten the sense of contact and belongingness causing social disengagement.	Causal with low external validity
Traumatic event[49]	A traumatic event is any “exposure to actual or threatened death, serious injury or sexual violation”	Causal with high external validity
Financial Uncertainty [50]	The chronic uncertainty in the sustainability and security of economic future.	Correlational with high external validity
Poor physicalhealth [51]	The degree to which the physical health is beingnegatively impacted by work.	Causational with low external validity
Work-life balance [52]	The degree to which an individual is able to achieve work-related and non-work-related goals.	Correlational with high external validity

The stressors noted in Table 1 have been summarized based on the work produced by [4; 8-9; 14] wherein the authors conducted a comprehensive review of studies on mental health published in the construction domain. This list only represents the work-related stressors found within the construction industry context. To ensure a reasonable scope, stressors that are not work-related (e.g., COVID-19, politics, major societal events etc.) [10-11] were not included in the analysis. Additionally, stressors that had significant overlap in their definitions were combined into one unit of analysis (e.g., work overload, hours worked, and work burnout were considered part of one theme: job demand) as a separation was not warranted from a clinical standpoint. Finally, stressors that have been noted in literature as potential negative coping strategies (e.g., substance abuse, addictions etc.) [12] were not included because it is not possible to consistently determine if they are direct, mediating, moderating, or after-the fact causes of poor mental health [13].

Causal Evidence: All the stressors noted in Table 1 are negative in nature and have been found to have causal links to mental health. For example, sexual harassment, sexual assault, and bullying, across different contexts and experimental constraints [32-37] impact the neurochemistry of human beings albeit to varying degrees. Because of the strong generalizability of this work, construction researchers may directly apply this knowledge to minimize the work-related antecedents associated with these stressors by introducing targeted interventions. Put simply, construction researchers do not need to reinvent the wheel showing relationships between these stressors and poor mental health.

Associative Evidence: Although stressors such as isolation and poor physical health have been noted to be causal factors of poor mental health, there are more pronounced interacting effects of individual differences (e.g., sex, ethnicity, age, education level etc.) that potentially confound the nature and strength of the relationship between these stressors and mental health [22-23]. For example, the stress of a divorce impacts physical health in men and women differently [41]. This implies that CEM researchers need to study individual differences across stressors with lacking causal evidence to understand how other moderating and mediating factors can impact relationship between the stressor in question and the physiological and psychological health of employees. Without deeper clinical or quasi-field experimentations, the generalizability of some of these stressors and interventions cannot be determined. Finally, stressors such as job demand and work-life balance have become highly relevant with on-going debates around their impact onto an individual’s mental health especially post-pandemic [43]. To the best authors knowledge, the few clinical trials that have been conducted found no *causal* relationship between these stressors and wellness [44]. Thus, any large- scaled interventions to address these stressors would be premature since the antecedents of such stressors and the corresponding individual differences have not yet been proven across the population.

Although these precursors of poor mental health deserve our attention, there is little to suggest they are unique to the construction industry. In fact, the same stressors also appear in other industries such as transportation, mining, and medicine [45-48].

Despite the positive efforts to treat mental health issues with respect and seriousness, we are seeing an increase in suicide rates over the last decade. These trends suggest it is possible that the stressors unique to construction have yet to be identified. For example, does the industry have higher suicide rates because there is an over-representation of white/Caucasian males that also happens to be the demographic that at this time is disproportionately dying by suicide [53]? Or is it possible that the stressors are internalized differently among the key demographical groups represented in the construction workforce (e.g., toxic masculine culture)? Or are there confounding factors (e.g., masculine culture) that makes these stressors more prevalent and pervasive in the construction industry than other industries [78]? We actually have still yet to explain with evidence why construction has a disproportionately high rate of mental illness and suicide rate.

Another gap in the body of knowledge is the overreliance on correlational evidence stemming from quasi-field experiments. Correlational fallacies are rarely acknowledged in mental health research, which is highly concerning. The field of construction safety has several examples of false conclusions stemming from correlations like the Heinrich’s pyramid. This model emerged from correlation-based evidence showing every 300 near hits (incidents resulting in no injury) correspond to 29 minor accidents, and 1 major accident, which has finally been shown by empirical evidence of stagnant fatality rates and declining total recordable injury rate to not be causal in nature, something Heinrich himself had to clarify[58]. People used the model in a manner it was never meant to be used. However, the pyramid for years guided safety leadership and decision-making yielding ineffective interventions and solutions. We are at risk of repeating such mistakes (i.e., treating associative evidence as if it is causal) in mental health research by over relying on correlations and failing to perform controlled trials to determine the presence of stressors, the nature of those stressors across different demographical groups, and to establish their hierarchy of importance i.e., which have the biggest and most statistically significant effect sizes of negative impacts on individual's mental health. There are very few construction studies with quasi- experimental field data, and none to the best of authors knowledge that leverage experiments with control groups. In many cases, this is not unreasonable or surprising since conducting clinical trials is might not feasible for CEM researchers and practitioners in most cases. However, the lack of discussions within publications on the limitations of the work should be addressed. Appropriate caution in language should be required by editors and peer-reviewers when presenting findings within publications to appropriately forewarn practitioners on the limitations of the work being produced.

It is undeniable that construction workers are susceptible to suffering from chronically diagnosed mental illnesses, and physiological health issues stemming from chronic stress. However, the work cited above and the meta-data does not make it clear that construction workforce is *uniquely* challenged by some specific stressor(s). Research is needed to understand what makes construction workers occupationally more susceptible to clinically diagnosable mental health issues especially as it relates to suicide ideation. If research is limited to the types of correlational studies already present in the literature, we may fall prey to confirmation bias and drawing causal inferences from potentially spurious relationships. Keeping ourselves focused on work-related stressors only and using validated approaches to confirm their presence on the jobsite would foundationally set us up for success. The success would translate into us having a better understanding of the work-related stressors for construction workers. Finally, only by confirming the external validity of the impacts of these stressors on mental health across relevant demographical groups can we begin to create impactful employee assistance programs (EAP).

3 SCIENTIFIC EVIDENCE IN EMPLOYEE ASSISTANCE PROGRAMS (EAPs)

EAPs are defined as "workplace program designed to assist: (1) work organizations in addressing productivity issues, and (2) "employee clients" in identifying and resolving personal concerns, including health, marital, family, financial, alcohol, drug, legal, emotional, stress, or other personal issues that may affect job performance." by the EAP Association [54, pg. 6]. In other words, it is a list of programs launched by any organization to support primarily the well-being of its employee. Historically, it was launched to fight rising alcoholism and absenteeism in the workplace [56]. These efforts came to light as organizations accepted that increasing personal concerns amongst employee will result in a less optimal work culture and performance [56]. EAPs have been shown to be effective across different contexts and the construction industry settings. The authors recommend readers to review some of the citations [55] that discuss creation of an EAP within organizations where trained professionals are responsible for tackling stressors in workplace proactively and improve wellness of employees. In essence, EAPs can not only foster an empathetic culture within the company, but the evidence would suggest it would also reflect in the bottom line of the company, making their absence a mistake. However, like with any corporate program, not all are equally effective. Not only is there often lack of awareness amongst employees on knowing what EAPs actually are, there is also a general mistrust towards their touted effectiveness [57,60].

3.1 Peer-based Support

Consider the popular intervention proposed by many self-help gurus: peer-based support. Peer-based support is defined as "the provision of emotional, appraisal, and informational assistance by a created social network member who possesses experiential knowledge of a specific behavior or stressor and similar characteristics as the target population, to address a health-related issue of a potentially or actually stressed focal person." [65, pg. 329]. This is a multi-billion-dollar industry based around the self-help concept that people with a "mutual" problem can take control of their adverse situation through personal and collective efforts. Peer-based support is arguably a highly controversial intervention that has struggled to define its scope [63], prove its effectiveness medically across diverse demographics [60,63], or even stay impervious to frauds masquerading as experts sharing wisdom on diets, financial advice, and also mental health [66]. It is not surprising that many have sought to take advantage of expensive medical systems and the lack of access to instead suggest extremely harmful technology-based applications [67] to cash in on a global challenge. This is not to say that there are no strong proponents with robust evidence demonstrating the virtues of a self-help (e.g., informal personal, formal personal, group-based; [66]) approach to mental health.

Peer-based support is becoming the most popular intervention for construction organizations to adopt, despite the complexity and nuance involved. Although construction professionals feel compelled to action, many do not understand the nature and construct of mental health challenges or the role that they could play in mental health improvement. Pervasive ignorance of the nuanced and complex nature of mental health can yields actions that are counterproductive [61, 63, 64]. There is also a need for deeper investigation, as construction professionals are often woefully unprepared to engage in mental health improvement and suicide prevention conversations. To the best of authors knowledge, the different mental health first aid trainings being delivered to construction professionals do not, as yet, have robustempirical evidence demonstrating: (a) improved learning outcomes amongst diverse group of practitioners, (b) improved application of mental health first aid from the training, or (c) improved mental health outcomes amongst employees from diverse backgrounds receiving first aid from construction practitioners trained. There have been a few studies on this, but not only is the evidence not generalizable [79] but there were also potential ethical concerns discovered [80]. Additionally, we have to ask ourselves if the peers can ensure the psychoeducation/enrichment of others without jeopardizingtheir own well-being. We also need to ask ourselves if there are conditions within which our peers couldlack the skills to maintain gains or avoid regression. Finally, we need to ask if the peers are capable distinguishing coping strategies that could be beneficial from the ones that could be physically and psychological detrimental to individuals seeking help [66]. If the answer is even slightly hesitant, the authors suggest using abundance of caution so as to not further harm which is unfortunately a more commonplace phenomenon than people give credit [77].

Consider the intervention funded by Centre for Disease Control labelled 'Man-therapy' [https://mantherapy.org/about]. Man-therapy was not able to demonstrate statistically significant reductions in depression and suicide ideation numbers compared against a control group in a quasi-field experiment [75]. It did, however, show improvements in men wanting to seek professional mental health help while controlling for marital status, education, and sexual orientation [76]. As one digs deeper, the fundamental concept of 'Man-therapy' is to use stereotyped crude humor to engage men in the intervention, which is not a generalizable strategy. Additionally, the authors wonder how companies reconcile using Man-therapy alongside DEI statements, given that the construction industry is also notorious for being overly-masculine and sometimes a hostile working environment for other genders and minorities. Finally, the authors can assure readers that decades of research on cognitive biases suggests usage of 'Man-therapy' will likely exacerbate the presence of many cognitive biases that have made the fight against mental health challenging in the first place (see Table 2). There is absolutely no doubt that 'Man-therapy' as an approach can be effective (as the testimonials on website demonstrate), but to implement without due consideration on how it could reinforce stigmas through toxic mentalities or simply make any "male" feel less "manly" for not fitting the image of vulnerability shown therein. EAPs need to be sensitive enough to undertake a *number* of interventions in a tactful manner so that largest impact can be made. Practitioners need to actively communicate the diverse portfolio of interventions to ensure that some employees do not feel "othered" or neglected.

***Table 2*:** Biased Support of Peers

Work-related Stressor	Definition	Evidence QualityMedical)
Availability	The tendency to inflate the importance of information or likelihood of events that come to uswith cognitive ease.	Peers can engage in seeking information or providing resources that confirms their bias based on recent experiences. [59]
Anchoring	Taking a specific piece of initial information andforecast skewed outcomes.	Peers can lose focus from listening to intervening based on the miscalibrated opinions. Asking leading questions basedon the information. [59]
False Consensus	Incorrect beliefs and assumptions on how well one's opinions or values aligns with that of others.	Peers can incorrectly correlate the mentalhealth experiences, responses, and situation of others with their own. [59]
Representativeness	A conjunction error – the degree to which we attribute an individual, situation, or event has characteristics of population it is believed to havecome from event has characteristics of populationit is believed to have come from.	Peers can engage in "fitness for duty" assessments that makes them seek out patterns or attributes typically associatedwith "insert name" mental health issue. [59]

In general, human beings – laypersons – are untrustworthy because we function on affective heuristics
– how do I feel about this? [73]. Decades of evidence has shown that we value our emotional appraisalsmore than cognitive counterparts [74]. Table 2 shows some common biases emerging from peer-basedsupport intervention because really, none of us are immune to these biases. Indeed, there is significantresearch demonstrating not just us laypersons, but medical professionals also fall prey to these biases leading to reduced diagnostic accuracy [71]. To ensure that good intentions translate to positive impacts, it is crucial that EAP-based interventions are first tested in a controlled setting and community validation through peer-review. As it stands, there are severe limitations in research methodologies, practical efficacies, and validity in interventions being proposed and being *actively* adopted on sites.

Thus, clear strategies are needed to enable construction professionals to listen, observe, understand, and address mental health concerns of an increasingly diverse construction workforce in reasonable manner. As [66, pg. 8] noted "[f]or individuals suffering with more severe problems, it is simply not enough to be empathetic, understanding or mature; the therapist must be skilled in the selection of appropriate principles and strategies of change and the selection of effective interventions." If we need therapists and psychiatrists to lean into their respective cognitive and allopathic toolkits respectively, we need peers who wish act as mental health advocates to be reasonably well-versed in the empirically validated practices through rigorous training and periodically updated certification. Additionally, practitioners need to therefore ask this non-exhaustive list of questions before nominating someone to be a peer-supporter:

1. Are the peers effectively able to navigate their experiential biases?
2. Are the peers effectively able to identify individuals requiring help without resorting torepresentativeness bias?
3. Are the peers trained in personalizing their guidance for individuals from differentbackgrounds towards seeking professional help?
4. Are the peers acknowledging and understanding the impact of participating in EAP could haveon their own mental well-being?

Self-help groups can be incredibly powerful in acting as societal agent catalyzing individuals to accept issues and reach out for more help [66]. The intention behind Table 2 is to not be captious but to be cautious because the evidence is lacking. The challenge for us is that construction organizations cannot outsource the management of mental health by simply tasking individuals in safety or Human Resources who are likely untrained and unqualified to manage mental health issues. If we believe mental health issues are just as serious other diseases, we must function accordingly – wherein medical help is sought at all times from professionals. Peer-groups can be powerful agents in getting someone to agree to seek help, but not be the "fix" to the mental health issues. Having philosophical clarity on what we want to do based on rigorous scientific evidence will help us in launching interventions that are slated to succeed.

4 WHAT DOES SUCCESS LOOK LIKE?

A recent study by Hallowell et al. showed that measuring total recordable injury rates is poor safety performance metric [68]. The statistics of recordable incidents and fatality numbers do not allow us to predict future safety performance on business unit, project, or even the organizational level. The work has propelled safety community to discuss alternative measures of safety performance where for decades statistical randomness in injury and fatality rate was awarded or punished. So, we need to ask ourselves in mental health, a similar question – how do we plan to measure our success as it relates to improving well-being of workers? Not only is success measured using suicide rates a lagging metric whichhas determinantal impact on the culture given its after-the-fact nature, it may not be statistically valid assuicides compared against the overall size of the workforce are thankfully rare.

There are no internally, externally, and ecologically valid self-report instruments that could be used to measure the mental health of all construction workers. Most surveys or interview techniques, which is what the vast majority of current construction mental health research is using, cannot overcome the applicability problems stemming from demand characteristics [69] and poor reliability in diagnosis of personal mental health [70-71]. Consider the simple example of translating common surveys or assessment tools - there is research that has shown straightforward translations can be highly inaccurate [72]. Thus, we need proxy measures of well-being that in the short-term that can be used to assess well-being of workers without asking intrusive questions in a purely positivistic experimental setting triggering self-preservation heuristics and biases of workers (e.g., observer expectancy bias). Short-term goals such as reductions in absenteeism and annual health care claims have been proposed as proxy measures of well-being through the tracking of organizational costs. Although very promising, these metrics are also lagging and the predictive capacity of these metrics against long-term suicide rates in construction industry remains unclear. The report labelled “U.S. surgeon general’s framework for Workplace Mental Health & Well-Being” produced by the U.S. government sets out an ambitious agenda for organizations across the spectrum: protection from harm, connection and community, work-life harmony, mattering at work, and opportunity for growth [62]. Although, the framework is industry agnostic – its components can be taken to create an EAP model for future testing for our diverse field-based and office-based workforce. This is a research area within CEM context that is yet to see major contributions and therefore, remains the biggest gap in the body of knowledge.

5 CONCLUSION

The construction industry’s willingness to act is admirable but poor worker mental health is a problem that deserves attention grounded in serious scientific foundations. When it comes to mental health, sometimes doing nothing at all can be better than doing something that is not helpful, not least because it is a genuine (albeit rare) possibility that we instead cause lasting harm. There is sufficient evidence demonstrating that we all – medical community included – are dealing with significant biases as it relates to mental health. Some biases manifest in treating mental health issues with disdain and a “soldier on” approach while others manifest into swearing by techniques that will change the other person’s life based on experiences. The medical community acknowledges that mental health is a field with evolving sensibilities resulting from the piecemeal discovery of knowledge. As the professionals navigate the unknown number of neurological crevices of our brains, both not taking action and action without proper understanding can both be harmful. Instead, the research community should more rigorously peer-review any mental health publications by considering the internal, external, and ecological validity of the work by comparing it against relevant medical research that is showing incredible heterogeneity in clinical opinions and diagnosis when it comes to mental health issues, illnesses, and disorders. This includes having the professional humility to admit when we don’t know what we don’t know, and when medical professions are struggling with a phenomenon, it is rather unlikely that construction researchers are able to step into the breach. Future research should aim to better measure success, whilst constantly seeking to improve our understanding of stressors within the construction industry Professionally, as a community we also need to ensure vigilance when creating, evaluating, and managing interventions – and given the current state of research of mental health, it is possible that being overly cautious and interrogative will better serve the industry, and its workers, in the long run.

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A META-ANALYSIS ON WORK-LIFE CONFLICT ANTECEDENTS IN CONSTRUCTION

Shuang Dong[1], Shaojin XU[1], Yijia Zhang[1], Haoran LU[1]

[1]*East China University of Science and Technology*

Abstract

Work-Life conflict (WLC) is believed to play a detrimental role in construction management, since it has negative effects on health performance of construction practitioners and may therefore increase the probability of accidents. To explore the significant antecedents of work-life conflict (WLC) both in the work and life domains, and test whether role blurring is the primary cause of WLC through boundary theory, this study provides and meta-analytically examines an organizing framework and theoretical model of work life conflict in the construction industry. Based on 36 correlations from 9 samples, the analysis results indicate that social support (supervisor support, co-worker support), work demand (work hours, work pressure), and job autonomy and schedule control are the main antecedents of work life conflict in work domain; while in the life domain they are children demand, household demand, and partner support. Further analysis also demonstrates role blurring is the main factor affecting WLC in the construction sector. The corresponding suggestions are at last provided to help the organizations in the construction industry highlighting the importance of the socially-supportive workplace environment, reasonable workloads and work hours, and promote boundary tactics for reducing work-life role blurring experienced by construction professionals.

Keywords: Antecedents, Construction, Meta-analysis, Work-life conflict

1 BACKGROUND

Globally, the obvious and profound negative effects of work life conflict, which has been one of the most difficult stressors to manage plaguing the construction industry, has increasingly received considerable critical attention of researchers in the construction industry in decades. It is believed to be a major contributor of the surge of mental illness and suicide in the construction industry worldwide [1]. On the contrary, Lingard et al. (2007) reported that the high level of work-life balance was beneficial to improve productivity [2]. And more WLB is associated with more job satisfaction, increased organizational commitment, and turnover intention [3], and there is also a significant relationship between job satisfaction and value to the organization [4]. Accordingly, it is important to have a clear understanding of the variables that cause construction professionals' work-life conflict in order to provide direction for research and application.

The purpose of this study is to provide a quantitative review of the antecedents of work-life conflict in construction industry which: (a) Provides a theoretically sound and simplified model of work–life conflict and its antecedents; (b) test whether role blurring is the primary cause of WLC through boundary theory; (c) disentangles the antecedents of work-life conflict into the work domain variables (e.g., supervisor support, co-worker support, work time demand, workload demand, job autonomy and schedule control), life domain variables (e.g., partner support, children demand, household task demand) and role blurring.

Though a very informative quantitative review of work-life conflict and its antecedents currently exists [5], the present paper differs in several important ways. First, while Michel's review is not limited to one industry, this study focuses on antecedents of construction professionals' WLC [5]. Unlike other industries with a stable working environment, the construction industry is characterized by high work domain demand, which negatively affects construction professionals' work-life balance. Second, the study examines the direct effects of role blurring, including work contact, family contact, etc., to construction professionals' work-life conflict. In the current digital era, work-family conflict is growing due to the proliferation of communication technologies that increase roles blurring [6]. Thus, it is important to have a clear understanding of the direct effect of role blurring on work-life balance in the construction organization management. Finally, we examine the direct effects of the antecedents on work-life conflict, including supervisor support, co-worker support, work time demand, workload demand, job autonomy and schedule control, partner support, children demand, household task demand and the role blurring, within our model.

2 THEORIES AND HYPOTHESES

In this section, we link work–life conflict to its antecedents in the construction industry through primary theories (e.g., the boundary theory). Our organizing framework and theoretical model of work life conflict is displayed in Figure 1.

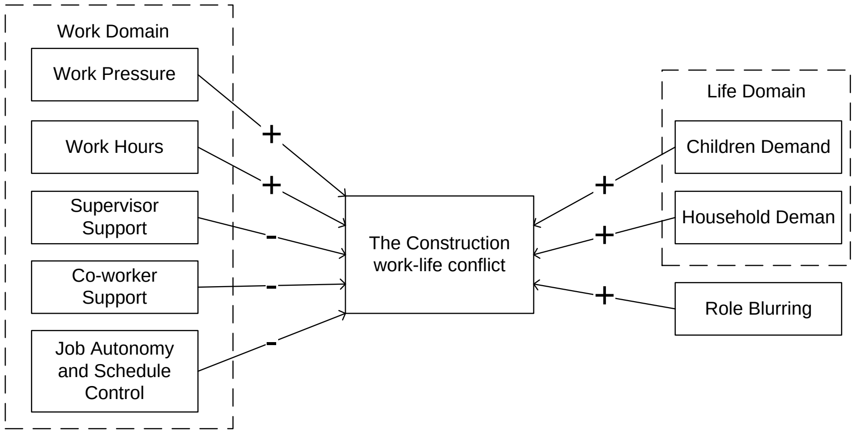

Figure 1. Proposed model of work-life conflict

2.1 Job demands-resources (JD-R) model

The job demands-resources (JD-R) model, within the work domain, highlights the importance of examining job-related demands and resources to understand job strain contributing to work-to-family conflict [7]. According to Bakker's JD-R model (2007), there are two different underlying psychological processes that play a role in the construction professionals' development of strain and motivation. In the first, job resources play a motivational role because they are instrumental in achieving work goals, fostering employees' development, thus reducing work-life conflict. For example, Family-supportive supervisor, which is defined as supervisors who care about employees' work-family well-being by encouraging behaviours that resolve work-family interference and having empathy for their need for work-family balance [8], has been demonstrated to be an essential resource in decreasing work-family conflict [9]. Second, job resources may buffer the impact of job demands on job strain, and different job resources can play the role of buffer for different job demands, then reducing work-life conflict. Job autonomy and schedule control, which has been identified as one of the most salient and effective job resources in buffering the negative effects of job demands, is crucial for employee health and well-being [10]. Specifically, in the construction industry characterized by the demanding environment, when professionals face the loss of resources, resources must be brought in to prevent the loss of resources, otherwise they will experience stress. The job demands-resources (JD-R) model has been extensively applied to examine the antecedents of work-life conflict [7] [10].

2.2 Boundary theory

Boundary theory focuses on the transition between different roles, and the process is influenced by two boundary characteristics, i.e. flexibility and permeability. Flexibility is the extent to which temporal and spatial boundaries are pliable [11]. Permeability is the extent to which a role allows an individual to be physically involved in the domain of that role, but psychologically and/ or behaviourally involved in another role [12]. Study generally shows the relationships between flexibility, permeability and the work-life conflict. Olson-Buchanan & Boswell (2006) reported that both directions of permeability (work entering the family domain and family entering the work domain) were associated with more work-to-life conflict [13]. Clark (2002b) found that the permeability of work border influenced work-life conflict in a different direction to the permeability of family border [14]. Matthews (2010) reported that work flexibility was related to work-to-family conflict, and not to family-to-work conflict [15]. Work and life roles can be arrayed on a continuum, ranging from high segmentation (i.e., with inflexible and impermeable role boundaries) to high integration (i.e., with flexible and permeable role boundaries) [12]. A high degree of segmentation reduces role ambiguity but increases the difficulty of crossing role boundaries. Conversely, high levels of integration reduce the magnitude of change but increase role ambiguity, facilitating the challenge of creating and maintaining role boundaries [12]. Boundary theory provides a perspective about work-life interface to understand work-life conflict.

2.3 Work demand

Work pressure, a work demand, is defined as an individual's subjective assessment derived from objective work conditions and personal psychological dispositions [16]. Individuals who have not adequately recovered under the influence of demanding condition may experience stress that work pressure turns into when meeting it requires high effort and time from individuals (Meijman, 1998) [17]. According to Bakker et al. (2013), in work domain, strains caused by work pressure can be transmitted to family domain through spillover and negatively affect family members through the process of crossover, thus leading to work-life conflict [18]. Moreover, work pressures may lead employees to devote additional non-work time and energy that should be spent on family, social, or activist activities to meet those work demands [19]. As a time-based job demand, work hours has been demonstrated to be an important antecedent of work-life conflict by numerous previous empirical investigations [20] [21] [22] [23]. Logically, work-life conflict will increase as more time is spent at work and less time is available for life. According to Bakker (2007), long working hours may turn into job stressors as the construction professionals have to spent no-work time to meeting tasks [7]. The job demands-resources model and spillover-crossover model both imply a positive relationship between work demand and work–life conflict [18]. Therefore, it is hypothesized that:

H1: work pressure is positively associated with work-life conflict.

H2: work hours is positively associated with work-life conflict.

2.4 Social support

Social support, which can be emotional and physical, and provided by supervisors, partners and co-workers [24], is defined as "social interactions or relationships that provide individuals with actual assistance or with a feeling of attachment to a person or group that is perceived as caring or loving" [25]. Social support provided by supervisor and co-worker in the workplace, has been identified as an important resource to reduce job strains and alleviate work-life conflict in the construction industry. Family-supportive supervisors can reduce construction professionals' work family conflict by replenishing job resources and alleviating the depletion of family resources [9]. Social support from co-workers and supervisors act as the resources for construction professionals to cope with work demand and reduce work family conflict [23]. Within life domain, social support provided by partner has been identified as an important resource to reduce life strains and alleviate work-life conflict [26]. In the demanding working conditions of the construction industry, spousal support also has a spill over effect, e.g., spousal social support reduces the perception of a heavy workload, which alleviate work-life conflict [27]. The job demands-resources model and conservation of resources theory all imply an inverse relationship between social support and work–life conflict. For example, under the influence of demanding work condition, construction professionals can reduce work life conflict by supplementing the depletion of work resources and relieving work stress through the support of supervisors and colleagues, and partner support can reduces work-life conflict by relieving stress or stressors in the life domain. Therefore, we hypothesize the following:

H3: Supervisor support is negatively associated with work-life conflict.

H4: Co-worker support is negatively associated with work-life conflict.

H5: Partner support is negatively associated with work-life conflict.

2.5 Job autonomy and schedule control

Job autonomy is the extent to which individuals have the freedom to decide when, where, and how their work gets done [28], and schedule control refers to the degree of "temporal flexibility in work schedules" [29]. According to boundary theory (Ashforth et al, 2000), the construction professionals enjoying high levels of job autonomy and schedule control typically have highly flexible and permeable work-life boundaries, which may lead them to adopt an integrated boundary management strategy that reduce the magnitude of role change but increase role blurring [12]. However, the fact remains that job autonomy and schedule control are viewed as effective resources for employees, which could buffer the impact of job demands on job strain, to manage work-life interface. Several studies have shown that professionals with higher levels of job autonomy and schedule control are better placed than other workers to manage the boundaries of their roles in the work-life domains and thus achieve work-life balance [22] [23] [30]. According to Bakker et al. (2007), job autonomy and schedule control, a job resource, are associated with greater opportunities to cope with stressful situations, which can have an impact on the health and wellbeing of employees [7]. Logically, a degree of employee autonomy in organizing work tasks and time will help employees to better manage the time and energy they spend on work and life domains, thus reducing work-life conflict. But under demanding work environment of the construction industry, professionals generally find it difficult to obtain job autonomy and time schedules from the organization. The job demands-resources model and boundary theory both imply an inverse relationship between job autonomy and schedule control and work-life conflict. Therefore, we hypothesize the following:

H6: Job autonomy and schedule control is negatively associated with work-life conflict.

2.6 Role blurring

Role blurring has been shown to be associated with work-life conflict, often disrupting family activities and responsibilities [31]. When there are no clear boundaries between work and life roles, it may be difficult for the individual to distinguish between the responsibilities and expectations of the different roles, which may lead to confusion, distraction or guilt because the individual is unable to meet all the demands. According to Glavin and Schieman (2012), work-life conflict increases when the boundaries between work and life roles are blurred, and this effect varies depending on the availability and intensity of certain job resources demands [31]. Logically, for individuals with high levels of work resources, the association between role ambiguity and work-family conflict may be diminished because even when role ambiguity occurs (e.g., multi-tasking at home, after-hours work contact, preoccupation with work after-hours, etc.), they have sufficient work resources to cope with potentially stressful situations. Conversely, for individuals who do not have sufficient work resources, when they experience role blurring, they may have to use time and energy that should be spent in the realm of life to complete work tasks. Both the JD-R theory and boundary theory suggest a positive relationship between role blurring and work-life conflict. Therefore, we hypothesize the following:

H7: Role blurring is positively associated with work-life conflict.

2.7 Life demand

Life demands can arise from family structures (e.g., ages and number of children) and responsibilities (e.g., household tasks and childcare) [32]. Our study divided life demand into children demand and household demand, and applies the JD-R model to the life domain to understand the role of life domain demands in work-life conflict [7]. Logically, similar to the work demands, work-life conflict is caused when the life demands spent time and energy that should be devoted to work. Strains in life domain caused by spending a lot of time and energy to meet life's demands may also be transmitted to work domain through spillover, which in turn increase job stress [18]. Bowen et al. (2020) reported that excessive family demands can interfere with the work domain in the form of family contact, which is positively related to work-life conflict [23]. Therefore, we hypothesize the following:

H8: Children demands is positively associated with work-life conflict.

H9: Household demands is positively associated with work-life conflict.

3 RESERCH METHOD

3.1 Literature search and inclusion criteria

The search for studies examining antecedents of work–life conflict was performed in two stages. In the first stage, a comprehensive search of the literature on WLB in the construction field was conducted on the Scopus database, and search terms were added and adjusted during the search process. The final rule is to employ the following words as Title/Abstract/Keywords (T/A/K) for search: "*construction*" and ("work life balance" or "work life balance" or "work life conflict" or "work life conflict" or "work life enrichment" or "work family balance" or "work family conflict" or "work family enrichment" or "work family balance" or "work family conflict" or "work family enrichment" or "work family balance" or "work family enrichment" or "work life balance" or " work-life conflict" or "work-life enrichment" or "work-family balance" or "work-family conflict" or "work-family enrichment" or "work-family balance" or "work-family conflict" or "work-family enrichment" or "work-family conflict to family conflict" or "family-to-work conflict" or "work-to-family conflict" or "family-to-work conflict"). Moreover, the search contained only published literature written in English by December 2022, and the last search was conducted in January 2023, and this process initially yielded 330 documents.

Manual reading of article abstracts or full text for literature screening was performed in the second phase. Studies were included if they fulfilled four requirements: (1) the study must be related to "WLB and/or WFC and/or FWC in construction field", (2) the study focuses on identifying or measuring the antecedent variables that affect WLB/WFC, (3) the study must be quantitative analysis of empirical articles, other theoretical, review, interview-type articles are not included. (4) the study reports the sample size and the correlation coefficient or other coefficient that can be translated into a correlation coefficient between WLB/WFC and at least one of the relevant antecedent variables defined in the hypothesis of our model. In total, 9 studies containing 9 samples met our inclusion requirements. These studies reported a total of 36 effect sizes with a total sample size of 4145 that were used in our meta-analyses. A summary of studies and sample characteristics can be provided by the corresponding author upon request.

3.2 Literature data analysis

The number of studies included (L) and the samples included (N) were both 9. All papers were journal articles (L=100%), covering five journals in total, most SSCI/SCI indexed. Construction Management and Economics is the highest number of publications (L=5, 55.56%). Most of the literature was published in 2018 and later (L=7, 77.78%), with only two from 2010 & 2012. A cross-sectional design was adopted for all studies. To ensure comparability of the meta-analysis, cross-sectional results were both retained in this paper as far as possible.

The average sample size of the nine included sample clusters was 461. The studies both explicitly reported the country/region in which the sample was located, covering four countries and regions, of which four belonged to South Africa (44.4%), three to Australia (33.3%), one to Canada (11.1%) and one to China (11.1%). It was also found that in the literature where ethnicity proportions were reported, Whites were the main component, generally accounting for 80%. In general, developing countries' construction industries are increasingly interested in the study of professionals' WLC.

Among the final dataset there were 4145 participants, and we divided the occupation types into on-site workers and office workers based on where the professionals work. Among the final dataset there were 1388 (33.5%) on-site workers, 2719 (65.6%) office workers, and 38 (0.9%) participants did not indicate their occupations. Most participants were male (82%). There were 2442 (58.9%) participants with children demand, 1342 participants without children demand, and 361 (8.7%) participants did not indicate their children demand. The majority of participants (n=3358, 81%) were partnered, 397 (24.3%) were single and 390 (9.4%) participants did not indicate their marital status. 4 samples give a phased distribution of participants' ages in 10-year intervals, while the remaining five samples give only approximate distribution intervals.

Table 1. Demographic characteristics of the sample

Variables	Mean	Median	Max	Min	Percentage of samples
Sample source					
Published	2018	2020	2022	2010	100.00%
Type of Publication		Journal Paper			100.00%
Data type					
Cross-sectional Data vs. Longitudinal Data		Cross-Sectional Study			100.00%
Sample characteristics					
Sample	460.56	373	851	89	100.00%
Country or Region		South Africa			44.44%
On-site Workers %	43.45%	53.85%	100.00%	0.00%	33.49%
Female %	17.72%	17.94%	36.90%	7.87%	18.46%
Married or Living with a Partner %	67.30%	86.96%	100.00%	0.00%	81.06%
Children Demand %	50.00%	49.05%	100.00%	0.00%	58.91%
Work Hours ≥ 40 %	58.54%	76.00%	84.00%	24.00%	28.21%
Mean Age	41.31	38.2	48.695	34.5	100.00%

3.3 Meta-analysis

Hunter-Schmidt meta-analysis paradigm (2004) is decided to be applied in our study, which is a comprehensive meta-analysis technique based on the random-effects model, which can correct sampling error, measurement error and range restriction error of the effect sizes [33]. Sampling error is caused by each study only drawing a part of the sample from the population; measurement error is caused by using imperfect measurement tools; range restriction error is caused by using different ranges or standardization methods to calculate effect sizes. By correcting these errors, one can obtain more accurate estimates of the true effect sizes and calculate their variability and confidence intervals. This paradigm can use a series of correction formulas to eliminate these three types of errors that affect the accuracy of effect sizes. Specifically, we corrected the psychological variables (e.g., work pressure, work-life conflict) for unreliability with Cronbach's alpha coefficients reported in the studies; and the self-reported variables (e.g., time demand) and other non-psychological measures (e.g., number of children), which are assumed to be measured without error, were not attenuated. For the multiple correlations that were available for a single antecedent and work-life conflict or the multiple dimensions of work-life conflict and the single antecedent, according to Hunter & Schmidt (2004), we combined these into a composite variable before meta-analytic examination [33]. For example, we combined the work interference with family (WIF), family interference with work (FIW), behaviour-based work-family conflict into a composite variable

4 ANALYSIS RESULTS

Result is reported in Table 1, and in the discussion we refer to our corrected correlations. Our discussion of result is based on Cohen's (1988) classification of correlation magnitudes, (i.e., >0.5=large, >0.3=moderate, and >0.1=small), and we refer to meaningful relationships as those that have an effect size magnitude of $|\rho| > 0.10$ [34]. It appears that the relationship between work-life conflict and the antecedents of work and life domain, role blurring are all consistent with the hypotheses of this study. Result supports all hypotheses.

Table 2. Effects of work domain, life domain antecedents and role blurring on WLC

Antecedent	k	N	r	ρ	SD ρ	90% CI	
Work domain							
Work demand							
Work pressure	5	3355	0.5944	0.6562	0.0543	0.6038	0.7085
Work hour	5	1703	0.1411	0.1504	0.1204	0.035	0.2658
Work resource							
Supervisor support	6	1974	-0.3409	-0.3833	0.0591	-0.4447	-0.322
Co-worker support	2	1184	-0.2539	-0.2751	0.024	-0.3379	-0.2123
Job autonomy and Schedule control	5	2123	-0.2092	-0.235	0.1122	-0.3415	-0.1286
Life domain							
Partner support	3	1874	-0.2363	-0.2572	0.1328	-0.4134	-0.101
Children demand	4	2145	0.1338	0.1404	0.1009	0.0332	0.2477
Household demand	2	1063	0.246	0.2578	0	0.2013	0.3144
Role blurring	4	2544	0.3161	0.3550	0.1587	0.1956	0.5144

Hypotheses 1 and 2 predicted work demand within work domain would be positively related to WLC in the construction industry. Work pressure (ρ = 0.66) had a large relationship with WLC, work hours (ρ = 0.15) had a small relationship. A surprising finding for these hypotheses was that work hours for construction professionals was not a strong predictor of work-life conflict. We feel this is due to the fact that the number of office professionals is more numerous than the number of on-site workers in the reported samples, who frequently work longer hours than employees in the office. For example, Lingard and Francis (2004) reported that, in Australia, on average, on-site workers engaged in direct construction activities work 62.5 hours per week, and employees in on-site offices work 56.1 hours per week, while those in headquarters or regional offices work 49 hours per week [35]. As opposed to office staff, on-sites workers have to work longer hours to complete their tasks, which makes them more likely to experience WLC. Therefore, in our meta-analysis work hours is not a robust antecedent given the occupational distribution of the reported samples. Overall, these results suggest that, in the construction industry, as work demand increase, WLC also increases.

Hypotheses 3, 4 and 5 predicted social support within the work and life domains would be negatively related to WLC. Results support both hypotheses. In the construction industry, supervisor support (ρ = -0.38) had a moderate negative relationship with WLC, while co-worker support (ρ = -0.28) had a small negative relationship with WLC. Meanwhile, partner support (ρ = -0.26) had a small negative relationship with WLC. Overall, these results suggest that as social support in work domain increases, WLC decreases; similarly, as social support in the life role increases, WLC decreases.

Hypotheses 6 predicted job autonomy and schedule control as an effective resource for the construction professionals to manage work-life interface would be negatively related to WLC. Result support hypothesis. Job autonomy and schedule control (ρ = -0.24) had a small negative relationship with WLC. It is unanticipated that job autonomy and schedule control was not a strong predictor of work-life conflict. Given the characteristics of work in the construction industry, we feel that this is due to the fact that few professionals are able to adopt an integrated work-life boundary management strategy in this industry, especially on-sites workers. Moreover, the direct effect of job autonomy and schedule control on work-life conflict may be influenced by the work demands in relation to work pressure and work hours. When professionals with high levels of job autonomy and schedule control are unable to complete their tasks, they may take their work back home and devote more time and energy that should be spent on life roles, thus increasing the risk of experiencing WLC. According to JD-R model, job autonomy and schedule control, as a valuable resource that is difficult to obtain in the construction industry, can alleviate the job strain on professionals and thus reduce work-life conflict [7]. Overall, this result suggests that as Job autonomy and schedule control increases, WLC decreases.

Hypotheses 7 predicted role blurring disrupting work roles and family activities and responsibilities would be positively related to WLC. Result supports hypothesis. Role blurring (ρ = 0.36) had a moderate positive relationship with WLC. Expectedly, role blurring is not a strong antecedent of work-life conflict. We feel that this is due to the availability and intensity of certain job resources demands of different job types. Due to the nature of the construction industry, on-site worker with the low levels of job autonomy may not experience the role blurring. Moreover, while the construction professionals who can work remotely have a high level of job autonomy compared to workers on site, they also may neglect the demands of their families or perform poorly at work than causing work-life conflicts, when they don't have sufficient resources to cope with the tasks needed to be done. Overall, this result suggests that as role blurring increases, WLC increases.

Hypotheses 8 and 9 predicted life demands divided into children demand and household demand in our study would be positively related to WLC. Results support hypotheses. Children demand (ρ = 0.14) and household demand (ρ = 0.26) both had a small positive relationship with WLC, and the finding for children demand should be a much more robust finding than that for household demand given the number of studies examined for each (k=4 vs. k=2). Moreover, the effect of life demand on WLC may be influenced by the partner support, because the partners can help employees with life domain demands and thus accommodating the employees' job demands. Given the high demands associated with the construction environment, spousal social support is especially important to on-site workers [27]. Therefore, possibly influenced by partner support, life demands are not the strong antecedents of work-life conflict. Overall, this result suggests that as life demands increases, WLC increases.

5 DISCUSSION

This study provides the first meta-analytic examination of work demands and work-life conflict in construction industry. More specifically, we examined the direct effects of the work pressure and work hours on WLC, and our results indicated that the work demand of both forms are the significant antecedents of WLC. Further, work pressure is the strongest predictors of work-life conflict. Given the demanding environment in the construction industry, work demands in relation to work pressure and work hours are inevitable for the professionals, especially on-site worker. Therefore, our results imply that, compared to the general industry, the construction professionals inevitably experience job strains, which may be transmitted to life domain through spill over and negatively affect life role through the process of crossover, thus leading to work-life conflict [18]. In addition, our study novelly examines the direct effect of construction professionals' life demands (family demands and children's demands) on work-life conflicts. Specifically, the results suggest that the life demands are the significant antecedents of work-life conflict, which was concluded differently in Michel's study [5]. The construction professionals may have more difficulty meeting life demands due to the demanding work condition compared to other professionals who have a stable work environment, thus increasing the possibility of work-life conflict. Therefore, in the construction industry, for those construction professionals, the demands from the work and life domains are frequently difficult to meet, leading to experience work-life conflict which has negative effects on health performance of construction practitioners that may increase the probability of accidents, and reduce the performance outcomes for individuals, families and organizations.

Boundary theory suggests that in construction industry, workers enjoying high levels of job autonomy and schedule control typically have highly flexible and permeable work-life boundaries, which may lead them to adopt an integrated boundary management strategy that reduce the magnitude of role change but increase role blurring. This process may lead to construction worker experiencing work-life conflict. The JD-R model, in contrast, argues that job autonomy and schedule control as a job resource play an motivational role fostering construction workers' development and buffer the impact of job demands on job strain, then reducing work-life conflict. Our study provides the first meta-analytic examination of the direct effect of job autonomy and schedule control on work-life conflict in the construction industry, and the results clearly show that job autonomy and schedule control is one of the significant antecedents of work-life conflict. The results tie not well with the Michel's study (2011) wherein the effect of schedule flexibility and job autonomy on work-family conflict, and we feel that the difference may be due to the demanding work requirements of the construction industry [5]. From the above discussion, the conclusion can be reached that, for the construction professionals, high levels of job autonomy and schedule control as an effective resource can buffer the impact of job demands on job strain and facilitate self-management of the work-life balance, thus reducing work-life conflict.

Regarding role blurring, different studies have measured it in various ways (e.g., multi-tasking at home, after-hours work contact, preoccupation with work after-hours, etc.), but both have concluded that it is positively correlated with work-life conflict. We believe that although role blurring may be presented in different forms, it has the same effect on working life conflict (i.e., it creates role conflict by interfering with the activities and responsibilities of another role). Therefore, our study unified the form of role blurring and provided the first meta-analytic examination of the relationship between role blurring and work-life conflict in the construction industry. The result suggest that role blurring is one of the significant antecedents of work-life conflict. Overall, when role blurring occurs, the responsibilities of construction professionals in their work and life roles will be disrupted, thus increasing work-life conflict.

6 CONCLUSION AND IMPLICATIONS

The current work contributes to the construction industry work–life conflict literature and impacts the field in at least two ways. First, our study provides a meta-framework was developed from work and life domain, boundary-spanning antecedent. While there have been previous meta-analyses within the work-family conflict literature, none have been conducted among the construction professionals. The precursors and comprehensiveness allow the future research to conduct a finer grained analysis of the constructs within the study, along with additional moderator analyses. Second, with the better understanding of construction industry work-life conflict and its antecedents, implementation of these findings can progress. In our model, many of the antecedents are potentially under the control of the individual, the organization, the supervisor and co-worker, the partner in life domain, or various laws and regulations. Therefore, the findings could be used for reduction of construction work–life conflict at multiple levels. For example, in the construction industry, known for its demanding work condition and long work hours, supervisors can reduce professionals' WLC by ensuring that work demands are reasonable, as work demands are the important antecedents of WLC. Organizational managers can use the theoretical framework we provide to initially develop strategies for managing the work-life balance of their employees in order to improve performance outcomes for individuals and reduce the negative impact of work-life conflict that may increase the probability of accidents. Overall, we suggest that organization in the construction industry should consider further the impact of work and life demands on employees' work life balance when develop the strategies, and provide the sufficient job resources to employees in managing their work-life interface.

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AN ILLUSTRATIVE STUDY OF THE CONNECTION BETWEEN WORK PRESSURE AND SAFETY RISKS ON CONSTRUCTION SITES

Fidelis Emuze[1], and Kgomoco Masilo[1]

[1] *Central University of Technology, Free State (South Africa)*

Production on construction sites tends to pressure workers, and when it is not monitored closely, it increases exposure to safety risks. This paper aims to depict the connection between work pressure and safety risks on construction sites. The illustrative case study sought responses to 'to what extent do work pressures lead people to increase their exposure to safety risks in construction operations?" On-site self-administered surveys were used to collect the study's statistical data from technical and management personnel physically present on a live project in South Africa. Participants in the structured questionnaire answered closed-end questions based on their lived experiences on construction sites. Data analysis shows that 'connection', which is the attraction between two phenomena, exit between work pressure and safety risk exposure. The responses reaffirmed the increase in safety risks on site when payment is delayed (management issue) and resource use (material wastage). The lack of enough supervisory capacity for tasks also increases work pressure, increasing safety risks—the need to break the link between work pressure and safety risk closes the paper.

Keywords: construction site, safety risk, work pressure, South Africa

INTRODUCTION

Safety in construction work has been a long-term issue in the sector. The sector is among the top sectors with the highest share of hazardous occupational accidents [1] [2]. Several efforts have been made to promote safety in the construction industry, such as the Occupational Safety and Health Act of 1970 in the United States of America (USA) and similar legislation in many countries. Yet, the sector faces life-threatening hazards, especially in some developing countries [3]. This submission is corroborated by the idea that construction is one of the most hazardous sectors in Ghana [4]. The industry is stressful and makes workplace pressure worse if not checked. Stress could induce unsafe behaviours by construction workers, especially frontline field workers [5]. Construction work has a high fatality rate and injuries because of violation of safety rules and regulations in site operations [6] [7].

safety violation is common in construction in developed and developing countries. For instance, the top safety violations reported by OSHA (Occupational Safety and Health Administration) for 2016 in the USA [8]. This includes fall protection (6,929 violations); hazard communication (5,677); scaffolds (3,906); respiratory protection (3,585); lockout/tagout (3,414); and powered industrial trucks (2,860). Others are ladders (2,639); machine guarding (2,451); electrical wiring (1,940); and general electrical requirements (1,704 violations). The OSHA contended that the list seldom changes, about 3 million workers are injured, and more than 4,500 workers get killed yearly [8]. Thus, construction site monitoring by key stakeholders, especially safety officers, site engineers, project managers, and regulatory agencies, must be balanced to mitigate risks and associated safety issues [9]. The construction site environment is complex for these stakeholders to monitor safety issues properly [10]. This is compounded by many targets assigned to the field workers [11]. Some deviations leading to construction workers taking shortcuts to either mitigate workload or improve productivity might threaten a safe working place and increase safety violations. Violations that later threaten a safe working place may start little and accumulate over an extended period [12] [13]. Workplace pressures can cause the failure of safety risk perception on hazards and lead to site accidents [14]. Dynamic situations caused by workplace pressures at construction sites can lead to violations linked with selective attention or distraction. A technology-based approach to tackle construction safety issues [15]. This call was made because of specific construction projects' complicated designs and methodologies. Ensuring a safe environment with the conventional approach is no longer feasible because many factors, including procurement methods, may heighten workplace pressure on construction sites.

This paper aims to depict the connection between work pressure and safety risks on construction sites. The illustrative case study sought responses to 'to what extent do work (production/financial) pressures lead people to increase their exposure to safety risks in construction operations?”

RESEARCH METHOD

The study adopted a positivist philosophy. Positivism is one reality with consistent meaning concerning matters [16]. Positivism is utilized where empirical-based results are embraced. The research employed a deductive type of research approach. The deductive approach aid researchers in finding answers to the research questions [16]. For the methodological choice, a mono-method quantitative questionnaire survey was adopted [17]. The 5-point Likert scale was adopted to evaluate the ratings of the identified items. The Likert rating scale ranged from 1 (strongly disagree) to 5(strongly agree). In the tables in the next section, the scale is represented by 1 = SD, 2 = D (disagree), 3 = N (neutral), 4 = A (agree) and 5 = SA (strongly agree). The study adopted mean item scores as 1.00 – 1.49 = strongly disagree, 1.50 – 2.49 = disagree, 2.50 – 3.49 = neutral, 3.50 – 4.49 – agree, and 4.50 – 5.00 = strongly agree [18]. This study’s respondents comprised technical and management teams on construction projects in Bloemfontein, Free State, South Africa. Out of 55 questionnaires returned from 60 questionnaires administered across the chosen population, 46 questionnaires were usable and analysed, as presented in Table 1. The response rate is 70%. This is satisfactory and aligned with previous work, which suggested a 20% to 30% benchmark with questionnaire surveys linked with the sector [19]. Table 1 shows that of the 46 respondents, 28% have diplomas, 56% have bachelor’s, 11% have honors, and 4% have master’s degrees. This indicates that most respondents were educated and could reflect on the questionnaire. Also, it shows that 7% have 21-25 years of work experience, 11% have 16-20 years of work experience, 27% have 11-15 years, 29% have 6-10 years, and 27% have 0-5 years of work experience. The extent of site experience of the respondents gives confidence to their perceptions on the subject matter. Regarding the descriptive statistics, the mean item score is based on the formulae [20]:

$$\text{Mean Item Score} = \frac{5(n_5) + 4(n_4) + 3(n_3) + 2(n_2) + n_1}{5(n_5 + n_4 + n_3 + n_2 + n_1)}$$

Where n_1= number of respondents who answered strongly disagree
n_5= number of respondents who answered strongly agree

Table 1: Background information of the respondents

Profile	Frequency	Percentage
Experience		
0 to 5	12	27
6 to 10	13	29
11 to 15	12	27
16 to 20	5	11
21 to 25	4	7
Total	46	100
Education		
Certificate/Diploma	13	28
Bachelor’s degree	26	56
Honour’s degree	5	11
Master’s degree	2	4
Total	46	100

RESULTS AND INTERPRETATION

The responses to the closed-ended questions administered to the respondents are presented in this section.

Construction workplace pressure

According to the responses of the 46 respondents, the construction workplace encounters pressures. The results categorized construction workplace pressure into three groups. This includes human factors, leadership and culture, and production and financial pressures. The results show that the pressure could escalate safety risks if not mitigated. Table 2 presents the extent to which construction workplace pressure can increase exposure to safety risks on construction sites and their severity levels. Table 2 also reveals that work overload is ranked first as the source of pressure in construction work with a mean score of 4.37, followed by unrealistic work demands with a mean score of 4.26, and task deadlines as the third with a mean score of 4.17. For others, refer to Table 2. This indicates that work overload, unrealistic work demands, and task deadlines are top work pressure antecedents that could cause safety risks in construction sites if not managed well.

Table 2: Factors contributing to work pressure and safety risks

Factor	SD	D	N	A	SA	MS	Rank
Work overload	0.0	4.3	13.0	23.9	58.7	4.37	1
Unrealistic work demands	2.2	2.2	13.0	32.6	50.0	4.26	2
I often feel pushed by deadlines	4.3	4.3	6.5	39.1	45.7	4.17	3
Organizational change	0.0	4.3	15.2	41.3	39.1	4.15	4
Poor interpersonal relationships	6.5	10.9	13.0	26.1	43.3	3.89	5
Assignments are not within my capability	2.2	13.0	21.7	28.3	34.8	3.80	6
Harassment between an employer and an employee	15.2	6.5	15.2	19.6	43.5	3.70	7
I am uncertain as to how my job is linked	6.5	10.9	26.1	21.7	34.8	3.67	8

Human factor pressures

Table 3 presents human factors that influence work pressure and safety risks. The table reveals that work promotion matter is ranked first among the human factors that influence construction work with a mean score of 4.39, followed by the effect of work on health with a mean score of 4.26, and performing work that suit values as the third with a mean score of 4.24. For others, refer to Table 3. This indicates that work promotion matter, the effect of work on health, and performing work that suit values as top human factor pressures that could cause safety risks on construction sites if not addressed.

Table 3: Human factor affecting work pressure and safety risks on construction sites

Factor	SD	D	N	A	SA	MS	Rank
I feel confident about how I will be rated for promotion	2.2	2.2	10.9	23.9	60.9	4.39	1
My work has a real effect on my health	0.0	8.7	8.7	30.4	52.2	4.26	2
I perform work that suits my values	2.2	4.3	8.7	37.0	47.8	4.24	3
Emotional exhaustion	2.2	6.5	8.7	34.8	47.8	4.20	4
I seldom receive work that involves multiple tasks	2.2	8.7	13.0	30.4	45.7	4.09	5
I often get interrupted when I do my work	2.2	15.2	4.3	32.6	45.7	4.04	6
I must go against a rule to carry out an assignment	2.2	15.2	8.7	28.3	45.7	4.00	7
I do not know if my work will be acceptable to my boss	4.3	10.9	10.9	30.4	43.5	3.98	8
I seldom lose concentration on my work	2.2	10.9	19.6	37.0	30.4	3.83	9
I deal with the conflicting interests of people	2.2	17.4	19.6	32.6	28.3	3.67	10
Lack of professional competencies	8.7	10.9	15.2	39.1	26.1	3.63	11

Leadership and culture

Table 4 presents the construction workplace pressures identified under leadership and culture pressures. Findings reveal that work responsibility is ranked first as the most leadership and culture pressure within the construction work with a mean score of 4.52, followed by good work performance irrespective of the group I find myself with a mean score of 4.20, and precise work description as the third with a mean score of 4.04. For others, refer to Table 4. This indicates work responsibility, good work performance irrespective of the group I find myself in, precisear work description as top leadership and culture pressures that could cause safety risks on construction sites.

Table 4: Leadership and cultural factors affecting work pressure safety risks

Factor	SD	D	N	A	SA	MS	Rank
I know my responsibilities at work	0.0	2.2	8.7	23.9	65.2	4.52	1
I can work the same regardless of the group I am with	0.0	6.5	15.2	30.4	47.8	4.20	2
An explanation of what must be done is clear	2.2	4.3	13.0	47.8	32.6	4.04	3
Resource non-availability affects assigned tasks	0.0	4.3	28.3	32.6	34.8	3.98	4
Lack of policies and guidelines to help me	0.0	4.3	32.6	23.9	39.1	3.98	5
Working within teams of varying interests	4.3	4.3	17.4	39.1	34.8	3.96	6
I am told how well I am doing my job	2.2	8.7	19.6	32.6	37.0	3.94	7
I receive incompatible requests from other people	2.2	6.5	28.3	21.7	41.3	3.94	8
Working under unclear directives or orders	2.2	17.4	17.4	23.9	39.1	3.80	9
Language barriers affect my work	2.2	15.2	21.7	23.9	37.0	3.78	10

Production and financial pressure

Table 5 presents the extent to which production and financial pressures influence safety risks. The table reveals that assigned deadlines for projects and enough workforce for work are ranked first with a mean score of 4.00, respectively, followed by payment delay with a mean score of 3.86, and material wastage as fourth with a mean score of 3.78. For others, refer to Table 5. This indicates that assigned deadlines for projects, enough manpower for work, payment delays, and material wastage as top production and financial factors that could cause safety risks on construction sites.

Table 5: Production and financial factors affecting safety risks on construction sites

Factor	SD	D	N	A	SA	MS	Rank
I meet assigned deadlines for projects	0.00	4.30	21.70	43.50	30.40	4.00	1
I get enough manpow to conclude the job	0.00	10.9	15.20	37.00	37.00	4.00	1
Delay of the project payment	6.50	2.20	28.30	28.30	34.80	3.82	3
Material wastage on projects	4.30	4.30	30.40	30.40	30.40	3.78	4
Lack of support when carrying out a task or job	2.20	10.90	23.90	34.80	28.30	3.76	5
Lack of funds to carry out the project	2.20	4.30	37.00	28.30	28.30	3.76	5
I often overspend on projects	4.30	6.50	32.60	32.60	23.90	3.65	7

DISCUSSION

The study aims to depict the connection between work pressure and safety risks on construction sites in Free State, South Africa. The illustrative case study sought responses to 'to what extent do construction workplace pressures lead people to increase their exposure to safety risks in construction operations'? A quantitative approach was used to interpret the data to achieve the aim. The results show that work overload, unrealistic work demands, task deadlines, organizational change, and poor interpersonal relationships are top work pressure that could cause safety risks in construction sites if not managed well. Thus, the findings agree that underestimating safety is underpinned by increased work pressure [21]. They suggested safety climate improvement and recognition of safety risk perception to mitigate hazards. Also, advanced technologies should be embraced for construction safety, including sensor-based technology and virtual reality [15]. This is an effective way to further construction safety because of the complexity of new designs.

The results in Table 3 suggest that factors such as work promotion, personal health, performing work, emotional exhaustion, and multiple-task engagement as top pressure points that could cause safety risks on construction sites. The results are consistent with previous observations [5] [22]. Often frontline construction workers perform the task quickly to get the work done rather than work safely [22]. The focus on production at the expense of safety remains a concern in construction operations. The literature also flagged health and well-being issues such as stress. For instance, stress affects the emotional exhaustion of people and may induce unsafe acts on construction sites [5]. They recommended stress management seminars and workshops into on-site safety training to address the challenges. Also, the results show the extent of leadership and cultural factors such as work responsibility, work performance, work description, and achieving goals with scarce resources as top influencers of work pressure that could cause safety risks on construction sites.

The literature says production and finance exert pressure on safety [12] [23]. Persistent work pressure on construction site work drives a drift to failure [23] [24]. In other words, it increases safety risks and leads to accidents. The same trend is discovered and presented in Table 5. The table suggests that production and financial pressures could increase safety risks on construction sites. Risk assessment (RA) must be expedited and deployed in construction projects. For example, a qualitative risk assessment will address issues at the sharp end of operations to keep workers and the public safe [25]. The knowledge and experience of safety workers should be engaged in RA exercises to ensure buy-in during implementation [14].

CONCLUDING REMARKS

This research has offered insight into the link between work pressure and safety risks on construction sites based on an illustrative case study research design. The response to the main question is that there is an 'connection' between work pressure and safety risks on site. Frontline workers and their managers in construction must therefore look for ways to break the connection. In effect, site management should control work overload, unrealistic work demands, and task deadlines to lower safety risks. Work pressures should not override safety concerns resulting in incremental tolerance for site shortcuts. Management control should extend to construction site production, finance, leadership, and cultural issues. In contrast, the site operatives should evolve the attributes of 'mindfulness' to ensure their actions or the working conditions do not increase safety risks. Additional suggestions include promoting a positive safety climate and culture, using technology in safety training and attention to well-being matters that affect the workforce.

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THEORIES OF COSTS OF HEALTH AND SAFETY COMPLIANCE AND NON-COMPLIANCE WITH REGULATIONS

Andrew. O. Arewa[1], David Tann[2], Oluwafemi G. Olatoye[3] and Femi Olubodun[4]

[1, 2 & 3]Engineering and Construction Department, School of Architecture Computing and Engineering, Docklands Campus, University of East London, London E16 2RD, UK. E-mail: a.o.arewa@uel.ac.uk, d.tann@uel.ac.uk, and u2218531@uel.ac.uk
[4]School of Civil Engineering and Built Environment, Liverpool John Moores University, 70 Mount Pleasant, Merseyside L3 5UX. E-mail: O.F.Olubodun@ljmu.ac.uk

Abstract

Globally, the economics of health and safety compliance and non-compliance with regulations remains absurd and elusive. Costs of health and safety compliance at enterprise level are elements that organisations find difficult to define or price adequately due to subtle, inconspicuous, and elusive nature. Conversely, evidence shows that costs of health and safety non-compliance with regulations in recent times are eye-watering and mind-boggling. Yet, theory that provides explanation of cost behaviours concerning health and safety compliance and non-compliance with regulations is rare. **Aim:** The aim of the study is to develop a theoretical concept that can be used to predict costs of health and safety non-compliance with regulations. **Research question:** put forward by the paper is: What are the predictable cost behaviours of health and safety compliance and non-compliance with regulations? **Research Method:** Phenomenological research strategy was adopted; with qualitative data collected via focus group discussions; in addition to detailed observation of 20 years real costs of health and safety non-compliance with regulations data. **Findings:** Reveal that costs of health and safety compliance with regulations are often ill-defined and elusive. Similarly, the study discovered that cost behaviour of health and safety non-compliance with regulations can be erratic and exponential in nature. Other finding reveals that for every health and safety failure (ill-health, injuries/fatalities), there are likely associated costs, that are contingent on specific legislations, rule of law, state (national laws), and commercial viability of organisation involved.

Keywords: costs of health and safety compliance and non-compliance, and theory.

1. INTRODUCTION

Theoretical cognition and learning about construction discipline are scarce, particularly theories about costs of health and safety compliance and non-compliance with regulations. [1] asserts that *"… lack of theoretical framework in construction is a barrier to progress and development of the subject area …"*. Moreover, there is a general perception that the construction industry has not gone far enough in seeking theories for better understanding of complex phenomena [2]. Studies about construction health and safety suggest that the subject area is footed on explicit and narrow theoretical frameworks. For example, known health and safety theories such [3] domino theory relating to casual factors of industrial accidents, [4] illness and medical theory,[5] Swiss-cheese model of how patient harm happens, etc are somewhat linked to other industries, except for the construction industry. [6] opined that there is a need for robust theoretical knowledge relating to costs of health and safety to challenge, explain, understand, and extend existing knowledge within the limits of critical boundary of assumptions. Besides, there are many high-profile health and safety failures, especially in high-risk industries that cost multi-billion pounds (£s) or dollars ($s), to provoke theoretical ideas about cost behaviours of health and safety compliance and non-compliance with regulations. The significance of the study is entrenched in [7] assertion that understanding cost behaviours of health and safety is important because it is vital to determine and predict the value proposition that organisations and individual practitioners attach to upholding health and safety standards. Thus, to enhance understanding of the research variables, there is a need for a thorough literature review concerning costs of health and safety compliance and non-compliance with regulations.

2.0 LITERATURE REVIEW

The need to examine theories of costs of health and safety compliance (i.e., cost of providing health and safety); and costs of non-compliance (i.e., punitive costs) with health and safety regulations cannot be overemphasised. Perhaps, due to large costs that emanate from unexpected adverse health and safety incidents. Safety cost is one of those cost elements that organisations find difficult to define or price adequately, due to its subtle, inconspicuous, and elusive nature. Though, some organisations do not price safety as a separate item in their tenders, some do, under the guise, assumption, or ignorance that safety cost is ring-fenced into production/process cost. [8] argued that economic adversity that arises from a failure to invest in health and safety can be immeasurable and mind-boggling. Despite economic risks associated with health and safety failures, many firms do not invest in preventive health and safety otherwise refer to costs of health and safety compliance with regulations. [9] report revealed that 'on average, small firms in construction sectors spend approximately £4,000 per annum, medium-sized firms spend slightly over £27,000 per annum, and large companies spend approximately £420,000 per annum or more. [10] avow that there is somewhat relationship between organisations costs of health and safety compliance and rate of fatalities. UK construction fatalities data in the last two decades suggest that large companies seem to have better health and safety performance metrics compared to SMEs. Perhaps, safety performance of large organisations is informed by the saying that *"to whom much is given, much will be required* [11]. Safety performance statistics of large companies are not surprising, compared to small firms because the latter invest more in preventative safety and better performance should be expected of them.

On the other hand, [12] argued that industry practitioners' worries are hinged on fines or punitive costs, otherwise referred to as costs of non-compliance with health and safety regulations. Possibly, due to historical harsh punitive costs incurred by many organisations for breaching safety and health at work regulations. However, there is a growing debate about the disproportionate effects of fines (costs of health and safety non-compliance) on organisations, particularly SMEs. For example, in 2016 Watling Tyre Service Ltd, a Small and Medium Enterprise (SME) engineering company was fined one million pounds (£1M) for breaching the UK Health and Safety at work Act 1974, regarding failure to safeguard the health and safety of both employees and non-employees. The case sent a shock wave to all practitioners and legal luminaries because in the past it was only large organisations with high commercial capability that often-attracted huge health and safety fines to the tune of a million pounds (£1M) for wrongdoings. Arguably, a clear inference from Watling Tyre Service Ltd and other recent cases, suggests that a complex landscape regarding costs of health and safety non-compliance appears to be evolving. Thus, there is a need for a theory that provides an explanation and understanding regarding costs of health and safety compliance and non-compliance with regulations.

2.1.0 Costs of health and safety non-compliance with Regulations and Rate of Fatalities

Detailed literature review of health and safety regulations *vis-à-vis* prosecutions in the UK construction industry shows that offences under the Health and Safety at Work (HSW) Act accounted for 48%, (2,193 of 4,571 cases) of all HSE prosecution cases reviewed between 2010 to 2022. [13] claim that *"the HSW Act accounted for nearly half of the total HSE prosecuted cases in 2009/10 (463 of 1,026).* Similarly, HSW Act prosecutions resulted in fines of £9,954,043, out of the total of £13,625,666" between 2010 to 2022. The average HSW Act offences based on 2,719 convictions between 2010 to 2022 is put at an average of £56,649 against the overall average of £17,008. Breaches of the HSW Act and its associated fines are common because offences relating to general duties appear to be more serious than specific regulatory breaches [13].

Other HSE prosecution data available reveal that on average there were confirmed 299 convictions between 2016 to 2022 in the construction industry alone. Predictably, between 2010 to 2022, 34% (101 of 299) of recorded offences were committed under the Health and Safety at Work regulations, attracting a total fine of £8,181,989; with 64 prison sentences. The Gas Safety (Installation and Use) Regulations 1998 resulted in 17% (51 of 299) convictions, with total fines amounting to £18,410 and 31 prison sentences. The Construction (Design and Management) Regulations 2015; attracted 14% (41 of 299) total fines amounting to £1,883,635; with three prison sentences. The Work at Height Regulations 2005 led to 12% (38 of 299) convictions, with total fines amounting to £860,486; with five prison sentences. The Control of Asbestos Regulations 2012 resulted in 4.34% (13 of 299) convictions with total fines amounting to £15,300; and four prison sentences. The Cooperate Manslaughter regulation led to 2.67% (8 of 299) convictions with two prison sentences and no option of fines from 2008 to 2014. Though recent data show significant increases relating to the Cooperate Manslaughter regulation 2007. The

Lifting Operations and Lifting Equipment Regulations 1998 resulted in 3.67% (11 of 299) convictions, total fines amounting to £2,500 with no prison sentences. The Provision and Use of Work Equipment Regulation 1998 led to 0.80% (23 of 299) convictions, total fines amounted to £30,000 with no prison sentences. Driving at Work Regulation 1997 and Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (2013) combined led to 0.80% 24 of 299 convictions, total fines amounted to £5,300: with no prison sentences.

The average fine for Health and Safety at Work (HSW) act offences concerning 1330 prosecutions cases in 12 years is put at £54,006. Other average fines are Gas Safety (Installation and Use) Regulations act 1998 led to £3,613; the Construction (Design and Management) Regulations cost £9,542; the Work at Height Regulations £8,526; Control of Asbestos Regulations £10,027; the Lifting Operations and Lifting Equipment Regulations equated to £1,250; Provision and Use of Work Equipment Regulation led to £1,020; Driving at Work Regulation 1997 and Reporting of Injuries, Diseases and Dangerous Occurrences Regulations led to £8,650. Between 2007 to 2015, there were fewer successful convictions related to the Corporate Manslaughter Act 2007. However, between 2007 and 2022 there have been cases of hefty fines and imprisonment for breaching the Act. For example, [14] prosecution data show that the average fine for the Corporate Manslaughter Act between 2014 to 2022 stood at approximately £330,500, with average imprisonment of approximately 6 years with no option of fine. It is pertinent to note that, the HSE vs Ozdil Investment Ltd case law (case number 4450027) is of paramount interest to construction practitioners. The case saw Koseoglu Metalworks Ltd fined £400,000 with costs of £21,236 legal fees, company director sentenced to 8 months imprisonment. Court details show that, Odzil Investment Ltd was fined £660,000 with legal fees of £53,115.34 and the company's directors were sentenced to 12 months imprisonment.

Overall, health and safety prosecution data usually come in piecemeal mainly from HSE and Crown Court due to lengthen court cases and incomplete court trials. However, available data show that on average, £8,068,423 was levied on health and safety offenders in the UK construction industry between 2010 to 2022. Indeed, average costs of health and safety non-compliance are likely to be higher due to ambiguity and pending HSE prosecution cases in the last quarter of 2022. Ultimately, the key lesson from prosecution cases suggests that non-compliance with health and safety regulations often creates a landscape for exponential punitive costs. Similarly, harsh, and stringent health and safety regulations have the potential to significantly reduce fatalities across high-risk industries in the UK.

2.2 Theory and its Importance

[15] concur that various definitions of the word "theory" exist. But from academic perspective, a theory is a related set of concepts and principles about a phenomenon and the main purpose is to explain or predict certain facts or occurrences. [16] posits that the development of theories usually follows three basic steps: (i) Speculative which involves attempts to explain what is happening or a phenomenon, (ii) Descriptive entails the gathering of descriptive data to explain a phenomenon and (iii) Constructive includes revision of old theories and development of new theory based on continuous research. The study intends to adopt constructive theory notion because the method is more rigorous and accurate for explaining and predicting facts.

2.2.1 Existing Health and Safety Theories

There are many theories within the health and safety subject area. For example, theories of Task dynamics, Domino theory, Hazard – barrier model, Accident casual factors theories, Health theory, Health significance theory, etc exist to help advance and explain health and safety practices. But there is no specific theory that explains costs of health and safety compliance and non-compliance with regulations. However, Human Capital theory framework propounded by [17] may help explain costs of health and safety compliance or investment in health and safety as illustrated in figure 1 below. The theory uses the construct that individual, or organisations invest in human capital (via education, training, and other practices) with an expectation that such investment will provide benefits in the form of higher earnings via avoidance of adverse health and safety incidents. The theory makes economic sense because if an organisation invests in its workforce (by providing safety training, purchasing PPEs, and devoting resources to safeguard their employees), such investment directly or indirectly has future benefits such as avoidance of colossal losses in form of punitive costs for non-compliance with health and safety regulations. Similarly, the Economics of Occupational Safety and Health theory advocated by [18] states that occupational injuries are random events, that affect activities of workers, firms, and the government. The theory suggests that wages of workers increase with more job risk; but from a holistic viewpoint, occupational risk-related costs are influenced by the following:

- Wage premiums paid to attract workers to risky jobs
- Costs of providing a safe working environment (investment in safety)
- Insurance payment to injured workers (sick leave and compensation benefits)
- Government fines for safety violations
- Injury-related costs such as workplace disruptions and loss of worker-specific skills

Perhaps, deduction from the two theories stated above suggests that investing in human capital, by implication costs of providing health and safety is underpinned by expectancy in form of return. The second strand from the theories is that there is a relationship between wages of workers, job risks and corresponding investment in safety denoted as safety costs. In reality, the supposition makes sense when viewed across average wage earnings in high-risk industries *vis-à-vis* job hazard and resources organisations commit to cushion adverse safety incidents. For example, [19] in a publication titled *"Safety hazards and motivation for safe work"* identified nuclear, aviation, military, oil and gas as high-risk industries that provide reasonably high wages to workers. [20] argued that there is a reason to believe that nuclear and aviation industries offer increased wages to workers that are commensurate to job risk and at the same time invest more in the safety and health of employees.

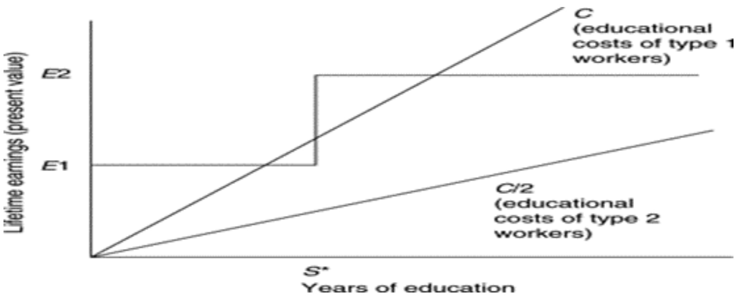

Figure 1.0: Earnings and years of education theory adapted from Human Capital and Economics

2.2.2 Theory of Increasing Penalties for offenders

Another theory that provides a somewhat supposition to costs of health and safety compliance and non-compliance to regulations is *"The Simple Theory of Increasing Penalties for Repeat Offenders"* put forward by [21]. The model explains rising penalties based on a factor that apparently has not been considered in the context of wage discounts associated with conviction. The model considers a population of risk-neutral offenders who commit offences (breaches of health and safety regulation) in two periods. On the assumption that an offender receives a private return of "b" amount of money from each act of offence that is committed and faces an expected penalty that depends on the probability of apprehension "p"; and a sanction that is potentially dependent on their conviction record. The theory subsequently made the assumption that on a precise note if a first-time offender in a specific period of time is subject to a sanction "S1" (measured in monetary terms) if caught while re-offending (i.e. those with a history of past conviction) are subject to a sanction of "S2". The model assumes that offenders who committed an offence or breach of regulations in period one but were not caught are treated as first-timers; that is if caught for a second offence or breaches in a different period. The sanction that deters rational offenders is then expressed in a reverse sequence, starting with the period two decisions of offenders. Thus, a mathematical expression or model can be derived as shown below. It is, however, assumed that an offender's expected return from committing an offence is b−ps1, while his return from legal employment is y. The offender is therefore deterred if:

$$Y \geq b - ps1$$

or if

$$s1 \geq \frac{b - y}{P}$$

On the other hand, if an offender has a criminal pass the expected return for committing a crime in period two is b−ps2; and the return from breaching regulation is y−ε. Therefore, an entity will be deterred if y−ε ≥ b−ps2.

$$S2 \geq \frac{b + \varepsilon - y}{p}$$

As noticed, the lower bound of the equation for S2 is larger compared to S1. This simply reflects the inferior labour market opportunities of convicted entities for an offence in this case, for breaching health and safety rules. But there is a need to take account of irrationally committed offences in period two with a probability α regardless of their period one behaviour. Therefore, rational offender calculation for expected lifetime income for committing an offence (or breach of health and safety regulations) in period one will be:

$$b - ps1 + (1-\alpha)(y-p\varepsilon) + \alpha[b-p2\ s2-p(1-p)s1]\ .$$

Note: pε is the expected cost penalty, while the term in square brackets is the expected return from irrational crime in period two (in addition to consideration for the offender's period one behaviour). Conversely, an offender's expected lifetime income for acting legally in period one is: $y + (1-\alpha)y + \alpha(b-ps1)$. The expected cost of punishing first-timers is thus $p[\alpha(1-\alpha)+\alpha2(1-p)]s1$, while the expected cost of punishing repeat offenders is: $p2\alpha2s2$. Summing all costs across the two periods and simplifying yields will be:

$$TC = p\alpha(2-p\alpha)s1 + p2\alpha2s2$$

Thus, differentiating (TC) yields the slope of iso-cost lines in (s2, s1) space:

$$\frac{ds2}{ds1} = -\frac{(2 - p\alpha)}{p\alpha)} < 0$$

$$S1^* = \frac{b-y}{p} \quad \text{and} \quad S2^* = \frac{b+\varepsilon-y}{P}$$

Note: Key assumptions considered in this theory are, since P is fixed, the cost of apprehension is assumed to be a fixed cost in each period. Therefore, it was ignored in the derivation of the formula. Another assumption is that society and offender weigh the cost of punishment equally; otherwise, if different costs are attached, as it is likely to be true for prison situations; then, it will call for an additional weighting factor [22]. Nevertheless, this factor was ignored because it has no impact on the conclusion of the model. A key inference from the theory of increasing penalties for offenders is that most studies about costs of health and safety do not factor-in the rationale for rising costs of punitive measurement for non-compliance to health and safety regulations. The theory makes sense considering the observed pattern of penalties incurred by most organisations for breaching of health and safety offences, and rising fines for new and repeat offenders.

3.0 RESEARCH METHODS

The study adopted a phenomenological research strategy. The research strategy allows respondents to express their perceptions and expectations based on their own experiences. [23] claim that phenomenological study brings to bear the experiences, understanding and perceptions of individuals (about a phenomenon) from their own perspectives. The study data were collected by means of Focus Group Discussions (FGDs) and scrutiny of archived data. Total of nine focus group forums were organised and intensively discussed issues about costs of health and safety compliance and non-compliance with regulations at various times.[23] are of the opinion that studying multiple perspectives of a phenomenon could help in the development of a theory, and generalisation of findings from phenomenological studies. [24] stated that 5 to 10 participants are acceptable for a typical FGD. Thus, this study adopted a minimum of five to ten participants per each FGD. Discussions and interactions in each FGDs were tape-recorded and transcribed. Microsoft Teams and word 2022 version were used to facilitate all transcriptions. The study was limited to costs of health and safety and related legislation in the UK because of availability of data. A purposive and convenient sampling technique was used to select eight construction companies that were fined in the last 20 years by the UK Health and Safety Executive and other organisations with sound safety records. Overall, the study participants were drawn from a poll of construction managers, health and safety officers, site operatives, site managers, engineers, government regulators, company's finance managers and company's directors. Participants with a minimum of five years construction and health and safety experience were considered for the study. Textual contents from each FGDs were inputted into Nvivo 12 software. All data captured were coded using keywords and phrases such as "cost", "costs of health and safety compliance", costs of non-compliance with safety regulations", "theory", "costs behaviours" etc. Data obtained were analysed using content analysis. Reasons for using content analysis include ability to easily extrapolate antecedents of interviewee's discussions, concerning the study subject matter, it provides valuable insight about the research data, code/text allows for unobstructed means of analysing interactions and better examination of communications using captured texts that emanated from the FGDs.

3.1 Validity of Qualitative Inquiry

The researchers were mindful of endless theoretical arguments about validity of qualitative inquiry often defined as “truth” and credibility usually referred to as “integrity of research” [25]. To avoid philosophical arguments about validity of qualitative research, the authors accepted the standpoint of [26] assertion that “there is a pure ‘form of truth’ which can be discovered (through construct, external and internal validity) using appropriate and most importantly valid research methods. For straightforwardness, the authors inferred valid qualitative research (interview data) to represent credible social worlds (construct) or different interpretations of words that constitute meaning to the study research variables. Thus, validity of the **phenomenological Inquiry** was addressed through three fundamental areas: **production** (design of interview questions, interview process and recording of the data), **presentation** (replicability, valid inference, and arrangement of the data), and **interpretation** (meaningful discussion of data).

3.2 Presentation of Findings from FGDs Inquiries

Participants in the FGDs were asked to evaluate their views about two key cost elements i.e., costs of health and safety compliance and non-compliance with regulations. Some contents from the FGDs were subsequently trimmed for better understanding and spontaneity of the interaction between study participants and the researchers. Some textual excerpts were expressed verbatim as illustrated below for a better understanding of participants’ viewpoints regarding the research variables. For example, when asked: **what is your notion about costs of health and safety compliance and non-compliance with regulations in the construction industry?**

> *“… costs of non-compliance with health and safety regs. are worrisome, scary, colossal …”* – (similar views were upheld 11 times by study participants).

Probing question: On average, can you give us a rough estimate of costs regarding compliance with health and safety regulations in your organisation?

> “… *difficult to quantify, tricky and usually not ring-fenced* …” (similar views expressed 12 times by study participants).
>
> “… approximately 8 to 13% of total preliminaries costs … in the construction sector safety budget is meagre cost compared to Aviation and Nuclear industries…” (similar views expressed 5 times by study participants).

Research Question: What is your view about remedial (prosecution) costs of health and safety?

> “… colossal, damaging, … unpredictable, disproportionate, illogical, …” (similar views expressed 17 times by study participants).

Other inferences from the study FGDs reveal that the construction industry has a poor reputation for non-ring-fencing costs of health and safety compliance compared to other high-risk industries. Also, there was overwhelming acceptance that costs of health and safety non-compliance (punitive costs) are rising in the past 2002 years.

3.3 Review of Injuries, Fatalities and Average Fines from 2007 to 2022

Table 1.0 presents categories of injuries, fatalities and average penalties for breaching health and safety regulations in the UK construction sector. The data suggest that categories/nature of injuries, fatalities, and breaches of specific health and safety regulations influence average penalties (fines) levied on individuals and organisations.

Table 1: Fatalities and Fines for Non-Compliance with Regulations adapted from [27]

Categories of Fatalities	Nature of Injuries and Fatalities		Average Penalties
Category A - Non-fatal injuries	I	Struck-by hazards: injuries caused by struck by debris and various objects	Fines range from £0 to £112,953 on average plus imprisonment, depending on behaviour of the offender.
	Ii	Falls**:** tripping and falling injuries	
	Iii	Overexertion: Strains and sprains injuries caused by Lifting, twisting, and turning	
	Iv	Exposure: injuries due to exposure to electric current, allergenic, extreme temperature, etc	
	V	Vehicle strikes **-** struck by machinery or moving objects	
Category B -ill Health	I	ill health from noise or noise Induced Hearing Loss (NIHL)	Fines ranges from £250 to £500,000 on average
	Ii	Musculoskeletal Disorders (MSDs)	
	Iii	Hand-Arm Vibration Syndrome (HAVS)	
	Iv	Respiratory Diseases	
Category C - Fatal Injuries	I	Amputations	Fines range from £5,000 to £1,000,000 on average plus imprisonment, depending on behaviour of the offender
	Ii	Injuries likely to lead to blindness or being partially sighted	
	Iii	Fractures to bones other than fingers, thumbs, and toes	
	Iv	Crush injuries causing brain or organ damage	
	V	Serious burns or scalding	
	Vi	Hypothermia or heat injuries	
	vii	Injuries requiring resuscitation or a 24-hour hospital stay	
	viii	Scalping requiring hospital treatment	
	Ix	Loss of consciousness caused by head injury or asphyxia	
Category C: Death & Other severe injuries	I	Death	Fines ranges from £250,000 to £10m on average plus imprisonment.
	Ii	Severe injuries such as paraplegia, quadriplegia	
		Etc	

Table 2 put forward 16 years summary of identified fines i.e., costs borne by individuals and organisations in the UK construction sector for non-compliance with health and safety regulations. The data reveal that on average, SMEs are often disproportionately fined for non-compliance compared to large construction firms.

Table 2: Summary of Fines for Non-Compliance with health and safety from 2007 to 2022

Year	Large companies	SMEs	Individual	Total No. of Known cases	Mean Costs of Fines	Total Amount of Fines
2007	7	133	41	181	13,926	2,534,576
2008	11	106	39	156	16,677	2,618,337
2009	8	105	25	138	14,585	2,027,257
2010	7	103	19	129	12,587	1,636,296
2011	8	99	20	127	21,589	2,763,370
2012	5	104	31	140	16,578	2,337,538
2013	8	110	19	137	15,579	2,411,653
2014	9	108	29	146	22,411	5,428,887
2015	8	187	26	221	27,540	6,111,751
2016	7	172	51	230	38,793	9,310,251
2017	5	167	107	279	35,233	8,897,625
2018	9	188	105	302	35,998	8,905,644
2019	7	201	96	304	37,221	9,045,740
2020	5	65	67	137	21,563	3,899,427
2021	6	68	108	182	27,004	3,901,998
2022	8	91	103	202	34,876	7,978,366

Table 3: Decline in Health and Safety Fatalities Rate from 1973 to 2022 adopted from [28]

Year	1973/74	1977/78	1983/84	1993/94	1998/99	2003/04	2008/09	2014/15	2019/20	2020/21	2021/22
Average Fatalities	651	499	498	296	253	236	179	142	111	142	123

The also show that fines imposed on construction organisations increased exponentially from 2014 to 2022 as illustrated in figure 2 below. Table 3 presents 50 years of statistics (1973 to 2022) that illustrate a steady decline in fatality rates across UK industries. Data in Tables 1, 2 and 3 were extrapolated and used to develop a scatter diagram base on cartesian coordinates. The diagram display values of average fines imposed on construction organisations denoted in y – axis and years / category of fatalities denoted on x – axis as illustrated in figure 2. Figure 2 calls for multiple interpretations and in conjunction with table and 1 and 3. The horizontal top value in hundreds denotes decline in fatalities rate *vis-à-vis* years as illustrated in table 3. Similarly, the bottom horizontal wordings (category A, B, etc) in figure 2 denotes categories of injuries/fatalities *vis-a-vis* fines (£) imposed on organisations for breaching health and safety regulations. Figure 2 is significant because the diagram can be used to predict costs behaviours (fines) that emanates from non-compliance with health and safety regulations in the UK.

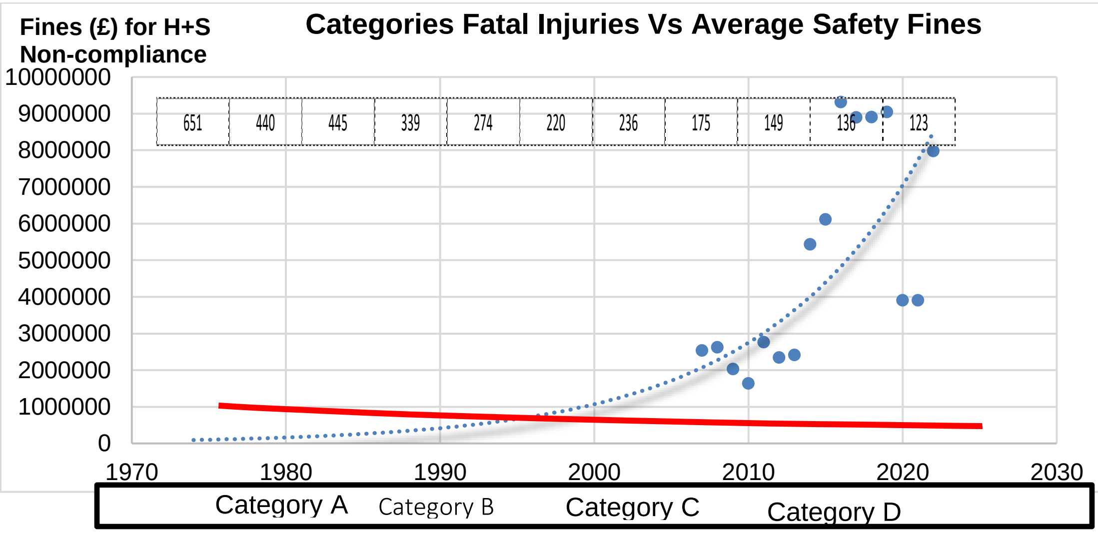

Figure 2: Graphical Model for Predicting Categories of Injuries and Health and Safety Fines

4.0 DISCUSSION

The study identified that many costs are associated with upholding health and safety standards and non-compliance with regulations. However, costs of non-compliance were identified as the most worrisome and alarming outlay to businesses. Indeed, the unpredictable nature of safety incidents and its attendant cost effects on individuals, organisations, and society at large make costs of health and safety complex and difficult to understand. There is no clear cut of what constitutes costs of health and safety compliance i.e., expenses that individuals and firms commit to upholding health and safety standards. Other findings from the study revealed that cost behaviours for non-compliance with health and safety regulations has the potential to increase exponentially as illustrated in figure 2. The huge increase in costs of non-compliance appears to be driven by regulatory authority and judicial ideology that penalties for safety failures must be high enough to make a difference or act as a deterrent to individuals and corporate entities. Review of selected case laws regarding cost behaviours for non-compliance with health and safety regulations for example Watling Tyre Service Ltd, an SME company fined £1m, BP Deepwater horizon accident with estimated cost $61.1billion, HSE vs Ozdil Investment Ltd case laws to mention but a few showed that costs of non-compliance with health and safety have potential to decimate about 40% of annual profit most organisations. Besides, there are many instances of companies that collapsed due to imprisonment of company's directors and harsh punitive costs for non-compliance with health and safety. From the UK perspective, it is fair to argue that enactment of the health and safety Act of 1974, and subsequently targeted health and safety legislations largely contributed to a steady decline in fatalities from the 1970s till date. Indeed, findings from the study lay a good foundation for theoretical reasoning as postulated in the succeeding section.

5.0 CONCLUSION

Fundamental lessons from the study show that cost behaviours of health and safety compliance and non-compliance with regulations vary significantly, due to array of factors. For example, study participants' views, and analysis of archived data suggest that many construction companies have meagre budget for preventative health and safety practices. In fact, some companies do not budget for health and safety activities. On the other hand, costs of non-compliance (punitive costs) with regulations appear to be the driving force that compels individuals and businesses to take health and safety seriously. For example, nearly all study participants concur that costs of non-compliance with health and safety regulations are colossal, damaging, unpredictable, disproportionate, and illogical from a business viewpoint. Therefore, the key theoretical construct or supposition to be deduced from the study, particularly figure 2, i.e., graphical model for predicting fatal injuries and average costs (Fines) are as follows:

i. To every health and safety failure (ill health, injuries/fatalities) there are likely associated costs (fines), that are contingent on legislations, rule of law, state (geographical location), and commercial viability of organisation.
ii. Targeted health and safety legislations, enforcement and basic rule of law are fundamental to reducing fatalities, and continuous safeguarding principles in the workplace.
iii. Fines (i.e., costs of non-compliance with health and safety regulations) are prone to future increases, if sentencing guideline continue to target corporate turnovers. The aim is to make offenders sit up and take health and safety responsibilities seriously.

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PUBLIC SAFETY DURING ELECTRICITY SUPPLY

Dorial Sebothoma, John Smallwood

Department of Construction Management, Nelson Mandela University, South Africa

Abstract

Public power utilities have a long-standing commitment of zero injuries in their communities in terms of the workplace and the public. However, illegal connections are made to the South African electricity network without Eskom, the public power utilities' permission - an electricity connection is considered illegal when it is made to the Eskom network without Eskom's permission. The aim of this study is to evolve a framework of interventions to minimise illegal connections and minimise electrical risks.

The study investigates the range of problems that arise for the electricity provider when members of the public steal live electrical wires or when they illegally connect electrical wires, which results in them encountering live electrical wires, thereby causing serious injuries and fatalities. The socio-economic realities and the entitlement thereof that is experienced by the members of the public lead to illegal connections. Furthermore, the members of the public are unaware of the dangers of illegal electrical connections.

The quantitative research approach was adopted, which entailed the administration of a questionnaire to members of a community. The gathered data was analysed to compute descriptive statistics in the form of frequencies and a measure of central tendency in the form of a mean score (MS).

The salient findings include that often children are hurt or killed by illegally connected cables. Furthermore, illegal electricity connections and public electrical contact risks can be minimised by installing energy meter tampering detection devices, anonymous tip offs, safeguarding the assets against unauthorised access, regular monitoring, fining the perpetrators, continuing provision of basic electricity to low income earners by municipalities, reporting of any illegal connections to the electricity provider, removal of illegal connections by the electricity provider, using authorised qualified electricians to connect electricity, municipalities using budget to electrify all houses that are illegally connected, and educating the residents.

Conclusions include: Eskom perceives public safety as a risk relative to power supply; despite the public tending to shift the responsibility of public safety to Eskom, they 'take it seriously', and the public lacks knowledge of visual electrical communication tools such as safety signs, tags, and labels.

Recommendations include: community liaison including the major stakeholders to evolve a strategy to address the problem holistically; the development of programmes aimed at raising awareness with respect to the nature of electricity, and 'de-normalising' illegal public connections to and contact with infrastructure electricity supplies; enhanced South African Police Services' interventions to mitigate illegal electrical connections, and promotion of renewable sources such as solar energy.

Keywords: Community, Electrical supply, Illegal connections, Public, Safety.

1 INTRODUCTION

Electricity is an integral part of modern society, without which living would be difficult; however, contact with it can result in injuries and fatalities. Most electricity fatalities are accidental, and they result from the passage of both low and high voltage electric current, through the body [1].

During recent years, the African continent has experienced an increase in the number of electrification projects. This was caused by the rapid growth in population and economic development. However, most regions still do not enjoy the benefit of these electrification projects due to the energy crisis facing most parts of Africa, which are due to incompetence and corruption. The challenges affecting energy utilities resulted in never ending crises, which lead to high electricity operational costs, and energy theft [2]. During the past decade, South Africa has experienced severe electricity supply challenges, and the electricity supplier has warned consumers against infrastructure and electricity theft that it says costs some R20bn per year and are a 'leading cause' of blackouts [3].

South Africa is a politically charged country and citizens can mobilise political support to ensure that communities receive basic needs. The electrification process was slow in overcrowded areas and the length of time taken to raise projects in these areas led to illegal and unsafe connections. Public incidents result in increased costs due to insurance claims and legal fees. Furthermore, the communities that are mostly affected are those in Living Standard Measure (LSM) 1-4, which includes mostly unemployed people, low-income earners, and where most of the people are uneducated. The people in these environments are willing to take risks and they usually put their needs before their safety.

Public power utilities have a long-standing commitment to both the workplace and the public, as they have a goal of zero injuries [4]. Furthermore, ignoring electrical safety instructions may put public safety and property at risk [5]. Therefore, government's main concerns are that illegal connections are dangerous and often result in serious injury or even death.

There is a paucity of scientific literature relative to the incidence and impact of illegal electrical connections in South Africa, their impact on public safety, and the mitigation thereof. Virtually all South African literature is courtesy of media reports in the print and electronic domain, which generally focus on the impact on public safety, due to the occurrence of related fatalities. This in turn constitutes the research gap i.e., the contributors to, perceptions relative to, and possible solutions to mitigate illegal electrical connections. Given the research gap, the aim of the study reported on is to evolve a framework of interventions to mitigate illegal electrical connections and minimise the related risks. The objectives are to determine the:

- Extent to which five areas experience illegal electricity connections;
- Extent to which ten contributors contribute to illegal electrical connections;
- Possible solutions to mitigate illegal electrical connections;
- Extent to which ten sources of information contribute to the safe use of electricity, and
- Perceptions with respect aspects of illegal electrical connections, the impact thereof, and aspects of electrical safety.

2 LITERATURE REVIEW

2.1 Contributors to illegal electrical connections and electricity theft

Poor and disadvantaged areas, such as urban squatter camps, often suffer from poor coverage of infrastructure or from a lack of quality and maintenance of the electricity equipment, which is attributable to the informality of the neighbourhood [6]. Most people in informal areas lack the resources to build proper houses such that the government can electrify their homes, therefore they resort to illegal electricity connections [7].

2.2 Means of electricity theft

The methods of stealing electricity are as follows: (a) direct connection from distribution lines; (b) grounding the neutral cable; (c) putting a magnet on the electromechanical meter; (d) inserting a disc to stop the rotation of the coil; (e) hitting the meter to damage the rotating coil, and (f) interchanging the input connection with the output connection [8].

2.3 Impact of illegal electrical connections

Electricity theft constitutes the most severe and dangerous impact among an electricity provider's non-technical losses as fraudulent electricity consumption decreases the supply quality, increases generation load, causes legitimate consumers to pay excessive electricity bills, and affects the overall economy [9].

Illegal electrical connections lead to the overloading of the electricity network, which can lead to continuous tripping of the electricity network, which in turn results in damage to property [10].

2.4 Methods that can be used to reduce illegal electrical connections

When a person discovers an illegal connection or electricity theft, they should report or give an anonymous tip off to the South African Police Services [3].

The public, especially children, need to be educated with respect to the dangers of illegal electricity supply [11]. An example includes the 'Cleaner Joburg' awareness campaign that educates the people of Johannesburg about the dangers of illegal connections through sharing video clips, street billboards, departments dedicated to visiting communities, churches, and youth clubs to talk about the dangers of illegal connections and how a plan can be created to alleviate this problem.

Different strategies are in place to combat electricity theft. However, in South Africa, electricity theft is not a statutory offence. This contrasts with the approach adopted in countries such as China, Canada, India, Australia, and New Zealand, where legislation provides for such an offence. Although electricity theft is not a statutory offence, prosecutors would like electricity thieves to be punished. In this context, there are conflicting High Court decisions on whether electricity theft is a common-law offence or indeed an offence at all [12].

3 RESEARCH

3.1 Method and sample strata

Zithobeni, a township situated within the Tshwane Metropolitan area in Gauteng Province, South Africa, constituted the geographical delimitation of the study. The South African Police Service (SAPS), in conjunction with Tshwane Metropolitan Municipality launched the community street committee's initiative to improve safety and reduce crime. Street committees are made up of street or area representatives, elected within a community, who voluntarily serve the community within which they operate and reside. The entire Zithobeni street committee consisting of 86 community members constituted the sample, which contributed to external validity.

The questionnaire has its origin in the review of the literature. However, given that limited, if any studies, have focused on illegal electrical connections, no guidance in the form of previous findings existed. A pilot study, which included the pre-testing of the questionnaire on 20 respondents enabled the identification of any potential problems that can occur during the gathering of data during the primary study. The respondents were requested to identify any irregularities in the questions, and anything that they deemed difficult to understand, which has reference to content validity.

A total of 35 responses were received, which equates to a response rate of 40.7%.

The data was captured in MS Excel, which was imported into the Statistical Package for Social Sciences (SPSS) software, Version 25 for analysis. The data analysis entailed the computation of descriptive statistics, a measure of central tendency in the form of a mean score (MS) to interpret the responses to five- or six-point Likert scale type questions, and the ranking of factors. The computation of the standard deviation enabled ranking of factors in the case of tied MSs i.e., the factor with the lower standard deviation was ranked higher than the 'tied MS' factor with a higher standard deviation.

3.2 Findings

In terms of gender, 62.9% of the respondents were female, and 37.1% were male.

The 45 – 54 years age group was represented by 42.9% of respondents, followed by 35 – 44 years (25.7%), and 25 – 34 years (20.0%). The remaining two categories represented 11.5% of respondents.

In terms of occupation, 42.9% of the respondents were teachers, 22.9% police officers, 8.6% nurses, 14.3% unemployed, and 11.4% self-employed.

BTech or Bachelors (37.1%) predominated in terms of highest qualification, followed by NDip (31.4%), Grade 12 or less (20.0%), SAMTRAC (5.7%), and degree (5.7%).

In terms of years lived in Zithobeni, 0 – 10 years (48.6%) predominated, followed by 11 – 20 years (28.6%), and > 20 years (22.9%).

Therefore, given the age groups, qualifications, level of employment, and tenure of respondents in the area where the study was conducted, the responses can be deemed informed, which enhances the reliability of the findings.

Respondents were required to indicate the frequency of purchasing electricity - 28.6% of respondents purchased electricity once per month, 34.3% twice per month, 14.3% three times per month, and 22.9% four times or more per month.

Table 1 indicates the extent to which five areas experience illegal electricity connections in terms of percentage responses to a scale of 1 (minor) to 5 (major), and mean scores (MSs) between 1.00 and 5.00. 'U' represents unsure, and 'R' represents rank.

The MS of 1 / 5 (20%) area is > 4.20 ≤ 5.00, which indicates that informal areas / squatter camps experience illegal electricity connections between a near major extent to major extent / major extent.

The MS of 1 / 5 (20%) area is > 3.40 ≤ 4.20, which indicates that the densely populated areas experience illegal electricity connections between some extent to a near major extent / near major extent.

The MSs of 3 / 5 (60%) areas are > 1.80 ≤ 2.60, which indicates that linear settlements, rural areas, and scattered settlements experience illegal electricity connections between a minor extent to a near minor extent / near minor extent.

Table 1: Extent to which five areas experience illegal electricity connections

Aspect	Response (%)						MS	R
	U	Minor ……………………………. Major						
		1	2	3	4	5		
Informal areas / Squatter camps	0.0	0.0	5.7	2.9	0.0	91.4	4.77	1
Densely populated	5.7	0.0	8.6	20.0	22.9	37.1	3.76	2
Linear settlement	8.6	20.0	31.4	17.1	11.4	11.4	2.37	3
Rural	17.1	25.7	22.9	20.0	2.9	11.4	2.00	4
Scattered settlement	22.9	20.0	22.9	22.9	2.9	8.6	1.89	5

Table 2 indicates the extent to which ten contributors contribute to illegal electrical connections in terms of percentage responses to a scale of do not, and 1 (minor) to 5 (major), and MSs between 0.00 and 5.00. Given that the all the MSs are > 3.00, in general, the contributors contribute to illegal electrical connections to a major, as opposed to a minor extent.

The MSs of 3 / 10 (30.0%) contributors are > 4.17 ≤ 5.00, which indicates that the uncontrolled increasing number of informal settlements, unemployment, and illegal invasion of land by community members contributes between a near major extent to major extent / major extent.

The MSs of 4 / 10 (40.0%) contributors are > 3.34 ≤ 4.17, which indicates that the criminal activities by members of the community, easy access of electrical equipment where public members can easily connect illegally, continuous increase of electricity prices, and lack of information about the dangers of electricity contributes between some extent to a near major extent / near major extent.

The MSs of 3 / 10 (30.0%) contributors are > 2.50 ≤ 3.34, which indicates that using non-qualified, and unauthorised members to connect electricity, culture of entitlement, and not meeting the growing electricity consumption needs by ensuring the electrification of all community members, contributes between minor, and near minor extent to some extent / some extent.

Table 2: Extent to which ten contributors contribute to illegal electrical connections

Contributor	Response (%)							MS	R
	U	DN	Minor ……………………………. Major						
			1	2	3	4	5		
Uncontrolled increasing number of informal settlements	0.0	0.0	0.0	2.9	2.9	42.9	54.3	4.51	1
Unemployment	0.0	0.0	0.0	0.0	14.3	31.4	51.4	4.38	2
Illegal invasion of land by community members	2.9	0.0	0.0	0.0	5.7	40.0	51.4	4.34	3
Criminal activities by members of the community	0.0	0.0	0.0	0.0	37.1	20.0	40.0	4.03	4
Easy access of electrical equipment where public members can easily connect illegally	5.7	0.0	0.0	2.9	31.4	28.6	31.4	3.71	5
Continuous increase of electricity prices	2.9	0.0	0.0	17.1	20.0	25.7	34.3	3.69	6
Lack of information about the dangers of electricity	0.0	0.0	5.7	5.7	40.0	17.1	31.4	3.63	7
Using non-qualified and unauthorised members to connect electricity	5.7	0.0	2.9	20.0	8.6	51.4	11.4	3.31	8
Culture of entitlement	20.0	0.0	0.0	8.6	8.6	37.1	25.7	3.20	9
Not meeting the growing electricity consumption needs by ensuring the electrification of all community members	25.7	0.0	0.0	2.9	20.0	8.6	42.9	3.14	10

Table 3 indicates the extent to which possible solutions will mitigate illegal electrical connections in terms of percentage responses to a scale of 1 (minor) to 5 (major), and MSs between 1.00 and 5.00. Given that the all the MSs are > 3.00, in general, the possible solutions will mitigate illegal electrical connections to a major, as opposed to a minor extent.

The MSs of 2 / 11 (18.2%) solutions are > 4.20 ≤ 5.00, which indicates that installing energy meter tampering detection devices, and anonymous tip offs, will mitigate illegal electrical connections between a near major extent to major extent / major extent.

The MSs of 9 / 11 (81.8%) solutions are > 3.40 ≤ 4.20, which indicates that safeguarding the assets against unauthorised access, regular monitoring, fining the perpetrators, municipality continuing to provide basic electricity to low income earners, reporting any illegal connections to the electricity provider, removal of illegal connections by the electricity provider, using authorised qualified electricians to connect electricity, municipalities using budget to electrify all houses that are illegally connected, and educating the residents will mitigate illegal electrical connections between some extent to a near major extent / near major extent.

Table 3: Possible solutions to illegal electrical connections

Solution	Response (%)						MS	R
	U	Minor …………………………… Major						
		1	2	3	4	5		
Installing energy meter tampering detection devices	0.0	0.0	0.0	5.7	25.7	68.6	4.63	1
Anonymous tip offs	0.0	0.0	0.0	8.6	48.6	42.9	4.34	2
Safeguarding the assets against unauthorised access	0.0	0.0	5.7	20.0	22.9	51.4	4.20	3
Regular monitoring	0.0	5.7	0.0	8.6	42.9	42.9	4.17	4
Fining the perpetrators	0.0	5.7	0.0	20.0	22.9	51.4	4.14	5
Municipality continuing to provide basic electricity to low-income earners	0.0	5.7	0.0	22.9	25.7	45.7	4.11	6
Reporting any illegal connections to the electricity provider	0.0	5.7	0.0	17.1	42.9	34.3	4.00	7
Removal of illegal connections by the electricity provider	0.0	5.7	17.1	2.9	34.3	40.0	3.86	8
Using authorised qualified electricians to connect electricity	0.0	14.3	2.9	8.6	45.7	28.6	3.71	9
Municipalities using budget to electrify all houses that are illegally connected	0.0	5.7	0.0	17.1	45.7	25.7	3.69	10
Educating the residents	5.7	0.0	25.7	14.3	14.3	40	3.51	11

Table 4 indicates the extent to which ten sources of information contribute to the safe use of electricity in terms of percentage responses to a scale of does not, and 1 (minor) to 5 (major), and MSs between 0.00 and 5.00. Given that all the MSs are > 2.50, in general, the sources of information contribute to the safe use of electricity to a major, as opposed to a minor extent.

The MSs of 4 / 10 (40%) sources are > 3.34 ≤ 4.17, which indicates that social media such as Facebook, television (TV) or radio show, schools, and electricity provider's presentation contribute to the safe use of electricity between some extent to a near major extent / near major extent.

The MSs of 6 / 10 (60%) sources are > 2.50 ≤ 3.34, which indicates that parents, newspapers / magazines, other family or friends, pamphlets, and community meetings contribute to the safe use of electricity between a near minor extent to some extent / some extent.

Table 4: Extent to which ten sources of information contribute to the safe use of electricity

Source	Response (%)							MS	R
	U	DN	Minor …………………………… Major						
			1	2	3	4	5		
Social media such as Facebook	0.0	22.9	17.1	0.0	31.4	14.3	14.3	3.94	1
TV or radio show	5.7	0.0	0.0	5.7	22.9	28.6	37.1	3.80	2
Schools	0.0	0.0	5.7	8.6	40.0	25.7	20.0	3.46	3
Electricity provider's presentation	5.7	17.1	11.4	14.3	14.3	25.7	11.4	3.46	4
Parents	0.0	0.0	5.7	14.3	40.0	22.9	14.3	3.34	5
Newspapers / Magazines	0.0	0.0	22.9	5.7	20.0	25.7	22.9	3.21	6
Other:	14.3	17.1	2.9	0.0	2.9	0.0	2.9	3.21	7
Family or friends	0.0	0.0	8.6	28.6	25.7	22.9	14.3	3.06	8
Pamphlets	5.7	0.0	5.7	17.1	37.1	20.0	14.3	3.03	9

Source	Response (%)							MS	R
	U	DN	Minor ……………………………. Major						
			1	2	3	4	5		
Community meetings	0.0	8.6	28.6	8.6	37.1	11.4	5.7	2.83	10

Table 5 indicates the extent of agreement with twelve illegal electrical connection-related statements in terms of percentage responses to a scale of strongly disagree to strongly agree, and MSs between 1.00 and 5.00. Given that all the statements are positively stated, the concurrence should be agree as opposed to disagree, which is the case. It is notable that the concurrence relative to all the statements is agree to strongly agree / strongly agree (MSs > 4.20 ≤ 5.00). Furthermore, 5 / 12 (41.7%) MSs are in the upper half of the MS range, namely > 4.60 ≤ 5.00.

Table 5: Extent of agreement with twelve illegal electrical connection-related statements

Statement	Response (%)						Mean Score
	Unsure	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	
Often children and toddlers who have nothing to do with illegal connections are hurt or killed by illegally connected cables	0.0	0.0	0.0	0.0	22.9	77.1	4.77
Knowledge of visual electrical communication tools such as safety signs, tags and labels are essential and can prevent incidents from happening	0.0	0.0	0.0	0.0	34.3	65.7	4.66
Illegal connections can expose you to electrical contact incidents	0.0	0.0	2.9	0.0	28.6	68.6	4.63
Homeowners should closely monitor the electrical requirements of each outlet and circuit to ensure that they are not overloaded	0.0	0.0	0.0	0.0	37.1	62.9	4.63
Power outages affect the functioning of schools, clinics, hospitals, and traffic lights, and negatively affects the country’s economy	0.0	0.0	0.0	0.0	37.1	62.9	4.63
Illegal connections overload the electricity network beyond the capacity for which it was designed, which leads to system tripping, resulting in unplanned power outages	0.0	0.0	0.0	2.9	34.3	62.9	4.60
Electrical cords are often pulled, scraped, run over and experience wear and tear after some time and that pose a safety risk	0.0	0.0	0.0	5.7	31.4	62.9	4.57
Electrical safety training reduces electrical contact incidents	0.0	0.0	0.0	2.9	37.1	60.0	4.57
Most people understand that connecting illegally can be dangerous, but they continue to make illegal connections	0.0	0.0	0.0	2.9	37.1	60.0	4.57
It is dangerous for the technicians to disconnect illegal connections as community members often respond with violence	0.0	0.0	0.0	5.7	37.1	57.1	4.51
Illegally connected wires can also make contact with other items such as roofs, gutters, and washing lines, making these items live, which can cause electrical contact incidents	0.0	0.0	0.0	0.0	45.2	44.8	4.48
When exposed live wires fall in the water, electricity can instantly travel to your body	0.0	0.0	2.9	2.9	48.6	45.7	4.37

DISCUSSION

The finding that informal areas / squatter camps predominate in terms of the extent to which five areas experience illegal electricity connections corroborates with the literature [6; 7]. Furthermore, their invariable proximity to electrical infrastructure facilitates illegal electrical connections.

The finding that all ten contributors contribute to illegal electrical connections to a major, as opposed to a minor extent, corroborates with the literature [2; 6; 7]. Furthermore, it informs that the challenge is multi-dimensional and that there are socio-economic issues such as uncontrolled increasing number of informal settlements, unemployment, and illegal invasion of land by community members, which predominate, and which are beyond the control of the electricity supplier, which further corroborates with the literature [2; 6; 7].

The finding that all ten possible solutions will mitigate illegal electrical connections to a major, as opposed to a minor extent, corroborates with the literature [6; 7; 8. Solutions include education, creating awareness, technical interventions, enforcement and prosecution, municipal socio-economic-related interventions, and public assistance.

The finding that all ten sources of information contribute to the safe use of electricity to a major, as opposed to a minor extent, corroborates with the literature [11], and highlights the need for a multi-faceted approach.

The extent of agreement with twelve illegal electrical connection-related statements highlights the nature of electricity theft, the impact thereof, the need for electrical safety education and awareness, and that community members are knowledgeable. Furthermore, the findings corroborate with the literature [3; 6; 7; 8; 9; 10].

The implications of the findings are profound. First, due to the socio-economic realities faced by South Africa, informal settlements continue to be established, and in the case of existing, expand daily. Second, the high level of concurrence with the statement 'Most people understand that connecting illegally can be dangerous, but they continue to make illegal connections', underscores the futility of creating awareness, and to inform regarding the dangers of illegal electrical connections. However, the electricity supplier is legally required in terms of the Occupational Health and Safety Act (OHSA) [13], and Section 14 'Conditions of License' of the Electricity Regulations Act [14], to ensure that the systems supplying electricity to users are done so in compliance with the required health and safety requirements. Furthermore, the 'Tipping Point: How Little Things Can Make a Big Difference' authored by Malcolm Gladwell [15] identifies three rules of 'epidemics. In terms of the second rule 'Stickiness Factor', there are many techniques to make something stick, including the use of stories, audience participation, and repetition. This technique is certainly applicable in terms of the 'message' regarding the overall impact of illegal electrical connections, including death. The third rule 'Power of Context' focuses on the immediate environment or 'context'. In the case of informal settlements, the environment is characterised by non-weatherproof dwellings, pools of water, in which illegal electrical conductors may lie, and unsafe reticulation of electrical conductors, which entails potential contact with people and other structures. The context presents a volatile cocktail in terms of potential death and should be included in stories, audience participation, and repetition.

CONCLUSIONS

Communication, both formal and informal, is vital before any activities can take place due to the importance of consultation, creating awareness, and ensuring 'buy in' in terms of solving electricity supply-related problems.

Programmes aimed at de-normalising illegal electrical connections and public contact with electricity are necessary. These should be reinforced by visible policing, and legislation that enables sanctioning of offenders.

The mitigation of informal settlements and dwellings is a holistic and necessary intervention as illegal electricity connections are a function thereof. Given that this is unlikely, it can be concluded that the framework of responses should focus on de-normalising illegal electrical connections, raising the level of awareness with respect to electricity safety, and the dangers of illegal electricity connections, even if doing so is futile in cases.

RECOMMENDATIONS

Given the importance of communication, meetings, and other forms of communication between the electricity supplier and communities are necessary, and should involve the ward councilor, community forums, and street committees, before any actions are taken to solve electricity supply-related problems.

Programmes aimed at de-normalising illegal electrical connections and public contact should be jointly evolved by the electricity supplier, community forums, and street committees, and facilitated by the ward councilor. Such programmes should include ‘working safely with electricity’ and address the need for morality e.g., ‘Cleaner Joburg’ awareness campaign [11]. The South African Police Services should work hand in hand with the electricity supplier and contractors in terms of responding to illegal electrical connections. Ultimately, electricity theft should become a statutory offence in South Africa as in other countries as highlighted in the literature [12],

Given the need to mitigate informal settlements and dwellings, urban planning is critical, as legislation, policing, and enforcement. If informal settlements are upgraded, then electrification should be a major component thereof.

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A SCIENTOMETRIC ANALYSIS OF RESEARCH ON RESPONSIBLE SOURCING IN THE CONSTRUCTION INDUSTRY

Sambo Zulu[1], Maria Unuigbe[2], Neema Kavishe[1]

[1]Leeds Beckett University, Leeds, United Kingdom

[2]University of Central Lancashire, Preston, United Kingdom.

Abstract

There is currently a drive towards sustainable buildings world-over. Considering the definition of sustainability, sustainable buildings need to demonstrate their performance in respect of environmental, ethical, social, and economic perspectives. One of the challenges for sustainable buildings is to demonstrate to all interested parties that the products and materials contained in any construction phase have been sourced responsibly. Issues concerning the welfare of workers, health and safety practices and environmental sustainability in the upstream supply chains, have brought the question of responsible sourcing to the fore. While other industries such as retail and food have embraced responsible sourcing, this has been slow in the construction industry. Responsible sourcing requires that companies take into account a triad of environmental, economic and social sustainability when managing relationships with suppliers. Although there have been studies on responsible sourcing in the construction industry, there is a limited review that evaluates the current state of research on this subject. The objective of this paper is therefore to undertake a comprehensive literature review of research papers relating to responsible sourcing in the construction industry using bibliometric analysis. While the focus of the analysis is on the main research areas, issues such as timeline trends, authorship, research outlets and research topics are explored. The results of the analysis provide a domain-knowledge map of research on responsible sourcing in the construction industry and the identification of knowledge gaps for future research.

Keywords: Responsible sourcing, sustainability, bibliometric analysis, triple-bottom-line

1 INTRODUCTION

The construction industry plays a significant part in sustainable development and its processes and products impact on the environment. The industry is one of the largest consumers of resources[1] and a significant contributor to environmental degradation [2]. The industry is also regarded as impacting the environment due to the large volumes of waste generated from its processes[3] and it is one of the biggest energy consumer and carbon emitter [4]. It is estimated that the construction industry contributes 40% of raw materials consumption, 36% of energy consumption, 40% of solid waste generation, and 40% of greenhouse gas emissions [5]. Consideration of construction materials is therefore important as they play a crucial role in various aspects of a building, including thermal performance, internal comfort, acoustics, and durability [6]. The extraction, manufacturing, consumption, and end-of-life options of materials have major social, economic and environmental impacts [7]. Indeed, construction material selection can have socio-economic impacts on the surrounding area of a construction project including, economic benefits to the local communities, the use of local materials resulting in the constructed buildings harmonising with existing structures, and other providing a social benefit [8]. According to [8], sustainable construction focuses on how the design and selection of sustainable building materials can complement the environment, improving living quality, user health, and comfort, rather than simply limiting the overall construction activity. Consequently, evaluating the environmental impact of materials consumption becomes critical [2]. The construction industry has been encouraged to adopt sustainable materials. Ding [8] defines sustainable building materials as those that are natural, offering specific advantages such as low maintenance, energy efficiency, improved occupant health and comfort, and increased productivity, while being less harmful to the environment. It's important to note, however, that not all natural materials are environmentally friendly. Therefore, sustainable building materials refer to materials that are either environmentally friendly or responsibly sourced [8]

One of the challenges for sustainable buildings is to demonstrate to all interested parties that the products and materials contained in any construction phase have been sourced responsibly. Issues concerning the welfare of workers, health and safety practices and environmental sustainability in the upstream supply chains, have brought the question of responsible sourcing to the fore. While other industries such as retail and food have embraced responsible sourcing (RS), this has been slow in the construction industry. RS requires that companies take into account a triad of environmental, economic and social sustainability when managing relationships with suppliers. RS is an important aspect of the broader sustainable supply chain management (SSCM) agenda. To some extent, responsible sourcing has become a question of the ethics of sustainability. Literature is awash with definitions of ethics. The general context however defines ethics in terms of what is right and wrong and also touches on issues of morality. Adnan (2012) viewed ethics as a system of moral principles, which impact people's judgement of actions, whether such actions are wrong or right. Such a definition is useful to place the context of the ethics of sustainability. Thus by implication ethics of sustainability can be construed as a system of moral principles which impact people's judgement when making sustainability-related decisions and actions. Meijboom and Brom (2012) argued that the notion of sustainability as a moral ideal is relevant to understand the possible role ethics can play in sustainability discussions. The roles of ethics in sustainability has therefore been demonstrated. For example, Schults et al (2005) studied the relationship between values, as ethics construct, and environmental concerns and consumer behaviour. Similarly, studies have looked at the impact of consumer ethical behavior as a determinant of consumer behaviour. For example, studies in sectors such as food production, demonstrate that consumers can be active contributors to sustainability by selecting food choices that are both healthy and produced respecting environmental and socially ethical standards (Ghvanidze et al, 2016).

The concept of Responsible Sourcing (RS) can be defined in various ways. According to BRE (2009), RS is a comprehensive approach to managing a product's lifecycle, starting from its raw state through manufacturing, processing, use, re-use, recycling, and ultimately, its disposal as waste with no further value. On the other hand, the International Chamber of Commerce (ICC) (2008) offers a more sustainability-focused definition, stating that responsible sourcing involves companies considering social and environmental factors when managing relationships with suppliers. It is worth noting that there is no universally agreed-upon definition of responsible sourcing, as highlighted by ICMM (2015). In different contexts, terms like 'sustainable,' 'ethical,' 'green,' or 'conflict-free' may replace 'responsible,' while 'purchasing' and 'procurement' may be used instead of 'sourcing.' However, the specific terminology used may carry particular connotations. In their study, Van den Brink (4) exclusively used 'responsible sourcing' to analyze research on practices within the mining sector.

To promote responsible sourcing of materials in the construction industry, the Framework Standard for the Responsible Sourcing of Construction Products (BES 6001) (BRE, 2009) and the Responsible Sourcing Sector Certification Schemes for Construction Products (BS 8902) (BSI, 2009) provide guidance for responsible sourcing of materials. BES 6001 provides guidance to construction product manufacturers to ensure and then prove that their products have been made with materials that adhere to responsible sourcing principles, including organisational governance, supply chain management and environmental and social aspects (BSI 2009). BS 8902 (BSI, 2009) on the other hand, is a framework for the development of a responsible sourcing certification scheme for the construction industry. The reference to the BS6001 standards provides an opportunity for supply chains to demonstrate that materials have been sourced responsibly and have achieved certified standards such as BS6001.

The drivers for responsible sourcing include among others, market pressures, government regulation or guidance and sustainability standards. For example, the UK government’s 2008 strategy for sustainable construction included a target of 25% of materials to be responsibly sourced by 2012 (HM Gov, 2008). Sustainability frameworks such as BREEM award credits for demonstrating using materials that have been responsibly sourced are also key drivers for responsible sourcing. Considering the importance of responsible sourcing, Ball and Booth [9] suggest that rather than relying on the morals of clients, it is recommended that responsible sourcing is made mandatory on all construction projects.

Although there have been studies on responsible sourcing in the construction industry, there is a limited review that evaluates the current state of research on this subject. The objective of this paper is therefore to undertake a mapping of research papers relating to responsible sourcing in the construction industry using bibliometric analysis. Having conducted a bibliometric analysis of the research on responsible sourcing, the paper ends with the identification of key research themes on the subject, thereby providing a timely summary for researchers and managers alike and the research gaps that need to be addressed in the future.

2 METHODOLOGY

This study used scientometric analysis to map knowledge relating to responsible sourcing in the construction industry. The approach is increasingly being used in built environment research.

Thanuskodi, [10] describes scientometric analysis as "The field of study which concerns itself with measuring and analysing scientific literature. Scientometrics is a sub-field of bibliometrics. Major research issues include the measurement of the impact of research papers and academic journals, the understanding of scientific citations, and the use of such measurements in policy and management contexts". Gavgani, [11] describes it as "The study of measuring and analysing science research. In practice, scientometrics is often done using bibliometrics which is a measurement of the impact of (scientific) publications". Using information technology, scientific index, and visualization techniques, the bibliometric method provides researchers with a way to understand the trends and connections between fields, specialists, disciplines, authors and publications[12]. Scientometric analysis can be used to explore linkages such, based on the bibliographic records of the literature, such as co-citation analysis, co-occurrence keyword analysis, and timespan analysis (See for example, [13] and [14]. Vosviewer, a software tool for constructing and visualizing bibliometric networks was selected to be used for the analysis of data. While other software has the capability to analyse bibliometric data, Vosviewer was selected as it is freely available online and offers the basic functionality needed for visualizing Scientometric networks [14].

In order to conduct a scientometric analysis, it is a requirement that bibliometric data from research publications are acquired. Figure 1 represents the process involved in the data acquisition and analysis. There are many options for this, such as google scholar, web of Science, Pubmed, and Scopus. Scopus was chosen for its coverage of recent publications in the field. However, in order to test this assumption, the authors, tried using the Web of Science and did not get different results. Therefore both Scopus and Web of Science would be ideal for the collection of bibliometric data.

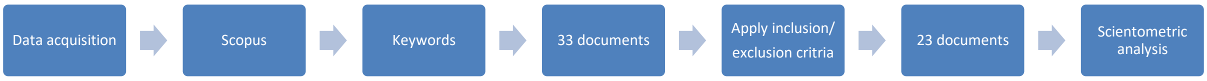

Figure 1: The research design

The search keywords used were a combination of 'responsible sourcing' and variations of 'construction industry' However, similar to the work of [15] the authors chose 'responsible sourcing' as the key search word with the exclusion of other synonyms such as green sourcing, green supply chains, ethical sourcing etc. The following was the search stream:

> *(TITLE-ABS-KEY ("responsible sourcing") AND TITLE-ABS-KEY (construction OR "built environment" OR building OR infrastructure))*

Owing to the limited number of studies on the subject, the search strategy did not place a limit on the period for the publications but restricted to collecting bibliometric data from documents that were classified as either, articles, conference papers, or short surveys. The initial search resulted in the identification of 33 documents. However, when the inclusion and exclusion criteria were applied, 24 articles were deemed to be representative of studies that related to responsible sourcing in the construction industry.

The scientometric analysis included the analysis of trends (publications per year), the co-occurrence of keywords, co-citation analysis (references, sources, authors) and co-authorship analysis (author, organization, countries). In addition, to build a picture of the key focus areas of current research, a cluster analysis of keywords was performed.

3 FINDINGS AND DISCUSSION

3.1 Timeline trends

Figure 2 shows the trends in research for responsible sourcing in the construction industry. This is an area that, despite its importance, is receiving research attention. The reasons for this are not clear. Therefore it was essential to compare the trends in research that focused on the built environment and the general responsible sourcing field.

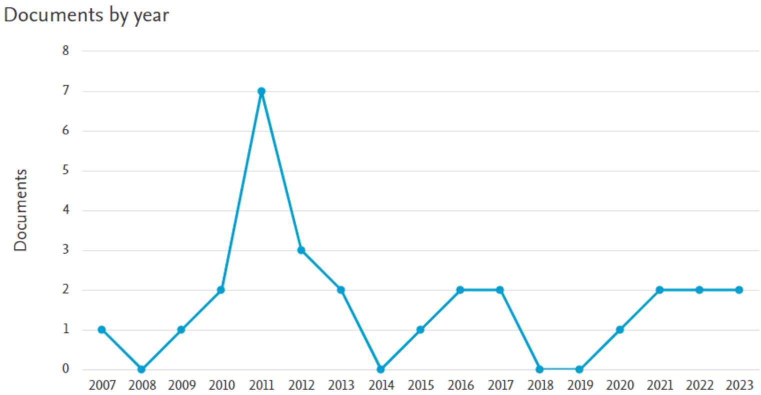

Fig 2: Responsible sourcing- construction industry

Figure 3, shows results for all publications relating to responsible sourcing in general. A comparison of trends shows that while research on RS in the construction industry peaked in 2011, there has generally been limited effort to develop knowledge in this area for the construction industry. In contrast, the data shows that the discussion on RS in general (all research fields) continues to grow with a significant number of articles written between 2016 and 2022. 2016 and 2022 were the peak in terms of the number of papers directly referencing RS. From the data, however, it is not clear, why there is a limited interest in responsible sourcing research in the built environment area of research.

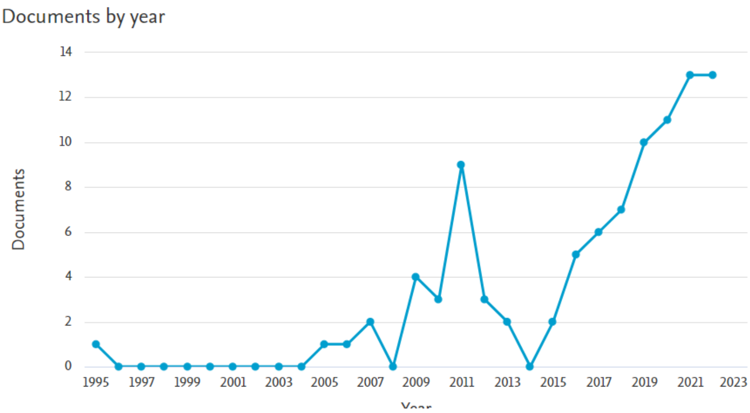

Fig 3: Responsible sourcing- all subject areas

3.2 Documents with the most citations

Table 1 shows the journal articles that have received the most citations. The articles by [2, 16-19] are the top five most cited articles. It is interesting to note also the relatively low total citations for the ten articles listed, with a total of 147 citations. This may reflect the lack of interest in RS research in the construction industry. It is noticeable that in the majority of cases, the studies focus on responsible sourcing practices and integration in the supply chain. There is a limited departure from this. The exception is the study on the Modern Slavery Act [20]an issue that is of growing concern in many industries.

Table 1: Most cited articles

Authors	Article title	Citations
[18]	Implementing sustainability in small and medium-sized construction firms the role of absorptive capacity.	53
[17]	Engaging small firms in sustainable supply chains: Responsible sourcing practices in the UK construction industry.	19

[16]	Briefing: Responsible for sourcing construction products.	17
[21]	Integrating responsible sourcing in the construction supply chain.	13
[2]	Investigation into contractors' responsible sourcing implementation practice.	10
[22]	The sustainable construction business: A missing ingredient in creating a sustainable built environment?	10
[19]	Analysis of responsible sourcing performance in BES 6001 certificates.	9
[23]	Developing a LCA-based tool for infrastructure projects.	7
[20]	The UK construction and facilities management sector's response to the Modern Slavery Act: An intra-industry initiative against modern slavery.	6
[24]	Responsible sourcing of construction products and materials - Results from an industry survey.	3

3.3 Top authors

The top three authors on RS in the construction industry include Glass, J, Nicholson, I, Upstill-Goddard, J, and Dainty, A. who co-authored most of their journal papers between 2009 and 2012, with one exception published in 2016. It is noticeable that they have not followed up their research since and have not published since their 2016 articles Other than these joint publications, there is no other author who has consistently published on this subject. I.e. all others have only published one article.

Table 2: Authors with the most publications

Author	Documents	Citations	Total link strength
Glass J.	9	133	21
Nicholson I.	5	97	14
Dainty A.R.J.	3	32	7
Upstill-Goddard J.	3	25	10
Achour N.	2	22	7
Frost M.W.	2	9	6
Ghumra S.	2	9	6
Parry T.	2	22	7
Watkins M.	2	9	6

3.4 Organisation

The data shows that most of the interest in responsible sourcing is from researchers associated with Loughborough University. A review of the publications shows that the authors represented in Table 3 below are connected with documents jointly published with researchers from Loughborough University. Taking institutions with at least two articles, it is clear that there is very limited interest beyond the united kingdom., and outside Loughborough University.

Table 3: Author Organisations

Organisation	Documents	Citations	Total link strength
Aggregate Industries, Leicestershire, United Kingdom	2	9	4
BRE Global Ltd., Watford, United Kingdom	2	9	4
Department Of Civil And Building Engineering, Loughborough University, Loughborough, United Kingdom	2	9	4
Responsible Solutions Ltd, United Kingdom	4	62	1

Responsible Solutions Ltd., Unit 12, The Office Village, North Road, Loughborough, Leicestershire, Le11 1qj, United Kingdom	2	32	0
School Of Civil And Building Engineering, Loughborough University, Loughborough, United Kingdom	2	63	1

3.5 Countries

This trend is also observed in Table 4 below. Most of the articles published on the subject are from researchers based in the United Kingdom (15 of the 24), with very little interest outside Europe. The only countries outside Europe, represented in the sample include Australia and the United States.

Table 4: Country of origin

Country	Documents	Citations	Total Link Strength
United Kingdom	15	151	1
United States	3	103	0
Australia	1	0	1
Austria	1	0	1
Germany	1	6	1

3.6 Top research outlets (direct citation analysis of outlets)

Our inclusion criteria included articles published in conference proceedings, journal articles and short surveys. It is notable that the of the top four outlets- i.e. those that have published at least two articles, two are conference proceedings. Of the journal papers, there is a lack of consistency in publishing research on RS. For example, ECAM and IJCM have each published one article.

Table 5: Research Outlets

Source	Documents	Citations	Total Link Strength
Concrete (London)	5	4	0
Proceedings Of The Institution Of Civil Engineers: Engineering Sustainability	4	37	8
Association Of Researchers In Construction Management, Arcom	3	22	0
Structural Engineer	2	1	0
Business Strategy And Development	1	6	0
Engineering, Construction And Architectural Management	1	53	4
Glass International	1	0	0
International Conference On Construction In The 21st Century	1	0	0
International Journal Of Agile Systems And Management	1	19	5
International Journal Of Construction Management	1	10	0
Journal Of Environmental Management	1	0	4
Journal Of Operations Management	1	102	0
Metszet	1	0	0
Paper Making And Distribution	1	0	0

3.7 Main research areas (co-occurrence of keywords analysis and cluster of research areas)

An analysis of the key research areas represented in the data collected was conducted. Author keywords were used as the basis of the analysis as recommended by [25]. The threshold for inclusion in the results was set at 3, meaning that only keywords which have been used in at least 3 documents would be included. A total of 40 keywords were returned. However, on further analysis, it was noted that only 34 items were connected and therefore included in the analysis. Figure 2 represents a network analysis of the keywords. The strength of the connections is identified based on the size of the nodes, the distance among nodes and connection lines among these keywords. In addition, the clustering of keywords was identified, based on various colours. Keywords with similar coloured keywords meant that they belonged to the same cluster and that they are closely linked to each other.

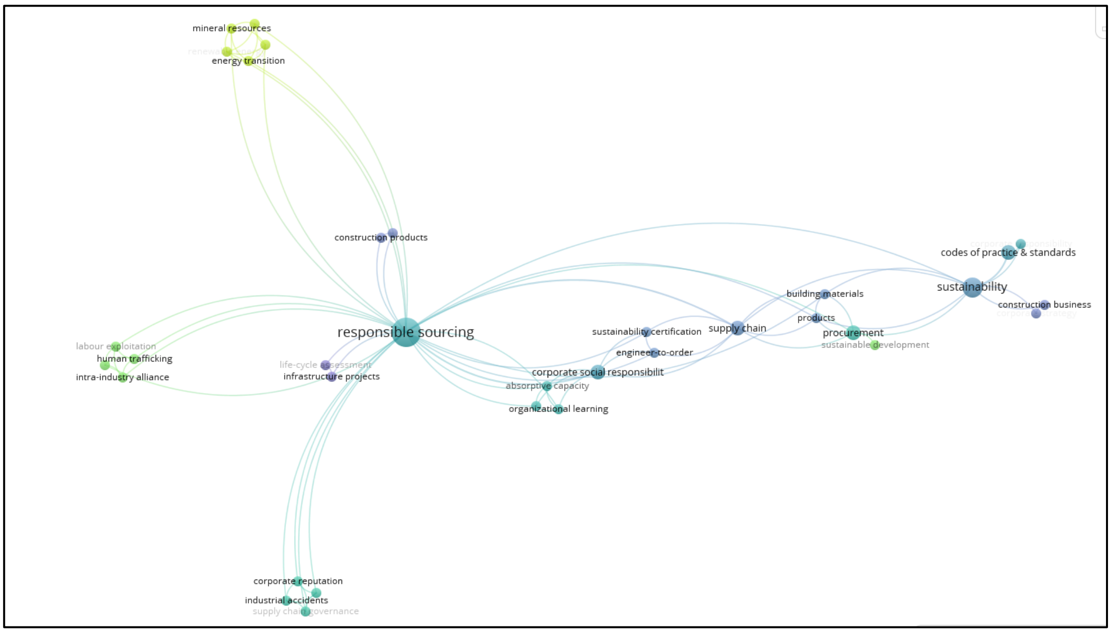

Figure 4: Research areas and clusters

As shown in Figure 2, there are ten main clusters identified by the different colours. However, further review of the clusters suggested a similarity of content and therefore, these were reduced to seven clusters as summarized in Table 6. It is evident based on the size of the nodes and the clusters, that most of the RS research has focused on the general context of RS or a sustainability context. Other research has addressed issues related to supply chain governance, RS in the context of specific building materials and products and RS as a corporate social responsibility issue. It is noticeable, however, that there are research contexts that have received limited attention such as natural resource justice, social justice and supply chain governance. Considering the RS is a growing research area of interest in other disciplines, it is pertinent, that efforts are devoted to this field within a construction industry context.

Table 6: Key Research Clusters

Cluster No.	**Research cluster**	**Key related issues**
Cluster 1	Responsible sourcing	Responsible sourcing, Construction products; sustainability indicators
Cluster 2	Corporate social responsibility	Corporate social responsibility, Absorptive capacity, engineer-to-order, organisational learning, sustainability certification, sustainability standards
Cluster 3	Building materials and products	Building materials, products, procurement, supply chain
Cluster 4	Sustainability	Sustainability, corporate strategy, code of practice and standards
Cluster 5	Social justice	Modern slavery, human trafficking, intra-industry alliance, labour exploitation

Cluster 6	Natural resource justice	Natural resource justice, energy transition, mineral resource, renewable energy, resource governance
Cluster 7	Supply chain governance	supply chain governance, corporate reputation, stakeholder reaction to industrial accidents

4 CONCLUSION

The study acknowledges the importance of responsible sourcing as another tool the construction industry can use to enhance its efforts to achieve its sustainability goals. There is evidence that the quest for social, environmental, and economic sustainability is pushing organisations to consider the sustainability impact of their sourcing activities. While there has been research on responsible sourcing in the construction industry, the scale of interest on the subject has not been clear. It was therefore the intention of this study to map research relating to responsible souring in the construction to identify, trends, key knowledge contributors, areas of research focus and potential future directions. It is evident from the analysis above, that while the topic received interest from 2009 to 2016, there has been limited research post-2016. Indeed, when the research trends for RS as a general subject are compared to that of the construction industry, the findings show that while in the former there is an increase of publications on the subject from 2013, this is not the same with the construction industry. The reasons for this trend in construction management research are not clear. We call for more research on this research topic considering its importance in helping the construction industry achieve its sustainability target. A review of the keywords also demonstrates some of the potential areas of research. While the focus of the studies on RS has mostly been from a general context, there are other areas in which researchers in the construction industry can focus their attention. We considered that sustainability can be looked at as an ethical issue. Therefore studies on RS from a natural resources justice and social justice context should be considered.

This study adopted a strict interpretation of responsible sourcing. As such the literature search focused on those publications that addressed responsible sourcing in the title, keywords, or abstract. However, we acknowledge that there are other terms, such as sustainable supply chain, green sourcing, or sustainable procurement. However, such terms can be interpreted as being broad or lacking in specificity. Therefore having considered the scope of existing literature, we would encourage others interested in the subject to conduct systematic literature reviews on responsible sourcing in the construction industry to help build a picture of research on the subject.

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BIM4OSH OBSERVATORY: CENTRAL REPOSITORY TO MONITOR THE STATUS OF BIM IMPLEMENTATION FOR OSH – PURPOSED ARCHITECTURE

Manuel Tender[1,2], Paul Fuller[3], Peter Demian[3], Vivien Chow[3], Firmino Silva[1], João Couto[4]

[1] *ISLA-Polytechnic Institute of Management and Technology, School of Technology (PORTUGAL)*
[2] *ISEP – Instituto Superior de Engenharia do Porto (PORTUGAL)*
[3] *University of Loughborough (UNITED KINGDOM)*
[4] *University of Minho (PORTUGAL)*

Abstract

Key Technological Developments (KTDs), in recent years, have led to a step change in dealing with Occupational Safety and Health (OSH) risk management. Building Information Modelling (BIM), part of a wider trend of applying digital technology in the Architecture, Engineering, Construction and Operation (AECO) sector, has the potential to optimize the management of risks and costs of accidents at work and occupational diseases. Understanding the way OSH management can be improved using BIM is important as new processes and standards need to be created and existing procedures adapted. Currently there is no centralized sharing mechanism where countries, companies or projects can share lessons learned to help their implementation. Furthermore, there is no formal mechanism to observe and monitor trends and dynamics in the use of BIM for OSH at National, European or industry levels. Digital4OSH is a research group comprised of multidisciplinary academics and industry partners whose aim is to encourage the use of KTDs to improve OSH outcomes. Following a pilot study carried in a complex infrastructure megaproject in UK, this group proposes the development of an Observatory to overcome these gaps. The Observatory would be built on a web-based platform that can be used to obtain statistical longitudinal OSH data and provide information about the progress of national and European implementation of BIM for OSH (through dashboards); to capture, centralize and share (through factsheets) lessons learned from previous projects; to create a repository of technical and scientific information.

Keywords: BIM, Improve Health and Safety Management, Digital technologies to HSW, BIM4OSH Observatory

1 INTRODUCTION

1.1 BIM adoption

The AECO sector has gradually adopted digital innovations, with Building Information Modelling (BIM) at the forefront. BIM, as a set of collaborative methods, processes and standards, along with the enabling information technologies, has become fundamental for responding to a growing need for optimization of processes, procedures and decision making, which runs through the entire life cycle of infrastructure and construction projects. Although governments are working worldwide to tackle delays in BIM adoption and the driving forces for implementing BIM for construction are growing globally, progress has been mixed. National level standardization and policy initiatives vary significantly with some countries advancing their digitalisation processes faster than others. Several countries have already accepted and recognized the value of BIM as a strategic enabler for construction requirements e.g. cost, deadlines, quality, OSH, environment, etc. [1] and are taking important steps to implement BIM policies and initiatives for both their public and private projects. It should be noted that each country has its own unique reality and characteristics (economic, societal, cultural, and political) that are going to require a bespoke approach to BIM. BIM adoption is generally led by complex or large-scale projects and large companies, with SMEs showing limited BIM adoption. In Europe, the European Union Public Procurement Directive 2014/24/UE was published in 2014 and recommends that, from 2018 onwards, electronic platforms would have to be used for public tenders [2]. In some countries BIM methodologies are already quite widespread and several advantages are linked to the use of BIM in the daily routines of companies. According to several studies, USA, UK, Finland, Singapore, Austria, Denmark, Germany, Singapore, South Korea, are leading in BIM adoption. Some countries with limited BIM adoption have already developed their national roadmap and/or are actively working on BIM standardization procedures. However, the adoption of BIM by the AECO industry remains limited, resulting in a gap between policy and practice, which is paradoxical as the industry is in theory the prime beneficiary of digitalisation [3]. According to several authors, a number of factors affect BIM implementation including: social issues e.g. lack of awareness for benefits, lack of demand from the contractors, subcontractors not interested in using BIM: legal and regulatory issues, e.g., it is not mandatory, lack of unified standards and norms; financial barriers, e.g. doubts about ROI, high initial cost; technical e,g., interoperability gaps, scarcity of specialists, absence of contractual requirement for BIM implementation; behavioural e.g. lack of BIM experts, inadequate training. These may all change over time. Although there has been a broad increase in industrial investment and research the area of OSH, BIM does not yet have the prominence in OSH that it has in other specialities, such as structures or MEP [4]. However, it must be said that the literature indicates that the construction industry, especially larger general contractors, are starting to adopt these kinds of technologies for use in OSH management [5]. The analysis of the studies already conducted shows that BIM appears to be a valid instrument for the planning of OSH and its use in the early stages of the project has been linked to an improvement in safety conditions (due to a more effective connection with the productive process and a decrease in the accident rate over the last decade [6]. Additionally the UK NBS Report 2020 [7] confirms that 70% of the respondents think that digitalization will improve construction health and safety. It should be noted that the lack of BIM integration methodologies can create coordination problems which could lead to an increased number of accidents at work [8]. However, there is little information about BIM for OSH implementation worldwide.

1.2 Rationale

A review of the literature and earlier research including a recent study based on the £4.2bn Thames Tideway Tunnel (Tideway) super sewer projects' Central Section, being undertaken by a Joint Venture made up of Ferrovial Laing O'Rourke (FLO), identified areas that need to be addressed if the use of BIM for OSH is going to be increased [9]. These may be considered gaps in the knowledge needed by practitioners if the successful take up of BIM in OSH settings is to be improved. The two main knowledge gaps identified justify why the Observatory is needed:

KNOWLEDGE GAP 1) It is difficult to observe and monitor the progress of BIM for OSH implementation and the differences between high maturity and low-maturity stakeholders [9] such as Project Owners, Contractors, Sub-contractors, Trade Unions, etc**.**

KNOWLEDGE GAP 2) there is no organized repository covering the capture, storage and dissemination of lessons learned [10].

To address these gaps, the development of a specific Observatory was proposed. In order to take the research forward, a number of research questions were formulated, related to the knowledge gaps, to provide the basis for the ongoing research project.

KNOWLEDGE GAP 1 ► Research Question 1: What is the current state of BIM adoption for OSH in each country and how can this be measured?

KNOWLEDGE GAP 2 ► Research Question 2: How can lessons learned (identifying good practices, enablers and barriers) be retrieved, stored, disseminated and replicated from completed projects and then be transferred, through an easy-to-use interface, to other projects to assist OSH practitioners and wider stakeholders to understand how BIM can be used to improve OSH outcomes?

The timing of this research is of the essence as accidents at work are still prevalent and BIM maturity is still poor in some countries. The results will be of interest to those involved in a variety of infrastructure projects, rehabilitation, housing, etc and also regulatory bodies, project owners, designers, safety coordinators in the design and the construction phases, contractors, health and safety technicians, consultants, suppliers, facilities managers, software providers, on a day-to-day basis or more occasionally.

In order to address these questions, Digital4OSH - an interdisciplinary (OSH, Engineering, New technology) R&D academic-industry team (involving ISLA, Loughborough University, University of Minho, Xispoli Engineering, BIMMS Management) proposes the creation of an BIM4OSH Observatory. So, the objectives of the platform will be to identify the particular actions that projects can take to influence the use of digital technologies to improve OSH outcomes by including OSH information in digital data sets; to identify the difficulties and the obstacles for the above; to identify the lessons learned from existing approaches to improve OSH outcomes using digitalization in industry practice; to create barometers that can help to identify dynamics and trends; to create online outputs to be shared with industry - to identify fields of development and improvement which can be the subject of future research. The aim is to apply it namely in projects like Tideway, HS2, new railways in Portugal, etc.

2 BASIS OF THE PROPOSED OBSERVATORY

2.1 Overview

Observatories can be defined as instruments for observing, noticing or perceiving that are employed to acquire qualitative or quantitative data from primary sources. The data can then be used proactively by investigators [11], to characterize a phenomenon through several hypotheses that can be used to predict logical, observable consequences of the hypothesis that have not yet been investigated. Observatories, due to their longitudinal nature provide more accurate and valid outputs than instantaneous snapshots in time. They have several advantages for project stakeholders including: establishing levels of BIM adoption that could be used as indicators of success for BIM programmes [12]; identifys market conditions and policy developments; monitors trends and dynamics; enables, through rich and multiple data, a good understanding of context and description and interpretation of patterns of change; avoids the pitfalls associated with the infrequent collection of cross-sectional snap-shots with findings being extrapolated backwards and forwards over time and outside of the timeframe the data was collected [13]; stimulates debate and reflection among stakeholders; enables a comparative assessment and benchmarking; provide strong political messages [11]; allow actions to be developed and the alignment of good practices; can be powerful motivators for change [14]; enable better decision-making. Important trials of observing real-world dynamics and trends are currently being made by several observatories that have been established in Europe:

European Construction Sector Observatory (ECSO) - set up in 2015 to regularly analyse and carry out comparative assessments of the construction sector in all 27 EU countries and the UK towards these objectives. It has published the report "Building Information Modelling in the EU construction sector" that examines the implementation of BIM in the EU, analyses drivers, opportunities and challenges and provides recommendations for EU political activity aimed at supporting and promoting BIM adoption [3]. The study does not include all 28 EU countries but analyses a representative sample: Denmark for northern Europe; France for Western Europe; Poland for Eastern Europe. ECSO also recently launched a newsletter focused on OSH to provide up-to-date information and the latest news of Europe's construction sector.

Transnational OSH e-observatory - set up to collect and enhance relevant information for about the issue of OSH in the context of posting abroad to provide services.

European Risk Observatory – set up in by OSHA to identify trends in new and emerging risks in occupational safety and health, to improve the timeliness and effectiveness of preventive measures.

Based on the review of existing observatory platforms the proposed Observatory will have four main components:

1) A Collaborative Platform – an online collaborative platform that hosts collection of information about BIM4OSH practices and enables the sharing of experiences.

2) A Barometer – a statistical data collection instrument (barometer) for measuring longitudinal implementation of BIM4OSH that will monitor trends in different countries and companies.

3) Lessons Learnt – a repository populated with real lessons learned from projects using BIM approaches that have already been validated and that can serve as anchor points for knowledge transfer to less mature stakeholders.

4) A Library – a source of information repository that includes theses, papers, legislative and normative documents, etc.

2.2 Collaborative platform

This section covers the first of the key components of the proposed observatory. It outlines the requirements for an online collaborative platform which will enable multiple stakeholders from different organisations to access, populate and retrieve information from a structured database. This will be a web-based collaborative platform that will act as a repository of information about results obtained.

A centralised database, supported on a collaborative web platform, is a system where multiple users can access and share information stored in a single secure central location. Such a platform allows different authorised users to access the database and make changes or updates, with access control and editing permissions set by the system administrator. It is designed to avoid duplication of information and make it easier to coordinate and manage the system. The collaborative web platform allows collaboration and information sharing between different users and works as a broker which allows users to feed it with data input but also consume information that others have stored.

The advantages of a centralised database on a collaborative web platform include easy access and collaboration between different users on a single point of centralised control; reduced data duplication

errors (avoiding redundancy); improved security and a considerable performance; dependence on single point of failure; and the possibility of real-time data analysis.
The collaborative platform incorporates scalability and evolution mechanisms in order to represent a constant dynamic of filling needs that the volubility of the markets transforms. Artificial Intelligence and machine learning exercise a fundamental component in the value proposition that the observatory offers to consecutively improve efficiency in collaboration and increase knowledge. Also the individual and collective (corporate) personalisation both at the interface and content level is one of the characteristics of this platform, as well as the integration with third party platforms in order to obtain and complement the information provided.
It is important to ensure that the platform and database are secure and protected from unauthorised access or privacy breaches. Some of the main security issues include: unauthorised access (it is necessary to prevent that only legitimated users access the levels of information that is relevant and been made available to each profile – mechanisms such as authentication and authorisation should be strongly enabled); protection against attacks (the web platform must be protected against cyber-attacks such as phishing attacks, malware, ransomware, among others – some important security measures should cover hardware actives such as firewalls, but also software such as antivirus, data encryption, among others); data backup and recovery (routine procedures for safeguarding information preventing of data loss or corruption and aim for permanent availability of information in case of problems, activating mechanisms for redundant access to information); monitoring and auditing (it is important to monitor the database in real time and log all activities carried out by users, so that any suspicious or unauthorised activity can be detected); data privacy (it is equally important to classify information of whether to make it public or private but, in addition, it is important to have mechanisms that ensure data confidentiality and that only authorised users have access to that information).
It is important to keep in mind that security should be a priority in all phases of the web platform building project, from planning to implementation and ongoing maintenance phases.
The platform will be built using software development methodologies based on Sommerville's [15]: 1) detailed definition of the objectives; 2) definition of the engineering requirements (functional and non-functional); 3) definition of the web architecture; 4) system modelling definition; 5) data model development; 6) agile software development; 7) system development and implementation; 8) testing and validation; 9) production and maintenance.

2.3 Barometer

Past research has called for the status of BIM adoption to be further explored particularly in OSH settings: e.g.
- If nothing is done on a European scale to tackle the barriers, then it might become difficult for BIM late comers to adopt BIM and work at the same standard as the BIM early adopters [16];
- Industry surveys of adoption levels could be used as indicators of success for the BIM programme [12];
- It is encouraged that measurements of pilot projects are used to demonstrate improvements [12];
- Notwithstanding the much-touted benefits of BIM as a means of increasing productivity, there are currently few metrics that measure such improvements [17];
- when BIM is introduced or specified at a project, organisational or national level, there is often a lack of clarity and common understanding of where to start, what to do [12];
- little guidance is available for organizations wishing to generate new or enhance their existing BIM deliverables [17];
- it is recommended to establish and participate in a common set of metrics (KPIs) to measure and monitor the uptake and effects of BIM in practice [12];
- Could produce measurements and reports of pilot projects and industry adoption levels to encourage the long term industry wide transition to digital method [12];
- There is no universal independent means or organized statistics / compiled information that ease the observation and monitoring of implementation, trends and dynamics of BIM for OSH implementation [10].

Most of the research into OSH interventions in construction projects has been cross-sectional rather than longitudinal studies [18]. Menard (1991) described the difference between cross-sectional and longitudinal studies as: 1) cross sectional has data collected once for each item over a narrow space of time; 2) longitudinal has data is collected over one or more time periods, the subjects or cases are the same or comparable from one period to the next and the analysis allows trends to be identified and monitored over time [13].

In the UK the National Building Specification (NBS) organisation conducts annual surveys of Architecture, Engineering and Construction (AEC) professionals concerning their views on BIM implementation. Surveys have also been carried out in other countries but at varying points in time making comparison of results difficult.

The development of a barometer that continually monitors the progress of BIM4OSH adoption will provide a longitudinal approach. It will enable users to: 1) observe BIM for OSH adoption and uses worldwide; 2) monitor what are the acceptance levels, trends and dynamics in each particular country through periodic statistical assessment. This type of instrument has several advantages including: the creation of quantitative and statistical metrics to measure BIM for OSH in order to assist improvements to be planned, realised and sustained; the progress of development of BIM4OSH implementation can be monitored; benchmarking is enabled between countries; it improves decision-making in BIM and OSH implementation; BIM technology suppliers can identify which countries they should prioritise; it promotes the importance of having national and European indicators. The barometer will be created using longitudinal data obtained through regular data collection and periodical statistical assessment (allowing comparisons over time). Two sets of indicators will be used: I1 – Level of use and implementation; I2 – Level of acceptance. The data collection instrument will be an on-line survey which has the capability of reaching a high number of respondents. The survey will have three major sections: the first for obtaining general information; the second to identify actual BIM uses for OSH (these questions were chosen based on main uses of BIM for OSH identified in previous research); and the third section covers levels of acceptance and BIM potential for improving OSH. Responses will be sought from several different types of stakeholders e.g. Project Client, designers, contractors, suppliers, subcontractors and with various roles both digital and non-digital plus a minimum of 2 years of experience in the field of construction. The measurements obtained will have the potential to structure and present information in a systemic way providing accurate measurement and observation of improvements from BIM for OSH adoption. The panel of respondents for the questionnaire and follow-up interviews will be developed by the research team and partners to assess their availability and affinity to the subject under study. The sampling technique to be used will have the objective of creating a random sample subject to the minimum experience level of two years. The questionnaire will be anonymous multiple-choice using a Likert scale to get a holistic view of respondents' opinions and will use the freeonlinesurveys.com platform which is compatible with the Digital4OSH teams' IT security requirements.

In terms of data analysis and to provide granularity, indicators will be used to establish measurements at: 1) Country or company levels; and 2) Global level. The advantages of this approach is that it takes into account different political and technical frameworks; promotes knowledge sharing; and evaluates the potential for successful use and acceptance levels of BIM for OSH. Using a global approach enables the creation of knowledge about global BIM for OSH framework, the ability to make comparisons between countries or companies, and promotes improvement and knowledge exchange. Stakeholders can benefit from benchmarking their progress and this can act as a motivator for less developed countries; it enables to a more deeper and global data interpretation and analysis for upgrading global strategies. Interpretation of results and discussion will take in account different realities, frameworks, legislation, and standardisation. Outputs will be in form of simple and objective dashboards (Fig. 1), available on the platform based on the two indicators that reveal, longitudinally, individual or global realities.

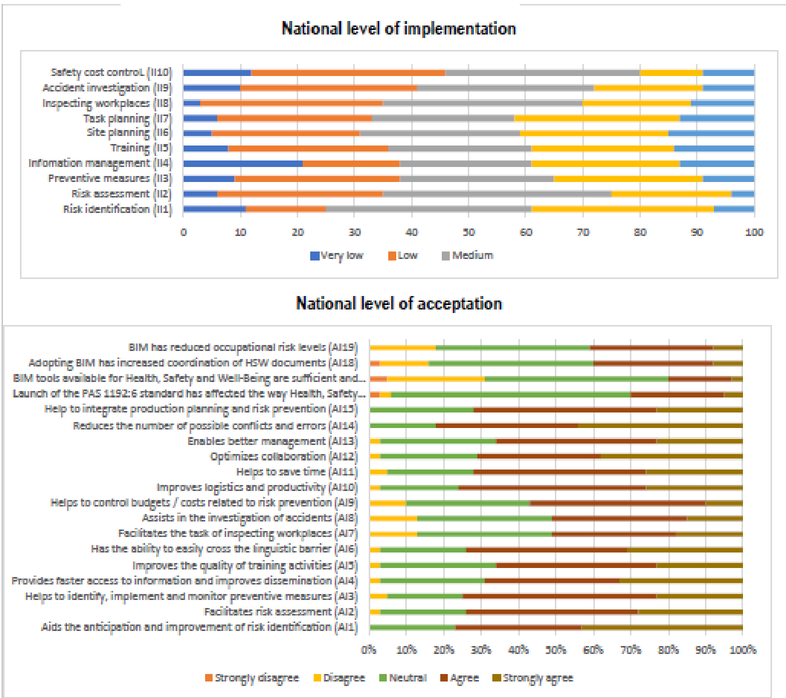

Fig. 1 – Example of national analysis dashboard

Dashboards have several advantages: they are interactive, personalizable and flexible mechanisms; provide at-a-glance views of relevant indicators; enable “rolling up” of information to present a consolidated view across a subject; gauge exactly how well an organization is performing overall and provide a "snapshot" of performance; visual presentation of performance measures; ability to identify and correct negative trends; measure efficiencies/inefficiencies; align strategic goals; saves time compared to running multiple reports; total visibility of all variables instantly; quick identification of data outliers and correlations; available on mobile devices to quickly access metrics; and provide a quick overview for decision-makers. Special attention will be given to the design of dashboards covering simplicity; ease of communication; readable in desktop or mobile formats; clear spatial arrangement. In the examples below dummy data has been used, this means no real data is shown. Dashboards will be gradually archived and upgraded periodically in order to enable to see changes between dates. This will allow the user to verify if implementation had improved in a country since a previous date.

2.4 Lessons learned

Lessons learned in construction projects is typically not carried out in a rigorous structured manner and the lessons tend to be ‘retained in project records and people’s minds which makes them difficult to access and share and this includes the capture and dissemination of OSH lessons [20].

A lesson learned has several characteristics: must be significant having a real or assumed impact on operations; be valid in that is factually and technically correct; and be applicable in that it identifies a specific design, process, or decision that reduces or eliminates the potential for failures and mishaps, or reinforces a positive result” [19].

Compiling lessons learned (namely successes, failures, opportunities and threats) from stakeholders with a high level of maturity in the use of BIM in the OSH domain has the following advantages: specifies the reasons for project success and failures to prevent similar errors being repeated; promotes mutual learning and the exchange of best practices between stakeholders; helps to identify, collect, construct and share examples based in methodologies that are already validated which can serve as anchor points; knowledge will be translated easily emphasising it’s value; helps stakeholders to create and implement effective initiatives;

The absence of lessons learned can lead to a knowledge gap that could affect profitability of future projects as the regular collection of lessons learnt in projects, their careful storage in the organizations historical information data base, and their meaningful utilization in subsequent projects are critical elements of project success and organizational competitiveness [21].

However, the literature has shown that lessons learnt interpretation is inconsistent, if carried out at all, creating wasted resource as mistakes and poor delivery are repeated time and again [19]. Reasons for not capturing routinely the lessons learned can include: no defined lessons learned process in place;

pressure to end projects and begin the next one; knowledge about lessons learned becomes 'buried' in project files which are not easily accessible.
There have been reports that have focused in sharing best practices, lessons learned and recommendations, e.g. EU BIM Task Group [12]. Several researchers identified the lack of material covering lessons learned about BIM in OSH and pointed out the need to develop BIM in the area of OSH using practical cases in order to create a database that could be used by those who are beginning to apply BIM for OSH purposes: further work should be considered which explore in more detail some of the areas identified and establishes the benefits of using digital technologies to improve OSH outcomes" [10]; there should be a focus on detecting weaknesses and threats, in order to try and find solutions for them" [22]; „Incomplete technology transition from construction safety research into practice" [23]; „there is a gap between the theory and realised benefits at the application stage by industry" [24]; "EU countries need to have a common ground by sharing the best practices, enabling BIM leading countries to pull the late adopters upwards" [16]; "should produce lessons learned reports which identifies areas for improvement" [12].
The proposed lessons learned repository will consist in collection, analysis, contextualization, and storage of lessons learned, best practices, difficulties and barriers, trends and underlying factors information about real-world longitudinal successful case studies based in projects from different stakeholders that have a good level of BIM implementation. This would enable the information collected to be retrieved from construction sites to that would act as novel "living labs" - in order to make theory real and effective. There are several advantages of doing this: it enables the collection, documentation and sharing of good practice based in approaches that are already validated and that can serve as exemplars; the lessons learned document will clearly specify reasons for project success and failures; organisations will be able to learn from past mistakes and the repetition of same mistakes will be reduced; it will facilitate good communications between stakeholders with different levels of BIM OSH implementation maturity; It will enable benchmarking and replication of knowledge in the form of a BIM4OSH 'Book of Knowledge'. Lessons learned will be focused on: prevention in design phase; Common Data Environment; document/contractual management; hazards and risk identification, mitigation, and control; training; on-site monitoring and implementation; emergency planning; accident investigations, skills and competences.
The process for retrieving lessons learned will be based on semi-structured interviews with stakeholder focus groups and direct observation on site. Collecting both quantitative and qualitative data will help understand the links between quantitative variables. It will also provide a form of triangulation allowing for a better accuracy of interpretation of results [25] compared to the use of just one method [26]. It will also provide a more complete analysis of the topics and assist in the identification of possible paradoxes and contradictions [30]. Direct observation will take the form of site visits will allow, using direct vision and hearing, a neutral, direct and face-to-face observation of the phenomenon (behaviours and attitudes) under study, without interfering or changing the reality. Individual and focus group (construction, OSH and BIM managers) interviews will be designed to uncover everyone's thoughts about BIM implementation for OSH and to understand advantages, disadvantages and barriers to this approach creating, this way, the "lessons learned". This information can be used not only to reveal and understand the "what" and the "how" but also to give more emphasis on exploring the "why" [31]. Interviews are divided in three parts: an initial part with global question (participant information; use and experience with BIM tools on OSH), a second part for exploring previous experiences with BIM for OSH, and a third part related to earlier survey findings in order to understand each point of view about the results obtained.
Outputs will be available in website in form of "Lessons Learned Factsheets" covering the project details, timescale, operational area covered, BIM4OSH focus, task description, challenge, solution, methodology, benefit analysis – current state/futures state, benefits measurement/targets, benefits realised, critical dependencies, risks/issues/mitigating actions [27], as illustrated in Fig. 2.

Country	United Kingdom — **Date BIM became mandatory**: 2012
Project name	**Thames Tideway Tunnel** — **Period**: 2017 - 2023
Project Summary	Sewer tunnel 25km long and 7.2m internal diameter located beneath the central section of the River Thames that will connect 34 combined sewer overflows discharging into the river during exceptional rainfall.
Project budget	746.000.000eur
Years using BIM	**12** — **Years using BIM for OSH**: **4**
Operational area	Training — **3D**: **X** — **4D** — **5D**
Construction site	Albert shaft construction located in the Central Section of the project being delivered by the FLO (Ferrovial Laing O'Rourke JV)
Task description	Concrete pour of internal walls and vortex generator while simultaneously pouring 3m secondary lining sections of the shaft using jump form several meters high.
Challenge	The construction sequence complex in terms of the many activities that were occurring in the shaft concurrently at different levels and also making users aware of these. Risks.
Solution	Creation of a3D model of the Albert shaft construction sequence, including all permanent and temporary works which can be exported in a format that would allow users to visualize it using a VR headset. A headset could then be brought to site so that the site team and operatives would be able to visualize the spatial constraints at each phase of the construction sequence.nd They could then highlight risks and propose solutions/improvements to the sequence based on their experience of using the VR headset.
Methodology	The site teams outlined the proposed construction sequence to the digital engineering team so that an accurate 3D model can be created. The 3D model was then shown back to the site team to ensure all high-risk areas are captured within the model and the key areas highlighted that need to be reached within the eventual virtual model. The 3D model was then exported into the 'Unity'software, , in order to create the virtual model. which coild then be viewed using avirtual reality headset. Each member of the site team would take turns using the virtual reality headset to get a notion of not only the spatial constraints that each phase contained but also the magnitude of the works ahead. Then each site member could highlighte concerns and highlighted potential problems or risks that they could see within the virtual model.
Benefit Analysis	**Current state** Poor engagement in construction planning Lack of accuracy in task planning Not all risks captured Information not always captured **Future State (Areas for improvement/benefit)** More accurate plans Improved identification of risks Better retention and access to information
Measurement method & target range	Actual time to complete task(s) vs programmed time (days) – 5 to 10% saving Actual cost to complete task(s) vs original budget (£) – 3 - 5% saving
Benefits realisation – key influencing factors	**Critical Dependencies/Barriers** Use of VR is critical Lack of buy-in – management & operatives Time & budget constraints **Risks/issues and mitigating actions** Time needed to develop 3D model Budget Availability of suitable facilities for VR sessions Training in use of VR

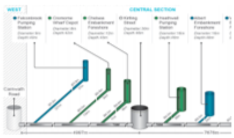

Figure 2 – Example of realisation card

3 DISCUSSION

The results of the Observatory will have a wide potential audience of end users who will be able to exploit the outcomes, both in terms of their professional roles and nationallyl and European-wide, as they will be of interest of stakeholders with diversified public and private project roles (e.g. project owners, designers, safety coordinators in the design and the construction phases, builders, health and safety technicians, inspectors, consultants, suppliers, O&M managers, software and hardware providers). The research will aid their need to create or use technical documents, on a day-to-day basis e.g. specifications, manuals and health and safety plans. The results will also be of interest to researchers, professors and students of the fields of BIM and OSH as they will provide a structured information base for the development of new academic projects. It will also benefit standardization bodies and add value to existing R&D programs including: Healthy Workplaces Campaigns of the "European Health and Safety Agency at Work" – EU-OSHA campaign 2023-2025 covering digitalization for OSH purposes; Longitudinal Tideway Tracer (University of Loughborough / Thames Tideway / IOSH – 2014/2017); European Risk Observatory - based at the European Agency for Safety and Health at Work (EU-OSHA); European construction sector observatory (ECSO), Working Conditions Portuguese Observatory.

4 CONCLUSIONS

The proposed approach is intended to enable a significant raising of the bar in terms of BIM4OSH adoption, bridge the gap between stakeholders of differing maturity, and will have a significant, credible, long-lasting impact and positive influence in scientific, technological and socio-economic areas both in the short and long term.

In scientific terms, BIM4OSH will enable stakeholders to: 1) understand gradual implementation of BIM for OSH enabling organizations to assess their BIM for OSH implementation level against others reducing the gap between involved stakeholders; 2) provide a centralized database of information about lessons learned from previous projects namely in terms of such important areas as prevention through design, risk assessment, etc. The research will have a technological impact as it will provide new approaches and tools for a longstanding problem; project performance will be increased and optimized

with reduced delivery times and costs through the provision of easy-to-use tools. The socio-economic impact will be to increase the competitiveness of academic and industry partners and increase the impact of research outcomes which will consolidate and enhance the research team‘s reputation for the improvement of OSH outcomes using BIM; improve stakeholders satisfaction regarding implementing OSH; and, last but not least, the most important impact: the reduction of accidents at work and occupational diseases through maximising the prevention opportunities offered by digital technologies and creation of safer and healthier workplaces for all in the digital new era.
Users of BIM4OSH Observatory will have specific benefits of participating including: improving their network capacity; the opportunity to provide training; align their strategies through validated approaches; understand the dynamics and trends in each country and in Europe; join Digital4OSH in funding opportunities.
Some challenges include particular characteristics of stakeholders and their organisations, reluctance to share knowledge; project time pressures. These can be studied and solutions to mitigate their effects developed.
The wider research team will build on existing relationships with other countries that have indicated their interest in participating in research based on the BIM4OSH Observatory.
At the end of the project, new routes for further research will be open, namely replicating the Observatory in order to improve the take up of other KTD for OSH uses e.g. Digital Twin., AR/VR, IoT, Drones, Robotics. Artificial Intelligence will also certainly have a place in further research on this theme.

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THE ANATOMY OF THE DIGITAL BUILDING LOGBOOK EMBODIED WITH HEALTH AND SAFETY DATA REQUIREMENTS

Pedro Mêda[1], Hipólito Sousa[2], Diego Calvetti[1]

[1]*IC – Instituto da Construção, CONSTRUCT/GEQUALTEC - Faculty of Engineering, Porto University (Portugal)*

[2]*CONSTRUCT/GEQUALTEC - Faculty of Engineering, Porto* University *(Portugal)*

Abstract

Presently, at the EU level, policy actions for the construction sector are turned to sustainability and circular economy. After a journey where legal requirements were pushed to increase construction sites' health and safety, a new challenge is presented. This novel endeavour is being twined with the digital transition because information technologies and digital-driven management can support improved sustainability. However, this also applies to safety. Many processes and reports have been successfully introduced to ensure improved conditions. Digitalisation can support and streamline how this is surveyed and accomplished to potentiate other goals. Digital Building Logbooks (DBL) are scoped as repositories for buildings' relevant data. Health and Safety information, following EU regulations, must be collected and recorded during the construction phase. These practices are mainly paper-based. This work explores the DBL concept and how Health and Safety related documentation can support its accomplishment. Induction theory and a use case using the DBL conceptual framework compose the methodology to deliver answers to the research question. Safety and Health are widespread but require continuous monitoring. The way to do it is by maintaining the gained momentum and by integrating requirements as part of new tools and trends. Acting this way, a transition is achieved by introducing innovations smoothly and making the most of existing processes.

Keywords: data-driven, digital, management, safety and health, traceability

1. INTRODUCTION

Digitalisation is a growing trend in the construction sector, seeking to raise its bar at productivity, efficiency, and competitiveness levels [1]. More recently, sustainability requirements associated with the environment and conscious use of resources are driving the industry towards a more energy-efficient and circular value-chain mindset and streams way of thinking, namely in what respects the use of construction products and their components/materials. Twin transition is the concept underlying industries' digital and green transformations [2]. It must be clear to all stakeholders that adopting digital tools can benefit the green deal goals and the opposite around. With this, it is meant to stress that many sustainability and circular goals rely on the ability to structure, collect, trade, trace, and maintain data, understood as digital data [3].

The Digital Building Logbook (DBL) is being presented as the platform/system of systems (SoS) to accomplish the mentioned requirements and for all relevant information associated with buildings [4]. Previous research from the authors aimed to demonstrate DBL's position as Digital Twins enablers at the building and city levels [5]. Three aspects need to be considered from the first moment when addressing DBL: 1) the data supported is mainly digital (metadata/datasets) and documentation; 2) the DBL framework mixes things that already exist and new functionalities, technologies, and tools to fill the gaps and merge/transform/manage data (incremental innovation) [6]; 3) it is meant to range the object lifecycle from the very beginning (land parcel data) to end of life (total deconstruction of the built object with potential reuse of components and products) [7]. According to Zhou, as digital technologies become widely used in designing buildings and infrastructure, questions arise about their impacts on construction safety [8]. Health and safety conditions on construction sites were among the European Commission's main concerns, hence the subject of a wide-ranging strategy to increase requirements, set mechanisms for training, and supervision, and ensure improved conditions to reduce work-related fatalities and accidents. Most of these actions translated into requirements, where all stakeholders engaged in construction sites must provide data. For example, the owners must inform authorities which construction works are being developed and where. Associated with these deliverables are others identifying potential risks that need to be mitigated from the description of the construction characteristics and how the works will be performed. Updating and adjusting these implemented processes to the new value-chain processes and data-driven strategies is challenging [9].

This research emerges from the awareness that health and safety procedures are central in construction. The legacy practices and the documents introduced by the existing regulations need, on the one hand, to become more digital and, on the other hand, to embody significant contributions for tools under development, such as the DBL.

The starting point is the Process-Based Framework for Digital Building Logbooks proposed in previous research (Mêda et al., 2022). The methodological approach involves induction by analysing relevant legal documents and deliverables (grey literature) to conceptualise the DBL use case. In this, answers to the question "Can Health and Safety related data following existing requirements support and boost DBL implementation?" are sought. An evaluation of benefits is performed considering the produced data. As well, how DBL-associated processes can streamline accomplishments, digitalisation and digital links to other relevant aspects associated with safety and health monitoring in construction sites [10]. The use case is structured from a national perspective using the legal framework, the defined information requirements, and the everyday practices related to health and safety in Portugal. From a construction value-chain context, framing the use case as a public contract following a "traditional" procurement route is relevant as this will lead to associated requirements, as it will be detailed.

Health and Safety information requirements and deliverables have the potential to embody DBL. Shifting to digital formats and metadata will significantly enable this new concept's maturity, which has been mostly approached from the energy certificate perspective. On the other hand, DBL functionalities will provide streamlined support for the health and safety processes that must be performed during the construction phase, namely regarding workers and equipment control. Finally, one of the main ambitions of the health and safety Directive is to ensure that technical data is kept, including risk identification, for future interventions—the DBL positions as the data keeper of that and other.

2. LEGAL FRAMEWORK

Health and Safety must be part of the Digital Building Logbook, either as a specific layer or as a group of labelled datasets. In order to fully understand the dimension of this sentence, this section explores the legal framework principles at the EU and Portuguese levels, evidencing the information needs, the deliverables, the stakeholders' interactions, and the responsibilities. Other legal diplomas addressing health and safety issues are evaluated to broaden the induction observation and make the use case as complete as possible. This aims to: 1) evaluate all the elements and documentation relating to the topic under discussion and 2) identify potential inconsistencies and/or bottlenecks.

2.1. Safety and Health Directive and the transposition to the Portuguese domain

A construction site is a place where high hazard exists and is continuous at all moments of its operation [11]. This condition is mainly due to the type of work being developed and the number of human resources and equipment that need to coexist, sometimes very close to each other [12]. The number of accidents and fatalities was and still is a problem nowadays, as each brings social, economic and reputational impacts on an industry that is one of the most critical engines for the country's development [1]. Given the untenable situation and in view of the imperative need to reduce occupational risks, the European Commission developed a specific Directive to work the subject in the 20th century mid-80s.

The 92/57/EEC Directive was meant to be adopted by all member states, setting the minimum safety and health requirements during construction works at temporary or mobile construction sites [13]. The document introduced safety and health requirements for different on-site workplaces and when performing different types of work. New profiles, deliverables and responsibilities were also created, such as the safety and health coordinator, the safety and health plan and duties for clients, project supervisors, employers and employees. Most of these aspects were later translated and detailed into the national domain as it will be explored. Before moving forward, it is relevant to highlight what is mentioned in the Directive's line c), Article 5:

"The coordinator(s) for safety and health matters during the project preparation stage appointed in accordance with Article 3 (1) shall prepare a file appropriate to the characteristics of the project containing relevant safety and health information to be taken into account during any subsequent works." [13]

The main objective of preparing this "file" is to ensure that some knowledge regarding the built object will remain for the future best supporting further interventions, where risks can be more easily identified. Above all, or at least at the same level, the file compiles other relevant documentation related to construction that is reasonable for the stakeholders to be aware of.

The work performed in Portugal led to the transposition and densification of the Directive into Decreto-Lei n.º 273/2003. This legal diploma, composed of 31 Articles and 3 Annexes, detailed for all construction works (public and private) the requirements, roles and deliverables associated with the health and safety minimum conditions [14]. Following the Directive assumptions, the safety and health coordinator was introduced as a new stakeholder with defined skills and responsibilities during the design and construction phases. Concerning the construction process, it is worth highlighting that the "*traditional* " procurement route is the most frequently used, mainly in public projects. Due to this, the law set up two different stakeholders and deliverables, one geared for the design phase and the other for construction. Specific requirements were laid down before the site work starting, Article 15, with the mandatory communication of its opening to the national authority supervising labour conditions [15]. Procedures for communicating accidents (fatalities or major injuries) were also set, as well as the structure and contents for the Safety and Health Plans during the design and construction phases, Articles 6 and 11, respectively [14]. The provisions from the previously endorsed Article 5 were considered in Article 16, referring the following:

"1 - The owner must ensure that a <u>*Technical Compilation*</u> *of the construction work is prepared, including the relevant elements to be considered during use and in future interventions, to preserve the safety and health of those who will execute them.*

2 - The Technical Compilation must include, namely, the following elements:

> *(a) Full identification of the owner, the design authors, the Safety Coordinators during design and construction, contractor identification, as well as subcontractors or independent workers whose interventions are relevant for the built object characteristics;*
>
> *b) Technical information relating to the design and its disciplines, including justifications, specifications, and the final drawings, namely those addressing the structural system, installations/services, and a Bill of Materials relevant to the prevention of occupational risks;*
>
> *c) Technical information associated with the installed equipment relevant to the prevention of risks during its use, conservation, and maintenance;*
>
> *d) Useful information for planning safety and health in future interventions, namely the accessibility and constraints associated with working in spaces that might present risks.*

3 – Handover can be pending if the contractor does not provide all the elements needed for the Technical Compilation.

4 – Technical compilation should be updated every time relevant interventions occur." [14]

The reason for fully transcribing the article is its detail, mainly the changes introduced during the handover phase and the assurance of legacy documentation for the future. Other national regulations also set requirements for delivering documentation at the end of construction works and with legacy purposes. Focusing on the Public Procurement Code, there is a requirement for delivering final drawings of the built object at handover. As part of the same diploma, there is also the need to submit periodic reports associated with the public contract in development. When the contract is for public works, these reports include technical aspects and some related to safety, as it will be further explored. The system supporting the submission of these reports is fully digital, meaning that all elements are metadata/datasets. Under the legal framework for urbanisation and building [16], there is also the need for setting the "Construction Workbook". Its structure is standardised and supported in different formats. This "legacy-driven construction documentation" requirement finds several inconsistencies that can happen due to the different fields of application (all construction works, public works, buildings with permitting process). However, it is relevant not to forget that the same process might need to comply with the three, and many try to do it. Although this constitutes a very interesting field for research, the present work focuses on exploring the safety and health-driven data and documentation. An additional awareness that deserves to be presented is that the Technical Compilation requirement is the broadest and, therefore, the one more construction works must comply with. In fact, final drawings are an element that must be delivered as part of this Compilation. Fig. 1 aims to systematise all the elements developed under the health and safety regulation, fostering an improved understanding of the details. As presented, three main deliverables are produced in each project, ranging from design to handover.

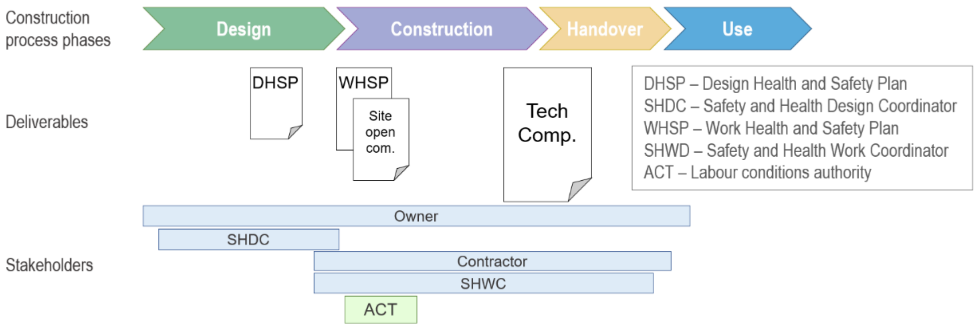

Fig. 1 – Safety and Health deliverables and stakeholders framed in construction phases.

Nowadays, they are presented as .pdf documents. However, looking at its content in detail, it is possible to find elements that are not safety and health exclusive, nor do they need to be introduced by hand whenever needed to deliver a document. Without entering too much detail, as this will be addressed in the next session, from Fig. 2 observation, some inconsistencies and benefits from introducing a digital record mindset can be found. Fig.2 aims to systematise, following a data perspective, all the elements expected to be part of each deliverable. On the "Health and Safety Plan", two items are underlined, namely "Stakeholders identification – site opening and updates" and "Accidents and Occupational Incidents Report". It is because they represent specific reports that are also detailed.

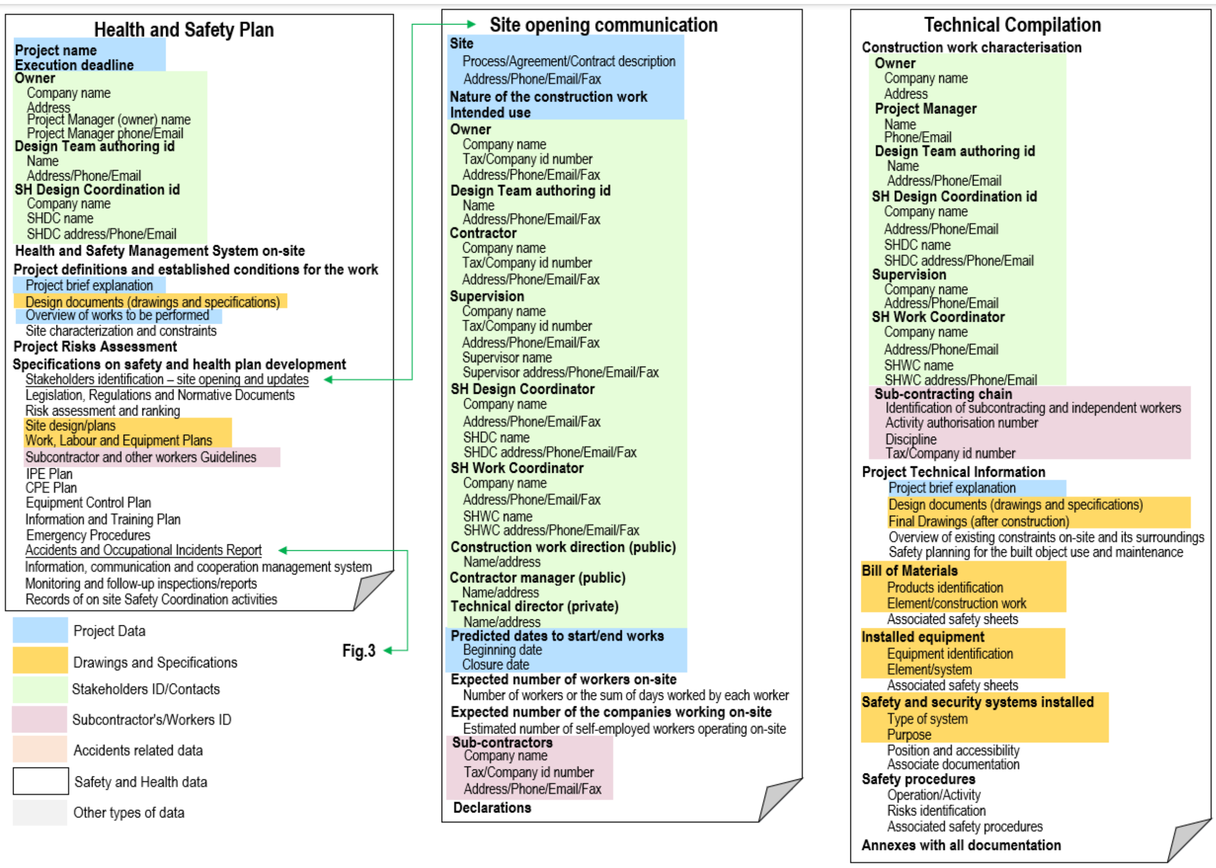

Fig. 2 – Information associated with each deliverable set on health and safety legal framework

One of the essential elements in health and safety plans is the report on occupational incidents. Although it should be detailed in this sub-section, given the relationship with other report and the need to save space, it will be presented as part of Fig.3. It is worth mentioning that Fig. 2 and Fig. 3 present different colours representing labels or groups of data that are meaningful for the use case detail in section 4.

2.2. Safety and Health outputs under the Public Procurement Code

With the Directive 2004/18/EC on public procurement, there was the intention to initiate a digital transition, where all tender notices, bidding processes and awarding would shift from paper to electronic platforms. From 2008, when Decreto-Lei n. 18/2008 came into force, transposing to the Portuguese domain that Directive prescriptions, e-procurement implementation started in Portugal. Gradually, all processes shift to electronic platforms. This forced a standardisation effort that translated into new technical regulations. Once the bidding process became stabilised using electronic means, the next step was to ensure proper control of the agreements development. Several reports were set to disclose events or the agreement status at a certain point. Several changes and revisions to the public procurement code have happened. The latest version of the legal diploma controlling the reports that must be submitted to the common public procurement portal, BASE.gov, is the Portaria n.º 284/2019 [17]. As mentioned, these reports range all types of agreements and scopes and the contract development until its end. When the scope of the contract is public works, the Final Report (Annex XV) and Events Report (Annex XVI) are applicable. The Final Report sets an extensive list of aspects of the contract development and how the construction went. The Events Report aims to systematise all relevant events during the contract development. Occupational accidents are among the events to be considered. This report should be submitted with the Final Report or shortly after its submission. Fig.3 presents, in addition to the Occupational accident report, the more relevant datasets for this research and use case related to Annex XV and Annex XVI reports [17]. As it will be visible, many elements overlap with items set on previous reports and documents.

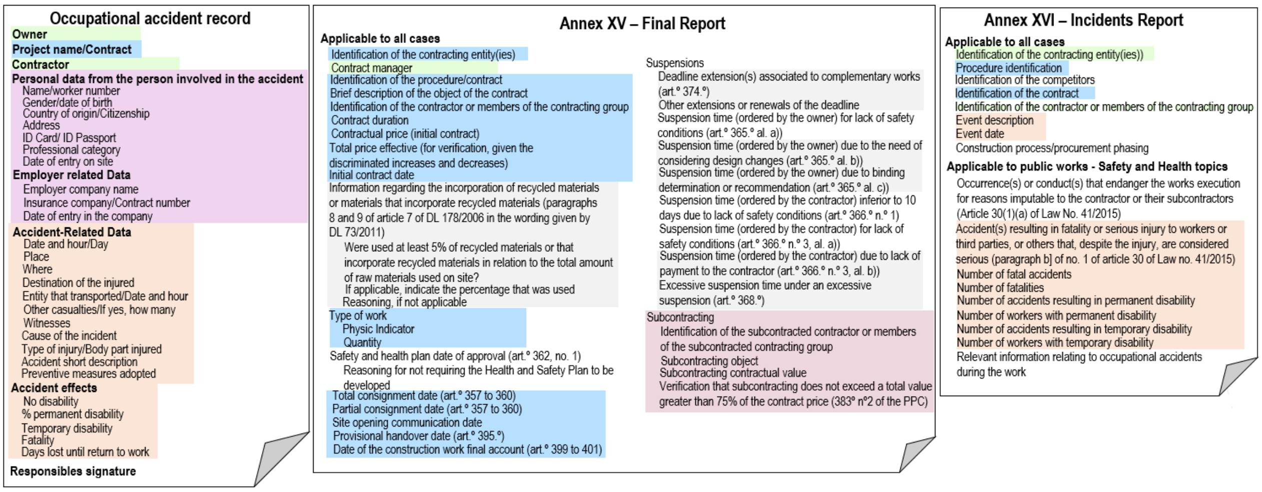

Fig. 3 – Information set on the accident report and reports that need to be submitted as part of the public procurement code requirements

3. DIGITAL BUILDING LOGBOOK EVOLUTION

The availability of consistent and reliable data is vital for all sectors of activity, and construction is no exception. This availability and consistency should be pursued at the product, built object, facility, city, and country scales, as only with it accomplished will it be possible to aspire for an efficient and sustainable built environment [5]. Following a deep study, Dourlens et al. proposed the following definition for the tool that should be able to solve all the abovementioned issues at the buildings level: *"A digital building logbook is a common repository for all relevant building data. It facilitates transparency, trust, informed decision making and information sharing within the construction sector, among building owners and occupants, financial institutions and public authorities. A digital building logbook is a dynamic tool that allows a variety of data, information and documents to be recorded, accessed, enriched and organised under specific categories. It represents a record of major events and changes over a building's lifecycle. Some types of data stored in the logbook have a more static nature while others, such as data coming from smart meters and intelligent devices, are dynamic and need to be automatically and regularly updated. Data may be stored within the logbook and/or hosted in a different location to which the logbook acts as a gateway."* [18] Although lengthy, the transcription of the definition substantial part is relevant to better frame the ambition set for this tool/platform, either in terms of functionalities or data to be supported.

Later, a Business Process Model Notation (BPMN) was proposed by Mêda et al., assuming that the DBL should be deployed from the very beginning; this is to say, from the idea for the construction, where the only existing information is the one related to the land parcel [7]. During Design and Construction, several steps were set linking to existing requirements, tools or assumptions set on BIM standards [7].

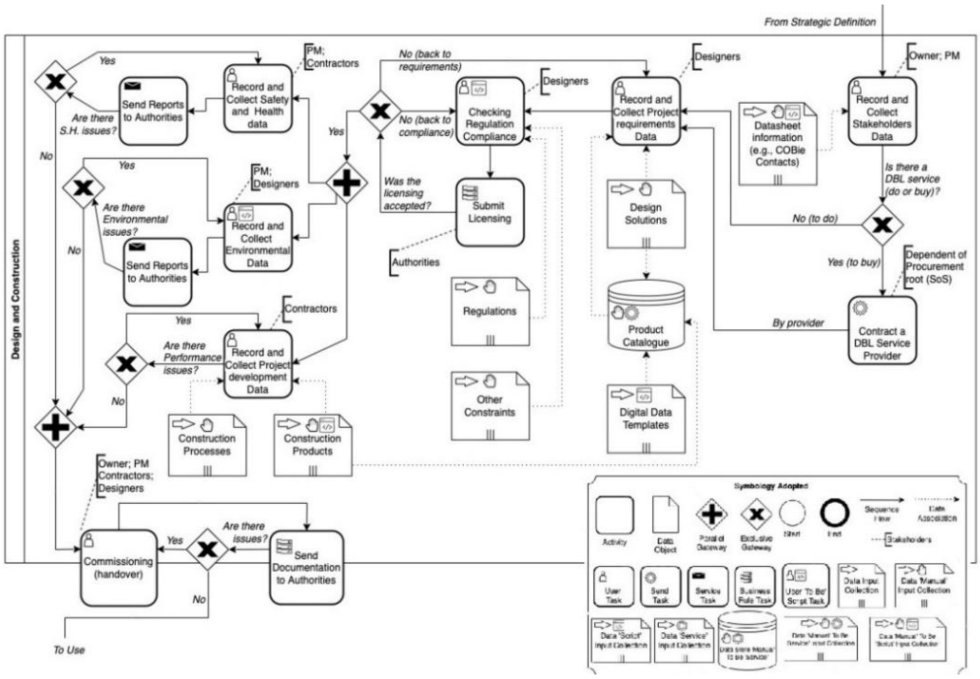

Fig. 4 - DBL BPMN flowchart framework – Design and Construction stage (captured from Mêda et al., 2022).

As shown in Fig. 4, the use of COBie [12], the link to catalogues of Digital Product Passports, compliance checks with permitting/licensing and the record and collection of Health and Safety, Environmental and Technical data were forecast. This organisation was set primarily due to the legal framework organisation and requirements, assuming that improved research should be made to understand the contents and eventual overlaps surrounding these layers. Böhms et al. followed most of the assumptions when detailing potential roadmaps for the DBL semantic Data Model [4]. It is undeniable that, at the policy level, the Digital Building Logbook is meant to ensure the collection and maintenance of all relevant buildings data. Its use can serve multiple purposes. As we described, the Health and Safety Directive sets the need for setting a file with all relevant information associated with health and safety issues for future interventions. This file is a mix of metadata and documentation such as DBL, and both are geared to preserve and support future interventions, to say, the built object life cycle. The intuition is that there is a clear overlap. If proper synergies are brought to the process from the beginning, significant contributions can be made to streamline the understanding and adoption effort on DBLs. That is what the use case aims to demonstrate.

4. DBL USE CASE

4.1. Data labels

Analysing in detail the content of the different deliverables associated with the safety and health legal framework (see Fig. 2 and 3), it can be realised that their structure aims to compile core data, which means the one on safety and health and essential supporting data. This second type of data is needed to provide the context, support the specific safety and health contents, or ensure the knowledge needed when shifting from design to construction or from handover to a new intervention, either maintenance, refurbishment, or other. Not surprisingly, part of the contents addresses the stakeholder's identification, focusing mainly on the contractor and subcontracting companies, their workers and equipment. These two data types were clustered and labelled with specific colours, "light green" and "light purple".

Before evolving on the reasoning for the defined labels, the understanding that public procurement reports are more based on metadata than the safety and health ones is essential. In this respect, the stakeholder's identification is "less needed" as relational links are set between the different reports. A stakeholders contact digital sheet is mandatory in BIM processes, namely those following ISO 19650 standards [19]. DBL should use those guidelines, as evidenced in Fig. 4. Considering these assumptions if safety and health deliverables become less document-based and more metadata-aligned, substantial improvements could occur, as will be further detailed. A second group of elements, also labelled in two types, addresses relevant data/information associated with the project, either for its identification or general characteristics or focusing on the technical aspects, drawings and specifications.

The first, labelled with “light blue”, addresses mainly administrative data related to the project, and both datasets and descriptions aim to characterise it from a more technical perspective. As stated, these are more suited to be set as metadata due to the type of contents and extension. The second, labelled in “light yellow”, refers to all technical documentation associated with the design, such as drawings and specifications from the different disciplines, contractor leaded technical documentation to support the bidding process and the preparation after awarding. In addition, the documentation developed during construction by different stakeholders, such as the contractor, supervision or others. Final drawings and handover documentation consolidation are also part of this group. As most of it is document-based, duplications can occur, sometimes with wrong or incomplete versions. Therefore, several challenges lie ahead when seeking to integrate these contents on a DBL.

The figures present a “light grey” label. It is used for elements that are, at this point, out of research scope. The contents relate to construction suspensions and the incorporation rate of recycled materials.

The “light orange” label refers to data associated with occupational accidents, performing a characterisation when they happen. Looking in detail at the information elements set, results Annex XVI should disclose data representing the sum of the different Occupational accident reports. Therefore, easy links could be set. The elements without colour or marked as “white label” represent either data sets or documentation directly associated with safety and health. At this point, it can be considered that this is the core information on the topic and will not fit in any other place. Looking in detail at what is expected in each one, it is possible to realise that similar challenges are placed. These relate to the records' evolution from design to construction and during its development. Also, the information links can be set from health and safety documents with the public procurement reports.

This process allows us to identify best and catalogue the contents set on the deliverables under analysis. In addition, exploring the details makes it possible to evaluate inconsistencies, improvements, links and what synergies can be structured with the DBL framework.

4.2. Analysis of inconsistencies and improvements

One of the main aspects to highlight from the health and safety deliverables is that, by being document-based, several data duplications exist, increasing potential inconsistencies. It is recognisable that the documents will have specific purposes and will be produced at different project moments. It is worth mentioning that the health and safety legal framework was established more than 20 years ago when digitalisation in construction was still not turned to these issues. To say that few or no updates were performed, reasoning why the deliverables come with this structure. Assuming all developments and guidelines associated with BIM, it can be stated that some contents could easily be turned into data sets. In this vision, they would not be part of the health and safety core data but would be linked to it. As mentioned previously, stakeholders’ identification, “light green” label, project identification and general characterisation, “light blue” label, are good examples of this situation. Considering the similarities between these elements in the health and safety and public procurement legal frameworks, significant improvements and synergies would result from harmonising and linking the reports. DBL could provide the information framework interacting with the different systems at this level [4], [20]. As mentioned, the public procurement reports in Portugal are supported by a specific tool, the BASE portal [17]. Regarding safety and health, a similar tool could be developed for these issues to be managed by the work conditions authority. This would be especially relevant for the occupational accidents-related data, labelled as “light orange”, ensuring a streamlined recording, communicating and clustering of these reports to support the Annex XVI automatic completion and submission.

It is worth detailing the subcontracting data, “light purple” label. As mentioned, duplicating information manually introduced in different documentation might lead to inconsistencies. This is especially sensitive when the data is from subcontractors and their workers, given the low level of administrative resources and the difficulties in assuming the workers allocated to a specific site. Streamlining this data repository and streams would lead to fewer incomplete processes and facilitate the work to several stakeholders on site, such as the safety and health coordinator, the work director (from the contractor) and the supervision team, providing more time for other tasks. This aspect is also relevant to what will be mentioned in the following sub-section. No endorsement is made to other labels regarding inconsistencies and potential improvements, as this will be addressed in section 4.4.

4.3. Potential links with other Health and Safety contents

The subcontracting information or metadata, “light purple” label, can be framed in two levels; company and workers. Most aspects related to the company level can follow the assumptions mentioned for the other stakeholders. However, when detailing and working on a digital way workers' data, several issues can be placed relating to legal protection of data and monitoring of workers during their time on site [21]. Previous authors' research addressed the first aspect extensively. Given the relationship and potential impacts/improvements with the "white" label documentation, the second should be detailed. The implementation of construction workers' electronic monitoring impacts significantly how, for example, "IPE and CPE plans" are implemented and followed, how the "Information and Training Plan" is set, as well as the "Information, communication and cooperation management system" definition. This is just to focus more on the health and safety plan contents. Without entering in detail, the collected data could be part of the "Technical Compilation", evaluating the contractor and subcontractors' performance, for example.

4.4. Integrating Health and Safety deliverables on the DBL Framework

Detailed aspects of the different labels were previously presented, and in some cases focusing on how these should become more digital to streamline interactions and contribute to more efficient processes. This sub-section focuses on the contents of the "light yellow" and "white" labels. This is because the first was still not mentioned, and the second is, as stated, the core of the health and safety data deliverables.

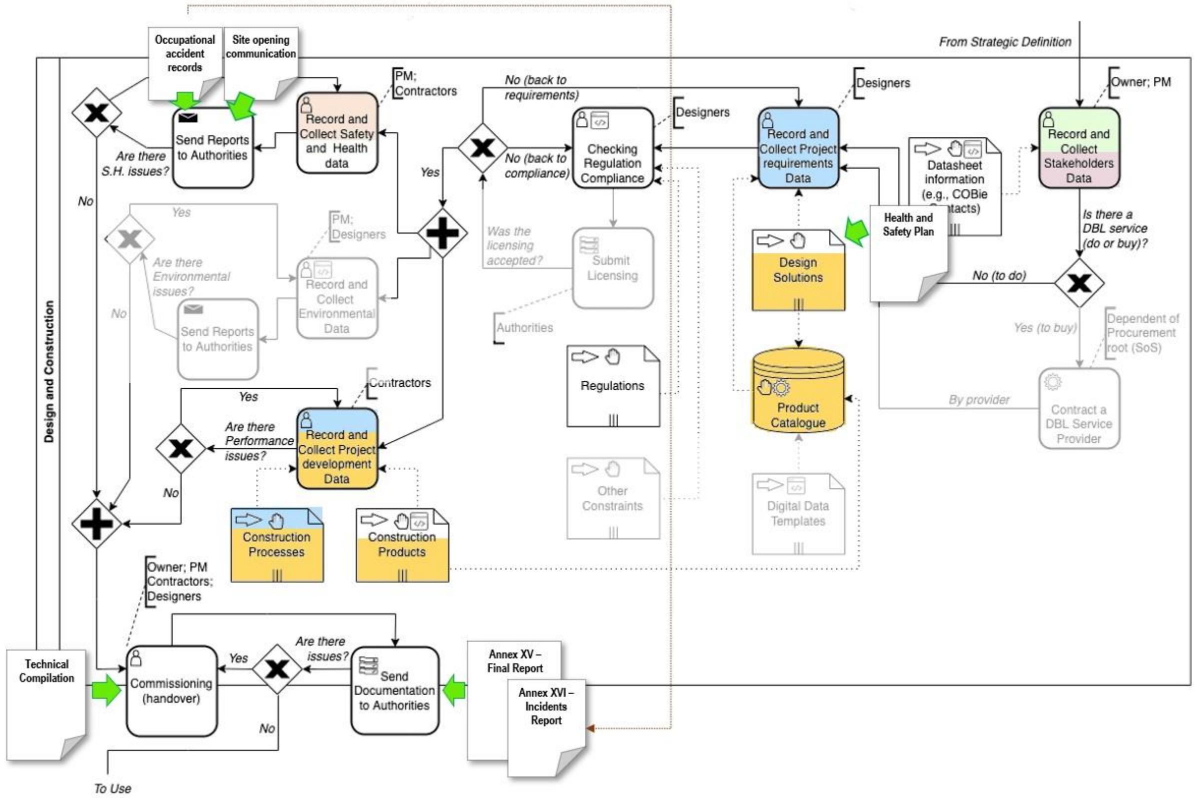

Fig. 6 - The anatomy of the digital building logbook embodied with health and safety data requirements

The "light yellow" label focus on project technical documentation, as stated, and its behaviour is highly conditioned by the way the construction process is set, namely in terms of the procurement route, agreements and relationship between agents. Trying not to get influenced by the differences these introduce, the technical documentation will evolve from design to construction, becoming more detailed and accurate. For safety and health, there are specific requirements as presented in the Technical Compilation. Without neglecting the "Final Drawings", the safety sheets associated with products, equipment and systems are crucial. The ability to collect them as part of the products/equipment/system ecosystem can make a difference. Recent developments in Digital Product Passports, product catalogues, and the definition of rules for common data environments and information containers are expected to bring improved capacities to accomplish the goals [5], [19].

On the other hand, Safety Procedures during operation might need more detail. One common aspect of this documentation and datasets is the versioning and update. Again, at this level, common data environment standards should be used as an inspiration [19].

4.5. Discussion

Although still in its infancy, the Digital Building Logbook is being presented as a tool to collect, use, link and maintain building-related data [4], [5], [7], [18], [20]. As so, many processes and tools being developed under the BIM methodology will mostly suit the DBL purpose, and this use case briefly aimed to demonstrate it. The DBL should also be able to interact with asset management/facility management systems, but this is not the scope of the present work. BIM maturity and adoption should not be seen as a critical problem. However, this must be considered partially as a constraint and as an opportunity. This second aspect concerns the way processes can be structured to take the highest benefit from the implementation very beginning. Focusing on the health and safety deliverables, it is clear that their content is highly compatible with the data and documentation that must be part of the DBL. If, in some cases, no changes are needed, other situations exist where changes and improvements are mandatory. Assuming a scenario where there would be the possibility to review the national framework on health and safety to adjust to DBL and that the contents would be maintained, the following image (Fig. 6) could be set as a preliminary framework aiming to guide the discussion. At this point, it is essential to mention that all assumptions are based on the Portuguese framework and that generalisation to a multi-country perspective would require a similar analysis in other geographies.

5. CONCLUSION

Considering the use case and all the details, the following statements can be systematised:

- Safety and Health requirements include datasets and documentation defined as core elements for DBLs. Stakeholders identification and project drawings and specifications are just a few examples among the many realised. The deliverables set on the Safety and Health legal framework, namely in the context explored as part of this research, overlap significantly with what is envisaged to be collected by the DBL. Health and safety deliverables use data from different sources. Although this is not a surprise, by evidencing some of them through the labels presented in Fig. 2 and 3, it becomes clearer how the elements can be aligned and streamlined.
- Several synergies and benefits can be achieved by digitalising safety and health-related data. This will demand updates on the legal framework at the EU and Portugal levels. For example, in the EU Directive it could be considered changing to “digital file” and following detail contents framing with DBL. Looking in detail to Portuguese deliverables, results that some of them would benefit from becoming fully digital, namely the Site opening communication, where most elements would come from other records. The Declarations should become part of a specific section of the Health and Safety plan that, although document-based, should consist of a mix of sections with metadata and other sections set as documents. To mention one example of each, the “Monitoring and follow-up inspections/reports” and “Emergency Procedures”, respectively, can be named;
- This study is limited because it does not profoundly explore all contents and represents a specific reality. However, apart from some singularities in the approach to health and safety and the construction process, one can expect to find considerable similarities due to the Directives. Assuming the abovementioned limitation, this research demonstrates that Health and Safety related data can support and boost DBL implementation, providing a positive answer to the research question. However, there is a need for harmonising the legal framework to set uniform requirements or implement changes based on automating and/or facilitating the provision of information/data. This effort links to other data within the domain of health and safety, namely to monitor best and collect information from site activities during the construction process;
- Future works will continue to explore other DBL data dimensions and, specifically, how health and safety deliverables and other associated deliverables can contribute to the twin transition effort, where DBL will assume a central role.

ACKNOWLEDGEMENTS

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A SCIENTOMETRIC ANALYSIS OF TRAFFIC ACCIDENTS ON LOW VOLUME ROADS: IMPLICATIONS FOR CONSTRUCTION WORK ZONES

Eric Asa[1], Fidelis Emuze[2], Bright Awuku[3] and Amma Agyekum[4]

[134]Department of Civil, Construction and Environmental Engineering, North Dakota State University, Fargo, (United States of America)

[2]Department of Built Environment, Central University of Technology, Free State, Bloemfontein, (South Africa)

Abstract

Traffic accidents on roadways result in fatalities, property damage and injuries. According to the National Highway Traffic Safety Administration (NHTSA), traffic accidents on United States of America (USA) roads claimed 42,915 lives in 2021, a 16-year high and an increase of 10.5% from the previous year. This paper aims to use scientometric methods to assess the state of traffic accident articles in general and construction to suggest gaps and directions for safety research. Major electronic databases (Web of Science) are employed in this work, reiterating that though low-volume roads account for about 70% of roadways in the USA, most attention and funding decisions favour high-volume roads. Regardless of volume, the data and the literature suggest that traffic accidents are high in construction work zones, with severity that cumulates in fatalities in varying regions worldwide. Further, a major scope exists for scaling up attention to traffic accidents and fatalities in construction to engage policymakers and scholars. The scaling of attention could be used to develop mitigation strategies, garner more research funds, and create solutions that save lives.

Keywords: Accident, Construction, Scientometric Analysis, Traffic, Work zone

1. INTRODUCTION

An increase in the deterioration of roads due to higher traffic volume and adverse weather events (from global warming) have resulted in an increased need for highway work zones to repair and rebuild roads. However, work zone designs implemented in the field reduce the capacity of roads, increase severity of crashes, increase probability of crash rates, cause traffic delays, expose drivers and construction workers to vehicle-to-vehicle and vehicle-to-worker collision and generally reduce safety on the impacted roadway [1], [2], [3]. Work zones are prevalent on US roads and occurs every 160.9 kilometers on average. A work zone is defined, albeit sometimes loosely, as a section of a road which is temporarily subjected to maintenance, construction, utility work and other essential road improvement activities [4], [5]. Work zones are established to ensure safety of construction/site workers and road users [4]. However, several studies have shown that work zones reduce traffic mobility, increase traffic accidents and lead to more severe crashes [6], [7], [8], [9], [10]. The challenges are more pronounced on low volume roads, where one direction of a two-lane road could be completely eliminated over the entire work area. Depending on the type of work being undertaken, the work zone could also be a complex maze of twists and turns for unfamiliar motorists; as there is no standard configuration of work zone designs. Traffic stoppage, merging and lane changing could present considerable challenges to drivers and be a death trap for unsuspecting motorists (who become sitting ducks) as trucks and buses try to stop or maneuver a work zone. There are also socio-economic costs associated with construction work zones.

Generally, traffic accidents result in property damages, personal injuries, and fatalities. According to the World Health Organization (WHO) study in 2018 [11], about 1.35 million people lose their lives to traffic-related accidents around the globe annually. On a global scale, it is the leading cause of death for youth aged between 5 and 29 [11]. It is estimated that 3,700 people are killed in traffic accidents daily around the world. The yearly cost of traffic accidents is estimated to equal 0.12% of the global GDP, approximately $1.8 trillion. The problem is more pronounced in low- and middle-income countries, where it could cost as high as 3% of a country’s GDP. In response, the United Nations adopted a decade of action resolution A/RES/74/299 (from 2021 to 2030) in September 2020 to reduce traffic fatalities and injuries by 50% in 2030 [12]. In the USA, traffic accidents and the resulting fatalities are considered the leading cause of death for persons aged between 1 and 54 [13]. About 42,915 people perished from traffic fatalities in 2021, an increase of 10.5% from 2020. In 2019, there were 14.2 million vehicle crashes, which resulted in 36,500 deaths, 4.5 million nonfatal injuries, and 22.9 million damaged vehicles in the USA. As 2019 is the year that economic figures are available, the economic cost of traffic accidents was $340 billion, equivalent to 1.6% of the US real GDP of $21.4 trillion [14].

Today, it is estimated that one traffic fatality occurs in a work zone per 4 billion VMT (vehicle miles of travel) and every $112 million of construction dollars [15]. In 2019, there were 842 fatalities and 39,000 injuries work zones in the US. Traffic fatalities increased by 10.3% whereas fatalities linked to work zones increased by 10.8% from 2020 to 2021. There were 863 work zone fatalities in 2020 and 956 in 2021. Work zone traffic fatalities involving commercial motor vehicles (CMVs) - trucks and buses - increased by 39% in the same period. Table 1 shows that low volume roads accounted for a disproportionately higher percentage of traffic fatalities in work zones on roads in the United States in 2020 and 2021 [15].

Table 1: Total Work Zone Traffic Fatalities by Road Type.

	Major Roads	Arterial	Low Volume Roads		
	Interstate/Freeways	Arterial	Collector	Local	Other
2020	306	384	65	22	3
2021	353	423	80	17	1

The federal government in the USA has provided funds to states under the Highway Safety Improvement Program (HSIP) to enable the states to reduce traffic fatalities and severe injuries on public roads [16]. The Fixing of America's Surface Infrastructure (FAST) Act stipulates the use of data to improve traffic safety on American public roads [17]. The Federal Government provides funding support to states to reduce traffic fatalities and severe injuries on public roads [16]. Though low-volume roads account for about 70% of roadways in the US, most of the attention and funding decisions favor high-volume roads as transportation decisions are driven by traffic volume (vehicles per day).

There is no single definition of low-volume roads, as several organizations and states use different traffic counts to define them. According to the Manual on Uniform Traffic Control Devices (MUTCD), roads with less than 400 vehicles per day are classified as low volume. However, in AASHTO's new geometric design guidelines, roads with 2,000 or fewer vehicles per day are considered low volume [18], [19]. Some states have slightly different definitions; for example, a low-volume road in Oregon has a daily traffic volume of less than 5,000. Thus, low-volume roads could be considered roadways with an average traffic volume of 2,000 to 5,000 vehicles per day. Despite the high proportion of traffic accidents on low-volume roads compared to their traffic volume, there has been limited research on low-volume roads. Extensive research has been performed on high-volume roads. Most transportation planning and decision-making processes are governed by vehicles per day figures.

It is evident that there is a continuous increase in traffic fatalities in work zones and our efforts to address them have not been very successful.

This paper is aimed at using a literature review approach termed scientometrics to assess the state of research on traffic accidents on low volume roads. The study also assesses the issues around construction work zones on low volume roads.

2. RESEARCH METHOD

Given the availability of extensive electronic databases (like Google Scholar, ASCE, SCOPUS, PUBMED, Web of Science, and others) on several research areas and disciplines, this research employed the Web of Science database as the source of research materials. Web of Science is the foremost, structured, and extensive electronic database. It houses about 65,045 journals, containing over 65 million technical papers in the social sciences, arts, natural science, and others, with about a billion cited references. It is considered the oldest science citation index. It has played a role in the development/use of scientometrics as it has been a major source of bibliographic data for such studies. At the project's genesis, a bibliometric search using the words "traffic safety" and "low volume roads" were used to obtain research data from the Web of Science. Fig. 1 summarizes the research approach. About 167 entries were exported as a text file for further analysis in VOSviewer.

The resulting data were inspected and analysed before storage for scientometric analyses in VOSviewer. To document construction-related research in traffic safety on low-volume roads, a second bibliometric search was performed using the words "traffic safety", "low volume roads", and "work zones". This strategy was used to emphasize the effect of work zones (roadway construction or maintenance) on traffic safety on low volume roads in this research. Preliminary analyses were performed on the data, and it was exported as another set of bibliographic data for scientometric analyses in VOSviewer [20], [21].

The bibliometric or scientometric analysis was performed in VOSviewer, free software for analyzing bibliographic data [19]. The software is based on the visualization of similarities (VOS) technique and provides a welcome alternative to the multidimensional scaling (MDS) algorithm. The results of the research are presented in the next two sections.

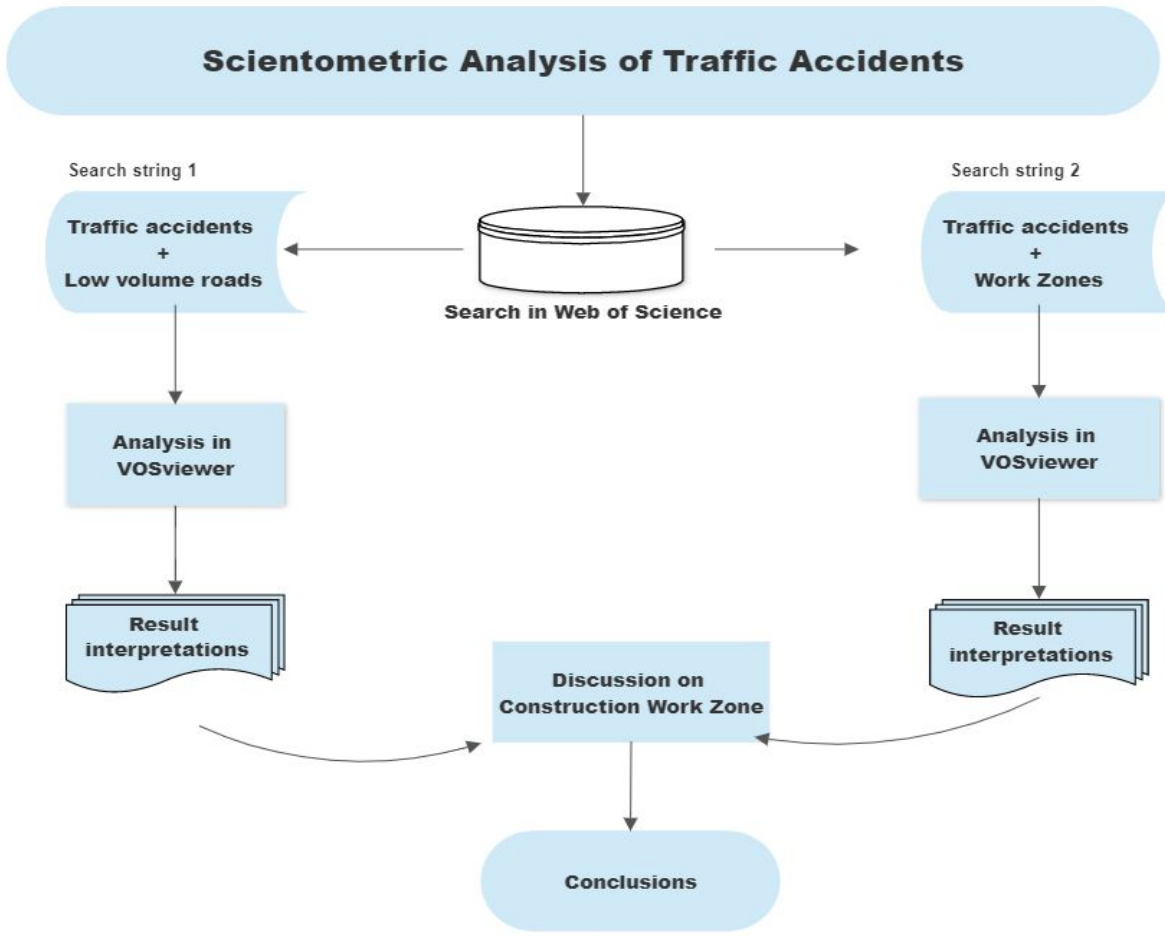

Figure 1: An illustration of the research process steps

3. RESULTS

3.1.1. Analyzing Traffic Safety and Low-Volume Roads in VOSviewer

In this section of the paper, VOSviewer software processes were employed to analyze the bibliographic data for traffic safety and low volume roads obtained from the Web of Science.

Keyword Co-occurrence Analysis: Keyword co-occurrence analysis in VOSviewer depicts the importance of certain words in a research area, and the direction and focus of the research area [22],

[23]. All three units of analysis – all keywords, author keywords and keywords plus – were employed in the co-occurrence analyses under the full-counting option.

(a). Co-occurrence and All Keywords: the threshold for a keyword to be included in the selected keyword list was set at 2, which yielded 973 keywords, with 153 meetings the threshold. Fig. 2 is the network visualization map of all keyword's co-occurrence analysis maps. There were 8 clusters. The predominant words across the map (from different clusters) were road safety, safety, impact, volume, management, accidents, model, and others. From the map, research in this area of knowledge started in about 2011 and covered such topics as motor-vehicle crashes, collisions, traffic volume, alcohol, injuries, and others. Around 2014, the research evolved into accidents, risk, management, behavior, volume, etc.

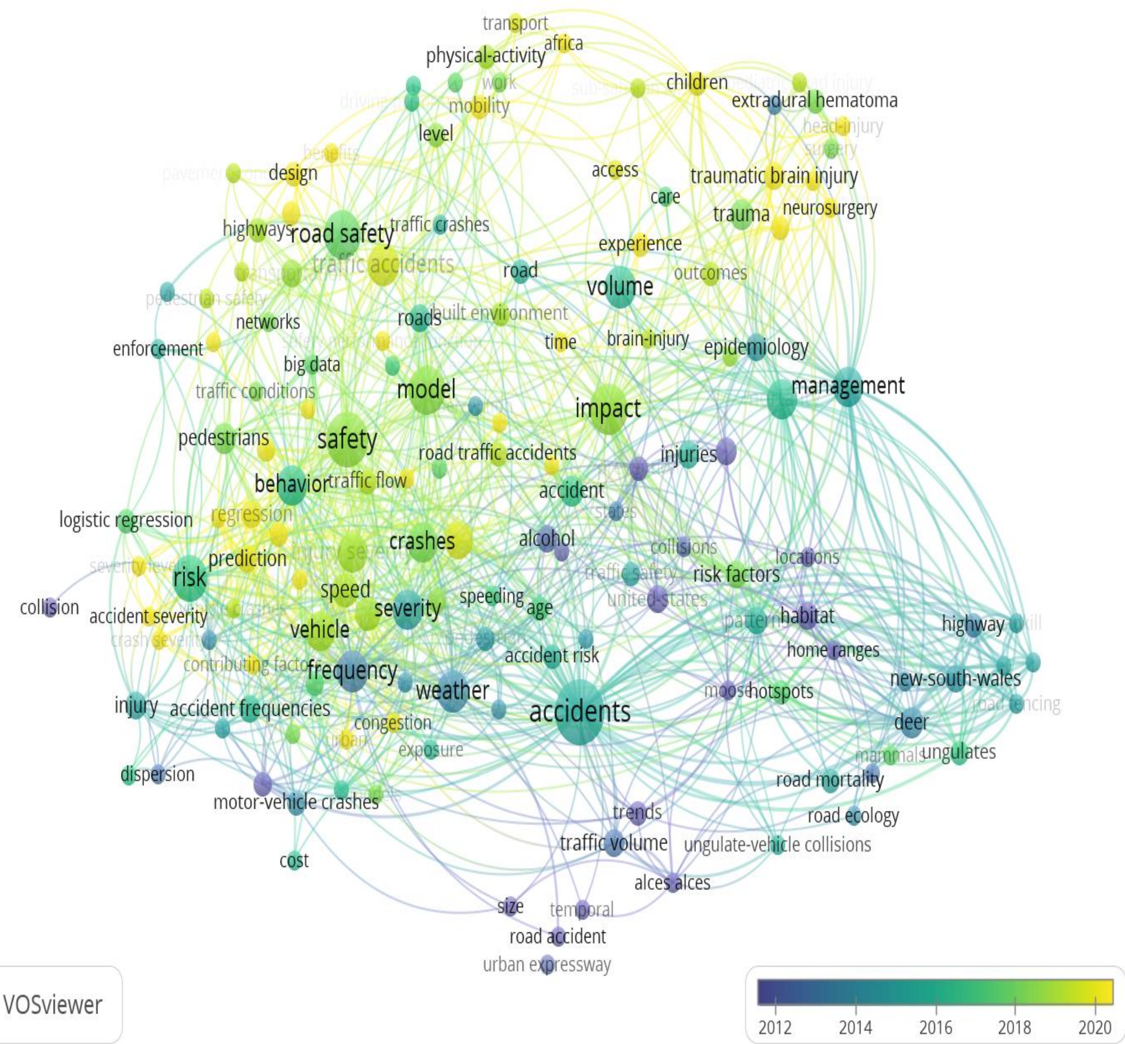

Figure 2: Overlay visualization of all keywords co-occurrence analysis

By 2018, impact, model, severity, speed, crashes, and others dominated the research words of authors. By 2020 and thereafter, neurosurgery, head injury, children, traumatic brain injury, accident severity, congestion and others were researched. Accidents were the predominant keyword, which indicates that accidents are severe and long-standing challenges on low volume roads.

(b). Co-occurrence Analysis and Author Keywords: the threshold for author keywords was set 2, resulting in 576 keywords. However, 56 met the threshold, but the most extensive set of connected items was 40. Road safety, ungulates, risk factors, traumatic brain injury and road fencing, had the highest combination of occurrences and total link length. Fig. 3 is the overlay visualization map of the results of the author keywords co-occurrence analysis. As depicted in Fig. 3, in early 2010, road ecology, moose (animals), habitat, accidents and others dominated the research agenda. Road safety, trauma, risk factors, injury severity, and ungulates captured the authors' attention between 2016 and 2018.

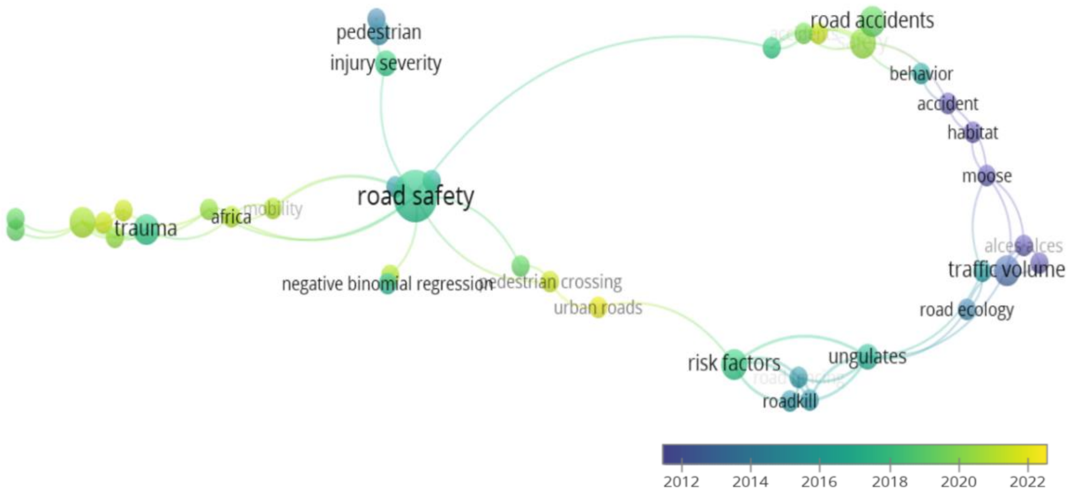

Figure 3: Overlay visualization of author keywords co-occurrence analysis

A little after 2020, road accidents, urban roads, pedestrian crossings, and others appeared in author's keywords.

(c). Co-occurrence Analysis and Keywords Plus: In Web of Science, keywords plus are an algorithm-generated string of words or phrases from titles of cited references used for in-depth paper descriptions. Employing a minimum number of occurrences of 2 resulted in 455 keywords, but 96 met the threshold. The first five keywords (with the highest combination of occurrences and total link strength) were accidents, safety, impact, vehicles, and model. The overlay visualization of keywords plus is shown in Fig. 4.

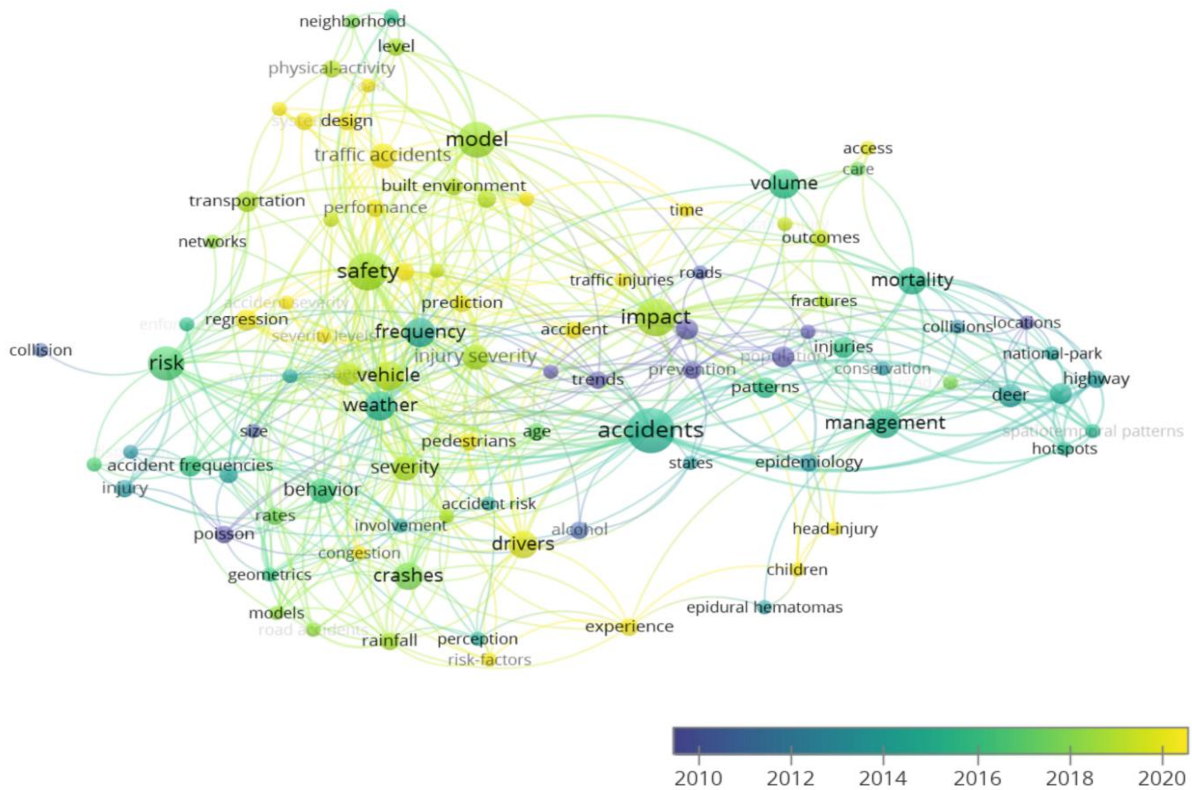

Figure 4: Overlay visualization of author keywords co-occurrence analysis

Around 2010, the keywords plus were prevention, alcohol, trends, location, etc. Between 2012 and 2016, considerable attention was given to accidents, management, frequency, weather, mortality, etc. Around 2020, model, safety, impact, vehicle, design head injury and others have become the predominant words.

3.1.2. Analyzing Traffic Safety, Low Volume Roads and Work Zones in VOSviewer

In this section of the paper, the search results of traffic safety, low volume roads and work zones were analyzed in VOSviewer software. The results are presented in this section.

(a). Co-occurrence and All Keywords: setting the threshold for a keyword to be included as 1, 47 keywords met the threshold. Some of the 47 keywords needed to be interconnected, and the set of 31 connected items yielded 4 clusters

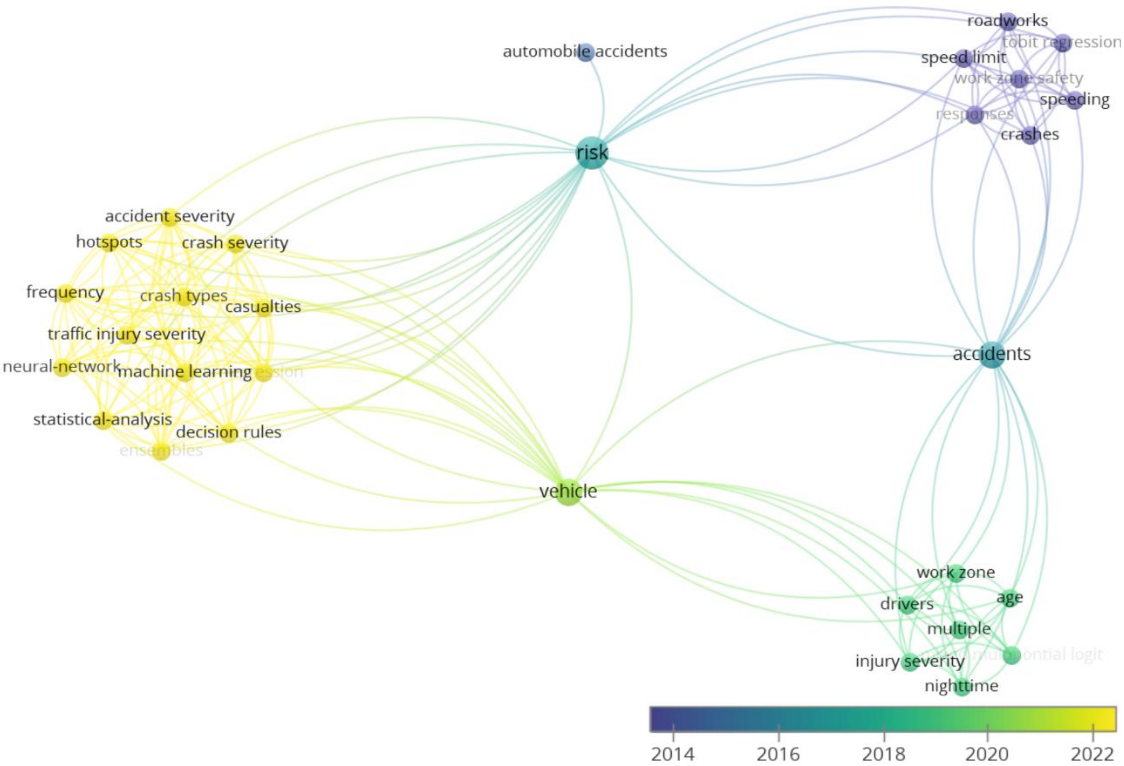

Figure 5: Overlay visualization of all keywords co-occurrence analysis

The top five words (with the highest occurrences and total link strength) were risk, vehicle, accidents, asphalt, and bridge. As depicted in Fig. 6, recent research on this area commenced in 2014 with the following research words: Tobit regression, work zone safety, responses, speeding, crashes, roadworks, and others. Around 2016, the two dominant keywords were automobile accidents and accidents. In 2020, the keywords evolved into the work zone, drivers, age, multiple, injury severity, nighttime, and likely vehicles. By 2022, the keywords are accident severity, hotspots, crash severity, crash types, machine learning, and others.

(b). Co-occurrence + Author Keywords: a threshold of a single keyword was used in the author keywords analysis, resulting in 20 keywords. Three of the four clusters which resulted from the keywords were as follows, cluster 2 (crash severity, crash types, ensembles, hotspots, and machine learning), cluster 3 (roadworks, speed limit, speeding, tobit regression, and work zone safety) and cluster 4 injury severity, mixed multinomial logit, nighttime and work zone).

(c). Co-occurrence + Keywords Plus: with a threshold of one keyword, 10 of the 27 items in the network were not connected. The top five keywords were risk, vehicle, accident severity, asphalt pavement, and bridge. In the context of keywords plus, as depicted in the overlay visualization (Fig. 6), the research started with responses, crashes, accidents, automobile accidents and others in the mid-2010s. Still, it evolved into drivers, age, multiple, and others from 2018 to 2020. In recent times (2021 and 2022), the research evolved into statistical analysis, casualties, traffic injury severity, accident severity, regression, neural networks, frequency, decision rules, etc.

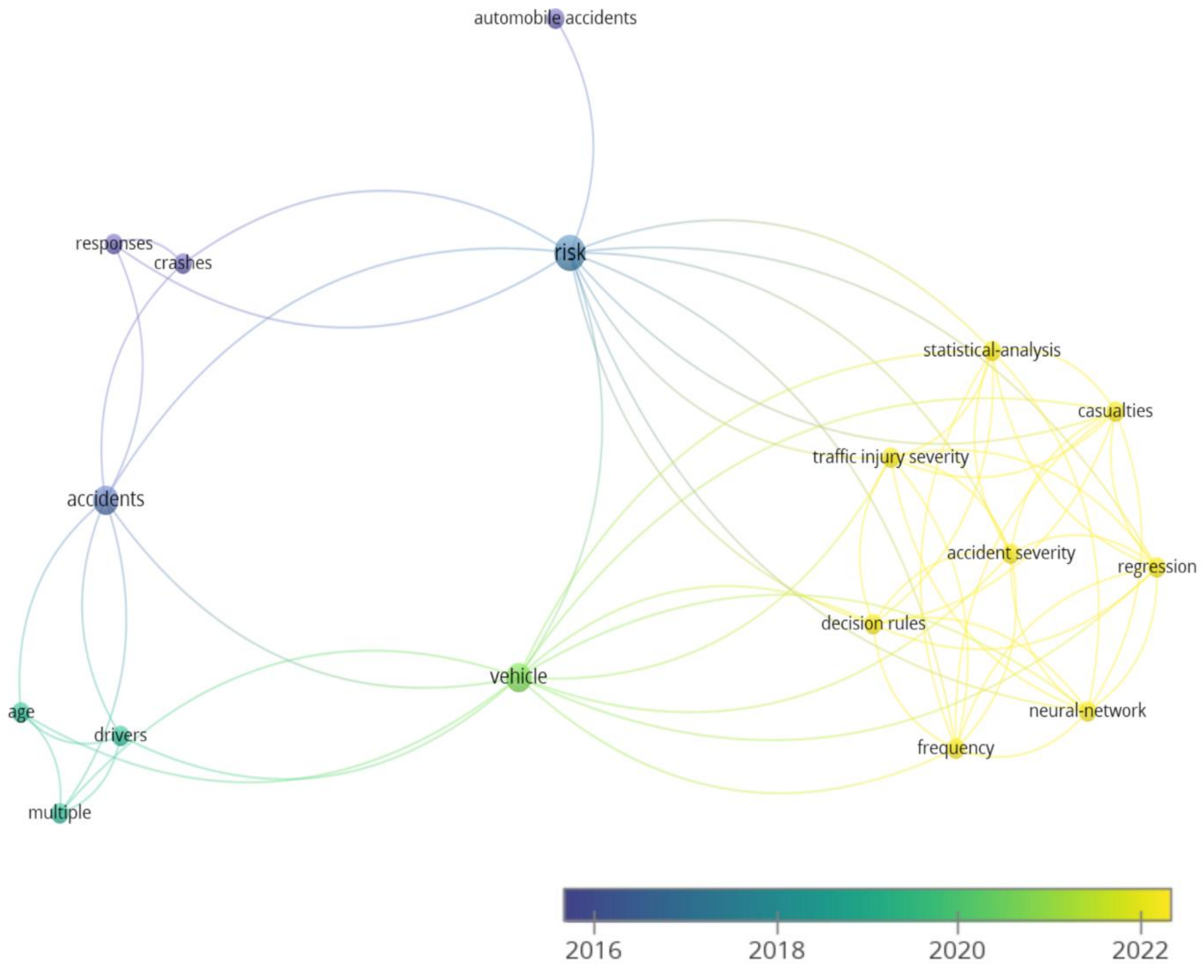

Figure 6: Overlay visualization keywords plus and co-occurrence

4. DISCUSSION

From the previous section, it is apparent that articles focused on construction work zones are limited despite the frequency, severity and casualties experienced in such places. Therefore, the paper's first point of departure is to call additional attention to traffic accidents involving either off-site or on-site construction workers.

Although construction traffic accidents have captured researchers' attention in Turkey and the USA, this is only the case in some countries, especially in South Africa. Despite previous reports on the devastating impact of traffic accidents in construction work zones [23], mitigations based on empiricism have been limited [24]. For example, between 2007 and 2011, the number of traffic accidents in construction was between 850 and 950 in South Africa, while 984 accidents and 63 fatalities occurred in 2010 [25]. Traffic is a major cause of death in South African construction. The same can be said of construction accidents in Turkey, where traffic was the leading cause of fatalities [26]. In both countries, the reasons for traffic accidents in construction relate to negligence, lack of proper safety measures (such as not wearing seat belts), and mounting or dismounting a moving vehicle [23], [27].

Knowing how traffic accidents occur and how to prevent them is vital to countermeasures to be deployed on-site. That was why several scholars sensitized the research community about the severity of accidents in construction work zones [28]. Based on case data from New York in the US, the study says that traffic accidents may happen when a worker is struck by a vehicle inside the workspace, a worker is struck-by a vehicle entering or exiting the workspace, or when a flagger is struck by a vehicle. Such events usually account for fatalities and injuries [18]. A range of unsafe traffic practices contributes to the high number of fatal accidents in construction in several countries (i.e., South Africa, Turkey, and the US). Even in Asia, countries such as Korea record between 400 and 500 fatalities in construction [29]. These practices may occur either on low or high-volume roads, and as shown in several figures in the previous section of this paper, the result is unwanted casualties. The 2013 South African study shows contractors use flatbeds and trucks to transport materials, plant and equipment, and people simultaneously. Such practices increase the risk of severe injuries and fatalities if a crash occurs on the road. The increase in risks is occasioned by the resultant overloading of vehicles moving materials and people simultaneously in construction.

Other fatalities to be avoided include ‘fall from the vehicle in motion while getting on / off’ and ‘fall from the vehicle in motion’. These sources lead to severe injuries, highlighted in the co-occurrence and keyword analysis data. Recent research shows a correlation between urban development-related construction activities and the frequency of traffic accidents [31]. Their study in China indicates a significant spatial correlation between the accidents caused by engineering transport vehicles and the number of engineering construction projects in a region. By implication, the drive for infrastructure development and other construction activities cannot ignore the possibility of traffic accidents linked to heavy-duty vehicles.

5. CONCLUSIONS

In this research, scientometric methods were used to assess the state of traffic accident articles in general and construction to suggest gaps and directions for safety research. The results show that, either in the North Hemisphere or Southern Hemisphere, traffic accidents in construction result in fatalities, property damage and injuries. Regardless of volume, the paper suggests that traffic accidents are high in construction work zones, with fatalities in varying regions worldwide. Further, there is a major scope for scaling up attention to traffic accidents and fatalities in construction to engage policymakers, contractors, and scholars. The scaling of attention could be used to develop mitigation strategies, garner more research funds, and create solutions that save lives.

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HEALTH AND SAFETY COORDINATION BETWEEN MAIN CONTRACTORS AND SUBCONTRACTORS ON A POWER STATION PROJECT

Yolisa Nkqayana[1], John Smallwood[2]

[1]*Department of Construction Management, Nelson Mandela University, South Africa*
[2]*Department of Construction Management, Nelson Mandela University, South Africa*

Abstract

Health and safety (H&S) coordination between main contractors (MCs) and subcontractors (SCs) on construction projects is one of the most important factors for the success of a project. The aim of this study was to develop a framework to improve H&S coordination between MCs and SCs on a power station project, and the objectives were to: ascertain the H&S measures used to assess the H&S risks towards the reduction of hazards and injuries; assess the enforcement mechanisms of H&S regulations, and examine the challenges encountered in terms of the coordination of H&S on the Medupi power station project. Moreover, this research addressed the significant issue of possible ineffective coordination of H&S guidelines and policies in the South African construction industry, as well as on the power station project.

A questionnaire survey was conducted to gain insight into the working conditions on site and to evaluate the state of H&S coordination, its implications, and compliance with the Construction Regulations by all parties concerned. The quantitative method was adopted, which entailed a self-administered questionnaire survey of MCs and SCs working on the power station project.

The salient findings include: MCs and SCs undertake three H&S-related interventions frequently, as opposed to infrequently; the barriers to the operation of the H&S management system (H&SMS) on the Medupi power station project are more than influential, as opposed to less than influential, relative to both the MCs and SCs; the importance of twelve measures to improve the H&SMS on the Medupi power station project are more than important, as opposed to less than important, relative to both the MCs and SCs, and there are shortcomings in terms of H&S coordination between the MCs and SCs.

Recommendations included a need for the following relative to H&S: management commitment, worker participation, hazard identification and control, education and training, programme evaluation and improvement, and optimum communication and coordination for employers on multi-employer work sites.

Keywords: Contractors, Coordination, Health and Safety, Management system, Power station.

1 INTRODUCTION

H&S management within the construction industry has not developed at the same pace as technological advances within the industry itself. Inadequate H&SMSs, and a poor H&S culture within contractor organisations were identified as the contributing factors to the high rate of construction accidents in developing countries such as South Africa [1].

The study focuses on H&S coordination at the Medupi power station project, which includes the various disciplines of building, civil engineering, electrical, and mechanical. The Medupi power station is a coal-fired power station consisting of six 800 MW units each, producing 4800 MW of power in total [2]. The Medupi power station project H&S statistics triggered a need to study H&S coordination between the MCs and SCs on this project to assess the enforcement of H&S regulations, and examine the associated challenges encountered in the coordination of H&S on the Medupi power station project. The target project lost time injury rate (LTIR) of 0.08 was exceeded for three consecutive financial years: 0.21, 0.18, and 0.11 [2]. These incidents are categorised as first aid, medical aid, and lost time injuries. Furthermore, the need for the study was underscored by the consensus that H&S coordination between MCs and SCs on construction projects is one of the most important factors for the success of a project [2]. However, the survey of the literature identified that limited research has been conducted relative to H&S coordination between MCs and SCs. Thus, the aim of this study was to develop a framework which would help improve H&S coordination between MCs and SCs on the Medupi power station project. Consequently, the objectives of this study were to ascertain the H&S measures used to assess the H&S

risks towards the reduction of hazards and injuries, assess the enforcement mechanisms of H&S regulations, and examine the challenges encountered in terms of the coordination of H&S on the Medupi power station project. Moreover, this research addressed the significant issue of possible ineffective coordination of H&S guidelines and policies in the South African construction industry, as well as on the Medupi power station project.

2 LITERATURE REVIEW

2.1 H&S Management Systems

Nine thematic areas are identified relative to construction H&SMSs: organisation structure; management commitment and involvement; employee consultative arrangement and participation; hazard control procedures; H&S competencies and training; accountability mechanisms; H&S audits; H&S performance measurement and reporting, and reviews [3]. However, based upon a study conducted in South Africa, there are three distinct types of H&SMSs within medium to large size contractor organisations: traditional / compliance motivated (Type 1); systematic / compliance motivated (Type 2), and systems / best practice motivated (Type 3) [3]. A traditional / compliance motivated H&SMS type is characterised by the outsourcing of H&S management responsibilities to external H&S management consultants. A systematic / compliance motivated H&SMS type is characterised by the presence of internal H&S competencies and organisation structures to execute H&S management functions and responsibilities. A system / best practice motivated H&SMS type is characterised by H&S management activities based upon the requirements of the OHSAS 18001 management system standard [3].

Therefore, MCs are responsible for establishing and enforcing H&S policies and procedures, providing the necessary resources, and effectively communicating H&S information to all people working on a site, including both their employees and those of SCs. Site supervisors implement and enforce the H&S policies and procedures as well as conducting hazard identification and risk assessment (HIRA), employee H&S training, accident investigations, and H&S inspections. Employees are responsible for following established H&S procedures, reporting H&S hazards, and participating in H&S training and meetings [3].

2.2 Legislation and Regulations

In terms of the South African Construction Regulations [4] clients are required to provide the principal contractors (PCs) tendering on a project with a project specific H&S specification, based upon a baseline risk assessment (BRA). The H&S specification should include: the H&S requirements on the project; any H&S information, which will affect the pricing of the work; a related geotechnical report, and a schedule of the hazards and risks. Furthermore, clients are required to: ensure that potential PCs submitting tenders have made adequate financial provision for H&S; ensure that the PC to be appointed has the necessary competencies and resources to undertake the construction work in a healthy and safe manner; discuss and negotiate with the PC the contents of the PC's H&S plan, which responds to the H&S specification, and thereafter approve the H&S plan, and conduct audits at least monthly to determine whether the PC and SCs are following the H&S plan. PCs in turn, must follow the same approach as required of clients relative to PCs, relative to the SCs appointed on a project.

In terms of the management and supervision of construction work [4], a PC must appoint one full-time competent person as the construction manager with the duty of managing all the construction work, and an assistant construction manager. Thereafter, the construction manager must appoint construction supervisors responsible for the various construction activities and ensuring H&S compliance on the construction site.

In terms of H&S personnel on projects, depending on the size of projects, and the degree of danger likely to be encountered or the accumulation of hazards or risks on the project, the Construction Regulations [4] require the appointment of a full-time or part-time construction H&S officer (CHSO) to assist with respect to the control of H&S on projects. The Occupational Health and Safety Act (OHSA) [5] in turn requires the appointment of H&S representatives on sites where there are 20 or more employees - one for every 50 employees. A key requirement is that H&S representatives are elected by the workforce.

2.3 Management commitment to H&S

H&S efforts without the full support of a firm's top management will meet with only limited success. A firm must have a written H&S policy that is clear and easy to understand, and that policy should outline the firm's belief that H&S takes precedence over other job-site considerations [6].

Top management, by taking the time to discuss H&S along with cost and schedule concerns whenever they are on site, can increase H&S awareness. Awareness of top management's concern for H&S reduces the tendency to place production concerns above all else and indicates to employees that the firm considers H&S and production equal partners [6].

Successful H&S managers also take the time to give positive and negative feedback to employees regarding H&S performance and issues. The expectation of top management in firms with exemplary H&S records is that H&S managers should be knowledgeable about all aspects of their projects' H&S programme and record. As a result, this expectation guarantees that H&S managers will be informed of H&S related issues and problems and be more H&S conscious [6].

2.4 H&S training

Employee training is defined as a systematic effort that is initiated by the employer to develop knowledge, skills and attitudes required by an employee to perform a given task or job successfully with the final goal to improve the organisation's performance [7]. Furthermore, training is part of human resource development, which aims to develop an employee's full potential irrespective of the possibility of its immediate use in the current job. Therefore, such a focus on human resource development can be attributed to the growing realisation that people are the main source of competitive advantage and that an organisation's success is determined by decisions that employees make and behaviours in which they engage [7].

H&S training and orientation are necessary elements of an effective H&S programme [6]. All parties involved must understand the firm's H&S policy and procedures and the hazards associated with the work, including managers, supervisors, and workers [6]. An H&S coordination-training programme should be provided for new employees when they first arrive on site. This training programme should address the firm's H&S policies, and project's H&S regulations, site coordination, personal protective equipment (PPE), and Occupational Health and Safety Act (OHSA) required training.

H&S induction training, job-specific training, supervisory and management training, and specialist training are advocated in terms of H&S training [6]. Risk assessment, fall protection plan training, and supervision training are all legal requirements and fall within the scope of the aforementioned types of training [4; 5].

2.5 Hazard identification and risk assessment (HIRA)

Regulation 7 of the Construction Regulations refers to the HIRA procedures that the contractor is required to perform before the commencement of the works [4]. It stresses the importance of the contractor's cooperation in terms of appointing a competent person to perform HIRA before the commencement of the construction work to identify the potential risks. This should be done to ensure that all relevant risks are documented and integrated to form part of the H&S plan implemented on the site. A clear approach needs to be defined as to how the hazards and risks are identified and quantified, respectively, and will be monitored and mitigated to ensure that the sites are kept accident and injury-free. Furthermore, the contractor is required to disseminate information pertaining to the hazards and risks to all employees [4; 5]. The contractor is further required to ensure that all employees are trained, and instructed by a competent person regarding potential hazards, and all the work-related procedures prior to commencement of any work. This ensures that all employees know what to expect, and how to carry out work to ensure the mitigation of such hazards and risks [4; 5].

2.6 Accountability for H&S mechanisms

A study conducted in South Africa [3] identified the following coercive and incentivised programmes: consequence management for violation of life saving rules and H&S controls; H&S as a component of performance appraisal for operational managers; project level H&S recognition and reward programmes, and bonus incentives linked to LTI targets. However, coercive, and incentivised interventions were the most used accountability mechanisms among contractors.

2.7 H&S performance measurement and reporting

The Construction Regulations [4], and the OHSA) [5] require reporting of injuries and incidents. PCs are required to report fatalities and permanent disabling injuries to the Provincial Director of the Department of Employment and Labour (DEL). Medical practitioners are required to report occupational diseases to the Chief Inspector (DEL), and the employer of an employee, who was examined or treated for an occupational disease (OD).

However, from a non-legislative perspective, clients such as the client organisation undertaking the Medupi power station project, which is the subject of the study, require reporting of H&S-related incidents and the provision of H&S statistics such as the LTIR [2].

Furthermore, the study conducted in South Africa [3] determined that in general, H&S performance data are recorded and reported on at management meetings, and in annual or more frequent external reports

Other authors contend that the performance of any H&SMS depends on continuous H&S monitoring and review for the improvement of the system [8]. Continuous improvement is thus an integral feature of an H&SMS. Findings of a related study inform that supervisory personnel qualification, experience, knowledge, H&S awareness, H&S training, and H&S commitment have a significant impact on performance measurement [8]. A further study conducted in Ghana determined HIRA, monitoring and evaluation, and H&S encouragement as the essential aspects of H&S performance measurement [9].

2.8 Review of H&SMSs

A study conducted in South Africa determined that H&SMSs are reviewed at defined intervals informed by project audits informed by H&S Committee comments, annual system audits, and H&S performance measures [3].

2.9 Communication

The standard communication provisions require that all levels of the organisation be informed with respect to the H&SMS, which requires that injuries and illnesses be reported promptly. In addition, employees are encouraged to recommend improvements to H&S matters. Consultations must also be scheduled with contractors and other interested parties when changes are made that affect the H&SMS, and any barriers to communication relative to hazards and risks, and H&S management deficiencies must be eliminated [10].

3 RESEARCH

3.1 Method and sample strata

The study was quantitative in nature and a total of 60 MCs and SCs working at the power station project, which was the subject of the study, were surveyed using a self-administered questionnaire. Construction managers or site agents, H&S officers, H&S representatives, and construction supervisors were the focus of the study due to their involvement with H&S on projects. Of the 60 questionnaires distributed, 29 (48.3%) were distributed to MCs and 31 (51.7%) were distributed to SCs. MCs returned 18 questionnaires, and SCs returned 31 questionnaires, which equates to a response rate of 62.1%, and 100.0% respectively. Overall, 49 questionnaires were returned, which equates to a response rate of 81.7%.

3.2 Findings

Respondents were required to indicate whether they had a formal H&S programme for employees. 100.0% of MCs and 90.7% of SCs responded in the affirmative.

Table 1 indicates the frequency at which MCs and SCs undertake H&S training for workers, keep records of incidents on site, and provide incentives on site for good H&S performance, in terms of mean scores (MSs) based upon percentage responses to a scale of 1 (highly infrequent) to 5 (more than frequent). It is notable that all the MSs are > 3.00, which indicates that in general, the H&S-related interventions are undertaken frequently, as opposed to infrequently. However, the MS ranges further inform.

Given that the MSs for both MC and SCs relative to ‘keep records of incidents on site’ are > 4.20 ≤ 5.00, the frequency is between more than frequent to highly frequent / highly frequent. Then, given that the MSs for both MCs and SCs relative to ‘H&S training for workers’, and ‘provides incentives on site for good H&S performance’ are > 3.40 ≤ 4.20, the frequency is between frequent to more than frequent / more than frequent.

Table 1: Frequency of H&S-related interventions

Intervention	MCs		SCs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Keep records of incidents on site	4.22	1	4.42	1	4.35	1
Provides incentives on site for good H&S performance	4.00	2	3.94	2	3.96	2
H&S training for workers	3.83	3	3.77	3	3.79	3

Table 2 indicates the degree of influence of four categories of barriers to the operation of the H&SMS at the Medupi power station project in terms of MSs based upon percentage responses to a scale of 1 (not influential) to 5 (very influential). It is notable that all the MSs are > 3.00, which indicates that in general, the barriers are more than influential, as opposed to less than influential, in terms of the operation of the H&SMS at the Medupi power station project.

The MS ranges further inform. It is notable that only one MS is > 4.20 ≤ 5.00, which indicates that ‘type of H&SMS’ is more than influential to very influential / very influential relative to SCs.

The other 7 / 8 MSs relative to ‘internal organisational factors’, ‘nature of organisation’, ‘contractor relations’ in the case of both MCs and SCs, and ‘type of H&SMS’ in the case of MCs are > 3.40 ≤ 4.20, indicating that they are between influential to more than influential / more than influential to the operation of the H&SMS at the Medupi power station project. This indicates that there is a need to develop mitigation strategies with respect to the barriers to the operation of the H&SMS at the Medupi power station project.

Table 2: Extent to which four categories of barriers hinder the operation of H&SMSs at the Medupi power station project

Category of barrier	MCs		SCs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Type of H&SMS	3.83	4	4.26	1	4.10	1
Internal organisational factors	3.83	3	4.00	2	3.94	2
Nature of organisation	4.11	1	3.65	4	3.82	3
Contractor relations	3.89	2	3.74	3	3.80	4

Table 3 indicates the degree of influence of 15 barriers between the four categories of barriers, to the operation of the H&SMS at the Medupi power station project in terms of MSs based upon percentage responses to a scale of 1 (not influential) to 5 (very influential). It is notable that 26 / 30 MSs relative to MCs and SCs are > 3.00, which indicates that in general, the barriers are more than influential, as opposed to less than influential, in terms of the operation of the H&SMS at the Medupi power station project. Those that have MSs ≤ 3.00 include ‘extensive casual and part-time workforce’ relative to MCs, and ‘extensive casual and part-time workforce’, ‘principal contractor simply requires subcontractor to have an H&SMS’, and ‘principal contractor simply imposes their H&SMS on subcontractors’ relative to SCs.

In terms of ranges, 2 / 15 ‘MC’ MSs relative to ‘inadequate resources’, and ‘system imposed by senior management without consultation’, and 1/ 15 ‘SC’ MSs relative to ‘words unsupported by practice’ are > 4.20 ≤ 5.00, which indicates that barriers are more than influential to very influential / very influential.

The MS range > 3.40 ≤ 4.20, which indicates the extent is between influential to more than influential / more than influential, includes 10 / 15 ‘MC’ MSs, and 8 / 15 ‘SC’ MSs. Relative to MCs, ‘off-the-shelf H&SMS imposed without modification’, ‘words unsupported by practice’, ‘SCs’ H&SMS inconsistent with MC’s H&SMS’, ‘inadequate training of employees in H&S consultation’, and ‘MC simply imposes their H&SMS on SCs’ are ranked third to seventh. Relative to SCs, ‘system imposed by senior management without consultation’, ‘inadequate training of employees in H&S consultation’, ‘off-the-shelf H&SMS imposed without modification’, ‘SCs’ H&SMS inconsistent with MC’s H&SMS’, and ‘small firm with limited resources and unfamiliar with systems concept’.

The MS range > 2.60 ≤ 3.40, which indicates the extent is between less than influential to influential / influential, includes 3 / 15 ‘MC’ MSs, and 6 / 15 ‘SC’ MSs.

Table 3: Extent to which barriers hinder the operation of H&SMSs at the Medupi power station project

Barrier	MCs		SCs		Mean	
	MS	Rank	MS	Rank	MS	Rank
H&SMS:						
• Off-the-shelf system imposed without modification	4.11	3	3.94	5	4.00	5
• System imposed by senior management without consultation	4.33	2	4.19	2	4.24	1
Internal organisational factors:						
• Inadequate resources	4.56	1	4.03	4	4.22	2
• Limited accountability mechanisms	3.44	12	3.61	7	3.55	9
• Words unsupported by practice	4.06	4	4.29	1	4.20	3
• H&S activities restricted to technical experts	3.50	10	3.39	10	3.43	10
• Inadequate training of employees in H&S consultation	3.89	6	4.10	3	4.02	4
• High labour turnover	3.39	14	3.19	12	3.27	12
• Extensive casual and part-time workforce	2.33	15	2.13	15	2.20	15
Nature of organisation:						
• Small firm with limited resources and unfamiliar with systems concept	3.50	11	3.81	6	3.69	7
• Labour hire firm with employees working on multiple client sites	3.72	8	3.52	9	3.59	8
• Disorganisation of work associated with presence of labour hire employees and contractors	3.61	9	3.32	11	3.43	11
Contractor relations:						
• MC simply requires SCs to have an H&SMS	3.39	13	2.23	14	2.65	14
• MC simply imposes their H&SMS on SCs	3.83	7	2.48	13	2.98	13
• SCs' H&SMS inconsistent with MC's H&SMS	4.00	5	3.58	8	3.73	6

Table 4 indicates the importance of twelve measures to improve the H&SMS on the Medupi power station project in terms of MSs based upon percentage responses to a scale of 1 (highly unimportant) to 5 (highly important). It is notable that all the MC and SC MSs are > 3.00, which indicates that in general, the twelve measures are more than important, as opposed to less than important, in terms of improving the H&SMS on the Medupi power station project.

It is notable that 11 / 12 MC MSs and 9 / 12 SC MSs are > 4.20 ≤ 5.00, which indicates that the measures are more than important to highly important / highly important in terms of improving the H&SMS on the Medupi power station project.

The remaining 1 / 12 MC MSs and 3 / 12 SC MSs are > 3.40 ≤ 4.20, which indicates that the measures are important to more than important / more than important in terms of improving the H&SMS on the Medupi power station project.

'Providing H&S procedures before commencing with work' and 'incident investigation and record keeping on construction sites' predominate ito the MC, SC, and mean MSs, followed by a cluster of measures ranked third to seventh, namely 'consideration of H&S matters during the design phase of a facility', 'H&S auditing by H&S committees', 'maintenance of construction site', 'provision of fire prevention and firefighting equipment during construction', and 'top management commitment to H&S'.

Table 4: Importance of twelve measures to improve the H&SMS on the Medupi power station project

Measure	MCs		SCs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Providing H&S procedures before commencing with work	4.89	1	4.81	1	4.84	1
Incident investigation and record keeping on construction sites	4.83	2	4.74	2	4.78	2
Consideration of H&S matters during the design phase of a facility	4.72	4	4.65	5	4.67	3
H&S auditing by H&S committees	4.61	6	4.68	3	4.65	4
Maintenance of construction site	4.61	8	4.68	4	4.65	5
Provision of fire prevention and firefighting equipment during construction	4.61	7	4.61	6	4.61	6
Top management commitment to H&S	4.78	3	4.48	7	4.59	7
Assignment of H&S responsibility to all levels of management and workers	4.56	9	4.45	8	4.49	8
Establishment of H&S training and orientation for site operatives	4.67	5	4.35	9	4.47	9
Incorporating H&S guidelines into the body of conditions	4.44	10	4.19	10	4.29	10

of contract for a project						
Motivation of construction operatives by instituting H&S awards	4.17	12	4.19	11	4.18	11
Informing factory inspectorate of the location of new construction sites	4.33	11	4.06	12	4.16	12

DISCUSSION

Both MCs and SCs undertake three H&S-related interventions frequently, as opposed to infrequently, which indicates commitment and coordination between MCs and SCs.

The barriers to the operation of the H&SMS at the Medupi power station project are more than influential, as opposed to less than influential, relative to both the MCs and SCs, which indicates that there are challenges relative to H&S coordination between MCs and SCs. However, there is a degree of congruence between MCs and SCs with respect to this issue. In terms of the H&SMS, an 'off-the-shelf' version, and imposing without consultation are significant barriers. In terms of internal organisational factors, inadequate resources, words unsupported by practice, and inadequate training are significant barriers. The Construction Regulations [4] are explicit with respect to clients and PCs being required to ensure that PCs and SCs have adequate competencies and resources to undertake the construction works in a healthy and safe manner, respectively. Words unsupported by practice is notable as the literature relative to the role and nature of management commitment to H&S [3] is explicit in terms of what management should do. Furthermore, the Construction Regulations [4] schedule a range of site management appointments and actions. In terms of training, the Construction Regulations [4], and OHSA [5] schedule a range of training that must be provided to workers. In terms of nature of organisation, and size of firm in terms of resources and non-familiarity with systems, and labour brokers, are significant barriers. In terms of contractor relations, SCs' H&SMS inconsistent with principal contractor's H&SMS is a significant barrier, which militates against MC and SC coordination. Review of the H&SMS is a thematic area of H&SMSs [3], and thus this issue should be 'automatically' addressed.

The importance of twelve measures to improve the H&SMS on the Medupi power station project are more than important, as opposed to less than important, relative to both the MCs and SCs, which indicates coordination between MCs and SCs in terms of experience, perception, and potential interventions. Furthermore, their importance indicates that there is potential to improve coordination between MCs and SCs, and H&S performance.

CONCLUSIONS

H&S coordination between MCs and SCs on construction projects in general is important and a key contributor to optimum H&S performance. Inadequate H&S coordination between MCs and SCs, may result in incidents, and accidents.

Consequently, H&S coordination between MCs and SCs in terms of the operation of the H&SMS at the Medupi power project is important, and there are four categories of barriers and 15 barriers that hinder its operation. Consequently, it can be concluded that there is a need to interrogate the appropriateness of the H&SMS on the Medupi power station project, and on future related projects to ensure that it is appropriate for both MCs and SCs and that it promotes H&S coordination between MCs and SCs.

The importance of twelve measures to improve the H&SMS on the Medupi power station project lead to the conclusion that the H&SMS can be improved. Furthermore, communication, including consultation is necessary to ensure alignment in terms of interventions and resourcing between the MCs and SCs relative to the H&SMS on the Medupi power project.

Top, middle, and site management commitment to H&S is important and is referred to as one of the two pillars of an H&S programme and H&SMS, which is highlighted in the literature [3]. However, including H&S as a value as opposed to a priority, providing adequate resources for H&S, involvement, participation, leadership by example and 'walking-the-talk' are the ultimate measures of management commitment, which are highlighted in the literature [3].

Worker participation in H&S is an explicit and implicit requirement of the OHSA [5] and is referred to as one of the two pillars of an H&S programme and H&SMS, along with management commitment. This is reinforced by a major South African study [3].

HIRA is a critical element of an H&S programme and H&SMS [3], in addition to being a legal requirement in terms of the Construction Regulations [4] and the OHSA [5].

Conducting investigations pertaining to incidents and accidents leads to best practice and positive results for all the parties involved in a construction project as reflected in the literature [8].

There is a need to assess and improve the operation of the H&SMS at the Medupi power station project, as well as inadequate commitment to H&S practices, and inadequate communication and consultation regarding the implementation of the H&SMS between MCs and SCs at the Medupi power station project. This conclusion is underscored by the inclusion of 'review of an H&SMS' as one of nine H&SMS thematic areas [3].

RECOMMENDATIONS

Given that H&S coordination is an important management function on construction sites to ensure the minimisation of hazards and risks, and accidents, it is recommended that the following practices be implemented to contribute to improving the H&S coordination on future Eskom construction projects.

Top management of both MCs and SCs should demonstrate their commitment to the elimination of hazards and to the continuous improvement of H&S in the workplace. They should communicate their commitment to workers by clarifying H&S project expectations and responsibilities. Furthermore, managers at all levels should make H&S a core organisational value and for their projects, and top management should establish project H&S goals and objectives. Finally, they should ensure the provision of adequate resources and support for the project. The aforementioned interventions are generally advocated in the literature [3; 8].

Workers and their representatives should be involved in all aspects of projects, including project goal setting, identification and reporting of hazards, investigation of incidents, and tracking of progress on-site. All workers at all levels, including those of both MCs and SCs, should understand their roles and responsibilities on projects, as well as what they need to do to carry out their responsibilities effectively. All workers should be encouraged to communicate openly with supervisors, and management, thus enabling them to report H&S concerns and present their suggestions for improvement without fear of retaliation. All potential barriers to worker participation in the project, for example, language, lack of information, and disincentives, should be addressed. Worker participation is a hallmark of an H&SMS [3; 8], and a requirement in terms of the Construction Regulations [4], and the OHSA [5].

HIRA is critical, and procedures should be put in place for the continuous identification of hazards and evaluation of risks in the workplace. H&S situations, including those that are routine, not routine, and emergencies, should be identified and assessed. An initial assessment of existing hazards, exposures, and control measures should be followed by periodic inspections and reassessments to identify new hazards. Furthermore, all incidents should be investigated with the goal to identify the root causes, and all identified hazards should then be prioritised for control. Management, supervisors, and workers should work together to identify and determine methods for the control, prevention, and ultimately the elimination of hazards in the workplace. A plan should be developed to ensure that controls are implemented, interim protection is provided, progress is tracked, and the effectiveness of controls is assessed, and verified. HIRA is a hallmark of an H&SMS [3; 8], and a requirement in terms of the Construction Regulations [4], and the OHSA [5].

All workers at all levels should be trained to understand the importance of H&S during a project and they must know how to carry out their assigned responsibilities on the project. Managers should receive training regarding H&S concepts together with their responsibilities for protecting workers' rights and responding to workers' reports and concerns. All workers should be trained to recognise H&S hazards in the workplace and to understand all the control measures that have been implemented. H&S training and competency are hallmarks of an H&SMS [3; 8], and a requirement in terms of the Construction Regulations [4], and the OHSA [5].

In terms of H&SMS evaluation and improvement, control measures should be evaluated periodically for effectiveness. This evaluation should include establishing processes to monitor H&SMS performance, verify the implementation of interventions, and to identify shortcomings. Thereafter, there should be an assessment of opportunities for further improvement. The review of H&SMSs to assess their effectiveness is well documented in the literature [3; 8].

In terms of communication and coordination on multi-employer work sites, MCs, SCs and labour brokers should commit to providing the same level of H&S protection to all employees. All parties should communicate the hazards present at the work site and the hazards that contract workers may encounter on site. MCs should establish specifications and qualifications for contractors and staffing agencies.

Before the commencement of the work, MCs, SCs, and labour brokers should coordinate the planning and scheduling of the work to identify and resolve any conflicts that may impact a project's H&S. The importance of communication relative to an H&SMS is well documented in the literature [3; 8; 9].

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MEASURING AND MANAGING HEALTH AND SAFETY PERFORMANCE ON MAJOR RAIL INFRASTRUCTURE CONSTRUCTION PROJECTS

Payam Pirzadeh[1], Helen Lingard[2], Amanda Benson[3], Joe Alderuccio[4]

[1]RMIT University (Australia)
[2]RMIT University (Australia)
[3]Suburban Rail Loop Authority (Australia)
[4]Suburban Rail Loop Authority (Australia)

Abstract

The construction industry has a disproportionately high incidence of work-related deaths, serious injuries and ill-health. Finding ways to better measure and improve health and safety (H&S) performance is a current concern in the construction industry. Yet, to date, there has been no consensus, in the industry or in academia, on how to design H&S performance measurement systems that enable effective and proactive H&S management. A study was conducted to understand how H&S performance can be best measured and effectively managed on major infrastructure construction projects. The study involved reviewing academic literature, industry reports and best practice guidelines, and conducting semi-structured interviews with 27 Australian and international industry H&S experts. The interviews sought to understand the experts' views on what constitutes effective H&S performance measurement. The interview data was analysed using an inductive thematic analysis approach. Seven themes emerged from the interviews. The themes reflected key aspects of an organisational H&S management system that industry experts identified as important and that should be incorporated into any H&S performance measurement framework. The study findings are informing the development of an evidence-informed H&S Performance Index designed to be scalable and flexible, allowing it to be adopted by clients and contractors irrespective of their size. The Index is intended to enable project teams to capture information reliably and consistently about the quality of H&S and adopt a participatory approach to managing performance and make informed decisions to provide sustained healthy and safe workplaces.

Keywords: Health and safety performance; Performance measurement and management; Major infrastructure construction.

1 INTRODUCTION

Performance measurement has been defined as using metrics to quantify the efficiency and/or effectiveness of action while performance management involves a process of measuring what matters, reporting these measures, reviewing performance, and taking action [1]. Performance measurement and management are key elements of organisational or management control systems. In many cases these systems operate in constantly changing environments with the objective of responding to changes, the correction of problems and the prevention of undesired outcomes.

Finding ways to better measure and improve health and safety (H&S) performance is a current concern in the construction, including major rail projects, where projects are delivered in dynamic environments, where management control occurs across inter-organisational boundaries (e.g., between client and principal contractor, principal contractor, and sub-contractor etc). Each organisation may have different priorities and expectations, which makes it difficult to establish and implement a consistent performance measurement and management system. To date, there has been no consensus, in the industry or in academia, on how to best measure health and safety performance to enable effective and proactive health and safety management.

2 AIM

The research presented in this paper sought to understand how H&S performance can be best measured and effectively managed on major infrastructure construction projects. The research involved reviewing academic literature, industry reports and best practice guidelines, and conducting semi-structured interviews with Australian and international industry H&S experts to identify best practice H&S performance metrics used on construction projects. The research findings informed the development of an evidence-informed H&S Performance Index. Before describing the methods and presenting the results, we summarise the literature relating to H&S performance measures in construction.

3 PROBLEMS WITH TRADITIONAL MEASURES OF H&S PERFORMANCE

Traditionally, construction organisations have relied on measures of the frequency with which undesirable health and safety outcomes have occurred as an objective indicator of performance. Thus, there are standardised ways to calculate rates such as lost time injury frequency rates (LTIFRs) and total recordable injury frequency rates (TRIFRs). Such indicators are useful because they are: easy to collect, easily understood, easy to use in benchmarking or comparative analyses, and useful in the identification of trends over time [2].

However, these measures have been criticised on different grounds. First, because recordable incidents and injuries have a statistically low probability of occurrence over short time frames, they are usually neither valid, nor stable when measured at a single construction project [3]. Hallowell et al. [4] question the statistical validity of total recordable injury rate and indicate a high degree of randomness and wide confidence intervals (i.e., low precision) for injury rates which make the comparison of specific injury frequency rates between typical reporting periods meaningless.

But a more fundamental criticism of incident/injury rates is that they are retrospective indicators, capturing things that have already gone wrong in a work system. They measure the absence, rather than the presence of health and safety in workplaces and therefore cannot be regarded as a direct measure of the level of health and safety in a work system [5]. Consistent with this view, the preoccupation with measuring adverse outcomes has been widely criticised [6].

The use of injury/incident rates, particularly if they underpin incentive schemes, can cause reporting problems. Tying incentives, such as management performance appraisals, bonus payments, or future tendering opportunities to injury/incident rates can encourage underreporting [7]. Research also shows that workers who perceive that they have low levels of job security are less likely to report injuries and incidents [8]. When underreporting occurs, data fidelity is compromised, and erroneous conclusions can be drawn from analysis of performance.

Kjellén [9] also argues that injury rates fail to differentiate between severe injuries and minor ones. Hallowell et al. [10] report that variation in total recordable injury rates has no association with the incidence of fatalities. They argue that fatality incidence follows a different pattern to the TRIFR, suggesting that serious incidents (e.g., fatalities) occur for varied reasons. O'Neill et al. [11] similarly argue that grouping injury events together, which is frequently done when calculating TRIFRs and LTIFRs, serves to conceal severe injuries (e.g., those causing fatalities and permanent disabilities) because the number of low consequence incidents typically far exceeds the number of severe injuries.

4 CHARACTERISTICS OF EFFECTIVE H&S PERFORMANCE MEASUREMENT

A key function of effective measurement is to anticipate events in the future and trigger proactive and corrective actions. Consequently, H&S performance indicators should be based on a thorough understanding of the factors (both immediate and distal) that contribute to accidents and injuries [12].

There is a growing recognition that both qualitative and quantitative approaches are valuable in understanding H&S performance in an organisational context. For example, Hinze et al. [13] recognise the importance of having a selected organisation-specific combination of quantitatively and qualitatively valid safety performance indicators. Peñaloza et al. [14] similarly emphasised that safety performance measurement systems should include both quantitative and qualitative data.

Oguz Erkal et al. [15] identified four criteria against which predictors of serious injuries and fatalities in the construction industry should be assessed for their effectiveness: 1) indicators should be reasonably and consistently measurable using available resources; 2) indicators should be actionable, i.e., measurement of an indicator could reasonably trigger serious injury/fatality prevention action; 3) indicators should be simple, i.e., measurement should be easy to understand, define, and explain to workers and managers, and 4) indicators should be predictive, i.e., factors that are measured have a significant influence on the occurrence of serious injury/fatality events.

It is increasingly recognised that, in addition to capturing indicators that can predict adverse outcomes, H&S performance measurement should also include indicators of positive H&S outcomes [9, 16]. This is consistent with Hollnagel's [17] position that a state of safety reflects more than the absence of risk.

Measuring the presence (rather than the absence) of safety enables managers to identify, understand and create the conditions required for success, as opposed to simply counting failures [18].

Guo et al. [19] suggest that the practicability of safety performance indicators is a crucial factor in their effectiveness. Factors impacting practicability include the extent to which an indicator of performance is compatible with practical management requirements and is not susceptible to manipulation. The UK Health and Safety Executive [20] argues that performance measurement should drive appropriate behaviour in relation to workplace H&S. In some instances, indicators are reported to be subject to misuse or manipulation [21]. For example, poorly chosen metrics can sometimes lead to a focus on the frequency of a H&S-related activity (e.g., counting the number of safety meetings or safety walks by managers), without capturing the quality of the activity, thereby not reflecting the effectiveness with which workplace H&S is being managed in an organisational context. Hallowell et al. [10] argue that, unless the quality of the implementation of a H&S management activity is captured by H&S performance measures, organisations will be unable to distinguish between strong/meaningful and weak/ineffective implementation. When combined with targets and incentive schemes, the measurement of H&S performance by using simple frequency metrics can prompt people to ‘manage the metrics’ rather than focusing on improving the H&S performance in a workplace.

Reliability is also a characteristic of effective safety performance measurement [22]. In this context, reliability refers to the extent to which performance indicators provide consistent results when different people use them. Reliability of measurement is particularly important when performance is being compared between different work areas or between different points in time.

While much of the commentary on effective measurement focuses on safety performance indicators, the importance of effective measurement applies equally to work-related health performance.

5 ALTERNATIVE TYPES OF H&S PERFORMANCE INDICATORS

As a result of the limitations associated with the exclusive use of retrospective injury or incident data for the measurement of health and safety performance within organisations, there has been a shift to new and diverse types of health and safety performance measurement. Ways to quantify the state of health and safety, irrespective of the occurrence of injury or incidents take various forms and include the use of health and safety leading indicators, precursor analysis, safety risk analysis, and safety climate assessment [15].

The emphasis of new ‘alternative’ forms of safety measurement is on identifying and measuring specific indicators that predict safety performance at some future point in time, rather than counting injuries or incidents over time [15, 23]. For example, Alexander et al. [24] identified 16 precursors of construction fatalities. Examples include schedule pressure, fatigue, distraction, and improvisation. Hallowell et al. [10] similarly explored combinations of and interactions between work tasks, environmental conditions, human conditions, and management systems that predict future safety performance. In particular, the inclusion of human factors in measurement models for safety is important in an industry like construction in which project-based workers make decisions and respond to events in a work environment characterised by change and uncertainty [15].

In the development of alternatives to traditional outcome-based safety indicators, the terms leading, and lagging have been borrowed from the fields of economics and finance, yet, as Kjellén [9] argues, the terms were introduced to the field of safety without full consideration of their meaning as it applies to safety performance. As a result, they have been used inconsistently.

Leading indicators of safety are defined in different ways. Hopkins [3] states that “lead indicators are those that directly measure aspects of the safety management system, such as the frequency or timeliness of audits” (p. 460). However, Hopkins [3] also points out that the measurement of safety-relevant activity does not provide a direct measure of the state of safety in a particular situation. For example, measuring the frequency of management activity as a proxy for safety performance may not reflect a safer workplace because this could potentially produce behaviours that are designed to manage the indicator rather than the real issue of workers’ safety. Leading indicators of safety have also been described as “precursors to harm that provide early warning signs of potential failure” [25].

The underlying logic is that the measurement of leading indicators provides an opportunity to detect and resolve safety issues before incidents or injuries occur [26]. However, there are some important conceptual questions about how the terms leading and lagging are understood in relation to workplace safety performance. In some interpretations the distinction between what is leading versus lagging lies in the position of the indicator in relation to the occurrence of harm - with lag indicators measuring harm directly and lead indicators measuring the precursors to harm. Alternatively, Hopkins [3] notes that any kind of failures, irrespective of whether they produce harm, should be considered lagging indicators. In this interpretation the distinction between leading and lagging depends more upon whether an indicator measures something positive, e.g., the functioning of the safety management system, or negative, e.g., the failure of a particular system defence or risk control mechanism. Leading indicators of safety have also been defined as aspects that change before the actual level of risk exposure changes, irrespective of whether harm eventuates [9].

Importantly, describing indicators as leading or lagging suggests the existence of a time-dependent and directional relationship between safety performance indicators and safety-related outcomes. A longitudinal analysis of five years of data collected at a large transport infrastructure construction program in Australia, revealed that some indicators that were referred to as leading indicators sometimes operate as lagging indicators of safety performance [27]. For example, an increase in frequency of toolbox talks and safety observations was found to decrease the TRIFR in the short term. However, over a longer period, the direction of causality between these two indicators changed, such that a decrease in the TRIFR predicted a subsequent decrease in the frequency of toolbox meetings. This suggests that some of the management activities were triggered by changes in the frequency of occurrence of incidents/injuries. Lingard et al. [27] highlight the cyclical nature of this relationship between indicators, where managers respond to an increase in incident/injury rates by focusing greater attention on safety management practices, however, as the incident/injury frequency rate falls, so too can the increased attention placed on safety management in a workplace. Lingard et al. point out that this type of cyclical behaviour does not produce sustained improvement in safety performance over time.

The above discussion highlights how the distinction between what leads and what lags can sometimes be unclear, although the terms leading and lagging indicators of workplace health and safety have been widely adopted in industry.

6 RESEARCH METHOD

A qualitative research approach was used. Data was collected by conducting semi structured open-ended interviews. A purposive sampling strategy was used to recruit participants for the interviews. Participants were identified through researchers' industry networks. Invitation emails were sent out to identified construction H&S experts asking their willingness to participate in the study. They were also asked to forward the invitation to other H&S experts whose knowledge were relevant to the research aims. The invitations were sent to both Australian and international experts. 27 industry H&S experts from 22 Australian and international construction and rail organisations indicated their willingness to participate in the study. 9 experts worked in client organisations, 15 worked in contractor organisations, and 3 were safety specialists working as consultants or union representatives. 19 experts were men and 8 were women.

These experts were interviewed to understand their views on what constitutes effective H&S performance measurement. The interviews covered three main topics:

1. How participants measure H&S performance in their projects,
2. How participants use collected H&S data to manage performance, and
3. What participants consider to be the best/most useful indicators of H&S performance.

Two researchers administered each interview online. The length of interviews ranged between 28 – 64 minutes. The mean length of the interviews was 51 minutes. The interviews were audio recorded and transcribed. Some participants also provided project documents including H&S performance reports and lists of H&S metrics used in their organisations. The interview transcripts and the content of documents were analysed using an inductive thematic analysis approach. The research questions were used as a guide to conduct the inductive coding and identify themes. The theme comparison and organization process were undertaken by two researchers and continued until consensus was reached, i.e., researchers were satisfied that all data were represented by the themes and subthemes in a meaningful manner [28].

7 RESULTS AND DISCUSSION

The themes and subthemes identified from the interviews are listed in Table 1 and are discussed below.

Table 1: *Key themes and sub-themes from the interviews*

	Theme (indicator)	Subtheme (key aspects)
1	Incident and injury data	• Opportunity for learning from past performance
2	Leadership engagement in H&S	• Leaders' visibility and conversations they hold with the workforce • Quality of leaders' H&S engagements • Shaping H&S leadership behaviour • Leaders influence in stopping unsafe work
3	Proactive risk management	• Risk anticipation • Hazard reporting • Quality of assurance activities & focus on workforce engagement • Timely implementation of corrective actions • Resourcing, competency, and role clarity
4	Interactions about H&S	• Developing the capacity to engage in conversations about H&S
5	Incident investigation and lessons learnt	• Ensuring the quality of investigations & recommendations • Open and honest conversations • Sharing lessons and improved safety practices
6	Occupational health and wellbeing	• Health and wellbeing considerations • Potential for harm
7	H&S culture	• Reporting and interpreting H&S performance • Assessing safety climate

7.1 Use of injury and incident data

While acknowledging the 'rear-view' nature of incident-focused measures, majority of the interview participants indicated that lag measures (i.e., incident frequencies) are used in their organisations to track and report H&S performance. Injury-related measures, in particular Total Recordable Injury Frequency Rate (TRIFR) and Lost Time Injury Frequency Rate (LTIFR), were the most widely used lagging metrics. Learning from incidents was mentioned as the key benefit of collecting incident-related performance data. Participants also explained that government bodies and clients typically require lag indicators to be reported. However, a number of participants believed that there needs to be more emphasis on learning from the incidents rather than focusing on incident numbers and rates. For example, a contractor Executive General Manager commented that: "*It's annoying that clients keep asking for them* [injury rates] *and that there's so much time and energy spent on how many injuries have you had. You go "Well that doesn't matter. What did we learn from them and what are we doing?*"

Some participants noted the limitation of TRIFR and LTIFR in that these metrics are not sensitive to the severity of incidents because they combine all injuries in one metric. This observation is consistent with argument made by Kjellén [9] and O'Neill et al. [11] that grouping injury events together, which is frequently done when calculating TRIFRs and LTIFRs, serves to conceal severe injuries because the number of low consequence injuries typically far exceeds the number of high consequence injuries. Alternatively, some organisations use, or intend to develop, additional measures that focus on consequences, such as time lost (e.g., days lost or hours lost per thousand days worked) or the financial consequences of injuries, e.g., the cost of the wages reimbursed as workers' compensation and the medical treatment costs within a 12-month waiting period. Another suggested approach was to allocate a higher weight to more serious incidents when calculating frequency rates.

7.2 Leadership engagement in H&S

Leaders' understanding of H&S priorities and their visibility on site and their engagement in H&S management activities was highlighted as a key indicator of H&S performance by several participants. A contractor Managing Director noted measuring "*how often the leaders of the company, of the project, of the team, how often are they going onsite, are they visible, and are they talking about the safety on the project? And I think, it's cliché', but you know the standard you walk past is the standard you set.*"

Frequently mentioned KPIs included tracking the frequency of safety leadership walks, leadership interactions with frontline staff, and inspections undertaken by the leadership team. The influential role of leaders in stopping unsafe work was particularly highlighted. A client Safety Director noted the benefit of Stop Work Orders made by managers in that they allow for a re-set and re-evaluation of the work process. As the Director explained, Stop Work Orders can be powerful means of reinforcing the importance of H&S on site by sending the message to workers that "*they're not going to be held to account to work to deliver on time if it means working unsafely.*"

Some organisations have put programs in place that aim to shape H&S leadership behaviours. For example, a UK-based contractor has developed a program that is focused on how managers and supervisors create the right environment for promoting H&S. As the SHE Director explained: "*We really look at the different levels, …we're looking at actually shaping the behaviour of the directors right the way through … So, are the sector directors having those* [H&S management] *conversations? Are the managing directors having the conversation with sector directors? So, we're starting to measure the things that we want to happen more and more.*"

Participants also noted the importance of ensuring the quality of leaders' engagements in health and safety and their interactions with the workforce, while also acknowledging difficulties associated with measuring the quality of these activities. Some organisations have adopted KPIs focusing on leadership visibility and engagement with frontline workforce and require members of their leadership team and supervisors to document their leadership activities and interactions with frontline workforce and upload the evidence (e.g., inspection reports, photos, reports of conversations with workers and, most importantly, the outcomes of those conversations) to their H&S management and reporting platforms. For example, an alliance HSE Leader explained their KPIs which focus on active field engagement and include both quantitative and qualitative measures. These approaches resonate with the argument put forth by Hallowell et al. [10] that, without capturing the quality of the implementation of H&S management activities by H&S performance measures, organisations will be unable to distinguish between strong/meaningful and weak/ineffective implementation.

7.3 Proactive H&S risk management

Several interviewees noted the importance of risk anticipation and mentioned processes in their organisations which focus on work coming up in short periods (e.g., 30 or 60 days) in project plans, identify critical risks, and ensure they are effectively controlled. For example, a contractor Managing Director mentioned "risk anticipation" as a pillar of their H&S strategy. This Director went on to explain how risk anticipation enables the workforce to deal with changes on a high risk worksite by ensuring that critical-risk controls remain effective and stop unsafe work: "*We want our people to be really conscious of that and there's nothing wrong if something changes, but the first instinct needs to be to stop, go back to your methods, go back to your design, etc, etc, and reassess the risks before you start again.*"

Frequent nature of H&S risk assessment and control helps to accommodate the dynamic nature of the work and site conditions in risk management process. The dynamic and complex nature of construction environment makes risk management challenging [29]. The focus on work coming up in short-term (e.g., in a month) enables a more realistic view of risks as work conditions will be clearer in the short-term and there will be less reliance on assumptions about how work is performed. This helps to implement risk control solutions that suit specific work conditions rather than relying on generic solutions.

A key aspect of proactive risk management highlighted by the participants was hazard reporting. They identified hazard reporting as an important and positive indicator of a good H&S culture, workforce engagement in H&S management, and a precursor to reducing incidents. Two participants went on to explain that their past data shows that a decrease in reporting hazards leads to an increase in incidents. HS&E Director of a UK-based contractor stated that "*we've got data over the last 10 years or more now to demonstrate this – is if we can increase hazard reporting, we see a drop off in accidents*".

Assurance activities, such as audits and inspects, were frequently mentioned as methods of monitoring the effectiveness of critical risk controls, identifying gaps in H&S risk management, and ensuring H&S related procedures are followed. A UK-based client Head of H&S described how audits were used as a mechanism to verify the effectiveness of risk control solutions and improvement actions across a large construction program. While often frequency of assurance activities is recorded in organisations as a H&S metric, participants noted the importance of ensuring the quality of such activities. Some participants explained that in their organisations, inspection and audit reports are reviewed by managers to verify their quality. For example, one OH&S Manager mentioned verifying internal audit results with external third-party evaluations.

To ensure timely and effective rectification of issues, most participants indicated they track the timely completion of corrective actions and improvement initiatives in their projects. For example, when asked to identify the most effective indicators of H&S performance, a client/operator Safety Advisor commented: "*I'm a bit of a fan of the corrective action management because it's showing – to me – it's showing someone's commitment to improvement…*"

Furthermore, interviewees noted the positive impact of having a well-resourced project with appropriately skilled, experienced and capable workers at all levels. This was considered as "*an indication of good health and safety"*. Thus, some organisations monitor the adequacy of resources and workforce capability to undertake work in a healthy and safe manner. A contractor Executive General Manager (HSEQ) described: "*We've got a safety capacity index which we've just started using and the resourcing is part of that…*". To address capability needs, many contractor organisations provide training to their workforce and some organisations extend the training to the subcontractors. Participants stated that they typically measure the number of training sessions or training hours completed as an indicator of training performance. In addition, some organisations use behaviour observations and skill assessments to ensure the effectiveness of training. For example, the Managing Director of a Hong Kong-based contractor mentioned the verification of competency and assessment of safety behaviour and skills for high-risk trades which is done by an independent consultant on their project sites.

7.4 Interactions about H&S

The frequency and quality of H&S related interactions was identified as a key factor in effective H&S management. A client Safety Director underlined the importance of developing the capacity within the workforce to engage in conversations about safe work methods and procedures. Another contractor Managing Director noted: "*We want to have much more interaction between the frontline guys delivering and the guys who are preparing the work. So, we are measuring now the number of … toolbox talks or task launch meetings, but the idea is that we really tried to create an environment in which all of the team has an opportunity to get together and to share what's coming and how it will be executed safely.*" Similarly, maintaining H&S-related conversations among the workforce was considered a key success factor to safely deliver a large construction program in the UK.

An Alliance HSE Leader explained a process aimed at promoting workforce engagement in H&S by having conversations with them, understanding their perspectives, agreeing on follow up actions, and providing feedback in relation to the issues they raise. The HSE Leader went on to emphasize that conversations with workers are important in understanding how activities are undertaken on site and in identifying improvement initiatives through workforce engagement. Previous research has similarly highlighted the significance of developing a clear understanding of work activities and closing the gaps between "work as done" and "work as imagined" (see e.g. [30]).

7.5 Incident investigation and sharing lessons

Several participants stated their organisations measure the frequency of accident and near miss investigations and use the findings from investigations to improve their H&S performance. Participants noted several factors in relation to the effectiveness of investigations including ensuring the timeliness of investigations, the quality of recommendations from investigations and sharing findings. Thus, some organisations have developed KPIs that focus on whether investigations are done on time, quality assessments of investigations are done on time, and actions arising from investigations are closed on time. For example, the HS&E director of a contractor company explained: "*we measure the quality of those investigations on a red, amber, green kind of scale, and that's another one of our lead indicators.*"

A client General Manager for Safety noted specific meetings conducted to discuss incidents, ensure the incident reports include sufficient details and decide follow-up actions. Similarly, a client Deputy Director for Safety Operations referred to the observance of 'Chatham House Rules' during incident review meetings to encourage open and honest discussions about the incidents and lessons learned. The deputy director noted: "*I see those as being really positive and powerful, and I treat them as a lead indicator because I do believe that it then has action.*" Further referring to the usefulness of sharing lessons, the Deputy director commented: "[The findings] *may transfer to another area* [of project] *and if that prevents an incident in another area, then it's a win.*"

A client Safety Delivery Manager stated that investigation findings are used on their projects to produce fact sheets for safety advisors to inform their conversations with the workforce, develop improvement actions and monitor control measures. Conversations with the workforce were identified as being critical for disseminating vital information to those who need to implement improved ways of working.

Keeping the workforce informed about improvement actions and investigation outcomes can enhance buy-in from the workforce and increase the likelihood that the improvement actions and recommendations lead to behavioural changes and H&S improvements.

7.6 Occupational health and wellbeing

Most interviewees recognised that occupational ill-health outcomes are sometimes difficult to measure due to their long latency. In particular, the time lag between exposure and outcome combined with the mobility of the workforce in construction makes it hard to link ill-health outcomes with hazards and work exposures. Nevertheless, participants noted the importance of tracking and managing occupational health and wellbeing performance. A contractor HSE Director explained: "*I still think there is a bit of a view that* [health's] *secondary to safety, which is obviously what we're trying to eliminate. If we see good performance in the health bit, it's normally quite a good indicator that an area is taking everything very seriously*."

Four participants indicated their organisations have developed maturity matrices to assess the health performance of their projects. One participant reflected on his experience as the client Head of Health and Safety on a large construction program in the UK and explained that a 'near hit' metric was developed to focus on the potential for ill-health. The metric captured the instances of exposure to health risks. Another client organisation stipulated contractual requirements for fatigue management on their projects, requiring contractors to provide evidence of effective shift management that involves analysing, auditing, and managing fatigue risks.

Mental health was highlighted as a key area requiring attention in construction although participants also identified difficulties in measuring mental health, as workers' experiences are also influenced by factors outside the work environment. Nevertheless, some participants referred to programs that have been implemented in their organisations to promote mental health and wellbeing (e.g., mental health training and mental health champion programs).

7.7 H&S culture

Participants explained that a strong, positive and mature organisational culture is an important precondition for effective H&S performance management. One participant noted: "*… it really depends on how people see the KPIs and the safety, I would say the safety culture and the safety maturity* [affects] *how successful those KPIs can actually be.*"

The culture of an organisation was identified as having a major influence on the way that senior managers understand H&S performance measurement and its role in managing H&S performance. A contractor HSE Leader highlighted the progression of their organisational performance reporting from tracking failure to measuring positive performance: *"…back in the day, it would have all been around TRIFR, LTIFR. It would have been all that data that, would have been in the headlines. Now, our Board report includes that information but it's quite subordinate to the other measures around critical risk, engagement, leadership involvement. It's getting that prominent to have and make sure that, the conversations are based upon that first and foremost.*"

The culture of an organisation was also identified as having an impact on the reliability of H&S reporting, through nurturing the right mindset among the workforce that reporting issues leads to improvement. Some participants commented that there is considerable value in trying to measure aspects of organisational culture that are linked to excellent H&S performance, while admitting that measuring culture is hard. Several participants indicated that they use or have used safety climate/culture surveys at their projects. For example, reflecting on his experience on a large construction program, a UK-based client Head of H&S explained that the use of climate surveys can act as a 'reality check' of leading indicator data reported by contractors: *"… if managers were reporting 'we always treat complaints seriously' and the climate survey said '*[they] *never listen to us', then we would say, 'Look, there's a mismatch here. You are underreporting problems, overreporting how good you are and your climate survey from your own staff, … doesn't bear out what you're self-reporting"*.

The use of the climate data enables workers' perceptions of safety leadership and quality with which safety was being managed to be understood from the perspective of the workforce. In the construction industry, the strong link between safety climate and various aspects of safety performance has also been reported in many studies (see for example, [31]). Importantly, recent studies of safety climate in construction project environments have also found that safety climate changes over the life of a construction project, often in response to project events, time pressures etc. [32]. Undertaking periodic safety climate assessments enables project management teams to understand the positive and negative factors impacting on project safety performance from the perspective of workers and supports early intervention when cultural problems are identified.

8 CONCLUSIONS

The themes identified from the analysis of interviews in this study reflect key aspects of an organisational H&S management system that industry experts identified as important and that should be incorporated into any H&S performance measurement framework. The themes have been collated into 4 components to develop an evidence-informed Health and Safety Performance Index. The components are:

1) Health and Safety Leadership, informed by themes 2, 4 and 7 in Table 1.
2) Risk Management and Governance, informed by themes 1, 3, 4 and 7.
3) Learning and Sharing Lessons, informed by themes 1, 5 and 7.
4) Health and Wellbeing, informed by themes 6 and 7.

Work is underway to refine the specific metrics in each component and develop data collection tools that accompany the Index. The H&S Index is designed to be scalable and flexible, allowing it to be adopted by clients and contractors irrespective of their size. The Index is intended to enable project teams to capture reliable and consistent information about the quality of health and safety and adopt a participatory approach to managing performance in a project environment and provide sustained healthy and safe workplaces. The study relied on interview data from 27 H&S experts from Australia, UK and Hong Kong. Future studies may consider collecting data from a larger sample of experts covering more counties. The study did not look into differences between client and contractor organisations as the study intended to inform the design of H&S index that can be adopted by clients and contractors.

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POST-PANDEMIC WORKFORCE ISSUES IN THE CONSTRUCTION AND TRANSPORTATION WORKFORCE

Sarah Hubbard[1], Joe Sobieralski[2], Bryan Hubbard[3],

[1]Purdue University, School of Aviation and Transportation Technology (USA)
[2]Embry Riddle Aeronautical University, Department of Management and Technology (USA)
[3]Purdue University, School of Construction Management Technology (USA)

Abstract

This research explores employment issues and drug testing for the private construction and public road agencies. Construction companies and road agencies, like numerous other employers, have been faced with increasing difficulties in the hiring and retention of their skilled workforce after the pandemic. A very competitive market for workers in the U.S, changing labor force demographics, and the need for employees with diverse skill sets intensify the workforce challenges. One employment restriction that exists for construction companies is drug testing. The aim of this paper is to investigate potential workforce challenges related to drug testing in the private construction and public local road agency sectors. Drug testing is required to ensure safety, and may be required by law, depending on the job. With the legalization of recreational marijuana (aka cannabis) and medical marijuana in many states within the U.S., marijuana use has become more widespread. Depending on the type of testing, marijuana can be detected from 1 to 90 days after use. This research presents general trends in the construction workforce and presents the results of a survey to determine the most pressing workforce issues, including the impact of drug testing in the construction and public road agency workforce. Although the workforce issues in both the private and public sector have been challenging, there is no evidence based on these survey results to suggest that drug testing requirements have contributed to the workforce challenges.

Keywords: Work Force, Drug Testing, Construction Safety

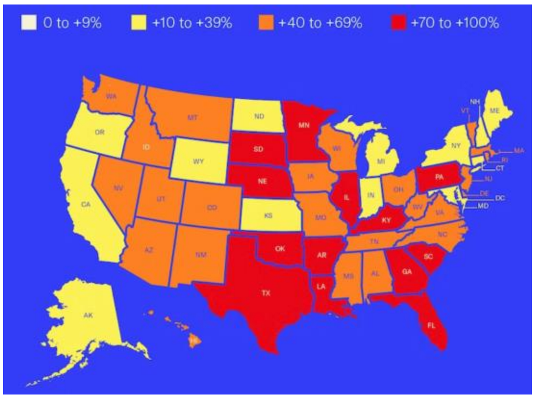
1 INTRODUCTION

The post pandemic era has caused significant disruptions to the entire workforce in the US, and 2021 shattered employment records when 47.4 million people left their job during what has been called "the Great Resignation" [1]. All sectors of the economy have faced labor issues, including the construction and transportation sectors. A key theme of the post-pandemic workforce has been disruption, in fact, the Great Resignation has also been called the Great Reshuffle since hiring rates have outpaced the rate that employees have quit their jobs.

1.1 Workforce Statistics

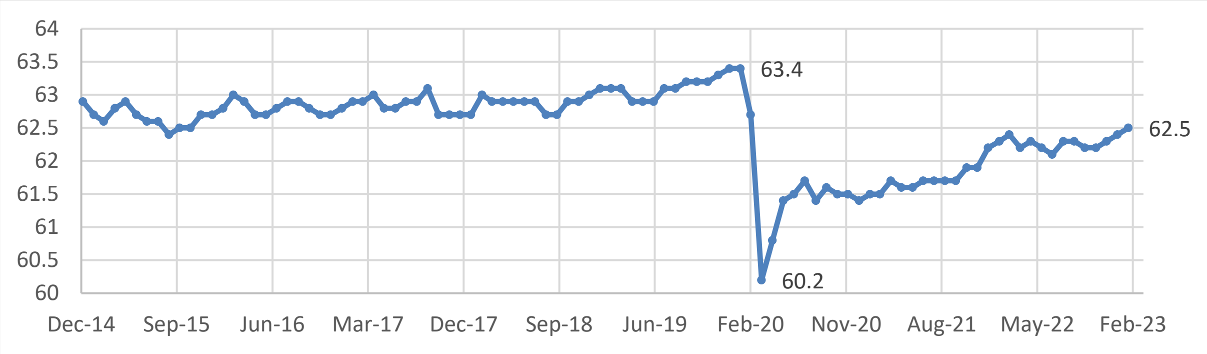
Across the US, there are only 68 workers for each 100 jobs [2], making it difficult for organizations to fill essential positions. While this reflects a robust economy, it also reflects very tight competition for workers. Workforce challenges have been faced throughout the country, as shown in Figure 1.

Figure 1. Percent Increase in Job Openings by State from February 2020 to Feb 2023
Source: [2,3].



Labor force participation is one metric for the national workforce that highlights the number of working age people either working or looking for work. Labor force participation has held fairly steady in recent months and is 62.5% in February 2023, this is significantly greater than the low of 60.2% in April 2020, but the US still has not recovered from the pre-pandemic level of 63.4%, a gap that reflects 2.46 million workers who have left the workforce since February 2020. Workers have left the workforce for a variety of reasons, including early retirements, and a reduced need for household income due to increased unemployment benefits, stimulus payments and child tax credits [2].

Figure 2. Labor Force Participation in Last Decade [3]



Not all jobs have been equally affected by recent changes. Industries least affected by worker shortages, not surprisingly, are those that are compatible with remote work. Construction and public roads work requires on site duties, and is definitely not a remote work kind of task. Additional challenges also exist for workers in the U.S. that require a Commercial Driver's License (CDL) following a rule change for the CDL in February of 2022. These changes made it a much more competitive marketplace when hiring drivers and operators with CDLs. In the construction industry, some firms report that concrete could not be delivered because there were no drivers available. Some firms even started hiring their own drivers and buying their own trucks.

A tighter labor market has been met by increasing salary demands which are evidenced by a wide variety of data. In early 2023, the Association of General Contractors (AGC) reported that average hourly earnings in construction increased 3.2 in 2022, ending at $30.73, which is 10.1% higher than the private-sector employment average of $27.90 [4]. This increase is attributed to labor shortages as evidenced by Department of Labor statistics that indicate that the number of job openings in construction totalled 360,000 in May 2022, which was the highest May total in the 19 years that this metric has been recorded [4].

In addition to an overall competitive market for workers across all sectors, construction also has additional restrictions due to the critical safety considerations. One restriction to hiring workers in the construction industry is the requirement that new employees pass a drug and alcohol test, which is often a condition of employment. Drug testing is common in the U.S. to ensure a safe work environment and may also reduce insurance rates and worker compensation rates. Drug testing is required by law for some positions in the construction industry, including positions that require a CDL.

1.2 Drug Use

A second issue that has occurred is rising drug use and substance abuse. During the first year of the pandemic, more than 99,000 people in the U.S. died due to drug overdose, an almost 30 percent increase from the previous year [5]. Marijuana use has increased 13.2% and hallucinogenic drug use has increased 4.7% from 2011 through 2021 among young adults aged 19 to 30 years old [6]; 43% of young adults reported using marijuana in the last month in 2021. Alcohol remains the most used substance among adults. Sixty-six percent of young adults report alcohol use in the last month; 32% report binge drinking (5+ drinks in a row) and 13% report high-intensity drinking (10+ drinks in a row) in the past two weeks [6].

Given these statistics, it is not surprising that positive tests increased 12% in the construction sector in 2021 compared to 2020 [7]. The rate for positive marijuana tests in construction grew 16% but was still significantly below other industries at 2.9% [7]. Trends for Construction and other sectors are shown in Table 1.

Table 1. Drug Use Trends by Industry Sector

Sector	2017	2018	2019	2020	2021
Accommodation and Food Services	4.6	4.9	5.1	6.2	6.5
Construction	4.1	4.1	4.2	4.1	4.6
Transportation and Warehousing	2.5	3.9	4.0	4.4	5.5
Utilities	2.8	2.9	3.4	3.5	3.7
Public Administration	3.3	3.5	3.3	3.3	3.5

Source: Quest Diagnostics as reported by [7].

Data from Quest Diagnostics based on more than 11 million test results suggests that there are concerns for employers in safety sensitive sectors such as construction. Increased positivity rates and higher rates after accidents raises questions about how employers can best manage issues related to employee health and safety, as well as workforce recruitment and retention [7].

This paper presents the results of a workforce survey of contractors and public road agencies. The objective of this paper is to assess employment challenges and determine how drug testing has affected private construction and public road organizations. Background information, including information about drug-free workforce policies and common practices for drug and alcohol testing in the U.S. construction industry provides a context for the survey results. The results of the survey are presented and discussed, both in the context of the historic challenges and future possible changes to testing procedures.

2 BACKGROUND

2.1 Drug-Free Workforce Policy

A drug-free workforce policy is common in the construction industry in the U.S. to ensure a safe work environment. As part of these policies, construction companies perform drug and alcohol tests on employees to ensure compliance and protect the workforce from safety issues related to substance abuse. Other important components of a drug-free policy include a formal written policy, employee education, supervisor training, and employee assistance programs [8].

There is no general requirement for construction companies to have a drug-free workplace policy, however, U.S. contractors that work on a federal contract over $100,000 are required to have a policy in place under the Drug-free Workplace Act of 1988 [8]. Each state also has their own drug testing laws [9]; these state laws may add requirements but cannot waive the federal mandates. In addition to federal and state laws, the United States Department of Transportation (DOT) and Federal Aviation Administration (FAA) have drug testing requirements to cover CDL operators and pilots, including remote pilots [10]. The CDL testing requirements affect many construction companies and road agencies since the CDL is required for large trucks (transporting materials and plowing snow) and other heavy equipment. Remote pilot requirements related to alcohol and drugs affect construction companies and their subcontractors that use small unmanned aerial systems (sUAS) [11] for job site tasks such as documentation, material management, and inspections.

There are incentives to have a drug-free workplace related to cost of insurance and worker's compensation. Thirteen states reduce worker's compensation rates if you implement a drug-free workplace [12]. Private insurance premiums may also be reduced with a drug-free workforce policy. Even without incentives, construction companies often perform testing as a part of their safety program to reduce risks of accidents related to substance abuse.

Under a drug-free workforce policy, drug and alcohol testing is done for the following circumstances [8]:

1) Pre-Employment,
2) Annual Physical Tests,
3) Reasonable Suspicion Tests,
4) Post-accident Tests,
5) Post-treatment Tests, and
6) Random Tests [8].

Testing a worker when an employer suspects impairment due to drugs or alcohol is called a "Reasonable Suspicion Test" and each state provides guidance on what is considered reasonable suspicion. General guidelines for reasonable suspicion include the following [13]:

- *"An employee was clearly using drugs and displayed physical symptoms such as odd behavior, slurred speech, or uncoordinated movement.*
- *A credible source or co-worker provided a report or proof of an employee using drugs at work.*
- *A worker displays significantly deteriorated work performance or erratic behavior.*
- *There is evidence that a worker possessed, sold, or solicited drugs at work.*
- *An employee contributed to a workplace accident with negligent behavior that could have been caused by drug use.*
- *There is evidence that an employee tampered with the results or specimens of a drug test." [13]*

2.2 Drug and Alcohol Testing

2.2.1 Legal Issues Related to Drug Use in the US

Medical marijuana was first legalized in California in 1996; as of early 2023, 37 states have legalized medical marijuana and 21 states have legalized the recreational use of marijuana [14]. The legalization of marijuana by states contradicts U.S. federal law which outlaws marijuana as a controlled substance. State legalization does not exempt any workers from the requirement for compliance with laws that pertain to workplace drug use and workplace drug testing laws.

The Supremacy Clause of the U.S. Constitution establishes that federal laws take precedence over state laws [15]. From a practical point of view, the discrepancy between federal and state laws currently means that people will not be prosecuted by the state for the recreational use of marijuana in states where it is legal, however, state law does not prevent federal prosecution for violations of federal laws related to controlled substances. Federal prosecutions of individuals possessing small amounts of marijuana are rare, and in 2013 the US Department of Justice (DOJ) announced it would rely on state and local authorities to address marijuana activities through enforcement of their own state regulations [16]. Regardless of state law, marijuana continues to be a Schedule I substance under the Controlled Substances Act of the United States [17]. This status reflects the fact that the US Food and Drug Administration (FDA) has not approved a marketing application for any marijuana product for any clinical medical purposes. Schedule I substances reflect a high potential for abuse, and no currently accepted medical use in treatment in the US, and a lack of accepted safety for use under medical supervision. There are three pharmaceutical products that have Tetrahydrocannabinol (THC), synthetic THC, and Cannabidiol (CBD) ingredients that have been approved by the FDA and are considered Schedule III, II and V drugs under the Controlled Substances Act [18,19].

According to Quest Diagnostics, one of the largest testing labs in the United States, drug positivity test results climbed in 2022 to the highest rate in 20 years [20]. The positivity rate for drug use was 4.6% in 2021, up from an all-time low 3.5% in 2010. The positivity rate for marijuana has also continued to rise in the general workforce. Increasing marijuana rates are attributed to the legalization of marijuana for both medical and recreational use in many states.

2.2.2 Types of Drug Tests

There are many different ways to test for drugs in the human body. The most common methods used for employment screening include urine, blood, and saliva [21]. Urine drug testing is the most common because it is non-invasive and less expensive, however, it cannot determine impairment. Blood testing is more invasive and is typically used for more legal investigations. Saliva testing is non-invasive and is done with a mouth swab. Saliva testing is becoming more popular because of the ease of collection, improvements in testing technology, and lower expense [21]. Hair testing is more expensive but can determine long-term use; it is not commonly used in employment testing.

A major change in drug testing policy is being proposed by the U.S. DOT, which will allow the use of saliva (oral specimen) for DOT drug testing [22]. If the U.S. DOT allows this type of testing, it is expected that private industry will follow and replace urine testing with saliva testing. There are a number of positive benefits for saliva testing as compared to urine testing, including reduced privacy issues when collecting a sample and elimination of the issue of a "shy bladder", aka paruresis, which means it is difficult to urinate around other people (sometimes people may claim shy bladder if they do not wish to participate in drug testing). Saliva testing also provides information on more recent drug use. While drug detection times vary depending on the amount of drugs consumed, urine testing typically has a detection time of 7 days (or longer for chronic users) and saliva testing will detect drug use up to 48 hours [23, 24]. Hair testing has the longest detection time and drugs can be detectable with a hair sample for up to 90 days.

2.2.3 Drug Testing in Private Construction and in Public Road Organizations

Drug testing in construction has become the norm and virtually all large construction companies in the U.S. conduct pre-employment drug testing and have a testing program in place to ensure on-site safety. This has not always been the case. In 1983, less than 1 percent of all employees had drug testing [25]. Drug testing is important in construction not only due to the high-risk environment, but also because there is evidence that drug and alcohol use in the industry is prevalent. One landmark study on drug testing in construction found that companies with drug testing programs had a 51% reduction in incident rates within two years of program implementation [25]. However, as noted by the authors and others (e.g., Sherratt et al [26]), the introduction of a new safety program which may or may not include a drug testing program may result in safety improvements and may be responsible for some of the improvements. Researchers have also raised the issue of a distinction between being impaired on the job versus using drugs on your own time and not being impaired while at work [26]; this may be an issue with current marijuana testing since current urine testing can result in a positive test when marijuana was used anytime within 7 days (or longer). The benefits to a company are reduced if they are losing workers due to a positive drug test when there is no impairment on the jobsite, especially if there is a shortage of skilled workers [26]. This is an area where the saliva testing proposed by the DOT may reduce some of these issues.

3 RESULTS

This section presents the results of a survey that was developed and deployed to better understand the workforce issues faced by construction companies and public sector local agencies, as well as the impact that drug testing has on the workforce. The private sector respondents were professionals in the construction industry participating in a meeting focused on higher education in the construction industry. The public sector respondents were professionals from local public agencies that maintain roads in Indiana, a Midwest state. The sections below highlight the perspective of both the private and public sector. The results reflect over 100 responses, with 36 responses from the private sector and 75 from the public sector. In some cases, respondents did not answer every question.

3.1 Recruitment and Retention of Employees

Survey results confirm that the majority of employers have had challenges recruiting employees, with almost three quarters (74% and 72% for private and public sectors) agreeing with this statement. In response to these challenges, the majority of employers (84% and 64%) have raised salaries or increased benefits to encourage more applicants. The private sector has a greater capability to raise salaries in the short term; many public agencies have a more difficult time raising salaries in the short term since they work on an annual budget and may require approval from elected officials to make salary changes.

Employers in the private sector have worked to support diversity to increase the number of applicants (74%), although fewer in the public sector have focused on this strategy to increase the workforce (33%). Although labor markets are tight, most employers have not lowered their requirements to increase the number of applicants; 14% of private sector employers have lowered employment requirements, and 32% of public sector employers have lowered employment standards. The majority of employers (68% and 55% for private and public sector) have worked to improve culture in an effort to retain employees. Public sector employers have been much harder hit by retention issues; while less than half of private sector employers (40%) report that employees have left for a better position elsewhere, almost three quarters of public sector employers have lost employees to a better position elsewhere (73%). Additional information is provided in Table 1.

There were a variety of strategies by employers that made changes to hiring requirements in an effort to fill job vacancies, as shown in Table 2. The most common strategy was to reduce the requirement for experience, followed by requiring less formal education and fewer skill certifications. In the public sector, a traditional requirement has been the requirement for a CDL, some agencies hired employees without the CDL and planned to work with them to get them this credential. It was much less common for agencies to make changes to the drug testing requirements or to the requirements related to criminal records.

Table 1. Employer Perspective of Workforce Recruitment and Retention Issues

	Private Sector			Public Sector		
	Disagree	Neutral	Agree	Disagree	Neutral	Agree
We have had challenges recruiting employees	11%	17%	**71%**	1%	27%	**72%**
Our employees have left for a better position elsewhere	17%	43%	**40%**	8%	19%	**73%**
We have lowered our requirements to get applicants and new hires	57%	29%	**14%**	32%	36%	**32%**
We have tried to support diversity in recruitment activities to get more applicants	0%	26%	**74%**	11%	56%	**33%**
We have raised salaries or increased benefits to stay competitive	0%	27%	**73%**	18%	18%	**64%**
We have worked to improve our culture to try and retain employees	6%	26%	**68%**	9%	36%	**55%**

Table 2. Changes to Hiring Requirements to Increase Applicant Pool
(1 = change most commonly reported)

	Private Sector Rank	**Public Sector Rank**
Required less experience	1	1
Required less formal education	2 (tie)	3
Required fewer skill certifications	2 (tie)	2
Changed drug testing requirements (e.g., oral swab vs. urine sample)	4	5
Changed requirements related to criminal records	5	4

There are a variety of challenges that agencies face when it comes to their workforce. Table 3 provides the perspective for private sector and public sector agencies regarding current workforce challenges. For both private and public sector agencies, finding people who are willing to work is a significant challenge (71% of private and 68% of public agencies face this challenge). Finding qualified workers is also a significant challenge for both private and public agencies (81% for both private and public agencies). Meeting current wage expectations, retirements (sometimes accelerated by the pandemic) and the integration of younger workers are greater challenges for the public sector than the private sector. Workers going to other sectors and to competitors was an issue for both private and public agencies, although public agencies had greater challenges with these issues, which are likely exacerbated by the challenges public agencies have keeping up with current wage requirements. Government policies were a challenge for some agencies (more so for public agencies), but were not the most significant challenge.

Table 3. Employer Perspective on Current Workforce Challenges

	Private Sector			**Public Sector**		
	Disagree	**Neutral**	**Agree**	**Disagree**	**Neutral**	**Agree**
Finding people who are willing to work	6%	26%	**68%**	3%	11%	**86%**
Finding people who are qualified to work	0%	19%	**81%**	1%	17%	**81%**
Meeting current wage expectations	3%	58%	**39%**	1%	16%	**83%**
Challenges integrating younger workers	19%	42%	**39%**	7%	57%	**50%**
Retirements	35%	35%	**29%**	7%	31%	**62%**
Workers going to competitors	6%	42%	**52%**	13%	30%	**57%**
Workers going to other sectors	26%	52%	**23%**	6%	27%	**67%**
Government policies	65%	29%	**6%**	10%	57%	**33%**

Respondents were asked to rank the factors that are most important when employees leave an organization, as shown in Table 4. The results indicate that the number one reason employees leave is salary, followed by advancement opportunities, better work life balance, and better benefits. Opportunities for remote work has received a lot of attention in the media, however it was ranked 5th out of the 6 choices, suggesting this may not be as critical for employees currently in the construction sector. This may be reflect the fact that many jobs in the construction sector are "in person" jobs, and employees would have to change employment sectors in order to work remotely. Despite conventional wisdom that suggests that culture fit is an important aspect of employee retention [36], responses in this survey indicate it is much less important than the other factors considers.

Table 4. Reasons Employees Leave an Organization (1 = most commonly cited)

	Private Sector Rank	Public Sector Rank
Higher Salary	1	1
Advancement Opportunities	2	3
Better Work Life Balance	3	6
Better Benefits	4	2
Opportunity for Remote Work	5	5
Culture that is a Better Fit	6	4

Drug testing requirements are common in the construction industry and in local public agencies that maintain roadways; these requirements ensure worker safety and are required for workers that have a CDL. All of the public sector respondents are in Indiana, where recreational marijuana is not legal; however, recreational marijuana is legal in the border states of Michigan and Illinois (north and west of Indiana).

Drug testing is a de facto industry standard in both private and public sectors, as indicated reflected by the fact that almost all of the survey respondents use drug testing (93% for private agencies and 96% for public agencies) and conduct drug testing after an accident (93% for private agencies and 88% for public agencies) as shown in Table 5. This exceeds the prevalence of drug testing in the US, with the 2022 Employer Drug Testing Survey reporting that 87% of respondents conduct pre-employment testing and 70% of respondents conduct post-accident testing [37].

Table 5. Drug Testing Practices and Organizational Impacts

	Private Sector		Public Sector	
	Disagree	**Agree**	**Disagree**	**Agree**
Recreational marijuana is legal in our state or states where we work	55%	45%	100%[1]	0%[1]
We use drug testing	7%	93%	4%	96%
We test after an accident	7%	93%	12%	88%
We use impairment signals	31%	69%	23%	77%
In general, positive drug tests have increased in the last year or two	83%*	17%*	94%	6%
When hiring, our drug testing policy is a competitive disadvantage	96%	4%	84%	16%

[1]Recreational marijuana is not legal in the State of Indiana, where the survey of public agencies took place, so this question was not included on the survey; the responses are included in the table to support comprehension of the surveyed population and a comparison.

Less common is the use of impairment signals on the job to access drug and alcohol use (69% and 77% for private and public agencies, respectively). There may be less need for the use of impairment signals, given the standard practice for drug testing and testing after an accident; moreover, agencies may not report the use of impairment signals if they have not had this as a trigger for a required drug test. The majority (83% and 94% for private and public agencies) disagreed with the fact that positive drug tests have increased in the last year or two; this is contrary to national trends, such as reports from the 2022

National Employer Drug Testing Survey that reported that 30% of employers report they have experienced an overall increase in positive drug tests in 2022 compared to 2021 [37]. The majority of employers (96% and 84%) do not believe that drug testing puts them at a competitive disadvantage, which can be presumably be attributed to the fact that the majority of private sector construction companies and public sector transportation agencies conduct drug tests.

4 CONCLUSION

Overall, after the pandemic both private sector construction companies and public sector local road agencies have had a difficult time maintaining their workforce. Challenges have included both retention and recruitment of new workers. Public sector employers have had a more difficult time keeping up with the increasing salary demands.

Although the workforce issues in both the private and public sector have been challenging, there is no evidence based on these survey results to suggest that drug testing requirements have contributed to the workforce challenges. Use of drug testing will continue to be an important practice to ensure safety for workers and the public in the construction and roadway sectors. Although industry has used the same testing practices for many years (i.e., urine tests), saliva tests are expected to become increasing common due to the ease of sample collection and the ability to capture recent drug activity. Advancing technologies for drug testing may allow more timely assessment of the worker's fitness for duty during the work hours of interest.

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THE IMPACTS OF WORKERS' AGING ON HEALTH AND SAFETY CONDITIONS IN THE CONSTRUCTION SECTOR IN BRAZIL

Rosana Leal Simões de Freitas[1], Elaine Pinto Varela Alberte[2]

[1] *Universidade do Estado da Bahia (BRAZIL)*
[2] *Universidade Federal da Bahia (BRAZIL)*

Abstract

The construction sector in Brazil is resistant to hiring workers over 60 years of age, justified by the possible reduction in performance due to advanced age. In this age group, the population tends to have some chronic diseases, such as hypertension, diabetes, and arthrosis, and physical losses associated with advancing age, such as presbycusis and presbyopia. In addition, workers in this age group tend to increase the costs of medical control required by law. This difficulty in hiring contributes to the migration of these professionals, aged over 60, to the informal market, where health and safety conditions are more unfavorable, thus contributing to the development of injuries, occupational diseases, and the worsening of pre-existing diseases, as well as deaths due to accidents at work. Based on an integrative literature review, this explorative study aims to analyze the consequences of aging in Brazilian construction workers related to health and safety conditions in the sector. From the results, it was possible to identify an overview of potential impacts on the health and safety conditions of the sector produced by the forced migration of elderly workers in the informal context. Also, the study discusses raising workers' retirement age due to the social security reform in Brazil, approved in 2019, requiring construction workers to remain in the formal market and to contribute to social security.

Keywords: health, safety, construction, aging, retirement.

1 INTRODUCTION

The aging process, a natural consequence expected in life, is a great challenge for those who experience it and those responsible for ensuring the workforce in a scenario focused on productivity and financial gains [1]. According to Fortuny [2], the population's aging should be considered an achievement of society. However, this demographic phenomenon also represents an increasingly important political, economic, and social challenge for developed and developing countries like Brazil. According to data from the Electronic Information System - SEI [3], Brazil presented an aging index (ratio between the extreme age components of the population, people aged 65 years or more, and those aged less than 15 years) with a variation of 159% (139% of the male population and 177% of the female population) between 1980 and 2010. And according to Miranda, Mendes & Silva [4], it is expected that in 2040, 23,8% of the Brazilian population will be represented by the elderly, establishing a ratio of 153 older people for every 100 young people and producing the need for physical adaptations, political, economic, and social adjustments regarding aging populational.

In this context, the construction industry scenario stands out, recognized for its strong potential to generate jobs and boost the economy. Recent data from the Inter-Union Department of Statistics and Socioeconomic Studies – DIEESE [5] confirm that the profile of the construction worker in Brazil corresponds to a young man with low education working in informal conditions. According to the institution, men are about 90% of the workforce in the construction sector. Approximately only 18% are over 50 years of age, about 45% have less education than expected for a 12-year-old individual, and only about 14% have more than five years in the profession with formal employment. Regarding the age group of those employed (both sexes), most are between 30 and 49 (about 55%).

Contrasting the projections presented with the expansion of the elderly population and the profile of construction workers, the implementation of anticipatory actions aimed at sustaining the social security system, and adjustments in hiring processes.

On the one hand, there is a need to increase the population's productive life expectancy and create attractions for maintaining the 60-plus age group in the formal market. In the quest to guarantee the remuneration of the retired public and those about to retire, changes in the social security legislation

(Constitutional Amendment No. 103 [6]) require a more extended period of contribution to Social Security, making the formal employment relationship, which establishes the compulsory payment. On the other hand, the current safety legislation (Ordinance SST MTP No. 567 [7]) expands the follow-up actions of health conditions with the evolution of age, making it more expensive to maintain workers in this age group in the list of contractors, making them less economically interesting for job-generating companies.

Based on an integrative literature review, this explorative study aims to analyze the consequences of aging in Brazilian construction workers related to health and safety conditions in the sector.

It is essential to highlight that the construction workers analyzed in this study are blue-collar workers who perform activities directly linked to the production process that requires physical effort, such as carpenters, plumbers, bricklayers, painters, electricians, and servants). The study did not analyze bureaucratic, administrative, and management workers (white-collar workers).

The research seeks to answer the following question: How do the regulatory context and the forced migration of older workers to the informal environment influence health and safety conditions in the Brazilian construction sector?

Two underpinning objectives have been designed to achieve the aim, namely, (a) identify a broad and diverse literature of research related to the subject, gathering knowledge both in the historical and general scope of aging studies, as well as in the more specific context on the aging of construction workers, and its influence on the contracting process, and (b) perform an integrated and systematized analysis of evidence collected in the selected literature and in the context of Brazilian laws and regulations related to the subject.

2 THE AGING OF THE WORKING POPULATION: REGULATORY ASPECTS AND OVERVIEW OF THE CONSTRUCTION SECTOR

The Brazilian normative panorama presents a set of laws and norms that seek to support and protect the population in labor activity and advanced age. Moreover, this legislation has been systematically improved, seeking to guarantee the best conditions for the work environment and workers' quality of life (Table 1).

Table 1 - Legislation associated with workers' health, safety, and guarantees.

#	Law or norm	Year	Subject
L1	Law nº 6.514 [8]	1977	To amend Chapter V of Title II of the CLT, related to occupational safety and medicine, and other measures
L2	Decree nº 3.214 [9]	1978	To approve the Regulatory Norms (RN), related to occupational safety and medicine.
L3	Decree WHS nº 24 [10]	1994	To approve the text of Regulatory Norm RN-7 – Medical exams
L4	Law nº 10.741 [11]	2003	To provide for the status of the elderly and makes other provisions
L5	Complementary law nº128 [12]	2008	To regulate the forms of registration and classification of the individual micro-entrepreneur - IME
L6	Constitutional amendment nº 103 [6]	2019	To amend the Social Security System and establishes transitional rules and transitional provisions
L7	Decree SSSSL nº 6.734 [13]	2020	To approve the new wording of RN-7 PMCOH (Program for Medical Control of Occupational Health)
L8	Decree WHS nº 567 [7]	2022	To change the RN-7 PMCOH (Program for Medical Control of Occupational Health)

The guarantee of the rights of the elderly population in Brazil was recognized and legalized through Law no. 10.741 (approved in 2003), called the Statute of the Elderly (L4). The law makes clear the illegality of discriminatory behavior by society and the employer concerning the age group of the worker. In addition, the legislation establishes the need for the Public Power to support private companies in guaranteeing the employability of the elderly [11].

Law no. 6.514 (approved in 1977) (L1), in turn, requires specific monitoring of workers' health, regardless of age group. The law indicates the mandatory medical examination on behalf of the employer, upon admission, upon dismissal, and periodically. Complementary exams may be required, at the physician's discretion, to determine the employee's physical and mental capacity or aptitude for the function they must perform [8].

In 1978, Decree No. 3.214 (L2) approved the creation of Regulatory Norms - RN, changing Chapter V, Title II, of the Consolidation of Labor Laws (CLT), related to Safety and Occupational Medicine, establishing the denomination RN-7 Medical examinations, for specific matters related to the control of workers' health [9].

The successive changes that took place from 1983 onwards adjusted the standard, initially restricted to the requirement of medical examinations, expanding its scope and action, thus becoming known as RN -7 PMCOH (Program for Medical Control of Occupational Health) through the Decree WHS nº 24, approved in 1994 (L3) [10]. The last revision of this RN carried out through Decree WHS nº 567, in 2022 (L8), currently in force, makes it clear in the item directed to the guidelines the responsibility, through the PMCOH coordinating physician, to monitor the health of the associated worker to the work environment [7].

However, Ramadan [14] warns that the PMCOH should not be restricted to managing occupational risks, focusing only on work-related diseases, but should include planned actions with a preventive nature for others unrelated to work, inappropriately referred to as "non-occupational" illnesses.

The monitoring of the worker's health, with a formal contract, through periodic examinations, is defined in requirement 7.5.8 of RN-7 (L8) [7]. It establishes that the frequency of monitoring must be reduced to one year, or for shorter intervals, at the discretion of the coordinating physician responsible for the PMCOH, for those with chronic diseases which increase susceptibility to occupational risks defined in the Risk Management Program. The other employees must present biennial follow-ups. This legal determination implies the need to closely monitor the elderly with chronic diseases resulting from aging biological systems, such as presbycusis, presbyopia, and musculoskeletal wear. It is important to note that the inadequate working conditions aggravated many of these health conditions that, for safety reasons, make the professional performance of these workers impossible.

In 2008, in turn, Complementary Law Nº 128 (L5) [12] was approved, which regulates the forms of registration and classification of the individual micro-entrepreneur - IME, allowing workers to act on their own, without formalizing the portfolio signed, contributing with the reduced percentage to social security (5% of the value of the national minimum wage), guaranteeing the right to old-age or disability retirement, illness or maternity aid, and ensuring the family's right to a pension in the event of death. It allows various professional categories to act as autonomous, legally, including those who work in construction, such as bricklayers, painters, plumbers, carpenters, and electricians.

And in this context, it is essential to note the data from 2013 presented by Cantisani & Castelo [15], which indicate that most construction workers (about 56%) are in informal conditions (acting on their own as self-employed or without registration in the work card).

Furthermore, at the end of 2019, new rules for retirement through the National Institute of Social Security were approved through Constitutional Amendment No. 103 (L6) [6]. It established that from 2023 all female and male workers should be 62 and 65 years old minimum, respectively, to be entitled to the social security benefit [16]. It established transition rules considering the number of points adding contribution time and the worker's age, creating difficulties in anticipating access to the benefit. The changes presented are justified based on considerations associated with the increase in life expectancy of Brazilians, established in the year 2022 to 77 years, based on the calculation of the Complete Mortality Table for 2021 [17]. Considering this scenario, construction workers who do not have a special regime associated with working conditions (dangerous or unhealthy) will only be entitled to receive the social security benefit when they have reached the minimum age established by law. It will not be possible to anticipate retirement associated with contribution time.

However, Sofal [18] states that if there is no change in the sector's mentality, no restructuring will work, as it alerts the prejudiced view of the "tool worker" in which physical vitality, effort, and machine continuity are sought. Aggravating this scenario, Martinez [19] draws attention to functional aging, which corresponds to the progressive impairment of workability, which may occur early, anticipating chronological aging. This situation concerns the worker's performance, with variations in abilities and functionalities, individually among people of different age groups throughout the individual's life. This phenomenon mainly comprises the decline in cognitive and physical skills (musculoskeletal, cardiovascular, and sensory systems). It is a complex multifactorial dynamic, determined by the characteristics of the workers, the conditions and organization of work, and factors in the family and social environment.

Neri [20] points out that professional development actions in organizations prioritize younger workers, noting that companies tend to exclude workers over 40 from training processes, claiming financial reasons since the investment does not show a return relating it to learning difficulties in the more mature phase of life. Mota [21], when analyzing the impacts of aging on men (the predominant actors in the construction sector), states that traits of discouragement, pessimism, and bitter humor in old age are not a rare condition since their servitude (meaning utility condition) was related to work. Thus, with no prospect of work and involvement in discriminatory actions related to aging, they are unable to renew life projects. Even though public policies established the right to work for the elderly, IPEA studies [22] show the growing perspective in Brazil on the performance of construction professionals in informality, failing to enjoy many rights recognized in practice, increasing the risk of illness and withdrawal from the labor market [23].

3 METHOD

The present research has an exploratory character and was developed in two stages: Identification of the literature (Step 1) and Systematic analysis of the content (Step 2). The first stage consisted of a bibliographic review to identify literature related to the theme. The study adopted Science Direct, Scopus, Scielo, Pubmed, and Google Scholar as search platforms. It used the following keywords: civil construction, construction site, elderly, aging, worker, formal worker, informal worker, presbycusis, presbyopia, hypertension, and arthrosis. Initially, the authors combined the words to search for texts associated with the study proposal's specificity. However, due to the scarcity of results, the keywords started to be used separately, thus expanding the possibility of accesses related to the theme. To support this search, the study analyzed books on longevity, work in old age, and worker health and safety.

At first, nine national and international works related to the study of aging associated with the formal or informal labor market were identified. However, among the related studies, only two focused on construction workers. Thus, the study identified the need to expand research on the construction market's behavior associated with the workers' socioeconomic profile. The new search sought to determine the perception of the aging process in construction and the effects of this process on the conditions for hiring professionals and/or on health and safety conditions in the sector. In this phase, the study identified eight more publications. The papers were grouped and coded according to the focus of each research, and their content was analyzed in an integrated manner. Table 2 presents the articles grouped in the AWE category - Aging and the Work Environment, while Table 3 presents the articles grouped in the HSW category - Health and Security at Work.

The second stage consisted of an integrated and systematized analysis of the evidence collected in the selected studies with the content of Brazilian standards that focus on aging issues in work environments in the Construction sector (Table 1). The legislation in Brazil about the elderly population was used as support, and the social security regulations and norms related to health and safety at work were analyzed.

Table 2 – Research related to Aging and the Work Environment (AWE)

Code	Objective	Methodology	Year	Sample
AWE 01 [24]	To know the meaning of the aging process in the labor market for seniors	Interviews	2010	6 (individuals)
AWE 02 [25]	To analyze aging in Brazil and its consequences on the labor market	Literature review	2014	NI
AWE 03 [26]	To analyze the occupational trajectories of retirees in informal construction work	Interviews	2014	20 (individuals)
AWE 04 [27]	To investigate the factors that influence the permanence of older people in work activities	Interviews	2016	121 (individuals)
AWE 05 [28]	To evaluate the contribution of the elderly to the labor market and related public policies	Literature review	2016	29 (researchs)
AWE 06 [29]	To know and analyze the relationship between aging and work	Interviews	2017	16 (individuals)
AWE 07 [30]	To analyze remaining in labor with socio demographic, clinical, and satisfaction factors	Qualitative analysis	2018	626 (individuals)
AWE 08 [31]	To analyze the labor market for the elderly and situations of violence faced by them	Literature review	2021	19 (researchs)
AWE 09 [23]	To discuss the relationship between old age, work, and workers' health in Brazil	Integrative literature review	2020	8 (researchs)

Table 3 – Research related to Health and Security at Work - HSW

Code	Objective	Methodology	Year	Sample
HSW 01 [32]	To study permanent disabling accidents construction sector	Interview / qualitative analysis	2003	6 (individuals)
HSW 02 [33]	To analyze the occupational and health profile of construction workers	NI	2004	287 (individuals)
HSW 03 [34]	To outline the construction workers' profile	Interview / Survey	2007	145 (individuals)
HSW 04 [35]	To analyze the informality of labor and health risks among injured workers	Interview / qualitative analysis	2008	17 (individuals)
HSW 05 [36]	To explore the body mass index (BMI) of workers at a construction company	Quantitative analysis	2012	376 (individuals)
HSW 06 [37]	To study the permanence of older people in the labor market	Case study	2021	5297 (individuals)
HSW 07 [38]	To identify risk factors of coronary artery disease in construction workers	Quantitative and qualitative analysis	2017	50 (individuals)
HSW 08 [39]	To understand the representations of work among informal construction workers	Case study	2008	8 (individuals)

The study used quantitative and qualitative research as sources of evidence. And the evidence was collected from reading the selected publications' content. The study systematized and categorized the evidence with the support of multicriteria analysis matrices, where it was possible to identify trends quantitatively and qualitatively.

4 RESULTS AND DISCUSSION

Content analysis of the selected bibliographies allowed the clustering of the evidence into six categories related to the subject of this study, namely:

- Aging and society: categorize the studies and evidence related to the aging of workers and their relationship with society, regardless of the area of activity.
- Informality: it groups studies and evidence associated with the hiring process and informal labor.
- Quality of life: it categorizes studies and evidence highlighting the well-being, socialization, activity, and satisfaction of active or inactive elderly workers.
- Economic need: it classifies the studies and evidence associated with the needs and financial difficulties of active or inactive elderly workers.
- Migration: it groups studies and evidence that address the displacement of workers to different segments of their original work or informal occupation.
- Health: it categorizes studies and evidence associated with the health conditions of active or inactive workers related to work safety conditions and aging.

The integrated analysis of evidence highlights the need to broaden discussions about the aging process associated with work activity (Fig. 1). Several studies highlight the performance of professionals in the informal condition associated with aging when social benefits cease to exist. Evidence was identified both within broader studies (AWE 02 [25], AWE 06 [29], AWE 07 [30], AWE 08 [31]) and studies related to the construction sector (HSW 01 [32], HSW 02 [33], HSW 03 [34], HSW 04 [35] and HSW 08 [39]).

There is a need to deepen studies related to the socioeconomic behavior of the elderly population, not yet classified as elderly but who do not present themselves as attractive in the face of formal hiring processes, given the increase in life expectancy and changes in Brazilian legislation, postponing the minimum retirement age. This reflection is confirmed by AWE 01 [24] when it identified that some data consider unemployed older people as inactive ones from a socioeconomic perspective, not establishing the unemployed title for this population. This statement is also corroborated by AWE 05 [28] when it warns of the need for broad discussion to reduce vulnerability, discrimination, and social exclusion.

Fig. 2 presents the association of the impacts identified in the health and safety conditions of the construction sector produced by the aging of workers, with the evidence presented in the researched studies. Impacts associated with safety result from the combination of evidence that reinforces the classification of this activity as one of the most dangerous in the world, leading to the rates of fatal and non-fatal accidents and years of life lost, as stated in HSW03 [34]. The absorption of labor represented by the poorest sections of the population, with a lower level of education, and the characteristic of high labor turnover are evidence that impact on the migration of workers to informality. Finally, the development and worsening of chronic diseases are often related to the high rate of unhealthy habits among workers in the sector, such as smoking, alcoholism, and unbalanced diet, as presented in HSW06 [37].

Variables

Variables: HEALTH AND SECURITY AT WORK (HSW)	AGEING AND THE WORK ENVIRONMENT (AWE): Ageing and society	Informality	Quality of life	Economic need	Workers migration	Healthy
Ageing and society		01, 02, 04, 05, 07, 08	01, 03, 05, 07	03, 04, 07	03, 07, 08, 09	05, 07, 08, 09
Informality	02, 04, 08		01, 04, 07	04, 07	02, 07, 08	05, 07, 08
Quality of life	02, 03, 05	02, 03		03, 07	02, 07	05, 07
Economic need	08	08	-		02, 07	07, 08
Workers migration	02, 03, 08	08	01, 02, 03, 08	08		07, 08
Healthy	02, 03, 05, 06, 07	02	02, 03	-	02, 03	

Quantity of studies: High – Low

Figure 1 - Interrelationship of the analysis variables shown in the selected bibliography.

Evidences

Impacts	EVD01 Worker impoverishment	EVD02 Workers' health condition	EVD03 Low appreciation of the elderly worker	EVD04 Low education as an element of exclusion	EVD05 Precarious working conditions	L1	L2	L3	L4	L5	L6	L7
Migration of workers to informality, or self-employment	AWE 01,02, 03, 04, 06,07, 08, 09	AWE 01,05, 07	AWE 01,05, 06, 07, 08	AWE 02,03,05,07	AWE 01, 02,03					•	•	
	HSW 01,02,04,06	HSW 01, 05	HSW 02, 03,	HSW 02,04,07	HSW 01,02							
Worsening of chronic diseases	-	AWE 07	-	-	AWE 02, 08	•	•	•				•
	HSW 02, 05, 07	HSW 03, 05, 07	-	HSW 05, 07	HSW 03, 05							
Expansion and aggravation of disabling accidents	AWE 08, 09	AWE 08	AWE 08, 09	-	AWE 08					•		•
	HSW 01, 02	HSW 01, 02	-	-	HSW 02, 03							
Increased incidence of musculoskeletal disorders associated with inadequate working conditions	-	-	-	-	AWE 08	•	•	•				•
	HSW 02,07	HSW 02,03, 07	-	-	HSW 02, 03, 07							

Quantity of studies: High – Low (AWE)
Quantity of studies: High – Low (HSW)

Figure 2 - Impacts identified according to the evidence collected and related regulations.

Observing the legislative panorama, it is noted that the change in L1 [8] in 1977 was the first step to establishing contractors' responsibilities for workers' health and safety. Through the Regulatory Norms, created in 1978 and systematically expanded and revised, an attempt was made to control and hold accountable those who did not guarantee the well-being of contracted workers. However, the legislative adaptations (L5 [12]), aiming to minimize the social and economic losses resulting from informality, are unable to exterminate deviations and do not eliminate the evidence of the impoverishment of older workers, who were unable to have guaranteed social benefits throughout working life, and who need to remain active in the labor market, exceeding the limit of 60 years, as determined in L6 [6].

Thus, workers' health is compromised by the high physical demand and ergonomic stress that contribute to the high prevalence of musculoskeletal symptoms (HSW 02 [33] and HSW 03 [34]). Such symptoms tend to worsen with body aging (AWE06 [29] and AWE07 [30]), which contributes to the migration of workers to informality, as they are no longer interesting for formal contractors, focused on increasing productivity (AWE08 [31]).

Although the average age of construction workers nationwide is 38.5 years [15], the research identifies the permanence of older people in this activity. The need to remain active in the labor market for those of advanced age can be justified by several elements, among them the growing number of families dependent on the income of the elderly, who, in the role of leading provider, delay the retirement process or return to activity employment, often informally, to reinforce the domestic budget [30]. This practice may also be related to the desire to escape the stigma of unproductivity since society assumes that advancing age restricts working ability [29]. The behavior of managers, negatively stereotyping those who are no longer young as unproductive and disabled, harms this age group in terms of job maintenance and job opportunities [31]. Evidence EVD 01, EVD 03, and EVD 04 (Fig. 2) contribute to the impact of the migration of workers to informality.

However, evidence of the impoverishment of workers with low education that are pushed into the informal market and evidence of the precariousness of working conditions negatively impact the worker's living conditions, contributing to the process of illness, including because of accidents, which are often disabling, at work, as stated by HSW04 [35] and HSW08 [39].

Furthermore, HSW07 [38] outlines projections for construction workers in the productive phase, indicating an unfavorable outcome related to the aging of human body systems associated with an unhealthy lifestyle and the lack of practices to prevent chronic diseases. This scenario tends to become unavoidable for workers who have yet to develop their work activity in companies that comply with labor legislation, especially the Regulatory Norms, and who do not effectively implement the PMCOH, as determined in L7 [13]. In these cases, chronic diseases tend to arise and worsen with aging, such as systemic arterial hypertension, coronary artery disease, or diabetes. And these diseases often develop silently, not being diagnosed during medical examinations related to hiring, permanence, and termination of work activities (HSW05 [36]). In addition, workers over 50 recognize the decrease in aerobic capacity, strength, flexibility, and agility when more physically demanding [29].

Finally, the decline in the worker's health can be monitored and controlled for those formally hired, not only through compliance with legislation through the PMCOH, as per L7 [13], but through legal provisions associated with a balanced diet, which favor the control of BMI (Body Mass Index). Research carried out by HSW05 [36] in a sample of 446 Brazilian construction workers, aged between 20 and 59 years (individuals not classified as elderly), indicates that a good part was overweight or obese (39,6%), a worrying situation since high BMI indices contribute to about 58% of cases of diabetes, 21% of ischemic heart diseases and between 8% and 42% of certain types of cancer [36].].

Fig.3 presents a diagram of relationships between evidence and impacts. The evidence and impacts are related and feedback on each other. The workers' low education contributes to exposure to precarious working conditions, resulting in their impoverishment and making access to adequate health conditions difficult. This scenario influences the low valuation of the workers since they will probably have their performance compromised by physical limitations. In turn, it is possible to associate the low valuation of the elderly worker with situations that will negatively contribute to health conditions, favoring impoverishment and making them subject to precarious working conditions, hindering the professional and educational evolution of the individual.

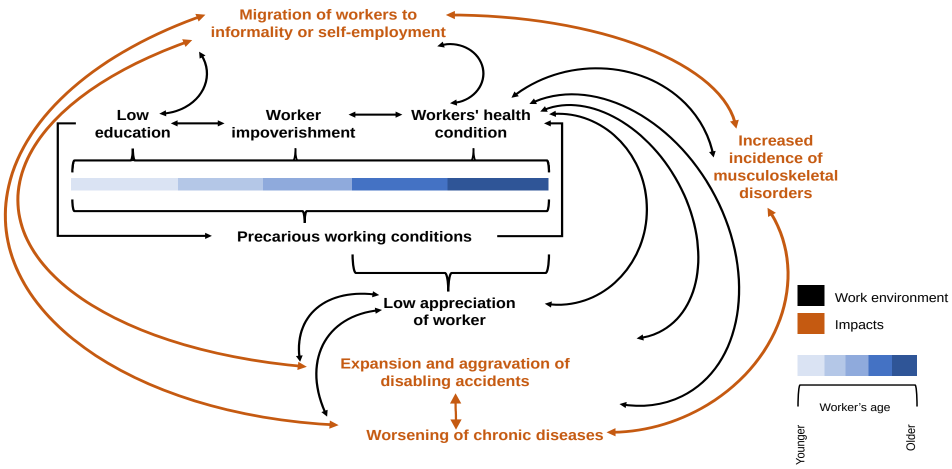

Figure 3 - Diagram of relationships between evidence and impacts

Among the impacts, it is possible to associate the worsening of chronic diseases with the expansion and worsening of accidents at work. The sector forces workers who have compromised health and suffered severe or disabling accidents to migrate to informality. These workers tend to present more musculoskeletal diseases since, in this scenario, there is no compliance with legal determinations associated with health and safety. Finally, musculoskeletal disorders make it difficult for construction workers to remain formal. So, to stay active, workers migrate to the informal sector, which favors the occurrence and aggravation of accidents at work, and the worsening of health conditions associated with chronic diseases. In this way, the evidence and impacts fuel a vicious circle, which tends to become more complex and robust over time and with the aging of workers, weakening and impoverishing them.

5 CONCLUSIONS

The works that guided this study show the need to broaden the discussion about the aging process and work activity. When evaluating the scenarios associated with the construction segment, one observes the exclusion of those who, despite having extensive experience in developing services, do not represent an attractive workforce.

The updating of social security legislation makes it impossible to anticipate the retirement process (which would guarantee income), even for those who started working at a young age, forcing workers, considered by contractors to be old, to seek survival and maintenance of families dependent on remuneration, migrating to informality, where exposure to the risks of accidents and illness is preponderant, accelerating the impairment of the physical conditions inherent to the aging process.

Evidence of the scenario experienced by construction workers with age (impoverishment, decline in health conditions, low market value, low education, and precariousness of the work environment) generate impacts such as the migration of workers to informality, the worsening of chronic diseases, the increase in the number and the worsening of accidents at work, and the increase in musculoskeletal diseases.

This study raises new questions regarding the future of construction in Brazil, recognized for generating many labor market vacancies and presenting a slow mechanization and technological development process. There is a need for adjustments in the organization of work to (1) attract young entrants, who may not show interest in the current scenario, (2) adequately value and maintain workers who are no longer classified as young people and who need to remain active and healthy, despite often already have compromised health, often because of accidents related to working conditions, and (3) break the vicious circle identified in the sector associated with low education, an unhealthy environment with high risks, and informality (which favors impoverishment), transforming it into a vicious circle guaranteeing the dignity of construction workers in all stages of their lives.

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EVALUATION OF TASK CHARACTERISTICS AFFECTING WORKER MENTAL WORKLOAD USING MIXED METHODS

Abdulaziz Alotaibi[1,2], John Gambatese[1], Wei-Hsuen Lee[1]

[1] *School of Civil and Construction Engineering, Oregon State University, Corvallis, USA*
[2] *Department of Civil Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah, Saudi Arabia*

Abstract

Worker performance with respect to safety and quality is influenced by the surrounding environment and task operations, the mental workload felt by the worker, and characteristics related to worker physiology. Previous studies have identified personal factors that affect a worker's mental workload, such as anxiety, stress, and depression. However, further investigation is needed to determine if task-related characteristics associated with task performance, work operations, and the surrounding environment influence construction worker mental workload as well. Therefore, the present study was conducted to investigate and evaluate task characteristics that can significantly influence the mental workload that workers face while performing construction tasks. A mixed-methods approach involving a combination of semi-structured interviews and field observations was used for data collection for the study. A total of 95 construction worker interviews were conducted and 11 crew observations of different construction trades on multiple projects in the US Pacific Northwest were performed to determine if there is a relationship between task characteristics and worker mental workload on typical construction sites. The study revealed that the mental workload of construction workers is significantly affected by various task constituents as workers perform activities, such as tasks that involve distraction, frequent interruptions, and repetitiveness. The contributions and outcomes of this study intend to assist construction specialists in determining the extent to which task-related worker mental workload is an issue present during operations and whether there is potential impact on worker safety and work quality.

Keywords: Construction workers, Mental workload, Task demand.

1 INTRODUCTION

The overall performance of construction projects has stagnated in recent years and safety performance plateaued [1]. According to the U.S. Bureau of Labor Statistics [2], the annual number of fatalities in the construction industry has gradually increased in the last decade. Due to the nature the construction industry's work processes and the varying roles different workers play, key performance indicators .e.g., safety and quality) can be very challenging to manage and implement effectively since the construction industry relies heavily on the involvement of workers and human interaction in the operations and work processes [3,4]. Therefore, most injuries and incidents on construction sites are caused by human error and erroneous behavior [5,6]. Given the human-centered nature of the construction industry, to improve safety and quality performance it is crucial to comprehend how the interaction between various task variables and worker mental states affects worker performance.

When comparing the construction industry to other industries in terms of safety, construction safety research and practice are frequently insufficient; as a result, there are more fatality incidents in the construction sector due to human factors such as unsafe behaviors [7,8]. One reason for this discrepancy is that construction workers are exposed to high levels of psychological hazards (e.g., cognitive demand, work under load, and safety concerns) because the profession traditionally requires demanding labor and hard work under pressure [9]. The main difference between construction and other industries is how many trades and multi-tasks are involved in a construction project, which could disturb quality, worker safety, and general well-being [10,11]. For example, the construction industry usually requires a wide range of skilled workers and crews. However, a lack of familiarity with or distractions while performing construction tasks creates additional concerns about worker safety and work quality. Likewise, work overload and mental workload have been regarded as contributing factors to incidents in occupational safety and construction engineering research, which results in increased incidents [12]. Hence, many construction workers experience excessive mental workload (MWL), which can increase error rates and lead to unsafe actions and irrational decisions resulting in injuries/fatality incidents and poor quality.

The construction industry is a significant source of labor globally and it's widely known that workers in this industry sector have high levels of stress and pressure [13]. Construction workers also experience high-stress levels due to the dynamic nature of construction and the work environment on construction sites. Numerous studies have shown that stress and mental workload (MWL) can increase the risk of incidents and quality defects [14]. MWL can also affect the cognitive performance of construction workers and can decrease their ability to identify potential risks within the work environment while performing tasks [15]. Work at height, working adjacent live electrical systems, and ironwork (steel erection) are just a few examples of hazardous tasks that are a part of construction projects and call for stricter MWL criteria in order to optimize performance, including worker safety and health, as well as high-quality building. Thus, performance criteria such as human safety and quality are also linked to mental workload (MWL) [16]. In general, exceeding work demands can lead to errors and performance issues for construction workers.

2 BACKGROUND RESEARCH

The construction industry is considered a high-risk sector for workers due to various factors affecting work-related stress, cognitive demand, and mental workload levels [17]. The term cognitive demand is used to describe mental workload; however, the present paper uses the term mental workload (MWL) instead. Mental workload refers to an individual's fixed cognitive capacity, similar to a lack of resources that can be used to meet the needs of various ongoing tasks [18]. Due to the nature of the construction industry, construction tasks can expose workers to various physiological demands, including heavy loads, challenging positions, and physically demanding and repetitive tasks [19]. Recent studies also found that high levels of job stress are known to affect the performance of workers in various work settings and characteristics, such as when carrying high workloads and performing complex tasks, which could cause high levels of mental workload and fatigue and lead to unsafe behavior and poor work performance [20,21]. Due to the increasing number of tasks and activities in construction projects, workers are more likely to experience mental workload issues than physical issues since their working environment can negatively affect their mental status. For example, the mental workload of construction workers may increase when they perform a task that has a short amount of time to complete or a complex task. In the present paper, MWL is envisioned as: (i) the mental tension a construction worker feels while executing a task due to stress, pressure, and a sense of overload; and (ii) a characteristic of carrying out work operations that expresses the feelings connected to the elements, circumstances, and resources that support the environment and the execution of the task. In addition, a recent neuroscience and psychological study found that mental workload considerations have also become more relevant due to the various factors and work settings that can affect the performance of workers [22]. Accordingly, MWL can be viewed as a subjective experience and a physiological response resulting in task-related behavior that is a function of task demands [23].

Task demands and MWL should be evaluated and managed so that a worker is neither underloaded nor overloaded to maintain their safety and the quality of work [12,24]. The effects of mental workload on the ability to perform tasks suitably could be significant. A worker's behavior can also influence the effects of mental workload and worker abilities because long-term exposure to a mentally demanding task can lead to mental fatigue and worse performance [25]. In the construction industry, workers are often unable to perform certain cognitive tasks due to the strain on their mental and physical resources. For example, workers suffering from fatigue and task demands are more prone to experiencing higher incident rates [26,27]. Prem et al. (2016) [28] revealed that specific work characteristics and job stressors affecting worker performance could lead to high cognitive processing demands.

A recent study has identified and confirmed task constituents (e.g., complexity of the task, time remaining to complete the task, distractions, interruptions, available resources, and switching between tasks) that affect a worker's perception of mental workload as they perform their task and ultimately task performance [29]. Definitions and descriptions of the task constituents are provided in Alotaibi and Gambatese (2022) [29]. These task constituents were developed as part of prior research [30]. Alotaibi (2020) [30] used a comprehensive literature review related to safety, quality, psychology, human factors, and personal management to identify potential constituents, and then utilized a Delphi process to confirm and develop the constituents and associated conceptual model for assessing worker mental workload on construction sites utilizing these constituents. Although some of the constituents that affect worker performance may increase the level of MWL, some may reduce it, and others have no impact. Consequently, constituents could be treated differently and classified into three categories. For example, when the availability of the needed resource is greater, MWL decreases. On the contrary, if a construction worker is conducting a complex task, MWL increases. Therefore, it is vital to identify a process that can combine these constituents to support the evaluation of MWL. Evaluating these constituents based on the construction worker perspective and the surrounding environment on typical construction sites is needed to improve the quality of work and worker safety.

The present paper targets understanding the task characteristics and constituents that affect the mental workload levels of construction workers. In this paper, the researchers also aim to evaluate the impact of task constituents on mental workload when construction workers perform jobsite activities. The research objective is to evaluate and analyze the effects of environmental conditions and task constituents on the mental workload of construction workers during operations using a combination of methods consisting of semi-structured interviews and field observations of different construction trades. A second objective is to determine the magnitude of the influence of each constituent on the MWL to which workers are exposed and determine how to minimize MWL that leads to hazardous exposures and quality defects. The study results are expected to be used by construction companies when assessing the performance of their workers.

3 METHODOLOGY

A mixed-method approach involving a combination of interviews and observations was used to conduct the study. Interview methods provide the opportunity for communicating various levels of subtleness and depth, and can allow for subjective responses [31]. Direct observation allows researcher to see the differences between what people have said in interviews and what/how they actually perform [32]., Researchers can improve the reliability and validity of their studies by using various quantitative and qualitative data sources. Thus, in the present study, quantitative and qualitative data were collected to improve reliability and validity [33]. After receiving Institutional Review Board (IRB) approval for research with human subjects, a non-probability sample of construction workers was created by emailing contractors dispersed throughout the US Pacific Northwest. A convenience sample of construction workers was acknowledged as an acceptable technique for sampling the population due to geographic, budgetary, and time restrictions [34]. The researchers did not randomly select the construction workers or the general contracting firms on whose projects the interviews were performed. The researchers contacted the contractors who indicated a project site was available for interviews and observations to schedule a day and time to visit the location and conduct the interviews and observations. Interviews were conducted with selected workers on the projects, followed by observations of the workers as they performed their work along with their crew members. The researchers were able to visit at total of five construction projects in the states of Washington and Oregon to interview and observe various construction workers with different locations, contractors, and trades. The sites visited were required to have work involving at least one of the following trades: carpentry, electrical, mechanical, piping/plumbing, and steel erection.

The participant population was construction workers who work in the following trades: carpentry, electrical, piping /plumbing, mechanical, and steel erection. These trades are representative of the primary trades present on most building construction sites, and their selection was intended to provide the level of detail needed to develop the knowledge and evaluation of the impact of task characteristics on mental workload. The researchers visited the construction project sites and initially met with the person in charge, typically the project superintendent. The researchers asked the superintendent which workers to approach for the interviews and observations. The participants in the interviews and observations were those the project superintendent indicated as potential participants. Next, the researchers approached the workers without their supervisors, asking them whether they were willing to participate in the study. The researchers informed the workers that they were not obligated to participate in the study and asked whether they were willing to participate in the interview and observations. If the workers answered "Yes," the research team provided a consent form explaining the purpose of the study and asked the workers to sign it to continue with the interviews and observations.

3.1 Interview Design and Validity

A semi-structured interview technique was used for conducting the worker interviews. The interviews usually took approximately 15-20 minutes and were conducted during the worker's break or after the work crew observation. The interview length depended on the responses the participant gave and the follow-up questions that the interviewers asked. The questionnaire aimed to collect data at an individual construction worker level. The first section of the interview questionnaire asked about the worker's background (e.g., education level, industry experience, and type of trade). The second part of the questionnaire gathered worker insights with respect to the mental workload associated with each constituent using a rating scale from 1 to 10, where 1 represents low and 10 represents high, in line with prior research [35]. For example, construction workers were asked to indicate the extent of the impact of each constituent on mental workload when they performed tasks. The questionnaire underwent five revisions by the research team and the Institutional Review Board (IRB) to improve its clarity and validity.

One of the most critical steps researchers can take to ensure that a study is representative of the population is randomly selecting the sample. However, in the present study, as another approach to support confidence in generalization the research team divided the population into subgroups intended to be characterized in the sample (e.g., trades) [36]. The research team selected the appropriate sample to ensure that the results could be generalized. The use of semi-structured interviews has been shown to improve the accuracy and reliability of the research. In addition, subgroups can help researchers identify the ideal sample size for their studies. The ideal interview size is between 15 and 30 participants, in line with previous studies [37,38]. Based on these studies, the researchers targeted at least 15 participants in each trade.

3.2 Observational Design and Validity

Field observations of the work crews were also performed. The observations involved site visits and formed the cornerstone of the data collection [39]. Each crew observation was conducted while the crew performed the work task(s) and took approximately 30-40 minutes to complete. An observation sheet was developed to assist the researchers with collecting a structured set of data during the observations. The observations focused on an entire crew to facilitate an evaluation on a crew-level basis. For the present study, the researchers targeted crews that had at least five workers performing the tasks given that the definition of a construction crew as part of a project team consists of 5-30 people [40]. The observation sheet included places to enter the type of trade, type of contract, company type, date, time, number of workers, and type of task, and a rating for each constituent. Each constituent was rated by the observers from 1 to 10, where 1 represents low and 10 represents high, in terms of its presence in the task. The observation sheet went through five rounds of revisions by the research team and IRB to ensure its accuracy and completeness.

Due to potential biases and subjectivity associated with the observational method, researchers have not universally embraced observations as a scientific research method [41]. Many researchers have argued that a biased personality plays a major role in the observational method [41]. To ensure the reliability of the data, the observers conducted three observations for each constituent. In each observation time, each research team observer entered a rating from 1 to 10 for each constituent. To improve the internal validity and reduce bias in the observation data, the following three internal controls were successfully applied to maximize the quality of the outcome of the study: (1) the research team used a rating scale from 1 to 10 to make the assessment less subjective and test validity [41], (2) the research team went from one project to another to put the controls in place, and (3) two researchers conducted observations, and compared and contrasted their findings to avoid inherent biases and issues that might occur from a single observer [42].

4 RESULTS AND DISCUSSION

4.1 Participants' Background Information

The first part of the interview questionnaire focused on the participant's personal demographic information to ensure participants were qualified to participate in the study and increase the quality and reliability of the study findings. The participants were asked to indicate their trade (i.e., carpentry. plumbing, electrical, mechanical, and steel) and the operations/tasks most involved in as part of the trade. All participants are involved in operations/tasks as part of at least one of the five trades. Each participant was also asked to provide a current job title. The researchers found that the participant job titles vary, as seen in Table 1, and include those at the laborer, foreman, superintendent, and general superintendent levels. Regarding working experience, approximately half of the participants (52.6%) have more than ten years of industry experience. Table 1 presents the average number of years of work experience for each trade, which ranged from 5 to more than 20 years. Lastly, when asked about familiarity with the task, 88.4% of the participants are familiar with the task that they were performing. As mentioned above, the sample size for interviews within each trade should be at least 15 participants and the authors targeted crews with at least five workers for the field observations. Table 1 shows the number of workers interviewed and the number of crews observed within each trade.

Table 1: Participant background information

Construction trade	No. of workers interviewed	No. of crews observed	Job Titles	Work Experience
Carpentry	20	3 crews	Carpenter, Superintendent, and Foreman	5-10 years
Plumbing/Piping	17	2 crews	Plumber/Pipefitter, Superintendent, and Foreman	10-20 years
Electrical	20	2 crews	Electrician, Foreman, and General Foreman	5-10 years
Mechanical	15	2 crews	Laborer, Superintendent, and Journeyman	More than 20 years
Steel	23	2 crews	Ironworker, welder, and Foreman	10-20 years

4.2 Impact of Constituents on MWL

As described above, the present study aimed to evaluate the impact of task constituents on MWL using semi-structured interviews and field observations. Field observations were used to confirm the interview results from the construction worker's perspective. Construction workers were initially asked to indicate whether the level of MWL influences worker safety and work quality when performing construction tasks. The majority of the construction workers interviewed within all five trades (59%) indicated that high MWL impacts worker safety and work quality and could lead to injury incidents and poor work performance. This result is in line with a recent study by Fang et. al. (2015) [43], which examined the effect of mental workload and mental fatigue on construction worker performance, and found that high levels of mental fatigue can lead to an increase in the number of errors which can decrease the ability of an individual to respond efficiently to a hazardous situation [43]. However, the current study revealed that 36.3% of workers indicate that MWL does not impact safety and quality other than relying on task characteristics and work conditions, and MWL could be impacted by family disruption, anxiety and depression, working over 40 hours a week, and lack of sleep. Previous studies have also found that workers are exposed to cognitive work demands, work stress, and MWL when they work more than 60 hours a week and when workers have anxiety and depression [17,23]. In contrast, in the present study, 4.7% of workers indicate that MWL impacts worker safety and work quality depending on the number of different tasks being worked on simultaneously, the deadline of the tasks at hand, having many tasks at hand with tight timelines, and having a short time to complete the given tasks.

The interviewees were also asked to evaluate the impact of each constituent (i.e., complexity of the task, uniqueness of the task, predictability of the task, repetitiveness of the task) present on the current worksite on MWL. The median rating value from the workers' responses for each constituent was used to determine the level of impact on MWL. The median value is less affected by biased responses due to skewed data and outliers than the mean [32]. The results show that, according to the construction workers' perspectives, most constituents have a moderate or above level of impact on worker MWL and work performance, as seen in Table 2. As described above, the research team observed crews while performing construction tasks to confirm the interview results. Correspondingly, as shown in Table 2, based on crew-level observations during the site visits, the research team found that most of the constituents were present on the site and impact MWL and worker performance. The impacts to MWL and worker performance may contribute to injury incidents and poor task quality.

No significant difference in the findings were found when comparing the results of the construction worker perspective and the research team observations. However, the results reveal that the differences in the impact on MWL vary based on the type of trade, the tasks the workers and crews are performing, and the work conditions and operations. To illustrate, the study found fewer impacts associated with steel workers than other trades. The research team observed that tools and structural steel members (beams and columns) required only a short amount of time to move to the site and put in place due to the use of a mobile crane lifting. However, Chang et al. (2009) [10] found that steel workers indicate work stress and fatigue are potentially more significant than other workers, such as farmworkers, electricians, plumbers, and concreters, due to the workers being unable to concentrate and straighten up while working. As a result, despite the observation results being close to the actual feelings and perspectives of the workers as shown by the median ratings of all 14 constituents in Table 2, the impact of task constituents experienced by construction workers varies depending on the type of trade and tasks performed. Therefore, the impacts of constituents on MWL are perhaps greater in certain trades than in other trades.

Table 2: Evaluation of the impact of constituents on MWL level by trade

Impact	Task Constituents	Median Rating of Impact on MWL									
		Carpentry		Plumbing		Electrical		Mechanical		Steel	
		I	O	I	O	I	O	I	O	I	O
Increase MWL	Complexity of the task	7	8	7	8	7	7	7	6	7	7
	Uniqueness of the task	6.5	7	6	6	6	6	7	5	5	5
	Crowding	6	8	7	9	7	8	8	7	6	5
	Coordination	8	8	8	9	8.5	8	8	7.5	6	5.5
	Interruptions	7	7	6	8	6	7	7	6.5	6	5
	Distractions	7	6	6	7	6	8	6	7.5	6	6.5
	Switching between tasks	7.5	5	6	8	6	7	8	7	6	5.5
Neutral	Duration of the task	6.5	8	8	8	6	8	8	7	6	5
	Value of the task	9	9	8	7	8	7	8	5.5	7	5.5
	Pace of the task	8	7	7	7	7	7	7	6	6	4.5
Decrease MWL	Predictability of the task	6.5	7	6	7	6	7	6	6.5	5	6
	Repetitiveness of the task	8.5	6	7	8	5	7	8	6.5	5	4
	Availability of resources	7	8	9	9	6	7	7	6	6	5.5
	Time remaining to complete the task	6.5	7	7	7	6	7	7	5.5	6	6.5
	Median	7	7	7	8	6	7	7	6.5	6	5.5

Note: Rating scale: 1 = Low impact; 5 = Moderate impact; and 10 = High impact.
I = Interview; and O = Observation.

Further analysis of the impact of constituents on the level of MWL was conducted by combining the responses of all trades, as seen in Fig. 1. The constituents were found to be highly impactful on MWL during work operations. The results reveal that the perspectives of third-party observers conducting observations of the work are generally consistent with those of the workers themselves. Complexity of the task, switching between tasks, predictability of the task, availability of needed resources, and time remaining to complete the task were found to be higher and slightly more impactful based on the crew level observations than individual worker perspectives. The results suggest that developing an understanding of task constituents in terms of their impact on MWL can help management positively influence workers and work performance, and lessen the adverse effects of task constituents on unfavorable safety outcomes among crews [44]. The results of the study are consistent with previous studies that show that increased mental fatigue and mental workload of workers are associated with time on task [45], a complex task [46], switching between tasks and project activities [47], predictability of the tasks [48], and the availability of needed resources to perform tasks suitably such as drawings and tools [15,49].

In contrast, coordination of the work, value of the task, and repetitiveness of the task were found to have a higher impact on MWL from a personal worker perspective than from the research team's observations, as seen in Fig. 1. The results reveal that coordination of the work is a significant factor in increasing MWL and there is work stress on workers when the subcontractors are unfamiliar with new technologies to avoid conflicts, such as Building Information Modeling (BIM), especially for mechanical, electrical, and plumbing (MEP) trades. In addition, construction workers indicate that the MWL is high when a valuable task is assigned to them, the task is to be completed in a short amount of time, and they are not familiar with the task, or they do not have sufficient experience. Accordingly, the value of the task can affect the work performance and MWL of an individual during a construction project. Furthermore, repetitiveness of the task was found to be impactful on worker MWL due to the boredom of doing the same task multiple times. There is a chance that workers will absent-mindedly make a mistake that leads to an injury incident as a result of boredom or overly demanding cognitive tasks. Finally, other constituents (i.e., uniqueness of the task, crowding, interruptions, distractions, duration of the task) have a similar impact on worker MWL based on both personal perspectives and third-party observations. Overall, the median ratings for all constituents are relatively the same. The median ratings are also all above 5, indicating at least moderate impact on MWL. Knowing the impact of the constituents enables reducing MWL on employees to enhance safety by reducing worker stress and improving work quality by reducing errors and rework.

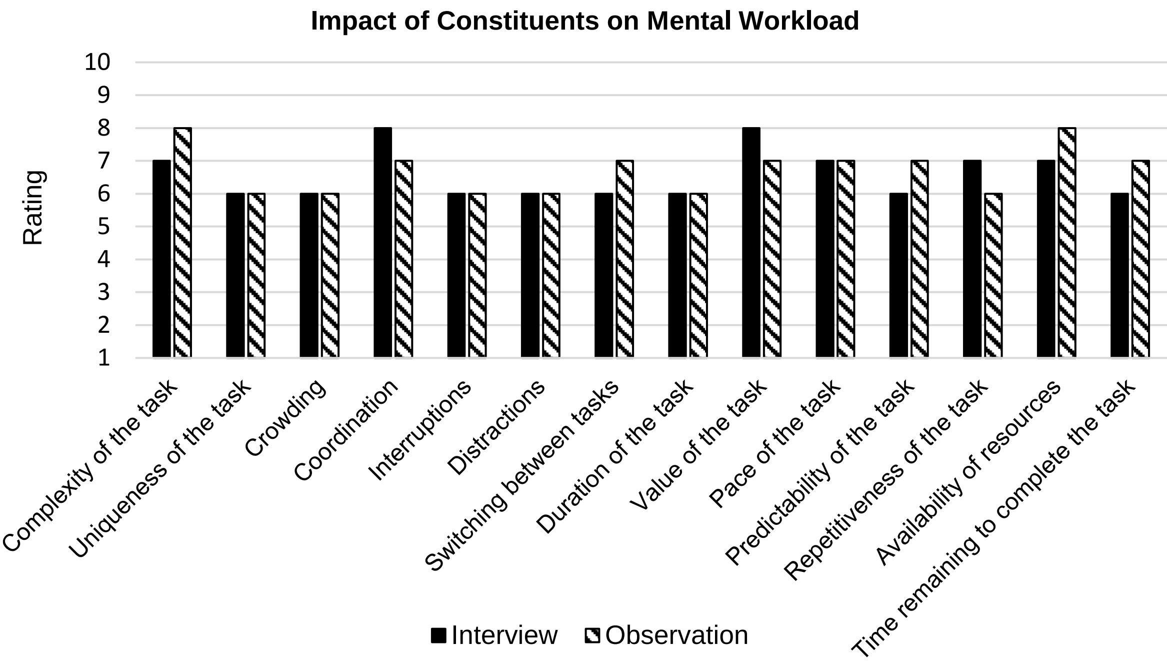

Figure 1: Impact of constituents on MWL based on interviews and observations for all five construction trades (95 construction workers interviewed and 11 crews observed)

5 CONCLUSIONS AND RECOMMENDATIONS

The present study was conducted to investigate and evaluate the impact of task characteristics (i.e., constituents) on construction workers' MWL. A mixed-method approach was used consisting of a combination of semi-structured interviews and onsite observations based on individual-level and crew-level basis. Five building construction sites at different locations in the US Pacific Northwest were visited to conduct interviews with workers and perform observations of crews within five different work trades. The study findings provide valuable insight into the constituents and task characteristics that affect the performance of construction workers. This knowledge can be used to help improve the quality of work and worker safety for the construction industry. The study findings can also be used to predict the likelihood of an injury incident or quality error, and as an active leading indicator of safety and quality performance. The construction industry can use these constituents to assess the degree to which task-related worker mental workload is a problem during operations in order to improve safety during the operations. Finally, the contribution of the study to the body of knowledge is an evaluation and assessment of each constituent that impacts the MWL of construction workers for five trades.

This study is part of a larger research study that attempts to create a quantitative indicator based on task constituents that objectively and genuinely reflects the level of safety and quality on construction sites as a result of measuring the MWL of construction workers. The study found that adverse effects of various task characteristics of different trades and tasks on the MWL can significantly impact the safety and quality of work performed by construction workers. The present paper has determined and evaluated the connection between constituents and MWL with respect to safety and quality. Future research could be conducted to investigate and identify modification/adjustment factors for each constituent to determine the co-relationship between the various constituents and the resulting compounding effects on MWL.

Mental workload evaluations can be classified into physiologic, secondary task, and subjective measures. The present study used a subjective-workload measure to help worker assess their cognitive demands while performing a task. The assessment utilized a rating scale in line with the rating scale used for the National Aeronautics and Space Administration task load index (NASA-TLX), which is well-known and frequently utilized. Future research should validate and calibrate the impact of constituents on MWL based on an experimental or case study approach using objective measures such as electrodermal activity (EDA) or other appropriate technique for determining MWL.

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OCCUPATIONAL HEALTH AND SAFETY COMPLIANCE PRACTICES AND CHALLENGES IN THE SOUTH AFRICAN CONSTRUCTION INDUSTRY

Maureen Khati and Kahilu Kajimo-Shakantu[1]

[1]Department of Quantity Surveying and Construction Management, University of the Free State, 205 Nelson Mandela Drive, Park West, Bloemfontein, Free State, South Africa.

ABSTRACT

There is a lack of clear-cut position on the implementation and compliance levels to Occupational Health and Safety practices in the South African Construction industry. The aim of this study was to assess the occupational health and safety compliance challenges in the construction industry in order to improve the status quo. The objectives included to; examine the occupational health and safety practices of construction firms and identify challenges encountered by construction firms in the implementation thereof. A quantitative survey using a questionnaire was utilised to collect data among some 300 respondents in construction, project management, architecture, quantity surveying firms and University estates departments. Quantitative methods including exploratory factor analysis were used to analyse the results. The results identified two types of occupational health and safety practices in the construction industry namely; employee protection occupational health practices and work environment protection practices. Key challenges encountered in occupational health and occupational safety implementation comprised; management related challenges, employee attitudinal challenges, training and logistical challenges and poor site management. The study concluded that occupational health and safety compliance is currently not optimized in the construction industry and this has serious implications for the efficiency of construction site management. It recommends the need for managerial support and commitment towards occupation health and safety implementation by making its compliance a strategic factor for project performance to enhance compliance.

Keywords: Construction sector, Occupation health and safety compliance, Occupational health and safety challenges, Occupational health and safety practices.

1 INTRODUCTION

According to the Constitution of South Africa, every worker has the right to return home alive, healthy and in good physical condition [1]. Occupational health and safety (OHS) of workers should aim at promoting and keeping up the most significant level of physical, mental and social prosperity of personnel in all occupants [2]. It should prevent adverse effects on health and general wellness caused by poor working conditions among employees and most importantly protect workers in their various workplaces from risks originating from adverse health factors. The adaptation of work to humans by [3] suggests that the main purpose of OHS on construction sites is to ensure work environments are safe for employees to enhance their productivity [4]. The construction industry remains a leading sector in terms of workplace fatalities compared to the other sectors of the economy [5].

A global report by [6] claims that while the construction industry employs 5% of the workforce, it accounts for 22% of all fatal injuries and 10% of severe injuries reported. [5] indicates that the construction industry remains a leading sector in terms of workplace fatalities compared to the other sectors of the economy. According to [7], the Indian construction industry employs about 7.5% of the workforce but accounts for 16.4% of the global fatal occupational. Although the Nigerian construction industry contributes 3.82% to the Gross Domestic Product (GDP) of the economy, the number of accidents, both reported and unreported, is still unabated [8].

Although occupational health and safety (OHS) practices are present in the South African construction industry, incidences of accidents still seem to be on the increase. A recent study in the South African Construction industry shows that almost 34% of construction industry fatalities are due to lack of compliance to occupational health and safety practices [9]. Prominently, construction keeps on contributing an unbalanced number of fatalities and wounds comparative with other industrial sectors, and there keeps on being significant levels of resistance with health and safety legislation by and large, and explicitly the construction development and other Health and Safety Regulations in South Africa [10].

According to [11], a key challenge that affects practices of OHS implementation in the construction industry is that of firms paying less attention to health and safety issues as they try to under-price their bids in the hope of being awarded contracts during competitive tendering. The other causes for non-compliance to OHS in the construction industry cited are the refusal by workers to wear their personal protective equipment (PPEs) since they deem it to be unnecessary [12], failure to adhere to safety practices [13], poor site management, bad attitude of workers towards safety, low levels of worker knowledge about safety, and lack of proper training [14] as well the lack of use of standardized safety devices [15]. The research is founded on the next moulds: Guidance and advice are required, for the building industry on the current Occupational Health and Safety regulations (2014) relevant to contractors, setting compliance targets for health and safety and evaluating the innovative factors of the OHS Act 1993 and the impact on the construction site.

The above discussed suggest that there is no clear-cut position on the implementation and compliance to OHS practices in the construction industry, especially in South Africa. In as much as some authors regard training and education as the key to OHS compliance in the South African construction industry [16], others regard compliance to OHS regulations as the key to OHS practices implementation in the South African industry [17]. This lack of clarity is identified by the present study as a significant knowledge gap requiring further interrogation. The present study thus focusses on identifying various challenges encountered by firms in the implementation of OHS practices in the South African construction industry with a view to enhancing compliance thereof. This study takes the view that the construction industry contributes enormously to any economy and as a result, the workers' compliance to occupational health and safety regulations is of utmost importance.

1.1 Occupational Health and Safety regulation and practices in developing countries

1.1.1 Health and Safety in the construction industry

International Labour Organisation (ILO) report on health and safety estimates that the construction sector contributes to one of each six deadly incidents that is documented in the working environment with a minimum of approximately 60,000 fatal accidents occurring yearly globally in construction sites which is representation of one fatal accident in each ten minutes [18]. According to OHS Act 85 of 1993 [19], all construction industry workers are obligated to be registered with either the compensation commissioner (Department of Labour, DoL) or the Federated Employers' Mutual Assurance Company Limited, (FEMA), and are required to report Occupational health and safety incidences within seven days of occurrence, and occupational diseases within fourteen days of diagnosis [20]. OHS Act 85 of 1993 [19] form the main Acts that tend to impact on health and safety as far as the South African Construction building industry is concerned.

Despite various contributions of stakeholders in the construction industry, health and safety is not improving commensurately [10]. A total number of 991 out of 4,693 deaths in the workplace in private sector 21% occurred in the building industry, which implies that one in every five worker death which are mainly attributed to workplace falling from great heights, being electrocuted, hit-by and wedged-in-middle incidents [22]. Occupational health and safety fatalities in the South African Construction building industry is three times higher than in other middle-income countries [23]. Their study shows that almost 34% of construction industry fatalities are due to lack of compliance to occupational health and safety practices. Examples of fatalities include the 2015 collapse of the Grayston Drive pedestrian bridge on Gauteng's M1 highway [24].

1.1.2 Overview of the Compliance in Global Construction building industry

In the literature, non-adherence to occupational health and safety in the Construction building industry is attributed to many reasons [25]; [12]. One of the reasons cited for non-adherence to occupational health and safety practices in South Africa is the limited resources in tackling occupational health and safety issues by Small Medium Scale Enterprises (SMEs) [26]. The other causes for the non-compliance to OHS in the Construction building industry cited previous studies is the refusal of workers to wear their PPEs since they deem it to be unnecessary [12], failure to adhere to safety practices [13], poor site management, bad attitude of workers towards safety, low levels of worker knowledge about safety, and lack of proper training [14] as well the lack of use of standardized safety devices [15].

The South African construction industry was found to be highly stressful and affecting the health and wellbeing of construction employees negatively [27] . This may lead to construction related accidents such as falling from heights, electric shocks, caving-in of excavations, and those related to carnage and heavy lifting machinery. Also, fatigue, carelessness, lack of discipline and distractions as a result of workers not having ample rest also causes accidents in the Construction building industry [28]. The incidence of such accidents could be associated with ignorance on the part of senior management on the implementation of OHS practices, lack of giving construction workers enough training on OHS practices, and poor communication on OHS related matters [28].

A study by [28] revealed twenty-seven safety variables which were examined under five groups; human, equipment, material, workplace and environmental factors. Another study conducted by [16] which sought to assess the health and safety norms in Southern Africa Built environment found that legislation was not the answer to OHS compliance in the South African construction industry. Rather it was important for OHS stakeholders in the construction industry to focus on providing training and education for firms in the construction on OHS practices on frequent basis. A recent study revealed that the need for construction firms to manage workplace hazards, organizational regard for health and safety practices as well as compliance to legislations were important motivators for OHS implementation in the South African Construction building industry [9].

Previous studies have identified various forms of challenges associated with the implementation of OHS practices in the construction industry. Tight project deadlines for construction firms shifts the attention to achieving project deliverables in real time thereby paying less attention to occupational health and safety [24]. The problems with time pressures is also worsened by poor work designs and planning inadequacies which negatively affect the project outcomes [25]. The time pressures and costs associated with OHS implementation makes it difficult for construction firms to pay attention to OHS training and education which intensifies their exposure to occupational risk [26]. Moreover, complacency on the part of construction workers makes them feel that they do not need any OHS training and education which compounds the challenges associated with the implementation of OHS [27]. The on-location safety training generally contains health and safety orientation before the start of day-by-day activities, regular crisis reaction drills, first aid managerial strategy, data update, key perils nearby, workshops and courses on safety for management notwithstanding other applicable on location training [28]. Notwithstanding, adopted safety practices at construction sites are below accepted standards and the majority of construction site labourers have low levels of education, which may account for their inability to understand and adopt the importance of health and safety rules on site [26].

2 METHODOLOGY

A quantitative cross-sectional survey research design was adopted, within a positivist paradigm because the study seeks to investigate problem of occupational health and safety compliance challenges in the South African construction building industry from an objective viewpoint. The researchers maintained an independent posture from the phenomenon being investigated as data was gathered through a questionnaire. The justification is that the study sought to make use of numerical data gathered to make statistical inferences about the phenomenon being investigated.

The study's target population comprised construction firms in the Free State, Gauteng and Western Cape provinces of South Africa, and the estimated number of construction employees being three hundred (300). There was no readily available sampling framework and hence the research was compiled from the existing University Estates database. The sample size was chosen based on the Kregcie and Morgan (1970) table for sample size determination [29]. Convenience sampling was used to ensure that employees who were available and willing to participate in the study were included in the study. The 100 completed useable questionnaires received back were analysed using the Statistical Package for Social Sciences (SPSS) software version 22 for data analysis. The collected data was coded by assigning numerical values to them and then entered into the SPSS software. Descriptive and inferential statistics were used to analyse the data.

3 RESULTS PRESENTATION AND DISCUSSION

3.1 Respondents' Demographic Profile

In terms of the highest educational qualification, the majority of the respondents were post graduates as they constituted 41.6%; 22.8% were high school graduates; 19.8% were under graduates while 15.8%

had attained primary school education as indicated in Table 1. It was found that majority of the respondents were site workers 31.7%); 27.7% were engaged as other stakeholders in the Construction building industry, 15.8% were project managers, 13.9% were contractors, 8.9% were health and safety officers while 2% were contract managers. This is an indication that the consulting players in the built environment are reasonably represented in the sample taken.

as indicated in Table 1.

Table 1: Respondent's Demographic Profile

Table1: Respondent's Profile

Highest Educational Qualification	Frequency	Percentage (%)
Primary School	16	15.8
High School	23	22.8
Under Graduate	20	19.8
Post Graduate	42	41.6
Total	101	100
Position in the industry	**Frequency**	**Percentage (%)**
Site workers	32	31.7
Contractor	14	13.9
Project Manager	16	15.8
Health and Safety Officer	9	8.9
Contracts Manager	2	2.0
Other	28	27.7
Total	101	100
Highest level of training	**Frequency**	**Percentage (%)**
None	29	28.7
Apprenticeship	6	2
Short Courses	13	12.9
High School	10	9.9
Under Graduate	11	10.9
Post Graduate	32	31.7
Total	101	100
Number of years in the Construction industry	**Frequency**	**Percentage (%)**
Below 5 years	33	33.7
6-10 years	31	30.7

11-15 years	12	11.9
16-20 years	12	11.9
Over 20 years	12	11.9
Total	101	100

The results further showed that a third of the participants have been in the construction industry for less than 5 years (32.7%), another third (30.7%) for a period of 6 -10 years; 11.9% of the respondents have been for the following number of years respectively: 11-15 years; 16-20 years and more than 20 years. According to the results, 97% of the respondents have undertaken projects in the construction industry, 2% have undertaken projects in the mining industry and 1% in the service industry.

3.1.1 OHS practices of construction firms South Africa

In Table 2, it was found that two factors were extracted and the total variance explained for these two factors was 75.23%. The first factor explained 46.73% of the variation while the second factor explained 28.5% of the variation using varimax rotations. According to the Varimax rotated factor matrix, the study identified eight items with factor loadings ranging from 0.730 to 0.827 and these were grouped and named as “Employee Protection OHS Practices”. For factor one which contributed to 46.73% of the variation, the name employee protection OHS practices was appropriate because the items that described the factor were more inclined to employee protection in the workplace and comprised of items such as “Workers do not work under the influence of alcohol”, “Workers do not smoke in flammable materials stores”, “Workers always use personal protective equipment”, “Equipment are transported safely at my workplace” among others.

Table 2. Total Variance Explained

	Initial Eigenvalues			Rotation Sums of Squared Loadings		
Factor	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	8.531	71.092	71.092	5.608	46.732	46.732
2	1.023	8.524	79.616	3.420	28.504	75.236
3	.691	5.755	85.372			
4	.394	3.281	88.653			
5	.329	2.744	91.397			
6	.272	2.270	93.666			
7	.210	1.748	95.414			
8	.175	1.459	96.874			
9	.148	1.230	98.103			
10	.098	.819	98.922			
11	.075	.628	99.551			

12	.054	.449	100.000			

Extraction Method: Principal Axis Factoring

The second factor identified had four items ranging between 0.785 to 0.775 and these were grouped and named as "Work environment Protection OHS Practices" as items the described this factor were more related to the protection of the working environment. Items that described this factor comprised the following "Adequate warning systems are provided at my workplace", the workplace is inspected regularly before any activity is commenced". The workplace is always tidied up at the end of any activity", "The use of appropriate tools and equipment is always ensured". This is consistent with the argument made by [18] that poor safety practices in the workplace tend to negatively affect construction work productivity and such poor practices include consumption of narcotics and alcohol while on site or bad safety behaviour as discovered in these finding.

3.1.2 Challenges encountered in the implementation of OHS in construction firms

The study made use of exploratory factor analysis to determine the challenges encountered by project managers in the implementation of OHS practices among construction firms in South Africa. According to a KMO value of 0.811, it was deduced that the sampling was adequate for exploratory factor analysis. The Bartlett's test of Sphericity was statistically significant (0.000) giving the indication that the items used for measuring challenges was well correlated with each other. Four factors were extracted as they had eigenvalues that were greater than 1 as shown in Table 3.

Table 3: Varimax Rotated Factor Matrix[a]

	Factor	
	1	2
I work in a safe and healthy work environment	.827	.418
Building materials are stored and transported safely at my work place	.812	.427
Equipment are transported safely at my workplace	.802	.410
Adequate warning systems are provided at my workplace	.469	.765
The workplace is inspected regularly before any activity is commenced	.311	.705
The workplace is always tidied up at the end of any activity	.306	.775
The use of appropriate tools and equipment is always ensured	.483	.720
Workers do not work under the influence of alcohol	.805	.385
Workers do not smoke in flammable materials stores	.777	.338

The organisation ensures proper stacking of objects or materials in safe locations	.803	.419
Workers always use personal protective equipment (PPE)	.730	.352
Training is provided for the workers on occupational health and safety	.741	.364

Extraction Method: Principal Axis Factoring.

Rotation Method: Varimax with Kaiser Normalization.

The total variance explained for the four factors was 59.39%. The 1st factor explained 22.71% of the variance and the 2nd factor explained 12.88% of the variance while the 3rd factor explained 12.39% of the variance. The 4th factor explained 11.41% of the variance. On the varimax rotated factor loading, the first factor was categorized with the heading "Management OHS challenges of construction firms". This category had factor loadings ranging from 0.547 to 0.704 and comprised of eight items. Sample items that describe management OHS challenges comprised the following: "There is lack of technical support from consultants and management regarding implementation of OHS guidelines", due to financial pressure, construction firms are less likely to invest in OHS, "tight project deadlines causes difficulties in adopting full safety practices" among others. In the literature review in chapter 3 above, it was discussed that there needs for an improvement in top management commitment from firms and employers towards dealing with the OHS challenges in the Construction building industry. As well the need to complete projects on time which supports the literature not meeting OHS compliance can lead to delays and other disadvantages of late completion [24]; [25].

The second factor was categorized with the heading "Employee attitudinal challenges" which had 3 items with factor loadings ranging between 0.637 to 0.768". Items that describe employee attitudinal challenges comprised the following: "Workers refuse to wear their PPEs since they deem it to be unnecessary", "there is unwillingness on the part of workers to adhere to OHS practices of the firms", "Workers have bad attitude towards safety at construction sites". In comparison with the literature documented in chapter 3 above, this finding is significant and is in line with the discussed which pointed out that personal protective equipment and protective clothing use is regulated by the OHS Act 85 of 1993 – Construction regulation (2014) and forms part of the requirements when ensuring OHS compliance and hence refusal of use or bad attitude towards their use would cause challenges in ensuring compliance with OHS [28].

The third factor was categorized as "Training and logistical challenges" and had three items with factor loadings ranging from 0.548 to 0.725. The items that describe the training and logistical challenges comprised the following: "Workers have low knowledge about OHS practices, workers are not properly trained on OHS at construction sites, "there is lack of sufficient PPEs on construction sites". The fourth factor was categorized as "Poor site management OHS challenges" and had two items with factor loadings ranging from 0.579 to 0.645. Items that described this factor were as follows "poor site management leads to non-compliance of OHS practices", the lack of use of standardized safety devices Factors which enhance Compliance in the implementation of OHS in construction firms

The exploratory factor analysis was used to determine the factors that enhance compliance to OHS practices in construction firms in South Africa. The total variance explained was 68.8%. Since only one factor was extracted, the study ranked the factors which are responsible for enhancing compliance to OHS in construction firms in South Africa using their factor loadings from the highest factor loading to the lowest factor loading as shown in Table 3. According to the factor loadings, it was found that the availability of a manual detailing safe working practices was the most prominent factor that enhanced compliance to OHS practices by construction firms in South Africa as it had the highest factor loading of 0.889. This is evidence that as a means to solve Occupational Health and Safety implementation challenges in the built environment, there is need for be specific consideration by the industry in documentation of OHS working practices as well as collection and achieving of historical data regarding the same.

Other prominent factors that enhance the compliance to OHS practices were ranked as follows: discussing and implementing control measures in order to minimize risk (Factor loading=0.884, Rank=2nd); managing health and safety by an accredited occupational health and safety management team (Factor loading=0.867, Rank=3rd); management commitment to health and safety (Factor loading=0.854, Rank=4th); training of workers to inspect their machinery, tools and equipment (Factor loading=0.852, Rank=5th); putting in place a committee responsible for safety and health training (Factor loading=0.847, Rank=6th); having an efficient occupational health and safety policy (Factor loading=0.822, Rank=7th) and encouraging employees to attend safety training programs (Factor loading=0.801, Rank=8th). In the literature, it was also found that one of the factors causing implementation challenges for OHS is low levels of adherence and implementation of health and safety guidelines in the sector, which ranked second in the factor loading.

Additionally, in the literature, it was recommended that appointment of an internal health and safety office could enhance compliance. This would go hand in hand with the discussion made by [30] that a competent OSH representative and officer who is well educated and trained should be employed to ensure OHS compliance is enhanced and training of other workers. The determinants for OHS compliance through enforcement of OSH regulations was also recognised by [31] and [32] which includes among other, registration and accreditation with governing bodies, adequate training of stuff members in in OHS compliance issues. Both the second and third ranked loading factors are also significant to the study and means that if improved could enhance compliance to OHS guidelines.

Other factors that determine the compliance to occupational health and safety practices among construction firms in South Africa comprise the following: existence of sufficient trained staff for health and safety (Factor loading=0.786, Rank=9th); creating individualized relationship with employees on health and safety (Factor loading=0.778, Rank=10th) and putting in place work site inspection checklists to ensure inspections are done thoroughly (Factor loading=0.731, Rank=11th). These constitute the bottom ranked factors but also contribute heavily to the research. It was discussed in the literature review among the determinants for OHS compliance that one of the common causes of lack of compliance was inadequate training of staff in in terms of OHS and workplace related issues. This ranked 9th in the loading but still carries a significant loading for the study and should be considered for implementation in order to improve compliance. Additionally, the use of personal protective equipment and protective clothing is discussed by [33] as well as stipulated in the Occupational health and Safety Act [28] and [3] as part of the code of practice for workers in the literature review to ensure their own individual safety. This ranked as 10th in the study and shows significance as weighting is more than average. In order to enforce the OHS regulations, the low levels of inspection and examination of the work place should be increased. This significant factor ranked 11th and since it is above average may still be considered an important finding.

4 CONCLUSIONS AND RECOMMENDATIONS

The study finds, two types of OHS practices were identified in South Africa's Construction building industry based on the results from the exploratory factor analysis, which included Employee Protection OHS practice and Work Environment OHS practices. This gives the implication that, to a large extent, the OHS practices of construction firms in South Africa are being centred on the employee and the working environment. Concerning factors that enhance compliance to OHS practices, the study identified factors that are related to the establishment of rules, regulations and policies on OHS, implementing control measures by putting in place OHS teams certified for such purposes and engaging employees into OHS training. The main challenges encountered by project managers in the implementation of OHS practices among construction firms in South Africa were found to be: management OHS challenges of construction firms, employee attitudinal challenges, training and logistical challenges and poor site management OHS challenges.

Based on the study's findings and conclusions, the following recommendations are made on how to improve the implementation and compliance to OHS in the South African Construction building industry:

(i) Management of construction firms must make OHS compliance a strategic factor in the success of their projects and must therefore commit more financial resources to OHS compliance in their organisations as this will help create a conducive OHS culture among construction firms in South Africa.

(ii) Employees who refuse to put on PPEs in the course of their work must be sanctioned to serve as deterrents for others and thereby help construction firms to maintain a healthy safety culture.

(iii) There is the need for construction firms in South Africa to frequently organize training programs for their employees by dwelling on the services of experts in OHS within the construction industry.

(iv) There is a need for construction firms to always ensure that logistics for enhancing OHS compliance such as the provision of PPEs for employees on construction sites become prominent in their OHS compliance agenda. This is because, building technology in the construction industry keeps on changing and as this happens new types of risks emerge over time for which employee knowledge on OHS must be frequently updated.

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HEALTH AND WELLBEING CHARACTERISTICS AND IMPACTS IN INFORMAL SETTLEMENTS: THEMATIC AND PRIORITY RESEARCH AREAS

Chioma Okoro[1], Abdulrauf Adediran[1], Nnedinma Umeokafor[2]

[1]*College of Business and Economics, University of Johannesburg (SOUTH AFRICA)*

[2]*School of Engineering, University of Greenwich, London (UNITED KINGDOM)*

Abstract

Informal settlements are characterised by congested living conditions, environmental and inequality impacts, illegal or unplanned housing structures and lack of essential and basic services. The objective of the study was to identify priority areas in research on the characteristics and socio-economic impacts of informal settlement conditions on the health and wellbeing of the citizenry. A systematic review involving bibliometric and content analyses was conducted. The study revealed that most studies about health and wellbeing in informal settlements originate from the United Kingdom, Kenya, and United States. There are three priority knowledge areas: marginalisation experiences affecting livelihoods; neighbourhood and housing impacts; and community and social environment. Further findings include that provision of adequate infrastructure and services in an equitable manner, local level health initiatives, attention to neighbourhood characteristics, housing, community, and social environment/networks/relationships would alleviate some informal settlements' wellbeing impacts. In addition, community engagement and intersectoral collaborations will enhance conscientiousness regarding wellbeing and health in informal settlements. The research emphasises the economic and social impacts of informal settlements on the wellbeing of inhabitants. More discussions and streamlined interventions could be initiated to improve conditions and thus health, safety, and wellbeing in informal settlements. The findings are useful to support future research and decision-making on informal settlements.

Keywords: health, housing, H&S, infrastructure, informal settlements, safety, wellbeing.

1. INTRODUCTION

African cities are projected to be home to nearly 60% of the continent's population by 2050 [1], with the urban population in South Asia and Sub-Saharan Africa doubled [2]. In addition to the pressure on existing facilities and infrastructure, urbanisation has multifarious impacts (positive and negative) on the wellbeing of humans and the environment [2]. While urbanization is associated with increased opportunities for socio-economic economic progress, it generally leads to changes in demography, social patterns and support systems, economic status, and psychological attributes [3]. Hence, urbanization results in informal settlements sprouting in many urban areas in African cities and globally. Informal settlements are characterised by congested living conditions, environmental and inequality impacts, illegal or unplanned housing structures and lack of essential and basic services [4-6]. These conditions are further exacerbated by the social and spatial marginalisation experienced by inhabitants of informal settlements [7]. Therefore, attention is essential to reduce the impacts of urbanisation. Moreso, increased attention is critical as countries struggle to emerge or recover from the COVID-19 crisis. The crisis highlights the suffering among 1.2 billion living in informal settlements/slums [8]. International development agendas such as the Sustainable Development Goals (SDGs) and UN Habitat III New Urban Agenda emphasise the need to provide adequate dwellings and safe, liveable environments for all by supporting local and national level policies [9,10]. National and provincial strategic development plans such as the National Development Plan 2030 also highlight health and safety as top priorities for all peoples in South Africa. However, Weimann and Oni [7] argued that there is a lack of adequate monitoring efforts on the health impact of informal settlement upgrading.

A few studies have explored aspects of health and wellbeing in informal settlements. For example, Chumo et al. [11] investigated drivers of health, safety, and wellbeing challenges in informal settlements in Nairobi using interviews and focus group discussions. The study found that individual community, societal and structural level factors that drive concerns around health and wellbeing.

Similarly, Chumo et al. [12] examined drivers of vulnerability to health and wellbeing challenges across different groups in informal urban space using governance diaries with 24 participants in Nairobi. Visser and Law-van Wyk [13] investigated university students' mental health and emotional wellbeing during the COVID-19 pandemic and ensuing lockdown and found that students residing in informal settlements were most at risk of experiencing emotional difficulties. Amoah et al. [4] examined the impact of informal settlements on water quality assessment. Other studies indicated a lack of health impact evaluations and trend analysis of informal settlement in the Global South, including South Africa [7,14]. Using the four dimensions of housing described by the World Health Organisation (WHO), Weimann and Oni [7] investigated influences of informal settlement upgrading on the health and wellbeing of vulnerable groups of residents. Further, in their study that explored 24 local and provincial policymaker perceptions on barriers and facilitators for intersectoral action using interviews, Weimann et al. [15] opined that hard and soft characteristics of informal settlements directly or indirectly impact health and should be the focus of more studies.

Therefore, this desktop study adopts Weimann and Oni's [7] approach to explore the socio-economic impacts of informal settlements on wellbeing. Therefore, the objective of the study was to identify priority areas in research on the characteristics and impacts of informal settlements on the health and wellbeing of the inhabitants. Findings from this study are envisaged to garner more collaboration and discourse among relevant actors to develop strategies to improve informal settlements' conditions; thus, contributing to positive implications and reducing the impacts of negative externalities of urbanisation on the citizenry.

2. INFORMAL SETTLEMENTS' CHARACTERISTICS AND IMPACTS

The proportion of urban dwellers (55%) in Sub-Saharan Africa that live in slums and informal settlements is larger than the global average (30%) [16]. With a rapidly urbanising population (66%), South Africa's urbanization process is often unplanned, and characterised by significant spatial inequalities and high levels of health disparities [17,18]. Data from Statistics South Africa (StatsSA)'s General Household Survey indicate that approximately 1 in 5 households in metropolitan areas lived in informal dwellings [19]. South African urban centres have become synonymous with rising housing backlog, strain on urban resources, large numbers of informal settlement dwellers that generally lack access to adequate basic services prior to government intervention [20]. Corruption and ineffective strategies combined with historical racial discrimination and segregation during apartheid regime through policies such as the Group Areas Act No. 41 of 1950 has also been cited as contributing factors to informal settlements development in SA [21].

Housing is a component of the urban system (built in line with political or civil society priorities, or in response to human need) and an underlying factor capable of shaping and determining human health – physical, mental, and social wellbeing [7,22]. Other social factors influencing health include quality of living environment, work stressors, behavioural and lifestyle choices when combined with underlying genetic conditions [23]. Mental and physical ill health are also common consequences of the compromised living and working conditions in slums [24]. Further, Cruz et al. [25] found that an increase in neighborhood violence and the fear of it is likely to result in a higher level of mental health and poor quality of life.

The WHO [26] considers four overlapping and interrelated dimensions of housing that contribute to health and wellbeing: the physical housing structure such as dilapidated shelters with inadequate ventilation and high levels of indoor pollution (house); the psychosocial and cultural home environment (home) such as high socio-economic stress experienced by families; the physical characteristics of the neighbourhood environment (neighbourhood) such as high-risk areas for natural disasters; accidents, injuries and the social environment and services within the community (community) such as high crime or gender discrimination.

2.1 Housing factor

Previous studies highlighted the prevalence and impacts of crowding in informal settlements increases dilapidation and the risk of exposure to, and transmission of infectious diseases such as tuberculosis (TB) as well as increased risk of mental illness [27,28]. Van Niekerk et al. [29] cited unsafe use of paraffin, coal and wood for cooking, heating, and lighting due to lack of access to electricity as contributing factors to injury and burn risk. Shortt and Hammett [30] further reported that injuries were more prone in shacks because of overcrowding and lack of designated cooking space. The cross-sectional study, which sought to investigate self-reported health changes in response to the upgrading of Imizamo Yethu informal settlement in Cape Town, found the presence of damp and mould associated with respiratory infections, allergies, and asthma. Concurring with these views, De Klerk et al. [31], Archer et al. [32] and French et al. [33] reported that pest infestation, skin and infectious diseases are common in informal settlements.

2.2 Home factor

Psychological and cultural factors such as stress and depression have been associated with socioeconomic status and how residents perceive their home [34,35]. Gibbs et al. [35] found that 57.9% of young females and 49.5% of young males (18–30 years) living in two South African informal settlements were depressed. Weimann and Oni [7] argued that while relocation from rural areas to urban informal settlements improved mental health by providing a sense of hope for obtaining government subsidised housing as suggested by Marais et al. [36], other factors such as recent environmental, service delivery improvements or educational interventions need to be considered as possible contributing factors.

2.3 Neighbourhood factor

Risk of infectious diseases such as diarrhoea in informal settlements is exacerbated by unsanitary collection and storage of water in containers due to the lack of onsite water facilities [37,38]. Residents' sanitation practices include the use of plastic bags, buckets, porta-potties, or open defecation, which are because of factors including safety, poor conditions of the facilities, lack of privacy and choice [39]. Govender et al. [38] reported households with high levels of diarrhoea likely due to high levels of faecal bacteria and Escherichia coli in surface runoff water from four Cape Town urban poor communities with informal backyard dwellings and low-cost housing.

According to Weimann et al. [15], the immediate neighbourhood environment, which includes the state and perceptions of the surrounding built and natural environment, may face varying challenges and impacts. For example, inadequate water and sanitation could promptly increase the risk of physical illness and disease (hard-direct); while healthcare access may have a more delayed health impact. This emphasizes the need for local level attention and initiatives to provide needed facilities.

2.4 Community factor

From a social environment perspective, Weimann and Oni [7], posited that the lack of community cohesion that exist in informal settlements may be intensified by the feeling of exclusion experienced by households who did not receive government subsidised housing. Brown-Luthango et al. [40] reported that residents' perception of safety did not improve even after receiving a formal house in informal settlements with prevailing high level of crime and gang violence. However, informal settlement reblocking is noted to have made residents feel safer and increased sense community cohesion [40].

Further, according to Weimann and Oni [7], within the context of informal settlements, community factors that affect the health and wellbeing of residents include services provided within the community, which may depend on other interacting factors including infrastructural pipeline, environmental (availability of water reservoir, for example), local government priorities and mandate, as well as social stresses such as high crime or gender discrimination. Goebel et al. [37] highlighted the importance of adopting a gender lens to informal settlement improvement strategies due to gender-related inequalities that may influence health patterns of informal settlement dwellers. Poverty, gender inequality and weak social networks in urban settlements have also been linked to intimate partner violence and HIV-risk [35]. According to French et al. [33], some of these impacts are compounded by exposure to flooding, climate change risks and environmental contamination.

3. METHODS

The study adopted a systematic review approach using bibliometric and content analyses. Bibliometrics is a quantitative analysis method that uses the external characteristics of scientific literature as research objects [41]. The bibliometric phase provided insight into key components of the literature, aggregated, and analysed at the country, author, journal levels and the academic structure of individual disciplines and knowledge focus [42]. The Scopus database was used to identify materials for the study. Scopus database is the largest abstract and citation database of peer-reviewed literature in the world, covering 15 000 journals in different fields [41]; thus, ensuring the integrity and authority of articles. Keywords including wellbeing, health and informal settlements were used in the search. Keywords give an idea of the issues relevant in the paper. A total of 63 documents emerged. However, 42 were included based on selected inclusion and exclusion criteria, as presented in Fig. 1.

Fig. 1: Inclusion and exclusion criteria

The full search string was: TITLE-ABS-KEY (wellbeing, AND health, AND informal AND settlements) AND (LIMIT-TO (OA,"all") AND (LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) AND (LIMIT-TO (DOCTYPE, "ar") AND (LIMIT-TO (PUBSTAGE, "final") AND (LIMIT-TO (LANGUAGE, "English").

The selected papers were analysed and visualised using the VOSviewer software version 1.6.18. The status and academic development of research were assessed broadly on wellbeing and health in informal settlements. Specific outputs included networks and relationships related to authors, sources, countries, and keywords using co-occurrence and citation analyses [43]. Co-occurrence analysis explores the frequency of nouns or phrases in literature to identify relationships between topics in the discipline that the literature represents [42]. By calculating the frequency of occurrence of two subject words in the same document, a co-word network of the association was formed. The strength of the relationships or collaborations with other countries was also highlighted as evinced by the total link strength (TLS). The first bibliometric analysis revealed the research hotspots or concentrated phenomenon in the informal settlement literature regarding health and wellbeing over time (in this case, a decade, to reveal the most current knowledge). The specific impacts were subsequently identified using content analysis of the most cited studies as evinced from the first bibliometric phase. A similar two-phase approach was adopted by Okoro [43]. A deductive approach was used to identify authors' views relevant and aligned to the themes established from the clusters. Findings from both phases were integrated in the discussion.

4. FINDINGS

Results emanating from the study showed that the top five countries publishing on informal settlements' health and wellbeing are the United Kingdom (UK) (21 documents, 237 citations, TLS=21), Kenya (12 documents, 96 citations, TLS=13), the United States (10 documents, 84 citations, TLS=12), South Africa (9 documents, 103 citations, TLS=7) and Canada (6 documents, 16 citations, TLS=9). The total link strength or collaboration was strongest with the UK, Kenya, and US.

The most cited author was Ayeb-Karlsson S. with 105 citations across three documents, while the strongest co-authorship links were between El Asmar K. and Habib R.R cited 36 times across three co-authored documents. The top seven sources with at least two documents per source were International Journal of Environmental Research and Public Health (3 documents, 43 citations, TLS=6), Frontiers in Public Health (2 documents, 0 citations, TLS=5), Social Science and Medicine (2 documents, 17 citations, TLS=4), Social Sciences (2 documents, 1 citations, TLS=3), and Plos One (2 documents, 9 citations, TLS=0), Sustainability (2 documents, 15 citations, TLS=0), and Trials (2 documents, 34 citations, TLS=0).

Analysis of author keywords using co-occurrence analysis revealed the top 25 keywords out of a total of 137. The co-word association is represented by clusters as shown in Fig. 2. Three groups/clusters emerged from the analysis. These included the following items:

- Cluster 1 (purple coloured) – Ten items including cash transfer, India, intimate partner violence, Kenya, marginalised and vulnerable, Nairobi, public health, urban informal settlements, and urban slums.

- Cluster 2 (green coloured) – Ten items including covid 19, green space, housing, impact evaluation, mental health, slums, social capital, south Africa, sub-Saharan Africa, and urban.
- Cluster 3 (blue coloured) – Five items including Conflict, displacement, gender, social networks, and urban health.

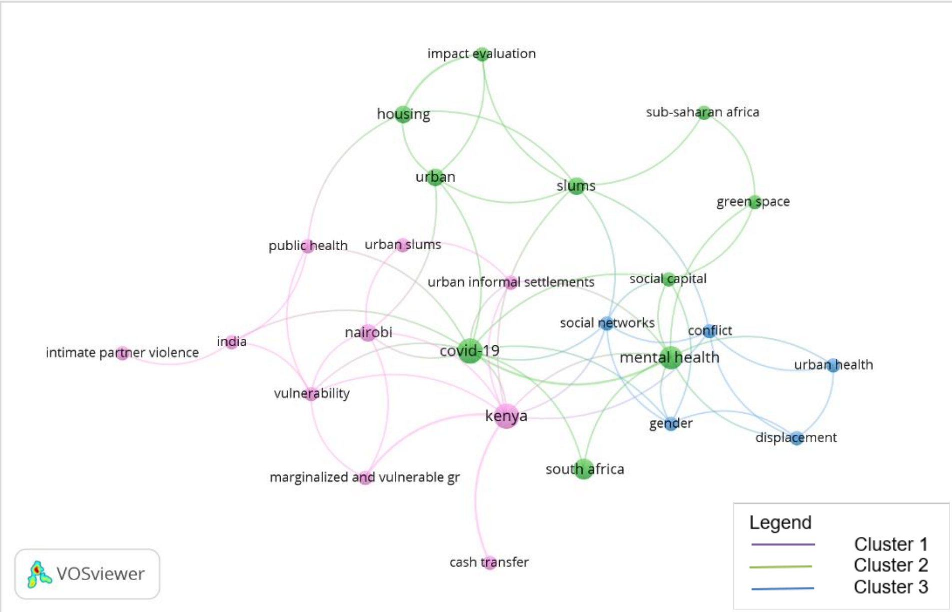

Fig. 2: Keyword analysis

The content analysis revealed views from the top ten cited studies (with at least 17 citations) centered around the established themes. The most cited document is an important metric because it highlights the most impactful and intensively researched topics [42]. Therefore, the top ten studies gave in-depth perceptions and reflected the most intensively researched areas on wellbeing and health characteristics and impacts in informal settlements. These are presented in Fig. 3 with their citation count indicated. The views from these studies are highlighted and integrated in the discussion section, in line with the deductively assigned themes/clusters.

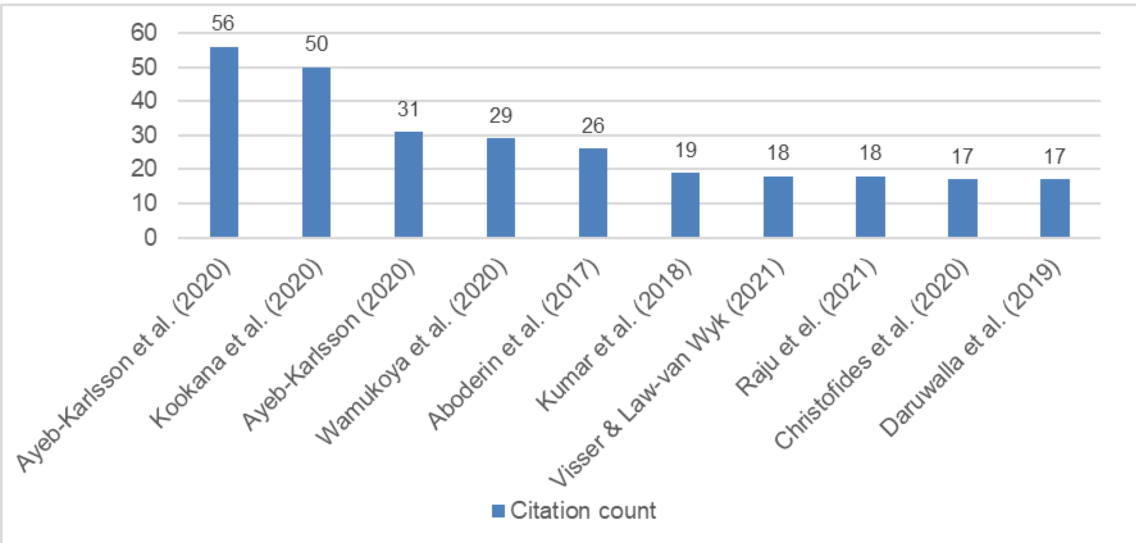

Fig. 3: Citation count of the most cited documents

5. DISCUSSION AND INTEGRATION OF BIBLIOMETRIC AND CONTENT ANALYSES FINDINGS

The above classification is slightly different from the WHO's [26] categorization of informal settlements' characteristics presented in Section 2. This is probably because of the overlap between impacts, which are highlighted in the discussed hereunder.

Cluster 1 - M*arginalisation experiences affecting livelihoods*

The first cluster included items relating to experiences that affect the livelihoods of the most vulnerable groups in communities. According to Karuga et al. [44], informal settlements inhabitants face specific vulnerabilities shaped by limitations on their opportunities and capabilities within the context of urban inequities, which affect their wellbeing. In addition, the multiple intersectionality of inequity (age, gender, identity, and disability) and positionalities within the urban informal systems of power create vulnerabilities for households/individuals, which in turn exacerbate their discrimination and exclusion. Such positionalities of intersecting vulnerabilities can lead to marginalisation and exclusion from mainstream social, educational, and cultural life; thus, affecting their cash transfer, gender-based relationships and dependencies, and public health.

The above views were shared by six of the most cited studies, which focused on marginalised and vulnerable groups in India and Kenya. Ayeb-Karlsson et al. [45], the most cited study, which used Q methodology and discourse analysis to explore psychosocial constraints in informal settlements that paralyse inhabitants mentally and geographically. Aboderin et al. [46], the fifth most cited study, analysed the health and social circumstances of two slum communities in Nairobi and advocated age-friendly initiatives to tackle challenges and impacts in informal settlements, especially for older dwellers considered as vulnerable groups. Similar views were expressed by Kumar et al. [47] (the sixth most cited) and Raju et al. [48] (the eight most cited), in their studies of adverse childhood experiences in Kenya's informal settlements, and public health challenges of migrants and urban slum dwellers during the COVID-19 pandemic in India, respectively. The authors concurred that vulnerable populations require strategically targeted welfare policies and intervention planning to support informal settlement, a view shared by Daruwalla et al. [49] and Christofides et al. [50] in their studies on violence against women.

Cluster 2 – Neighbourhood and housing impacts

The items here relate to neighbourhood and housing impacts. This is consistent with the WHO's [26] views on the impacts from the condition of housing and provision of basic infrastructure services. In agreement, the second most cited study, Kookana et al. [2], posited that limited resources in informal settlements worsen urbanization impacts. The study, which reviewed the urbanization-related challenges in developing countries in relation to globally Sustainable Development Goal 6 revealed that several cities are on the verge of water crisis and water distribution to informal settlements or slums in megacities is the most challenging. This is consistent with views expressed by the WHO [26] that informal cities' needs grow on an ad-hoc basis without adequate infrastructure provision, and this is challenging for urban leaders in addressing environmental and health challenges. Similar views were shared in the fourth most cited study, Wamukoya et al. [3], which used a descriptive-analytical approach to assess the historical dimensions, values, processes, challenges, and lessons learned from implementing a health surveillance system in two urban slums in Nairobi. The study sought an understanding of changes in the health and socio-economic status of urban slum dwellers, and the intra-urban and intra-slum differences. It also assessed household characteristics and availability of supporting amenities and services including energy, water, transport, gifts, toilet and garbage, personal hygiene, entertainment, rotating credit and saving associations, communication, salaries, electricity, healthcare, traditional or religious contributions, rent, school fees and other expenses.

Cluster 3 – Community and social environment

Items here were related to the social environment in informal communities. According to Ayeb-Karlsson [24], the third most cited in this study, these are non-economic concerns and damages in urban environments. The study noted that belongingness, identity, quality of life and social value draw people to settle. The study investigated the connections between urban climate-induced loss of wellbeing and mobility in an informal settlement in Bangladesh using storytelling methodology. As agreed by the WHO [26], better urban planning for green spaces fosters physical activity and positive social interactions. Poverty, gender inequality and weak social networks in urban settlements have also been linked to informal settlement characteristics and impacts like intimate partner violence [35], thus indicating a link with marginalisation experiences (cluster 1). Other studies concurred that the lack of community cohesion, belongingness, identity, quality of life and social value influence wellbeing in informal settlements [7,24]. Local health education and awareness campaigns, community engagement programs and social support structures could be emphasised to improve community cohesion and reduce disenfranchisement. The importance of social networks was also emphasised by Kabir et al. [6]. According to the study, social networks, which could be formal or informal, strategic, or reciprocated, are coping mechanisms in times of crisis or scarcity. Many residents foster close and trusting relationships, and a strong sense of community and integration in urban slums.

Further, more actors should engage in more expansive and collaborative thinking about strategies to improve informal settlements conditions in general, a view shared by Chumo et al. [11]. Increased collaboration between national and local governments, and momentum should be built to speed implementation of the UN Habitat III New Urban Agenda, which will help to provide basic services in a more equitable manner [8].

6. FUTURE RESEARCH

Although intersectoral collaboration was cited, for example, Weimann et al. [15], how the frameworks could work in reducing negative impacts and experiences in informal settlements was not explored. Also, according to Weimann et al. [15], there is dissonance between existing reactive, siloed approaches and the understood (and in policy documents, expressed) need for proactive, intersectoral interventions to be imagined and implemented for improving urban health and wellbeing sustainably. Future studies could focus on the nature and dynamics of such collaborations and engagements.

Further, only one study, the seventh most cited, was found that focused on university students [13]. More attention should be given to this important population group whose success at education and the future of an economy depends on their mental health and wellbeing. In addition, two useful tools for building resilience in social ecosystems are structured scenarios and proactive adaptive management, as expressed by Karuga et al. [44]. Resilience and adaptive management is necessary to monitor the progress of regulatory and managerial policies. Future research could focus on developing adaptive management and resilience frameworks targeted at vulnerable groups and incorporating economic and non-economic (social) welfare gains. The dearth of research into the subject in developing countries demonstrate the need for further research in this area, especially as informal settlements issues are greater there when compared to the developed ones. Additionally, there was no study found that measured the impact of informal settlements' characteristics on the health and wellbeing of the citizenry. Although Weimann et al. [15] acknowledged impacts, which may vary depending on geography scales (neighbourhood or community), gravity (hard or soft) and nature (direct or indirect), the extent of the impacts was not demonstrated or measured. This could be the focus of future quantitative studies.

7. CONCLUSION

The study explored priority areas in research on the characteristics of informal settlements that have implications for health and wellbeing of the settlers. Through bibliometric and content analyses, the study revealed that these can be categorised into marginalisation experiences that affect livelihoods, neighbourhood and housing, and community and social attributes of the settlements and residents. There is evidence that social networks are a coping mechanism for informal settlement challenges such as crisis or scarcity. Further, it was found that gender inequality, poverty and weak social networks are linked with partner violence which have implications for the health and wellbeing of the settlers. The study also found that these contributed to the status quo in informal settlements. Therefore, attention to neighbourhood characteristics and social networks/relationships to foster community engagement and enhance conscientiousness regarding health and safety standards in housing would go a long way in improving the status quo in informal settlements. Further, there is also an underrepresentation of studies in developing countries on the subject.

Informal settlement improvement efforts should focus on reducing crowding, providing access to basic services, and intervention/support systems within the community and governance. Vulnerable groups assistance programs and community engagement should be implemented to improve social inclusion/cohesion, which will in turn improve mindfulness, strength, and capacity to support individual and households' livelihoods. There is no shortage of studies exploring the concepts of health in informal settlements, including the current desktop study which is limited in the absence of primary data. However, there is a need for more empirical studies on health and safety in informal settlements, specifically on the impact of the characteristics. More research into the subject that focuses on developing countries is also recommended.

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MONITORING CLIMATE FORCERS FROM HEAVY CONSTRUCTION EQUIPMENT EMISSIONS IN A DIGITAL TWIN FRAMEWORK

Lylian M. Andrade[1], Jochen Teizer[2]

[1]Sustainable Construction Center, Danish Technological Institute (DENMARK)
[2]Dept. of Civil and Mechanical Engineering, Technical University of Denmark (DENMARK)

Abstract

Construction equipment operations are major sources of climate forcers, aka. Greenhouse Gas (GHG) emissions and air pollutants such as carbon dioxide (CO2), nitrogen oxides (NOx), and particulate matters (PM). For the past years, technologies including cloud computing, the Internet of Things (IoT) and Artificial Intelligence (AI) have been paving the way toward sustainability and net zero emissions worldwide. Amongst them, Digital Twins (DT) have increasingly gained attention in several industries for its abilities of autonomous monitoring, evaluation, prediction and optimization of processes and products. The construction sector, however, is lagging behind in the adoption of DT and innovative technologies in general. DT for construction applications are still at early development stages and fully developed examples are rare. Research yet lacks realistic demonstrations and practical implementations, in particular as it relates to emissions and pollutants that can impact the construction workforce or inhabitants of the often nearby public communities. This paper aims at an early prototype of DT for monitoring and forecasting emissions data from fossil-fuel powered heavy construction equipment. A framework is proposed for a web-based DT platform for construction sites that is based on Building Information Modelling (BIM), data obtained from equipment telematics and Portable Emission Measuring Systems (PEMS), for providing services such as data visualization, performance control, emissions monitoring, and emissions prediction. Two implementation tests were conducted – one with artificial data for validation of the data processing methods with ground truth information – and one with data collected with PEMS for evaluating the results with real emissions data. The initial results show that the applied methods perform successfully as applied to concrete pile driving activities. Although more tests are needed from real site operations, including the numerous and various other types of equipment, the work identified already some of the benefits towards greener construction sites and the limitations that require further work.

Keywords: Air pollutants, construction equipment site operations and logistics, greenhouse gas emissions, digital twin, internet of things, non-road mobile machinery, portable emission measurement system.

1 INTRODUCTION

The construction sector is one of the main sources of emissions globally. Typical construction processes use various construction equipment and resources, producing different forms of waste and pollution, and consuming significant amounts of energy. In the European Union (EU), the construction sector is responsible for over 35% of EU's total waste generation and an estimated 5-12% of total GHG emissions [1]. Consequently, the urgent need for greener construction is being addressed by several world climate agendas such as the European Green Deal, which aims for climate neutrality by 2050 through the green and digital transformation of EU sectors [2].

Over the past years, Building Information Modelling (BIM), Internet of Things (IoT) and Artificial Intelligence (AI) methods and technologies have emerged in the building sector, creating opportunities for improving sustainability on construction projects and reducing the environmental impact at construction sites. Drawn upon these, the Digital Twin (DT) concept – commonly referred to as the virtual copy of a physical asset – has been widely embraced across manufacturing industries for real-time monitoring, predictive analytics, and performance optimization of assets. Similarly, DTs have been drawing attention in the construction sector and are expected to have a high impact on the so-called twin transition (green and digital transition) of the sector, sustained by the European Green Deal objectives.

It has been noticed that research on DT within the Architecture, Engineering, and Construction (AEC) sector has mainly focused on building operation and facility management, i.e. indoor climate. Until recently, there has been little interest in implementing DTs at the construction stage. This is probably due to the dynamic nature of construction sites (change of facilities, equipment, materials, layout, etc.), and the involvement of several stakeholders, which increases the difficulty in monitoring processes closely. A few studies have identified that DT could be promising for optimizing construction workflow [3] as well as to reduce construction emissions [4]. Most of the previous research, however, is rather conceptual and missing technical implementation. Particularly heavy construction machinery, typically used in earth and foundation works, tends to consume large amounts of fossil fuels and release several types of pollutants. As identified by [4], using digital twins for monitoring and forecasting emissions from construction equipment could help minimize construction site emissions in the future. However, more studies on practical frameworks, technologies and commercial solutions for developing such digital twins are necessary to demonstrate meaningful results. This paper's purpose is to develop a DT for monitoring and forecasting emissions produced by heavy construction equipment and investigate its implementation in a real construction project.

2 DIGITAL TWINS AND HEAVY CONSTRUCTION EQUIPMENT EMISSIONS

2.1 Concept and history

The concept of the DT originated in 2002, when Grieves presented the "Conceptual Ideal for Product Lifecycle Management" at the University of Michigan. In his proposition of the "Information Mirroring Model" [5] was a product (or system) that would consist of the physical space (the real product), a virtual space that represents the physical product, and a bidirectional information flow between the two spaces throughout the product's lifecycle. In addition, the virtual space would contain other virtual sub-spaces that simulate the product in different conditions. The term "Digital Twin", however, was first mentioned in 2010, in National Aeronautics and Space Administration (NASA)'s technology roadmap by [6] and they defined it 'an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin'' [7]. Several definitions followed over the years and may vary significantly based on the application field, making it difficult to find a consensus across sectors. The Digital Twin Consortium, founded in 2020, for example, defined a DT as: "A virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity" [8].

It is also found in literature that terms such as Digital Model and Digital Shadow are sometimes used interchangeably with Digital Twins. The three terms, however, differ with respect to the way data is exchanged between the virtual and physical assets, as depicted in Fig. 1. According to [9], when the data between the physical and digital objects are exchanged manually (e.g., twin is not connected through the IoT) this is simply a Digital Model. If there is an automated data flow from the physical object to the digital object, but not the other way around, one may call it a Digital Shadow. If there is an automated data flow in both directions, it qualifies a Digital Twin. Moreover, many people tend to use the term DT incorrectly when describing as-built 3D models. While a DT in the construction phase includes the as-built 3D model, it also reflects both the real-world conditions at any point in time [10] and simulates predictions of future project states. This then can influence information-based decision making and lead to knowledge generation. Therefore, [11] conducted a comprehensive digital review and identified that over half of the publications reviewed actually studied a 'Digital Model' or 'Digital Shadow', although authors referred to it as a Digital Twin.

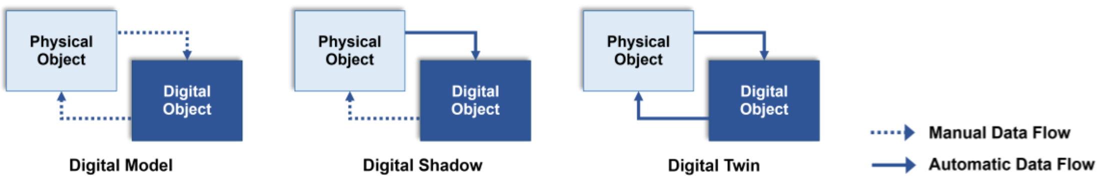

Figure 1: Data flow in digital models, digital shadows and digital twins (f.l.t.r. image) [9].

2.2 Features

While different DTs may have specific fit-for-purpose functionalities, some features are expected to be generic across sectors. [12] studied several DT use cases across industries and identified the following key abilities of Digital Twins: (1) Sensing for real-time data gathering, (2) monitoring is realized when the sensed data has been processed for real-time visualization, evaluation and acting, (3) knowledge storing that allows the DT to learn, reason and take decisions, (4) simulation as the capability to simulate real-world things and behaviours (based on different given inputs) with a high level of fidelity (a key DT feature), (5) prediction as the forecasting of physical states over time based on current and historical data inputs and outputs, (6) optimization to allow for solving an optimization problem in connection to operating the asset at maximum efficiency according to its goals.

While a fully realized DT would contain all these abilities, DTs may be developed for specific purposes and/or at stages where some features may not be required yet. Of the abilities described above, the DT presented in this paper will address sensing, monitoring, and prediction features.

2.3 Architecture and enabling technologies

As seen from the previous definitions, DTs are based on the synchronization of a physical asset with its virtual twin through highly efficient data exchange. Thus, the main components defining the dynamics of Digital Twins are: (1) the physical entity; (2) the virtual entity; and (3) the two-way data link between them [13, 14]. The data link is enabled by effective networks and devices (e.g., the IoT) that guarantee the connection and continuous data updates. The DT receives dynamic (frequently sensed) data from the physical entity and its surrounding environment and sends back to its physical twin (or to domain experts) predictions and recommendations for system maintenance and optimization [15]. According to [14], the final part (4) of a DT is the user's experience, since a DT is designed to meet specific goals and services for its users (managers, operators, etc.). The logical structure of a DT is depicted in Fig. 2.

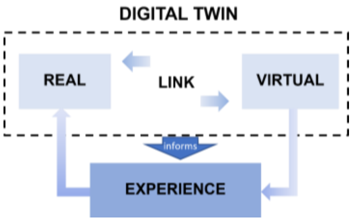

Figure 2: Basic structure of DT components [14].

2.4 Applications

The concept of DTs in the AEC industry has been heavily associated with BIM - a set of methods and technologies to leverage information management throughout the lifecycle of built environment assets. In fact, researchers believe that BIM laid the foundation for the emergence of the DT in this sector [16]. For this reason, a vast majority of studies on DTs in the AEC industry have relied on complementing BIM with IoT technologies for integration and visualization of data in building information models. A few studies have also investigated the integration of BIM and IoT technologies for monitoring activities and emissions at the construction site.

For instance, [17] proposed the concept of tracking the location of equipment, machine learning algorithms for processing the data, and finally integration of relevant information into a 4D BIM environment while supplying an additional web management dashboard for the end users. [18] investigated a framework for the integration of environmental and position data collected from sensors in a cloud-based BIM platform for safety and health monitoring. They concluded with several worthwhile applications for end users that can protect the lifes and health of the workforce. [19] presented another web application built with Autodesk Forge, for visualizing emission data produced by heavy construction equipment in a BIM-based construction site layout model.

These studies demonstrated that BIM and IoT integration facilitates the monitoring component of Digital Twins within building and construction. [3], however, stressed that DTs are not merely extensions of BIM models combined with real-time data from the physical environment. The DT should be a comprehensive solution that prioritizes closing control loops; therefore, it should not only monitor but also evaluate and improve through actionable decision making.

Meanwhile and although often lacking full-scale demonstrations, many researchers already studied DT frameworks in the context of building facility management. For example, [20] developed a DT framework for controlling energy efficiency and comfort in buildings based on a model predictive control (MPC) algorithm. [21] proposed a DT framework for supporting buildings operation and maintenance and demonstrated it with a case study at a university campus.

As for DT in the construction phase, research is relatively new. [12] conducted an extensive literature review to identify the main use cases of DTs at the construction stage: Automated site progress monitoring, real-time multi-layered data visualization, real-time safety performance detection, integrated handover to operation phase, nD BIM clash detection simulations, optimized construction logistics, integrated and adapted scheduling, and web-based supply chain data exchanges. Some of which are already explored, for example, [18] on DTs for construction safety.

With the purpose of reducing emissions in construction sites, [4] presented a first concept of a Digital Twin for Construction Emissions (DTCE) – a conceptual DT framework to monitor, predict and reduce emissions from site operations.

2.5 Quantification of heavy construction equipment emissions

Heavy equipment, also often referred to as Non-Road Mobile Machinery (NRMM) is responsible for a large amounts of GHG and air pollutants emitted during construction works [23]. Currently, most heavy construction equipment are still powered by diesel or petrol-fuelled engines [22, 24]. These engines produce various types of gases such as Nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC), which are not only harmful to the environment (e.g., global warming, acid rain and reduced soil nutrients) but also pose damaging effects on human health [25]. Exposure to high levels of PM and NOx can lead to respiratory illnesses, decreased lung functions and cardiovascular diseases [26].

[22] illustrated how drastically the EU emission standards and regulations limited NOx and PM for NRMM as it tightened these since 1999 for the Stage I to V vehicles [27]. Strict emission thresholds exist for CO, HC, NOx and PM in g/kWh (grams per kilowatt-hour) for the different engine categories. The emission standards' thresholds are based on dynamometer engine tests performed in laboratory, governed by ISO No. 8178. The test involves operating the engine on steady-state conditions (constant engine load and speed) at different operation modes [28]. It is, therefore, expected that engine emissions would vary and may exceed limits when operating in real-world conditions at complex and discontinuous duty cycles [22, 29]. Besides, even the newest manufactured machines comply with stricter standards, the engine's performance decreases by wear over time, increasing again the emissions [30].

Quantifying emissions from non-road machinery is intrinsically more difficult than from on-road vehicles due to NRMM's intermittent duty cycles [31]. According to [23], a large number of factors affect NRMM engines' emissions and many are difficult to measure. [23] identified several factors influencing equipment emissions and analysed their degree of impact on emission rates. The factors were divided into four categories and are shown in Fig. 3. It was found that engine power, equipment conditions and equipment operator skills were the most significant factors affecting fuel consumption and emissions.

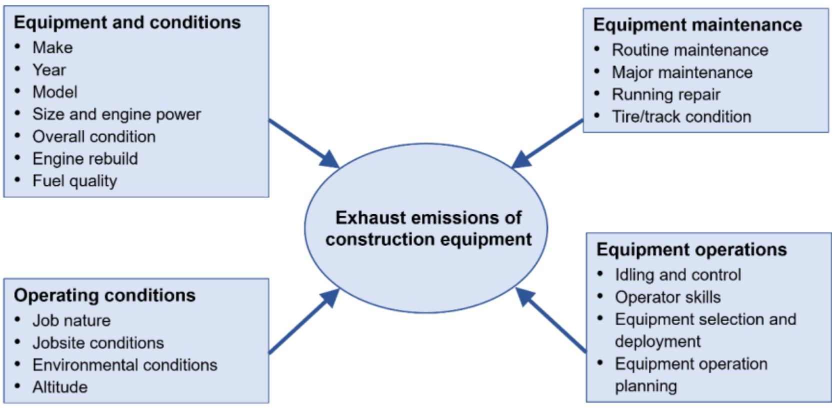

Figure 3: Impact factors on construction equipment emissions [23].

Another method for quantifying equipment emissions is to collect such data during field operation, through on-board measurement instruments. Currently, a common on-board instrument is the Portable Emissions Measurement System (PEMS). PEMS is a device mounted on vehicles that can measure second-by-second concentrations of gases and particles in the engine's exhaust [32]. In the literature, several studies have used and investigated PEMS to measure real-world emissions from heavy diesel equipment in use. [25, 28, 31, 33] collected PEMS data from several NRMM to obtain and compare time-based (g/h) and fuel-based (g/kg) emissions rates for different engine conditions and operation modes. All studies reported significant differences between emission factors for different operation modes. [25] found that equipment with older engines emitted higher levels of emissions, probably due to poorer combustion as consequence of engine wear. [19, 22] introduced the use of a Simplified Emission Measurement Systems (SEMS) for economical and practical implementation reasons.

3 METHODOLOGY

The aim of the research was to develop a framework of a construction site DT for monitoring and forecasting emissions from heavy construction equipment and investigate its implementation. The framework's main logic consists of integrating heavy equipment emissions data and construction data within a Digital Twin Platform (DTP) that can serve several applications. The DTP is a cloud-based web application for access in a web browser. Thus, three main processes outline the framework: (1) Developing the DTP based on a state-of-the art review and earlier work, (2) collecting construction-related data utilizing information exchange with the project management and implementation of IoT devices (e.g., equipment emissions data, construction site models, schedules, and other-related project information), and (3) processing and visualizing data within user-accessible dashboards of the DTP.

3.1 Development of Digital Twin Platform

Fig. 4 shows an overview of the DT framework which results in a DTP that provides services for its users (i.e., managers and workers, incl. equipment operators) for informed decision-making. Autodesk Platform Services (APS) consisting of web service Application Programming Interfaces (APIs) was selected. APS allows developers to build web applications and solutions leveraging BIM workflows and Autodesk products which the project used. The main programming language was JavaScript, supported by HTML (Hyper Text Markup Language) and CSS (Cascading Style Sheet), commonly used for web design. The DTP was built using NodeJS for the server environment.

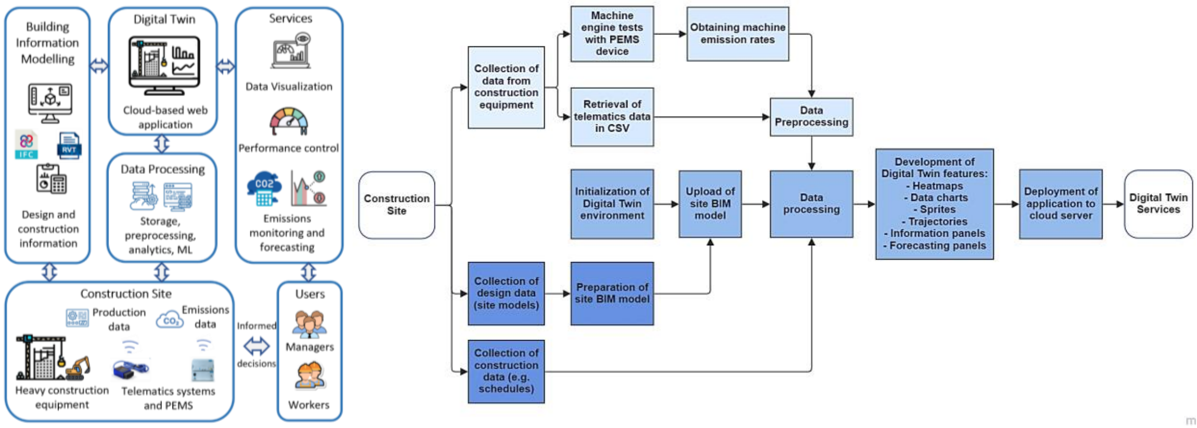

Figure 4: Overview of DT framework (left) and development steps (right image).

3.2 Design of construction site model

The construction site for the case study is called "Mindet 6". Located in Aarhus, Denmark, it is to become a 144 m multi-story office and residential building. At the time of this project, the construction was at the foundation stage where a secant pile wall was being executed (Fig. 5). The main construction site elements (containers, fences, gates, walking paths, roads, cones and machines) were modelled in Revit according to the provided site layout plan, pictures, and site visits. Two heavy machines were operating at the site at the time of data collection and were included in the model: A drilling rig (BAUER BG 36) and a supporting excavator (Hitachi ZX135US-6). When preparing the model for the DT, elements should contain enough information for a BIM Level of Detail (LOD) of at least LOD300. That is, the models' elements should be accurate in terms of quantity, size, shape, location and orientation.

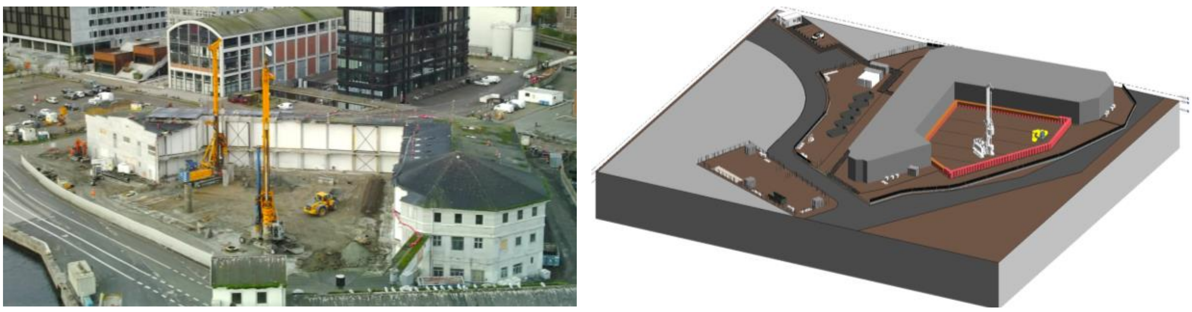

Figure 5: Case study construction site (foundation works and BIM-based site layout model).

3.3 Collection of equipment emissions data

The method for collecting equipment emissions data in this DT framework relies on combining machines' telematics data with emission rates obtained from the machines using PEMS technology. Most heavy-duty vehicles have CAN-bus (Controller Area Network) systems that enable the communication between the vehicle electronic control units. This allows for data to be logged, providing high frequency operational data on the machine, such as fuel consumption, engine speed, engine load, driving speed, among others. Here, the BAUER BG 36 recorded its telematics data at a 1 Hz frequency rate and logged it in a CSV (Comma Separated Values) file for post processing. In addition, a Real-time Kinematic Global Navigation Satellite System (RTK-GNSS) tracked the vehicle's location at the same frequency.

Through PEMS installed on the equipment, it became possible to perform measurements on the machine's engine. This determined the values of NO, NO2, CO2, CO -concentrations and PN (particle number) in the exhaust pipe, which can then be used to determine emission rates in grams per kilowatt-hour (g/kWh). Emission rates should be calculated for different ranges of power, e.g., based on speed and torque values, which would provide more accurate results during different operation modes.

3.4 Pre-processing and processing of data

The pre-processing consists of retrieving the raw telematics data and preparing it for further processing in the DT. This happens in another NodeJS environment developed in Visual Studio Code, which reads CSV files from a specified location and sends it pre-processed directly into the project folder of the DT platform for processing. Firstly, the telematics dataset is converted from CSV format to JSON format, so that it can be manipulated in the DT environment using JavaScript. JSON stands for JavaScript Object Notation, where data is given in the form of data objects. Afterwards, the JSON data is filtered by removing any objects with repeated timestamps or error values. Timestamps are also converted from Unix format to date format for better interpretation. When this is done, an iteration happens through the data that executes the following for all the data objects:

- Engine power (in kW) is calculated.
- Emission rates are added from the object's values of torque and speed.
- Emission values (in g/s) are calculated by multiplying the engine power (kW) by its respective emission rate (g/kWs).

The last step in pre-processing is manipulating the dataset to contain data objects minute-by-minute instead of second-by-second. The processing of the data happens inside the DTP application, since it requires interacting with the site model displayed in a BIM viewer. Firstly, the JSON file containing the pre-processed data is read and stored in a variable called data. Secondly, the Viewer's GeoLocation Extension is called, which helps with conversions between real RTK-GNSS coordinates and the model's coordinates within the viewer. It is important to understand that when a model is loaded in the viewer, the viewer's centre coordinates are different than the model's centre coordinates. When adding position data into the viewer, they need to be viewer coordinates. After activating the GeoLocation Extension, the GNSS coordinates of all data objects are converted into viewer coordinates.

3.5 Retrieving overall machine data

This part of the script retrieves all the data objects and extracts overall machine-related information into variables for quick access. These are total operation time, driving, drilling and idling times. CO2, NOx and PM total emissions, total fuel consumption and distance travelled. The method for associating machine data with specific elements is based on creating a bounding sphere that surrounds the machine at all recorded positions and testing the intersection of the bounding sphere against other elements' bounding boxes. The radius of the bounding sphere would be the maximum distance that the machine's arm can reach from where the position is recorded. If an intersection happens, it means that the machine is working on the building element (pile), as illustrated in Fig. 6. The purpose of using bounding spheres is that construction equipment can rotate and work on multiple different elements at a time. This makes it possible to retrieve and associate machine data such as drilling time, total emissions, average drilling speed and average engine power to the execution of each pile.

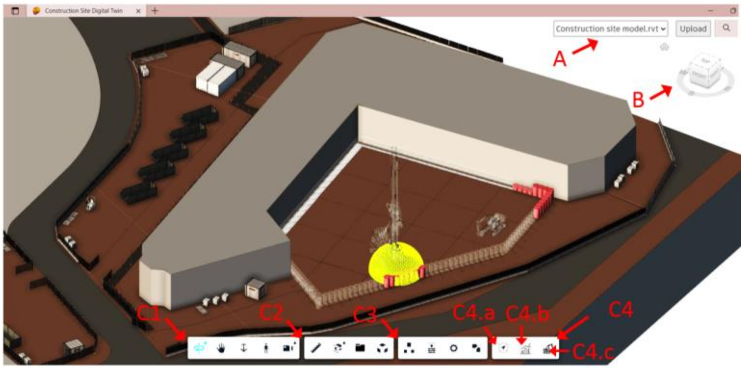

Figure 6: Web-based DTP.

3.6 Development of DT features and user interface

This section describes the four extensions that were developed for the DT platform that define features for data visualization, monitoring and forecasting, i.e., drawing of trajectories, displaying last recorded machine position, visualization of heatmaps, charts and information panels.

The DT platform is accessed in a web browser. Once the platform's viewer is initialized, the construction site layout automatically displays. The DT interface and markers in Fig. 6 show the main elements. On the top right of the page (marked with "A"), the user can upload and select models to visualize in the application. Marked with "B" is the ViewCube, an orientation and navigation tool common in BIM software for visualizing purposes, shows the current viewpoint of the model, allowing alternation between the different viewpoints. A toolbar ("C"), divided into four groups with buttons, allows the activation of different features of the DTP. The first three groups of tools ("C1-3") contain the platform's built-in buttons for model navigation and other viewing functionalities, such as camera interactions, walking-through the model from a First-Person view perspective, distance measurements, creating sections, model explosion, model browser, element properties, and viewer settings. "C4" has three buttons for the data features developed for this project's DTP, which are named: "Show live machine position" ("C4.a"), "Show activity overview" ("C4.b") and "Show machine overview" ("C4.c").

Fig. 7 (top image) show the corresponding elements of C4 that appear once clicked. The associated arrows, colours, and numbers in the figure associate the buttons with the elements they display. Accordingly, the last position of an equipment can be shown based on the processed data. The button "Show Machine Overview" opens a panel (marked as number "02"), containing in the model the overall machine information such as name, type, link to manufacturer specifications, operating times, idle times, distance travelled, fuel consumption, emissions produced (e.g., CO2, PM and NOx) and performance status. Clicking the same button for opening the panel allows other machines for selection. Selecting a each machine opens up a chart ("03" and "04") that offers a dropdown menu to alternate between other valuable pieces of information, i.e., engine power, emissions, fuel and vehicle speed over time. A button in the Machine Overview panel draws or erases the trajectory of the machines based on the position data ("05"). The button "Forecast performance" opens a panel for forecasting and comparing the emissions of different machines based on given inputs ("06"). Here, for instance, the user writes the machine model and a number of operating hours, and the output is the estimated amounts of emissions and fuel consumption, based on existing historic rates (average values, a user can set). Finally, the button "Send report" ("07") allows the user to send a pre-filled electronic mail containing relevant information to a designated recipient, for example, a message to maintenance staff.

The button "Show Activity Overview" ("08") in Fig. 7 (bottom) contains the overall information regarding the pile drilling and excavation activities, such as: start date, duration, number of piles executed or volume excavated, production rates, emission rates and activity states. The status is based on whether emissions or activity times exceed predefined thresholds. Similarly, the buttons "Forecast activity" and "Send report" display a panel for forecasting drilling emissions based on current data from the drill rig and an E-Mail window appears to send off a pre-filled work performance report ("09" and "10"). The button "Piles details" ("11") displays a chart that contains machine data associated to the production of each pile (e.g., emissions, time to construct, drill speed and average power consumption). By clicking on different piles in the model, the chart is modified with the piles' respective data. A list of all piles is displayed ("12") where a user can mark piles as "completed task". By clicking on the name of a pile in the list, the respective pile will be highlighted in the model. Lastly, the button "Piles heatmap" triggers heatmaps for the CO2, PM and NOx emissions of the piles ("13").

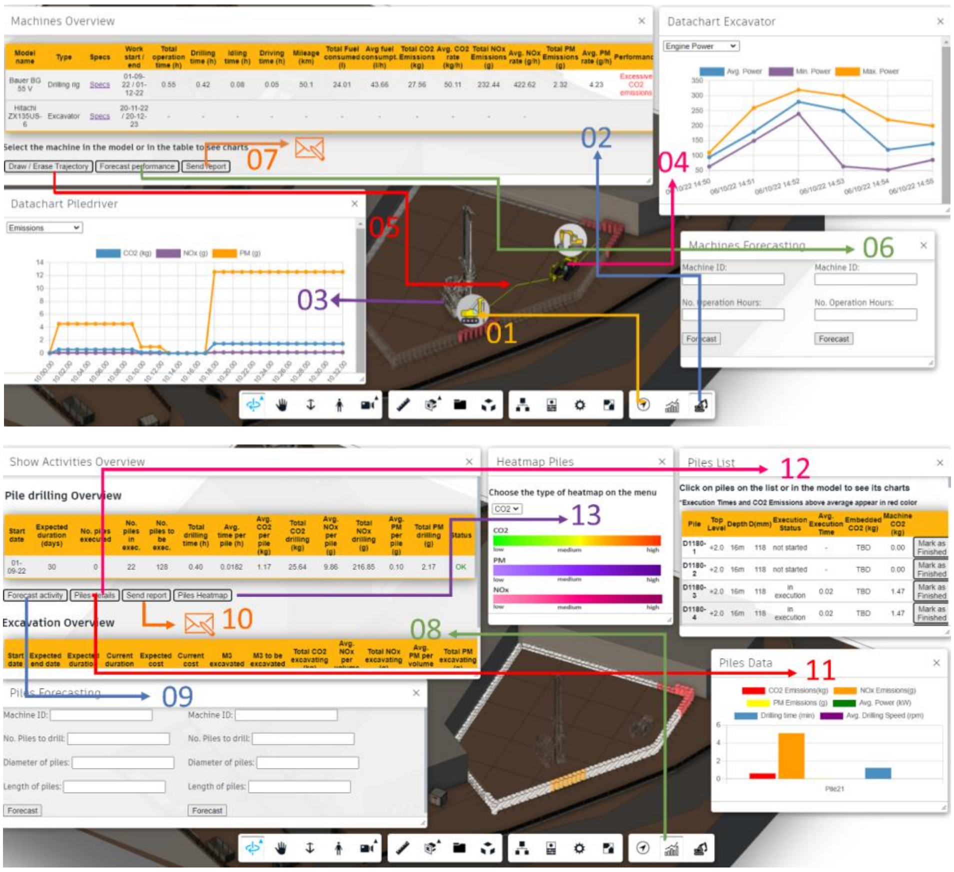

Figure 7: DT user interface: Groups and buttons (top image), activity overview panel (bottom image).

4 IMPLEMENTATION AND PRELIMINARY RESULTS

The implementation gathered PEMS and RTK-GNSS data from the pile driver (Bauer BG 36) for nearly 7 working hours. The purpose of this limited test was to evaluate how the platform performs and if valuable information allows as-performed activity analysis as well as forecasting future work tasks.

Continuous data processing in the developed DT environment took about five seconds per incoming buffer element. The error of the initially installed GNSS was high, as expected in the range of a few meters, recommending in the future to use RTK-GNSS instead.

The Machine Overview panel, shown in Fig. 8, displayed 6.85 hours (411 minutes) of total operation time, matching exactly the period of the dataset. The total amounts of CO2 and NOx emissions and the fuel consumption were also correctly shown. An alert for “Excessive CO2 emissions” was functional, given that the measured data 63.39 kg/hour exceeded the threshold for CO2 emissions that was set earlier to 30 kg/hour.

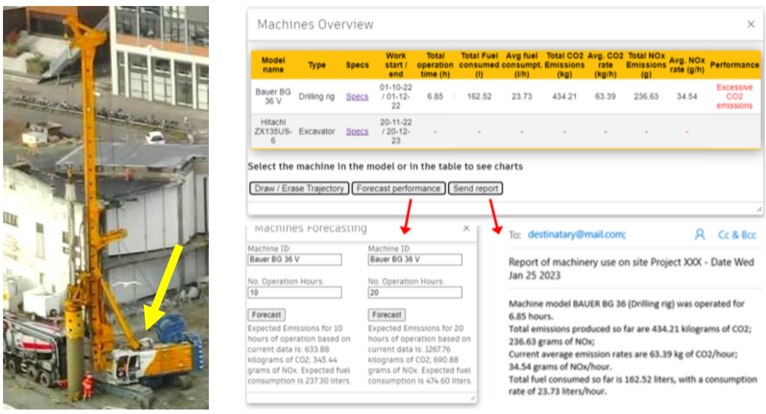

Figure 8: PEMS installed on BAUER BG 36 V.

An E-mail was successfully sent containing relevant information about the implementation test, including a forecasting report that in detail compared ten (633.88 kg of CO2) and twenty hours (twice as much) of the potential future operation. These were correct based on the given CO2 rate.

The machine charts of engine power, fuel consumption and emissions showed a similar pattern (Fig. 9). This seems logical, since emissions and fuel use often correlated with power consumption (the higher the power the higher the emissions). The engine power/load chart presents an interesting observation that the drill rig's emissions filter performs well during the drill tasks, but not so well when performing supportive tasks (e.g., lifting rebar cages, concreting; see green vs. red bracket, respectively). However, further experiments are necessary to verify this result.

The pile list and charts (Fig. 10) also provided useful insight into pile production time and amounts of emissions. Piles 23 and 24, for example, caused the highest production time and CO2 emissions. Lastly, the heatmaps indicate for various piles CO2 values in red, even for those that have little work time associated. Setting the threshold that a user can define is important not to mislead decision makers.

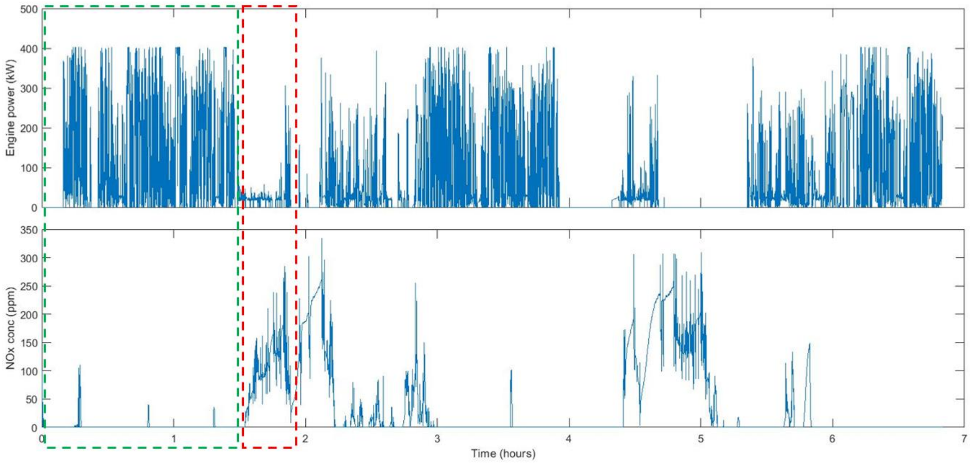

Figure 9: Engine load vs. emissions (with permission from DTI/Cordtz)

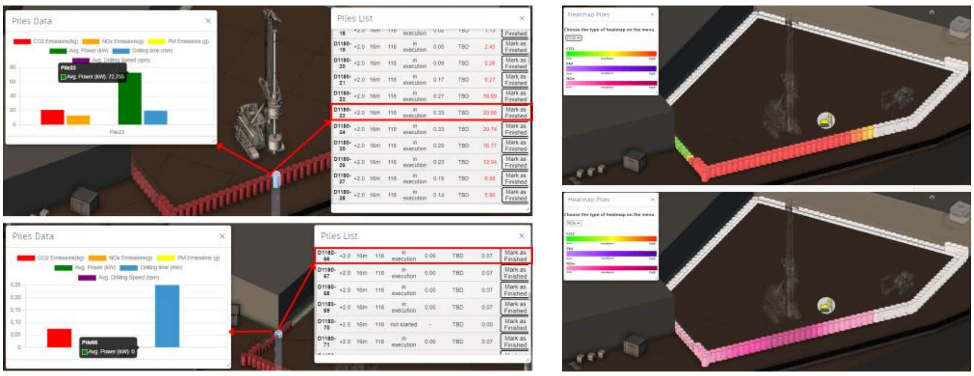

Figure 10: Comparing two individual pile performances (pile numbers 23 and 66 shown in the two left images); CO2 and NOx heatmaps in BIM viewer (two right images correspond to pile number 23 only).

5 CONCLUSIONS

Tracking and estimating emissions from heavy equipment through traditional approaches is considered challenging due to various factors involving equipment conditions and operation modes which often result in estimations that do not reflect the actual real-world emissions. This work proposed a DT framework for monitoring and forecasting construction equipment emissions based on a cloud platform, construction site layout planning in BIM, and data collection with PEMS and via CAN bus.

The developed DT framework architecture has demonstrated that web applications built with JavaScript and NodeJS were powerful solutions for granting users access to data in valuable interfaces. The DT using JavaScript provided a high degree of flexibility in customizing features and processing data at fast execution times. Other dashboards that gave restricted users access to such information can provide valuable insights into previously unavailable project data. For example, production states of individual work tasks were so far not linked to emission values. Charts and heatmaps that visualize data and link it to BIM elements allowed the association of equipment emissions with production data. This facilitated the identification of work site where more emissions were produced. Panels enabled the further autonomous comparison with predefined thresholds and issuance of alerts. The DT platform made simplistic forecasting of equipment emissions possible based on historical and current data, giving further information such as number of expected operation hours to perform a work task.

Still, human-based decision making (e.g., equipment operator, maintenance crew) could benefit from such newly generated information. This capacity can, in the future, lead to so-called building material passports as they become part of ongoing documentation efforts for the construction phase, for example, the European Taxonomy is a classification system for sustainable activities since 2022.

Overall, practicality was shown in performing tests with equipment operating on real construction site. Collecting machine emissions data minute-by-minute gave useful insights regarding to the specific construction task of secant pile drilling. Future studies are yet suggested for evaluating the DT framework in connection with long term observations of excavation activities that support detailed studies on real-time data processing and measuring its impact in decision making to reduce emissions. The need for RTK-GNSS data can be seen as a limitation of this study as it would have simplified the geo-referencing of emission values in BIM-based site layout plans and to the modelled elements. This suggest that site layout plan to be updated more frequently as one would expect it to happen in a DT.

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BARRIERS FACED BY AEC COMPANIES IN MACAO IN ADOPTING INNOVATIVE TECHNOLOGIES TO IMPROVE HEALTH & SAFETY

Kenneth Lawani[1], Farhad Sadeghineko[1], Michael Tong[1], Billy Hare[1] & Gary Ho[1]

[1]Department of Construction and Surveying, Glasgow Caledonian University, Glasgow G4 0BA, United Kingdom

Abstract

With the construction industry moving towards digitalisation, innovative technologies have become available to assist companies with improving construction Health & Safety (H&S) performance with varying success. Although these technologies have been touted as the solution for improving H&S, their adoption has been hampered by challenges and limitations surrounding these technologies. Several studies have been carried out to determine the adoption barriers of such technologies. However, existing studies does not include Macao Special Administrative Region (SAR), presenting a knowledge gap in this small Asian region. This paper aims to study technologies employed for H&S improvement purposes and determine the barriers with adopting such technologies, including Building Information Modelling (BIM), Drones, Virtual Reality (VR) and Augmented Reality (AR), Wearable Sensing Devices (WSDs) and Exoskeletons. This study explored existing literature to determine the type of barriers experienced within the construction industry and an online descriptive questionnaire with 40 AEC professionals operating in Macao SAR participated in the survey. The data collected were analysed and ranked to ascertain the top three barriers. The results indicate a lack of technology adoption in Macao's construction industry. Some of the participants were unaware of some of the technologies used for improving the H&S in building projects. The findings also revealed that a lack of demand from clients, senior management, and the government was a barrier to adoption and prevalent throughout the top three of all five technologies.

Keywords: Health and Safety (H&S), Macao SAR, Building Information Modelling (BIM), Virtual Reality (VR), Augmented Reality (AR), Exoskeleton, Wearable Sensing Devices (WSD).

1. INTRODUCTION

The construction industry is one of the fastest growing industries globally and significantly contributes to gross domestic product across different nations [1]. Studies have reinforced the growing awareness of occupational safety and health risks in the construction industry and it is progressively placing more emphasis on the adoption of innovative technologies [2]. However, no study has been conducted to identify the level of adoption of these technologies nor is there any that have reviewed the barriers regarding adopting these technologies within the construction sector in Macao Special Administrative Region (SAR). The construction industry is often perceived as amongst the most hazardous industries to work in because of the significantly high accident and fatality rates in comparison to other industries [3]. This has made the industry come under a lot of scrutiny for its health and safety performance resulting from the traditional safety management methods still being widely adopted that are reliant on traditional observations, instinct, and the perceived expertise of safety managers [4]. It is considered that the traditional practices of safety management are very manual, time-consuming, selective, inefficient, and error-prone [5]. The construction industry's acceptance and adoption of digital technologies have been slow, and it is believed that the continuous unacceptable performance in construction safety can be linked to this effect [6]. Furthermore, there are indications that construction safety performance of site operatives could be improved using innovative technology such as exoskeletons or wearable sensing devices [6]. Existing studies have identified innovative technologies being used on construction sites with associated barriers to their adoption, e.g., cost, and external influence [7, 8]. However, these studies do not reflect the views of the AEC contractors/workers in Macao where new legislation in innovative technology is sparse [9]. As the construction industry becomes more digitized, it is believed that innovative technologies are now available to assist companies with improving their construction health and safety performance and this paper explores such technologies and the barriers preventing architectural, engineering and construction (AEC) contractors in Macao from adopting them.

2. LITERATURE REVIEW

Macao (SAR) is a collection of small islands of around 30-square kilometres with a population of about 680,000 inhabitants, making it the most densely populated region globally [10]. As of the third quarter of 2021, the construction industry ranked the third highest in terms of number of operatives involved in accidents and the number of days lost due to accidents respectively [11]. This indicates that more needs to be done to improve the health and safety performance in the Macao construction industry, which is still considered to be a dangerous industry to operate in. The construction industry has adopted different types of technology and studies by [12, 13] both conclude that technology such as drones have the ability to move quicker than humans and can get to areas on site that would usually be difficult to access and they can be fitted with sensors, radar, and communication devices to carry out real time data transfer. From a construction health and safety point of view, one main application of drones on construction sites is carrying out inspections [12], and this can potentially eliminate several site hazards that would occur through traditional inspection methods e.g., falls from height. There are suggestions indicating that early utilization of BIM, and having the relevant information and models in place, can greatly assist with deciding how much construction work is carried out offsite with the potential to reducing site related accidents [14]. The adoption of Virtual Reality (VR) and Augmented Reality (AR) technologies within the AEC sector are essential as they can aid and ease communication [15], used to improve safety training delivery and workforce engagement, including undertaking some construction tasks remotely which removes construction workers from site hazards. There are suggestions that the traditional safety training and delivery methods are not as engaging enough and VR for safety training is gaining traction for construction professionals to aid in hazard identification [16, 17]. This is because the adoption of VR/AR could make hazard identification more efficient without the workers being exposed to real-life risks.

Wearable sensing devices (WSD) often come in the form of wristbands, smart hard hats, safety vests, boots, clips and tags [18, 19]. The invaluable benefits of WSD is its capability to track and transfer a wearer's information in real time whilst providing continuous monitoring on several construction hazards, e.g. individuals with high-risk health issues with WSD can potentially provide early warning alerts. One of the most important applications of WSD tested in the work environment is their ability to notify safety professionals or project team members when an injury or accident happens, whilst also pinpointing the exact location of occurrence [20]. Construction work activities are classed as labour-intensive and could require workers to manually carry out heavy-duty repetitive tasks like lifting or moving materials, paving, and surfacing [21]. Such physically demanding tasks expose workers to work-related musculoskeletal disorders (MSD) and studies conducted by [22, 23] suggests that the impact of MSD can be reduced using exoskeletons, as they can increase the ability of a wearer to move faster and lift or carry heavier loads whilst exhibiting greater endurance. Although extant studies indicate the benefits of the use of safety technology on construction projects, there are still reservations and some level of uncertainty within the industry regarding the adoption of these technologies. It is suggested that the principal reason for this slow adoption could be linked to the high capital spending and recurring maintenance costs that comes with innovative technologies [24]. Studies allude that initial upfront cost, lack of client backing, its disruptive nature and interference with normal working practices are some primary barriers [7, 8]. In addition, the lack of trust within the industry, poor engagement and collaboration [25] may not be beneficial for technological adoption. There is also the lack of encouragement or interest to implement BIM by the client or Government [26]. Issues such as the cultural resistance to change, introduction of digital transformation which some perceive as a highly disruptive enterprise that impact existing construction working cultures, hesitancy and lack of skills or motivation to adopt new processes have been identified by literature [27, 28] and all these leaves the construction industry behind in the push towards digitalization.

3. STUDY DESIGN

This study adopted the survey technique to reflect on the views of the participants regarding the adoption of innovative technologies in construction. The Microsoft Forms online self-completed questionnaire was deployed due to its flexibility and efficiency of data acquisition from a sample of workers involved in the AEC construction industry in Macau [26]. The closed-ended questions adopted a five-point Likert scale (1 = biggest barrier and 5 = smallest barrier) to indicate level of agreement of participants, regarding the adoption barriers for these technologies and to affirm participants' awareness of the technologies that their companies currently use. An initial pilot study was conducted to determine the validity of the questionnaires with five respondents in the Macao construction industry. Some questions were revised for clarity before finally deployed to construction industry professionals operating in, and familiar with the Macao construction industry practices. Purposive sampling strategy with snowballing was adopted [29] and [30] suggest that the snowballing approach is applicable when population size is small and challenging. Forty-nine returned questionnaires using a combination of messaging service apps - WhatsApp, WeChat, and emails containing the hyperlink to the questionnaire was used. As part of the data analysis, the raw data was cross examined and nine participants were excluded due to the participants not meeting the study requirements; for example, participants not employed in Macao and non-completion of the requisite questions.

This study ranked each barrier to adoption in terms of the most to the least impactful, an approach used by [7] in their study. The mean ($\bar{X}$) was calculated to determine the value of where each barrier was positioned in the Likert Scale. The standard deviation (s) was calculated to measure the variance between responses, with a value of ≤ 1.64 deemed acceptable [7]. To determine the relative importance of each barrier, the MNV (Mean Normalised Value) ((Actual $\bar{X}$ - Minimum $\bar{X}$) ÷ (Maximum $\bar{X}$ - Minimum $\bar{X}$)) was calculated and any value ≥ 0.5 is deemed a critical factor [7].

Cronbach's alpha reliability test was carried out to test the internal consistency of the questions based on the studies [15, 32], as follows:

$$\alpha = \left(\frac{k}{k-1}\right)\left(\frac{s_y^2 - \Sigma s_i^2}{s_y^2}\right)$$

The calculated values were 0.60 (BIM), 0.65 (Drones), 0.64 (VR/AR), 0.61 (WSDs) and 0.71 (Exoskeletons). The Cronbach alpha values for BIM, Drones, VR/AR and WSDs are below the stated 0.70. However, a value ≥ 0.6 is also deemed reliable and acceptable [31].

4. FINDINGS AND DISCUSSIONS

The demography of the final 40 study participants are shown in Table 1.

Table 1: Demographic information of participants

Category	Classification	Frequency	Percentage %
Company Type	Client	6	15
	Main Contractor	13	32.5
	Subcontractor	12	30
	Consultant	9	22.5
Total		**40**	**100**
Job Role	Front Line Staff	6	15
	Engineer	12	30
	Manager / Director	13	32.5
	Health & Safety Professional	6	15
	Commercial Role	3	7.5
Total		**40**	**100**
Company Size	< 20	13	32.5
	20 - 50	10	25

	51 - 250	7	17.5
	> 250	10	25
Total		**40**	**100**
Industry experience	< 5 years	6	15
	5 - 10 years	11	27.5
	11 - 20 years	13	32.5
	> 20 years	10	25
Total		**40**	**100**

The findings for the adoption barriers for BIM, Drones, VR/AR, WSD and Exoskeletons utilised the five-point Likert and ranked the adoption barriers from first to last. Using the sample (n) from the forty respondents, the mean (X̄), standard deviation (s) and the mean normalised values (MNV) were calculated to determine how each adoption barrier ranked. Any MNV value of 1 indicated the greatest adoption barrier.

The findings indicate that 22.5% (9) respondents currently adopt BIM within their organisations while 60% (24) of the respondents do not use BIM. The rest of the respondents 17.5% (7) alluded that they were unaware of BIM and unaware if their companies adopt BIM as a tool. The top four barriers (Table 2) regarding BIM adoption was "Lack of demand – Client, Local Government or Senior Management" (with X̄ value of 4.48, s of 0.78 and an MNV of 1.00), "Cultural resistance" (with X̄ value of 4.33, s of 0.86 and an MNV of 0.91), "Cost Concerns" (with X̄ value of 3.90, s of 1.19 and an MNV of 0.64) and "Lack of standard contracts incorporating BIM usage" (with X̄ value of 3.75, s of 0.95 and an MNV of 0.55). An MNV < 0.5 is not deemed a critical barrier and the findings suggest that the critical barriers to the adoption of BIM in Macau SAR A1, A2, A10 and A12 (Table 2).

Table 2: BIM adoption barriers

Barriers	X̄	*s*	MNV	Ranking
A2. Lack of demand - Client, Local Govt or Senior Management	4.48	0.78	1.00	1
A10. Cultural resistance	4.33	0.86	0.91	2
A1. Cost Concerns	3.90	1.19	0.64	3
A12. Lack of standard contracts incorporating BIM use	3.75	0.95	0.55	4
A3. Poor collaboration	3.63	0.95	0.47	5
A9. Lack of standards and unclear regulations for standardization	3.63	0.93	0.47	5
A11. Legal concerns - responsibility and liability for model	3.38	1.03	0.31	6
A5. Lack of skilled professionals	3.33	0.94	0.28	7
A8. Lack of experience	3.20	1.09	0.20	8
A6. Computer systems and various software interoperability	3.20	0.79	0.20	9
A7. Security concerns using BIM	3.00	0.88	0.08	10
A4. Limited training availability	2.88	1.18	0.00	11

n = sample; X̄ = mean; *s* = standard deviation; MNV = mean normalized value

The lack of demand from clients, Government or Senior Management is consistent with research carried out in China which identifies this as the main adoption barrier to BIM. The lack of support from senior management can create obstacles to BIM implementation [26], and client support is imperative as it affects whether BIM is used on a project. There are suggestions that the government can intervene by introducing new policies [26]. Cultural resistance was one of the main barriers suggesting that this is still an issue that Macao need to overcome. Cost was also identified as one of the top barriers preventing the adoption of BIM in Macao and [26] indicate that the expensive cost of software resulting in a marginal return on investment is a barrier to BIM adoption.

The findings (Table 3) suggest that the top seven barriers to drone adoption satisfy the threshold of being considered as critical factors (MNV ≥ 0.5). The critical factors are "Lack of demand – Client, Local Government, or Senior Management" (with $\bar{X}$ value of 4.35, s of 0.86 and an MNV of 1.00), "Liability and legal concerns using drones" (with $\bar{X}$ value of 4.05, s of 0.90 and an MNV of 0.86), "Can only be used on certain projects" (with $\bar{X}$ value of 3.83, s of 0.87 and an MNV of 0.76), "Other safety challenges/ concerns generated by drones" (with $\bar{X}$ value of 3.75, s of 0.87 and an MNV of 0.73), "Cost concerns" (with $\bar{X}$ value of 3.60, s of 1.06 and an MNV of 0.66) and "B4. Working area(s) / conditions too congested" (with $\bar{X}$ value of 3.60, s of 0.84 and an MNV of 0.66), and lastly, "Dynamic site conditions – hard to use drone" (with $\bar{X}$ value of 3.35, s of 0.89 and an MNV of 0.55).

Table 3: Drone adoption barriers

Barriers	$\bar{X}$	*s*	MNV	Ranking
B14. Lack of demand - Client, Local Govt or Senior Management	4.35	0.86	1.00	1
B5. Liability and legal concerns using drones	4.05	0.90	0.86	2
B12. Can only be used on certain projects	3.83	0.87	0.76	3
B8. Other safety challenges / concerns generated by drones	3.75	0.87	0.73	4
B3. Cost concerns	3.60	1.06	0.66	5
B4. Working area(s) / conditions too congested	3.60	0.84	0.66	5
B13. Dynamic site conditions - hard to use drone	3.35	0.89	0.55	6
B2. Advanced technical knowledge and experience required	3.18	0.68	0.47	7
B7. Extensive training and certification required	2.95	0.71	0.36	8
B9. Drone and operator communication difficulties	2.88	0.69	0.33	9
B6. Lack of regulations	2.68	0.97	0.24	10
B11. Drone awareness lacking	2.45	1.06	0.14	11
B10. Challenges operating drone at night	2.28	1.22	0.06	12
B1. Weather condition challenges	2.15	1.05	0.00	13

n = sample; $\bar{X}$ = mean; *s* = standard deviation; MNV = mean normalized value

The lack of demand from clients, either Government or Senior Management is not ubiquitous in extant literature and has not been ranked in current literature on drone adoption barriers. However, there are suggestions that the lack of support from owners and project managers influence the use of drones on site in Macau. Liability and legal concerns inclusive of personal injury, damage to property caused by drone pilot fault, privacy invasion, trespassing, land rights or insurance concerns are amongst the adoption barriers for drones on construction sites [13, 12]. The fact that respondents indicated that drones can only be used on certain projects suggests the lack of hands-on experience with the technology may be a moderating factor.

Table 4 depicts the top three factors that are considered as barriers to VR/AR adoption and meet the threshold as critical factors (MNV ≥ 0.5). The critical factors are “Lack of demand – Client, Local Government or Senior Management” (with $\bar{X}$ value of 4.53, s of 0.75 and an MNV of 1.00), “Cultural resistance” (with $\bar{X}$ value of 4.48, s of 0.82 and an MNV of 0.98), and “Cost” (with $\bar{X}$ value of 4.08, s of 0.97 and an MNV of 0.80).

Table 4: VR/AR adoption barriers

Barriers	$\bar{X}$	*s*	MNV	Ranking
C6. Lack of demand - Client, Local Govt or Senior Management	4.53	0.75	1.00	1
C4. Cultural resistance	4.48	0.82	0.98	2
C1. Cost	4.08	0.97	0.80	3
C2. Hardware & software not advanced or easily accessible	3.38	1.03	0.49	4
C3. Lack of skills or expertise to use	3.38	0.93	0.49	4
C8. Learning curve period / technology not matured	3.05	0.90	0.35	5
C9. AR performance concerns	2.65	0.89	0.18	6
C7. AR Connection Issues (i.e., Poor WLAN & WIFI)	2.43	1.01	0.08	7
C5. Possible emotional and mental issues with wearing equipment	2.25	1.06	0.00	8

n = sample; $\bar{X}$ = mean; *s* = standard deviation; MNV = mean normalized value

The lack of demand from either clients, Government or Senior Management in the adoption of VR/AR technology shows how highly influential the clients can be in terms of adoption due to the high-risk and low profit nature of the construction industry [15]. Cultural resistance by construction workers is significant in the adoption of VR/AR technology as workers still relish using traditional methods than have VR introduced into their normal working practices, and that stakeholders prefer to operate within their comfort zone which poses a problem for AR adoption. Furthermore, cost implications have been cited as major barriers for the adoption of VR/AR technology.

Table 5 shows the top five critical factors that are considered as barriers to WSD adoption. These include “Lack of demand – Client, Local Government or Senior Management” (with $\bar{X}$ value of 4.43, s of 0.87 and an MNV of 1.00), “Construction worker awareness and acceptance to wear” (with $\bar{X}$ value of 4.28, s of 1.04 and an MNV of 0.93), “Cost concern” (with $\bar{X}$ value of 4.18, s of 0.87 and an MNV of 0.89), “Security, privacy and legal concerns” (with $\bar{X}$ value of 4.15, s of 0.92 and an MNV of 0.88), and “Needs and acceptance from industry” (with $\bar{X}$ value of 3.95, s of 0.86 an MNV of 0.78).

Table 5: WSDs adoption barriers

Barriers	$\bar{X}$	*s*	MNV	Ranking
D8. Lack of demand - Client, Local Govt or Senior Management	4.43	0.87	1.00	1
D2. Construction worker awareness and acceptance to wear	4.28	1.04	0.93	2
D1. Cost concern	4.18	0.87	0.89	3
D3. Security, privacy and legal concerns	4.15	0.92	0.88	4
D5. Needs and acceptance from industry	3.95	0.86	0.78	5
D4. Analysis and response data issues	2.70	0.88	0.24	6
D6. Connectivity / loss or poor signal issues	2.38	0.93	0.10	7
D7. Battery life limitations / power consumption.	2.15	1.08	0.00	8

n = sample; $\bar{X}$ = mean; *s* = standard deviation; MNV = mean normalized value

It is affirmed that the lack of incentives and support from external influences such as the client, government, safety regulators and insurance companies could influence the use of WSD [7, 18, 19]. Furthermore, the construction workers may be unwilling to be constantly tracked, and the lack of trust towards such devices. Contrary to this perception, [33] show that construction workers (in Finland) are in fact interested in using wearables, as long as it is to improve safety, wellbeing, and data transparency.

Table 6 indicates the top 6 critical factors that are considered as barriers to exoskeleton adoption and these include “Cost” (with $\bar{X}$ value of 4.70, s of 0.61 and an MNV of 1.00), “Lack of demand – Client, Local Government or Senior Management” (with $\bar{X}$ value of 4.53, s of 0.78 and an MNV of 0.92), “Negative attitude – hassle to use/nonacceptance from workers” (with $\bar{X}$ value of 4.18, s of 0.87 and an MNV of 0.77), “Suit may lead to false sense of security” (with $\bar{X}$ value of 4.08, s of 0.53 and an MNV of 0.72), “Safety concerns - catch and snag, fall risks, hygiene issues” (with $\bar{X}$ value of 3.73, s of 0.78 and an MNV of 0.57) and finally, “Perception that falls and other safety hazards will increase (with $\bar{X}$ value of 3.63, s of 0.81 and an MNV of 0.52).

Table 6: Exoskeleton adoption barriers

Barriers	$\bar{X}$	*s*	MNV	Ranking
E1. Cost	4.70	0.61	1.00	1
E9. Lack of demand - Client, Local Govt or Senior Management	4.53	0.78	0.92	2
E6. Negative attitude - hassle to use / nonacceptance from workers	4.18	0.87	0.77	3
E8. Suit may lead to false sense of security	4.08	0.53	0.72	4
E3. Safety concerns - catch & snag, fall risks, hygiene issues	3.73	0.78	0.57	5
E2. Perception that falls and other safety hazards will increase	3.63	0.81	0.52	6
E7. Not versatile enough	3.45	0.90	0.44	7
E5. Durability concerns of the exoskeleton after prolonged use.	2.98	0.83	0.23	8
E4. Interference with PPE and tool belt	2.45	1.13	0.00	9

n = sample; $\bar{X}$ = mean; *s* = standard deviation; MNV = mean normalized value

Cost concerns including initial investment and uncertainty surrounding the ROI and a lack of cost-benefit analysis are key decision-making factors linked with the adoption of exoskeleton. The cost of implementing exoskeletons via a cost-benefit analysis is still blurred [21], and [15] suggests that because the construction industry is a high-risk/low-profit environment, such relevant information if not available presents a blockade for adoption. It is also highlighted that the government (as the client) should incentivize technology by providing grants or funds as these could expedite adoption [15]. The negative attitude of workers towards some technology is further reinforced by managers who are of the view that trying to convince workers to wear exoskeleton suits would be the biggest barrier, as no one wants to be the first and construction workers like to think they are strong and do not require extra support.

5. CONCLUSIONS

The construction industry is transitioning towards a digital era, with opportunities to improve health and safety using innovative technologies. This study focused on the barriers regarding the adoption of BIM, drones, VR/AR, WSD and exoskeleton technologies within the Macao AEC industry towards improving health and safety of workers. Although most respondents demonstrated a positive attitude towards safety technology, the Macao construction industry, like many other construction industries across the world is slow to adapt and adopt these technologies. The findings indicate that Macao AEC industry experience similar barriers as other construction industries around the world. The findings suggest that the main adoption barrier applicable to Macao, and prevalent in all five technologies, are a lack of demand from client/Government/Senior Management, cost concerns and cultural resistance. This potentially suggests that finding ways to resolve these barriers could be the driver for encouraging AEC companies in Macao to adopt some of these innovative safety technologies. There is currently no existing study in Macao with emphasis on these barriers faced by AEC industry in the adoption of innovative safety technological tools and this study could be the building block towards further research to assist AEC companies in Macao towards utilizing technology to enhance construction safety.

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DIGITAL CHALLENGES AND OPPORTUNITIES OF ADDRESSING ON-SITE PRODUCTIVITY AND SAFETY ON CONSTRUCTION JOB SITES: AN INTERNATIONAL PERSPECTIVE

A. Hassan, A. Mitra, M. Mulville, A. Hore

School of Surveying and Construction Innovation, Technological University Dublin, Ireland

Abstract

The slow pace of digital transformation in construction remains an impediment to the industry's evolution. Despite rapid developments in digital technologies, the vast bulk of data generated on construction job sites remains underutilised due to the limited use of real-time data capture. The diffusion of digital solutions in construction depends on successfully capturing critical real-time data that can inform and contribute to more productive work patterns and safer job sites. Nevertheless, the construction industry's fragmented nature has segregated the digital solutions offered by technology providers from the volatile challenges facing on-site construction practitioners.

This paper will present the early development of a nationally-funded Irish case study deploying a combined camera and sensors solution that enables measurable productivity and safety measures through passive data capture. Semi-structured interviews were conducted with highly experienced international construction practitioners to present the functions of the novel technology and explore the contemporary issues influencing on-site productivity and safety. Moreover, the qualitative data were subjected to thematic analysis to explore the extent of integration between the practical applications of the visualisation technology and the current demands of construction project managers.

Findings from this study revealed a recognisable disparity between the motivations and perceptions of the technology-developing firms compared to the demands and priorities of construction practitioners. The study aims to narrow the technology gap by understanding the business case for real-time data capture technology deployment on construction job sites. It also presents a successful example of the necessary collaboration between technology developers, building firms, research institutions, and public organisations towards digital adoption in construction.

Keywords: safety, Innovation, artificial intelligence, collaboration.

1. BACKGROUND

The construction industry is vital for national economic and social development since it provides essential infrastructure and buildings for human activities [9]. Expenditures in construction represent between 9% to 15% of GDP in most countries [10]. Nevertheless, the economic, competitive, and regulatory business environment presents numerous challenges to firms operating within this industry. Contracting firms face increasing pressures to improve their operational efficiency and effectiveness to combat the competitive threats to their survival. However, the construction industry is beset with inefficiencies related to on-site productivity and workplace safety [10].

The International Labour Organisation classified the construction industry as a primary contributor to work-related fatalities globally [31]. The number of fatal accidents in construction remains relatively high compared to other industries [22]. This phenomenon has been observed across the US, China, the UK, South Korea, and Singapore [21; 31; 44]. Moreover, the productivity gap between construction and other industries is a global challenge to the building sector [4; 37]. In the Irish context, there was slight growth in labour productivity between 2000 and 2016, and the productivity measured in Ireland stands 24% below the EU average [15].

Young et al. (2021) and Huang et al. (2021) argued that the primary reasons for the poor safety environment and productivity gap in construction are the modest intensity of innovation and continued reliance on traditional information systems. The scope of traditional information systems in construction management is often limited to recording basic information related to project design, schedules, costs, and resources [24]. On the other hand, the vast volumes of data generated in projects' planning, design, construction, operation, and maintenance phases remain underutilised [43].

The application of Artificial Intelligence (AI) and its subfields in progress tracking, health and safety monitoring, cost estimation, supply chain and logistics process improvements, and risk prediction have been associated with; increased operational productivity and efficiency, reduction of cost and time of building activities, better adherence to project schedules, higher quality of construction outputs and accompanying documentation, safer work environment, and improved design of buildings [1; 2]. Concerning safety management, previous studies revealed that on-site accidents were reasoned by the lack of proactive and preventive measures, such as risk source identification and control [29]. Therefore, adopting visual and analytical AI technologies, such as computer vision and machine learning, can potentially improve construction safety management practices [22]. It has been claimed that these technologies could facilitate hazard identification, support accident prevention, and improve safety training [18; 22].

Despite the crucial importance of digital transformation for construction firms to address the persistent and concurrent challenges above, the construction industry remains one of the least digitised industries [1]. The inception of construction digital solutions dates back to the 1960s through automated systems and robotics [10]. Over these decades, digitalisation has proven its capability to revolutionise the building process and provide numerous benefits to the Architecture, Engineering and Construction (AEC) sector [12]. Likewise, the unique nature of construction, being highly labour-intensive and the highest consumer of raw materials, mandates crucial endeavours towards adhering to the Industry 4.0 strategy, which promotes the importance of digitising and automating the business environment [27; 30]. Nevertheless, the uptake of digital solutions across the global construction industry faces several impediments, such as; cultural barriers, high initial costs, security, and skills shortages [1].

He et al. (2017) and Turk (2021) observed a gap between the rate of technology adoption among construction firms and the advances in technological solutions developed by innovation firms and research communities. Furthermore, they sought to explain the reasons behind this considerable gap between the construction and technology industries:

- Construction projects are unique, and their building processes broadly vary between projects according to various reasons (e.g., adopted building codes, client requirements, and regional laws). Hence, building projects often lack repetition, which is well suited for AI and information technology (IT) solutions;
- Tight schedules offer construction practitioners a limited opportunity to try new technologies;
- Skills shortage and complexity of attracting technology specialists into construction firms;
- The slow pace of change in the construction industry reasons by the absence of leadership and drive;
- The poor appetite of construction firms to invest in research and development (R&D);
- The complexity of exchanging data between different technology solutions.

2. TECHNOLOGY GAP

Among the key issues that have proven obstructive in unlocking the digitalisation potential in construction is the disparity between the construction problems and the solutions offered by technology providers. Oesterreich and Teuteberg (2019) referred to this barrier as the technology dimension. Perceived usefulness and ease of use were found to be the dominant factors for technology diffusion [26]. Lack of coordination between the two sides: problems that aggravate the construction processes and digital solutions provided by the technology startups contribute to further productivity loss [13].

A major cause of the technology gap is that project stakeholders interpret construction automation and digitalisation differently [8]. For example, building designers focus on digitalising planning and design activities, but contractors may understand it as using robotics to implement onsite tasks. In other industries, market disruption counted on the fact that digital technologies moved faster because of modular or compartmentalised adoption [13]. However, the dynamic and complex nature of construction projects encourages the fragmentation of the building process [26]. Despite this fragmented state, digital technology providers and researchers often focus on a singular objective or process. As a result, interoperability problems among different platforms create barriers to digital adoption on construction sites [38]. Likewise, digital solutions designed to address specific problems rarely provide significant value due to the interconnectedness of operational tasks [28].

Another significant reason for the technology gap is the cost of adopting new technologies. At an industry level, Low-profit margins prevent large contractors from the expansion into digitalisation [36]. Likewise, the immense initial capital investments to develop, deploy, and train employees inhibit organisational profitability from digitalization [38]. At a project level, tight schedules and cost pressures prevent the experimentation of new technologies.

Finally, the lack of standards prevents the mass adoption of digitalisation in construction [26]. The push for digitalisation has come from various avenues, including research institutions, technology startups, and R&D departments of global conglomerates. However, the inherent motivations from these quarters lack an overall collaborative vision to create complete digital transitions of construction processes [32]. As a result, the study in hand aims to address the technology gap issue by integrating the functions and applications of a construction technology under development with the contemporary construction industry demands.

3. CASE STUDY

The proposed A-EYE Technology is an early-stage research project funded by the Irish government and aligned with Ireland's Industry 4.0 Strategy 2020-2025 [15]. The project is developed with a collaborative vision to address the productivity, sustainability and communication challenges facing building contractors. The disruptive A-EYE solution is the result of integrating the pioneer innovation of two Irish construction innovation firms specialising in computer vision, artificial intelligence, machine learning, sensors technology, and project planning. Technological University (TU) joined the project consortium as the research performing organization (RPO) responsible for user-experience research management and dissemination of findings.

3.1. Project Scope

The A-EYE technology is developed to help address the productivity, sustainability, and communication challenges facing construction firms in the current complex business environment. This disruptive innovation aims to create a construction visualisation platform that enables measurable productivity advantages through passive data capture and real-time delivery of mission-critical information in an accessible form. A-EYE seeks to provide easy access to visualised data and documented proof of events in pursuit of efficient team-wide collaboration on construction sites.

A-EYE's control tower, supported by high-resolution cameras and tracking sensors, is uniquely positioned to provide complete project visibility and enables the most transparent visual communication between stakeholders. The following figure displays the intended application of the A-EYE visualisation platform to monitor and track construction activities, labour, and machinery to update project progress, detect irregularities, automate schedule amendments, and cut down on waste.

Most existing data organising, project scheduling, and reality capture technologies operate individually and mandate human intervention to connect these systems through manual data input. However, A-EYE's point of differentiation lies in the automated integration of reality capture and scheduling processes on construction sites. The following table summarises the functions and applications of A-EYE to address the prevalent worldwide on-site construction challenges.

Application	Anticipated benefits of A-EYE
Real-time scheduling and resources control	Adopting A-EYE technology on construction sites can help monitor concurrent activities and track labour and plant to detect irregularities, automate schedule updates, and reduce resource waste.
Real-time BIM	Integrating real-time data with a project's BIM allows for automating the model update process to reduce buildings' initial and lifecycle costs.
Budgets and billing	A-EYE aims to match the billing process with actual on-site progress by detecting materials' delivery time, quantities, and equipment up-time to resolve supplier disputes and cut unnecessary costs transparently.
Safety monitoring	Analysing video footage using A-EYE technology can provide real-time alerts in the event of safety violations. Signals can be delivered in case of equipment operating procedures violations, and personal protective equipment is not used on-site to prevent safety hazards due to labour faults or exposure to heavy machinery.
Performance Analytics and Estimation	One of the A-EYE's main objectives is to develop robust construction productivity measures using real-time and visual data. Measured productivity will include partial productivity (e.g., labour and machinery) and overall productivity of the construction process. Developing reliable productivity measurements in construction can create an accurate industry benchmark and improve future decision-making [39].

Table 1: A-EYE Technology Applications

4. METHODOLOGY

4.1. Research Method

Opinions, experiences, and predictions of people can be elicited by conducting qualitative studies [6; 33]. Qualitative research recognises the personal experiences of research participants, as well as the association between personal consciousness and external objects [3]. Hence, a qualitative research approach was adopted in this exploratory study to understand the range of perspectives international senior construction managers and technology developers hold about on-site productivity and safety management challenges [14; 23].

Qualitative research methods emphasise the comprehensive investigation of textual data gathered in a conversational format through interviews [25]. Semi-structured interviews were used to gather data since they provide an in-depth understanding of the phenomena under investigation and assist in the portrayal of multiple views [16; 34]. Firstly, the representative of the A-EYE technology-developing startups was interviewed to understand: the disruptive technology functions and practical applications, the technology's key points of differentiation, his perception of the current construction productivity and safety challenges, and how the disruptive technology aims to tackle these challenges. Afterwards, a series of semi-structured interviews were conducted with international construction managers to explore the extent of alignment between A-EYE and the digital demands of site practitioners.

The disruptive technology applications under investigation were initially presented to the participants. Moreover, interviews sought to explore the contemporary safety and productivity challenges in the global construction industry, how digital solutions can help address these issues, the shortcomings of the prevalent digital construction tools, and how this technology under development can improve on-site productivity and safety management.

4.2. Research Sample

Purposive non-probability sampling was deployed in this study since it is considered the most practical technique for exploratory studies [34]. The sampling frame included the representative of the A-EYE developing team in addition to five international construction companies. The construction industry is highly fragmented, and projects often involve a wide array of stakeholders [40]. Therefore, representing the construction industry diversity was deemed critical due to the small sample sizes associated with qualitative studies.

The chosen study sample included large construction contractors, global construction materials suppliers, and multinational technology development firms. Likewise, the selection criteria considered the geographical diversity of target firms. Participating companies were based in the United States, Ireland, the United Kingdom, Sweden, Poland, and Saudi Arabia. The unit of observation, target personnel, was defined as senior construction managers of contracting companies, R&D directors of materials producers, and directors of construction innovation firms. The following table provides a summary of the participants' profiles. Interviewees were assigned pseudonyms, ranging from A to F, to maintain their confidentiality. Also, firm size was measured according to the number of full-time employees as per the EU criteria [11].

Participant	Region	Position	Business Area	Firm Size	Practical Experience (years)
A	Ireland	Co-founder & Managing Director	A-EYE developing firm	Medium	>20
B	Saudi Arabia	Director of Digital Delivery	Construction contracting	Large	>30
C	Sweden	Managing Director	Construction contracting	Large	>30
D	Poland	Head of Innovation	Materials supplier	Large	>30
E	USA	Director of Operations	Construction contracting	Large	>30
F	Ireland	Director of Global Partnerships	Technology developing firm	Medium	>20

Table 2: Research Interviewees' Profiles

4.3. Data Collection Procedures

The ethical validity of the research procedures adopted in this study was carefully considered to ensure the findings' credibility [34]. The conduct of this study carefully considered the following ethical considerations: integrity, confidentiality, informed consent, and the privacy of research participants [35]. Ethical approval was gained from the TU Dublin research committee. The committee assessed the data collection process and procedures and confirmed their ethical validity.

Before the commencement of interviews, the consent of participants was gained through a formal letter of invitation. They were informed of the study's purpose. Also, participants were allowed to withdraw from the research at any stage to minimise potential response bias [23]. The research design ensured the participants' anonymity and the collected data's confidentiality. Each interview lasted approximately 45 minutes and was audio-recorded with the participants' consent. Audio records were later transcribed verbatim to facilitate the data analysis.

4.4. Interview Questions

Two interview sheets were designed to provide a comprehensive understanding of the disruptive technology under development and the on-site productivity and safety challenges under investigation (Appendix B). Questions were compiled based on a desktop study to review the latest peer-reviewed publications on construction productivity, safety management, and challenges to digital transformation in the building sector [e.g., 5; 20; 39; 41].

4.5. Data Analysis Method

Thematic analysis was adopted to examine the data gathered during the fieldwork phase. It is a widely used approach to identify, analyse, and report themes within qualitative data [17]. The thematic analysis provides a rich and detailed, yet complex, account of the interview data by examining narrative materials from life stories and breaking the text into relatively small units [7].

The thematic analysis process has followed the six-step approach articulated by Braun and Clarke (2006) due to its clarity and flexibility. The six steps can be summarised as follows: familiarising yourself with your data; generating initial codes; searching for themes; reviewing potential themes; defining and naming themes; and producing the report. The six-step approach guided the transcription, coding, analysis, and reporting of the gathered qualitative data. Data analysis was conducted using NVivo 12 software for data management [23]. A deductive thematic analysis approach was adopted since themes were identified during the desktop study phase. Interview transcripts were initially coded and then grouped into the following themes: AI benefits, safety management, construction productivity, barriers to AI adoption, and A-EYE Technology opportunities.

5. FINDINGS AND ANALYSIS

The step-by-step approach starts with familiarising with the transcribed interviews. Transcripts were reviewed several times, and initial ideas were highlighted to become fully immersed in the dataset. Likewise, any terms referring to a participant's identity or company were anonymised for confidentiality.

5.1. Data Coding

Data were coded to structure the transcribed discourse. The initial codes organised the data according to the general topics raised, which then yielded a starting point to develop relevant themes. A large number of codes (n=78) emerged; some included only one phrase, and others contained several sentences.

5.2. Establishing Themes

Themes emerged from the abovementioned initial codes by merging related codes into subordinate categories. The primary purpose of this phase was to explore the patterns and relationships between highlighted codes throughout the entire dataset [7]. The established themes were directly related to the study's aim and objectives and were developed by interpreting the underlying roots of codes. Five main themes were established and supported by coded data. All predetermined themes revolved around exploring the extent of integration between the functions of A-EYE Technology and the contemporary challenges on building sites. The following table presents an overview of the identified themes and a few relevant code examples.

No.	Theme	Relevant Codes
1	AI benefits	•National digital twin programme •Automating materials delivery orders •Addressing labour shortage
2	Safety management	•Zero incidents target •Strategic importance of AI •Safety standards differences between countries
3	Construction Productivity	•Skills shortage •Managing multiple projects •Lack of collaboration
4	Barriers to AI adoption	•Resistance of subcontractors •National restrictions on data storage •Resistance of unions
5	A-EYE opportunities	•Safety as a primary application •Creating a safety culture •Automating operational process workflow

Table 3: The Five Main Themes

5.2.1. AI Benefits

Participants generally agreed on the substantial importance of AI and its subfields in various stages and areas of the building process. Apart from the various benefits of AI applications in tracking on-site progress, safety, productivity, and output quality, Participant B ascertained that the strategic importance of AI stems from managing and aligning multiple sites concurrently. Another participant, operating in the materials supply field, stressed the numerous benefits of using AI technologies to automate the purchasing order process. "*It will be phenomenal in the sense of consistency and stopping errors from occurring and just having a better quality and faster information*." – Participant D.

Construction visualisation technologies were also considered essential to communicate and collaborate with stakeholders since the Covid-19 pandemic and the remote working trend's emergence. Likewise, Participant F noted that new construction acts in several countries to support and mandate digital transformation present a substantial opportunity for diffusing information and communication technologies (ICT).

On the other hand, Participant B highlighted several potential limitations to using AI on construction sites. First, he stated that the importance of these technologies stems from managing and coordinating multiple projects and numerous activities. However, these technologies become less feasible if their scope becomes limited to smaller projects and specific disciplines. This raised limitation is consistent with the arguments of Oraee et al. (2019) and Turk (2021), who claimed that the interconnectedness of construction activities and interoperability problems among digital platforms are primary reasons for the technology gap. Also, Participant B added that construction managers must define the purposes of gathering and analysing data to benefit from the abundant data provided by these technologies. "*Capturing data correctly and using it correctly are two different things. A lot of people start going out collecting data, but they don't actually know what questions they are trying to answer*." – Participant B.

Another interviewee warned the A-EYE development team about the anticipated rivalry in this market segment due to the existence of multiple proficient competitors. However, there remains room for A-EYE to provide unique value since the digital construction field remains in its preliminary stages. "*There are a lot of people doing this kind of technology. But we need to be casting our mind, in a wider format to ask what we don't have now, that could be potentially useful in the future*." Participant E.

5.2.2. Safety Management

Interviewees working for construction contracting firms agreed that AI technologies could significantly improve construction site safety culture and standards. *"From a safety perspective, it's a positive if they know that things are being watched. It keeps us on our toes and keeps them doing everything safely."* – Participant E. Differences between safety standards worldwide were considered a significant challenge to companies operating globally and cooperating with international clients. Hence, the advent of AI applications for monitoring staff compliance with safety rules and detecting potential hazards can leverage the strategic endeavours of multinational contractors to internationalise their operations. *"Health and safety is a huge element of these projects. We are running stats now with the number of zero incidents, of seven million hours have been worked on the projects across our campuses here, you know so there is a huge, huge emphasis."* – C.

5.2.3. Construction Productivity

Interviewees provided valuable input to explain critical reasons behind project delays, cost overruns, and unnecessary waste. A significant issue was the modest exploitation of technological solutions in use, such as BIM. Limited attention to early identification of design clashes resulted in excessive time and financial waste. However, several participants confirmed that the successful adoption of ICT facilitated team-wide collaboration and early detection of potential issues.

It was found that a primary challenge to exploiting ICT lies in the varying digital capabilities between construction stakeholders (e.g., architects, general contractors, and subcontractors). Participant D noted that the digital proficiency of stakeholders plays a vital role in supporting coordination and collaboration throughout a project lifecycle. Another participant highlighted the complexity of integrating information emerging from different stakeholders with varying levels of digital capabilities. *"Basically, everyone that has an input to the project. So, you spend a lot of time physically chasing down information to load. But even that depends on the standard of information"* – Participant C. Moreover, the lag between site activity and project control reporting was found to be a primary source of time waste among projects. The impact of this lag could be potentially reduced by adopting AI and ICT technologies that support visual communication between project teams.

5.2.4. Barriers to AI adoption

Despite the substantial benefits of AI adoption on building sites, interviewees reported numerous barriers to digital transformation in the construction industry. The modest tendency of contracting firms to invest in modern technologies stands as a barrier to the diffusion of digital tools. "*The biggest challenge really is the human challenge. If you're talking to a general contractor about this solution, they'll go, 'wow, that is brilliant, fantastic, really great.' But if you ask them to purchase it, they are like, ' hang on. Have you seen my margins?'*." – Participant F.

Another issue that obstructs the utilisation of AI technologies on construction sites is resistance to change by construction staff. This barrier has been reported by several interviewees who clarified that on-site staff resist computer vision technologies to avoid accountability. Although A-EYE Technology complies with the EU's General Data Protection Regulations (GDPR) since it does not intend to identify individuals on construction sites, the diffusion of computer vision technologies regularly faces ethical and legal hurdles. "*The challenge with these technologies, as I already mentioned, there's a large resistance to the technology because of the potential exposure of people*." – Participant B.

The same participant proceeded to explain that subcontracting firms are likely to resist the application of AI-driven construction cameras: "*You got to be very, very careful about these cameras, as I can tell you that most contractors, they will set the cameras up and they will use them against their own supply chain*." – Participant B. Finally, other participants stated that public authorities and labour unions often obstruct utilising such technologies on site: "*The union trust did not want them on the site because for any kind of claims or financial injuries or delays on their part. They didn't want that oversight*." – Participant E.

Ease of use remains a critical issue facing contracting firms aiming to adopt on-site cameras. While fixed cameras can fail to provide complete visibility of construction activities, using portable cameras is also challenging since their continuous manoeuvring is hectic and time-consuming. Likewise, the complexity of transferring data between different software solutions utilised on a construction project is a challenging task. "*Not every company uses the same platform even within a single project*." – Participant E. Another issue highlighted by a director of a contracting firm was the difficulty of sharing data with stakeholders due to restrictions set by the clients who insist on their ownership of a project's data.

5.2.5. A-EYE Technology Opportunities

There are numerous opportunities for A-EYE Technology to exploit. Existing digital solutions fall short in addressing a multitude of challenges to improving safety management and raising construction productivity. The 'safety management' theme appeared only once during the analysis of the transcript of Participant A, the A-EYE representative. He stated that A-EYE can improve on-site safety management and hazard prevention. Nevertheless, Interviewees argued that the safety monitoring function of A-EYE can be a breakthrough in the safety management discipline. "*The positives you can draw from it from a safety perspective is huge*." – Participant E. They ascertained the enormous potential for commercialising the A-EYE safety functions. "*Such a technology to creating a greater safety culture through the use of cameras would be welcome with open arms*." – Participant C.

On the other hand, several participants recommended amending A-EYE applications to match the prevalent industry challenges and achieve maximum commercialisation potential. For instance, the focus on automating the BIM update process was criticised by an interviewee who claimed that it does not have commercial benefits. Instead, he advocated that automating the construction workflow by supporting the collaboration between project teams can raise on-site productivity. "*Being able to map out the entire process, not just the physical installation of the system, that's where the data starts getting interesting because that's where you start to find all the lags and delays*." – Participant B.

Regarding process automation, it was found that automating the purchasing order process with the support of visual communication can enhance production efficiency, reduce errors, improve logistics efficiency, and raise client satisfaction. Another interviewee suggested that the A-EYE solution should be supported with mobile camera options with built-in chargers to facilitate capturing visual data in restricted areas. Finally, a senior director of a construction innovation firm insisted that relying on quantitative studies is essential to facilitate A-EYE commercialisation. "*We are going through a process now where we are saying that we must quantify and put the numbers in front of people*." – Participant F

5.2.6 Summary

In summary, the prevalent business environment provides AI technologies, such as A-EYE, with enormous opportunities to deliver unique value. The study findings ascertained that A-EYE is a promising disruptive innovation that can change the safety culture and raise construction productivity. Nevertheless, there are necessary amendments to the A-EYE technology on three levels: strategic priorities, system design, and industrial research process to ensure consistent alignment with market challenges and demands.

Regarding the strategic priorities of A-EYE technology, it was advised that the safety monitoring A-EYE function should represent a unique selling proposition. The A-EYE safety monitoring application was determined to possess significant potential since most competing AI technologies fall short of significantly improving the on-site safety management process. Likewise, it was advised that the focus of A-EYE should divert from automating the building information model and scheduling of activities into automating the construction workflow. Using A-EYE computer vision to leverage on-site collaboration between the design, construction management, quantity surveying, and quality control teams can cut time waste and reduce the volume of repeat work. Moreover, A-EYE can support the continuous engagement of clients throughout the project development and implementation phases to maintain client satisfaction. Finally, workflow automation and continuous engagement using computer vision should expand to include materials suppliers to cut unnecessary waste associated with orders errors and delays.

Concerning the system design, the A-EYE cameras system was recommended to include portable cameras to capture necessary visual data in confined workspaces. Additionally, A-EYE needs to have the capability of sharing data with other technological solutions due to the plethora of digital tools used on a project by different stakeholders. Finally, the importance of conducting quantitative research studies to objectively evaluate A-EYE's performance on construction sites was deemed essential to support the technology's future commercialisation.

6. CONCLUSION

Construction firms are facing a myriad of challenges that are hampering their performance and threatening their business survival. Poor safety management practices and modest construction productivity rates are primary impediments to the successful delivery of construction projects. Nevertheless, the advent of the digital transformation era presents a substantial opportunity for building firms to overcome these challenges. Digital solutions have proven considerable effectiveness in improving the safety culture on construction sites and raising productivity by supporting collaboration between project teams and coordination between intersecting activities.

The construction industry remains lagging behind other industries for realising the digital potential. The unique nature of construction projects exacerbates the complexity of utilising modern technological tools on building sites. Likewise, digital solutions developers may lack an understanding of the unique problems facing construction teams on building sites. Hence, the successful delivery of disruptive digital solutions requires close consideration of the construction industry's challenges. The systematic coordination between technology developers, construction researchers, and practitioners remains essential to address the prevalent technology gap segregating innovation and building firms.

In pursuit of continuous technological advancement, this study sought to explore the extent of integration between the A-EYE functions and the contemporary demands of worldwide construction practitioners. The research findings ascertained the substantial importance of the proposed A-EYE functions, such as safety management, monitoring and tracking, and real-time BIM. However, interviewees advised several amendments to the A-EYE applications, system design, and industrial research process to align the technology with the industry's needs and challenges. The feedback from senior practitioners operating in various construction industry segments presents a valuable opportunity for A-EYE's evolution to achieve successful diffusion and commercialization. The Irish A-EYE collaborative research project presents a successful example of the advised collaboration between technology developers, construction firms, research institutions, and public organisations to support the building sector's transition towards digital transformation.

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BARRIERS TO DIGITALISATION OF CONSTRUCTION HEALTH, SAFETY, AND WELL-BEING REGULATIONS ENFORCEMENT AND COMPLIANCE CHECKING

Nnedinma Umeokafor[1], Jochen Teizer[2]

[1]School of Engineering, University of Greenwich (United Kingdom)
[2]Dept. of Civil and Mechanical Engineering, Technical University of Denmark (Denmark)

Abstract

To improve health, safety, and well-being (HSW) in construction, enforcement and compliance with regulations are fundamental. While the attention to digital technology in the industry is gradually improving, practitioners have been using digital aids in form of wearable and connected devices (e.g., tablet computer linked to web-based software platform dedicated to safety management) for checking and auditing construction site safety performance, research into the area in terms of human-assisted compliance and enforcement of HSW regulations in the design and planning phase remains low. Using the systemic literature review methodology, the barriers to implementing such digital technologies in the enforcement and compliance with HSW regulations have been examined. The findings indicate that research into this area is still in the embryonic stage. However, the main barriers to compliance checking include typical technological factors (including its readiness and reliable use on construction sites), people (e.g., their acceptance, phobia for digital technology, and scepticism), organisational (e.g., exceeding or meeting contractual obligations), economical (e.g., the high investment both in the purchase and maintenance of the digitalization effort), and lack of relevant skills and knowledge. Further, regulatory authorities still struggle with integrating digital technologies into the existing enforcement approaches, and the nature of HSW data and types of risks are also barriers to them. This study is a desktop review hence empirical validation is required.

Keywords: Building and Engineering, Digital compliance, Health and safety regulations, Successful innovation, Regulatory compliance

1 BACKGROUND AND RATIONALE

While the health, safety and wellbeing (HSW) record of the construction industry is poor [1], attention to it is increasing, resulting in some improvement. While the extent of improvement is arguably disproportionate to the level of risks in the industry and its performance when compared to other industries, law and regulations, standards, activities, equipment and tools including the digital ones require more attention for optimum results. While there are many ways of improving HSW, two of them are adoption of digital technologies [2-5] and compliance with HSW regulations and standards [6]. There are two levels of enforcement and compliance with HSW regulations and standards.

The first level, HSW standards, statutory regulations, and guidelines are enforced by a national, regional, or industry regulator (an external actor) [7]. Commonly, the regulated (for example, construction contractors) can play a row in its development and enforcement (ibid). However, the enforcement of HSW regulations can be time-consuming, resource-intensive (capital and human), and in some countries - such as the developing ones - the dysfunctional legal systems mean that the regulator is unable to prosecute the regulated for any breach of legislation [8]. Additionally, some of these regulations do not keep up with technological innovations [9]. Barriers to the enforcement of HSW regulations are covered in detail in Umeokafor et al. [8].

Nevertheless, technological innovations, such as the application of big data analytics and associated technologies to HSW enforcement activities can contribute to addressing some of these challenges [10]. For example, HSW inspectors adopt a risk-based approach. Zhu [11] reports how the Norwegian Labour Inspection Authority has adopted big data and machine learning technologies for it. They developed and tested the Risk Group Prediction Tool (RGPT) which identified the risk levels of organisations, enabling them to focus their resources where required. This is beneficial to inspectorates with limited resources available for regulatory activities. Further, a study on the historical data on fire and buildings in Suzhou, China, has been analysed using neural networks and data machine learning algorithms, enabling the Suzhou fire brigade to establish fire risk prediction systems that increased the efficiency of fire prevention by six to eight times [10].

In contrast, digital technology applications by HSW regulators or in activities are still in the infancy stage, hence require further development and testing. Despite the plethora of research into the enforcement of HSW regulations in construction, there are still knowledge gaps in the literature in terms of digitalising it. This search by the authors shows that no studies focus on the barriers to digitalising HSW regulations enforcement from the regulators' perspectives.

The second level is the internal compliance/safety rule checking/HSW monitoring where organisations ensure their workers comply with regulations/policies/standards. These include in-house policies and standards or those adopted externally to meet the HSW guidelines and statutory regulations set at the first level above. Site inspection is one of the tools for this where safety officers/site managers/ fore persons walk around the site to detect unsafe working conditions and behaviours towards complying with HSW regulations [5, 12]. However, the effectiveness of this is limited, especially where there are many workers [12]. Traditional methods of performing safety checks including inspections often require labour-intensive manual input, which can be prone to errors and puts workers at further risk if hazard identification fails [12, 13]. This may happen, for example, to engineers in the project design or planning phase, who have limited or inadequate safety knowledge (aka. part of professional negligence). Further, conventional techniques, although carried out with high empathy can be time-consuming thus costly [5]. The ability of tools available to users in the field to predict the future, irrespective of the level of data that is available is also limited [3].

One of the solutions to the challenges is the implementation of digital technologies [2, 13]. For example, private block chain technologies can be adopted for HSW regulations, standards, and practice compliance and for audit when third parties such as insurance companies are involved [2]. Further, according to Khan et al. [14] there are two primary technologies for monitoring unsafe behaviours on construction sites, computer-vision, and sensor-based monitoring. For example, for sensor technologies, wearable technologies for monitoring compliance with HSW regulations and standards, resulting in real-time and valuable data is also possible [2]. In terms of computer vision-based monitoring systems, CCTVs (closed-circuit television) capture hazards including the persons involved, and machine learning or neural networks analyse the data captured [4, 15]. Furthermore, BIM-based automated safety checking also occurs. 'Rule-based Code Checking' validates the design phase by comparing Building Information Models against current codes and regulations translated into parametric rules' [16]. Also, Zhang et al. [5] report BIM-based automated safety where there is an automatic safety inspection which is reported to the safety or site manager demonstrating possible hazardous scenarios, the rationale, where and when that may occur, and the possible solutions. In this system, BIM models and projects' real-time progress information are combined with existing H&S regulations, guidelines, and best practices, and any activities that contravene the limits of the latter are automatically identified and relevant workable solutions are provided [5].

Despite the plethora of studies on digital technology for compliance checking (for example, [5, 12, 17, 18]), there are still limitations. For example, following a review of, at least 37 papers, Barata and da Cunha [2] found no studies that focus on integrating 'important sources of data for compliance (for example wearable and sensors technologies, augmented reality, internet-of-things), as it happens in audits required by OHSAS 18001 safety standards and legal regulations (p. 527). According to them, the extant studies mainly address the application of digital technologies to accident prevention and the reduction of its consequence, safety training, and fall hazard detection. Further, there are limited studies on the interaction between humans and technologies on compliance applications, and environmental conditions in construction health and safety (ibid). Few studies, e.g. Awolusi et al. [17], have covered this sparsely. Our review shows that no study focuses on identifying the barriers to digital technologies for safety compliance checking in a high level of detail.

Given the background established so far, the overarching aim of the current study is to investigate the barriers to the digitalisation of construction HSW regulations and standards enforcement and compliance checking. Hence, the following questions are set to guide the study:

What are the barriers in constriction to implementing digital technologies in the HSW:

(1) compliance checking?
(2) enforcement of regulations and standards from an external regulators' perspective?

A rather broad definition of ‘digital technology’ is adopted, in other words, the reviews’ focus is intentionally not a specific one.

2 METHODOLOGY

The barriers to implementing digital technologies in the enforcement and compliance with SHW regulations/standards were examined. A hybrid approach for the literature review, consisting of both a systemic literature review (SLR) methodology and the citation approach, was adopted in the study. The Scopus database was searched in March 2023, covering the year 2000 to 2023 with relevant keywords such as digital compliance, digital compliance checking, and health and safety. Figure 1 presents the overall six-stage research process including the systematic search while Table 1 details the second stage, identification, including keywords used. After the question was framed (Stage 1), the relevant literature was identified through a systematic search for the appearance of the keywords in Table 1 on the documents' titles, keywords, and abstract (TITLE-ABS-KEY) (Stage 2). In Stage 3, the abstract and title were read for relevance before the analysis and extraction of data in Stage 4. The findings were interpreted (Stage 5) and reported (Stage 6).

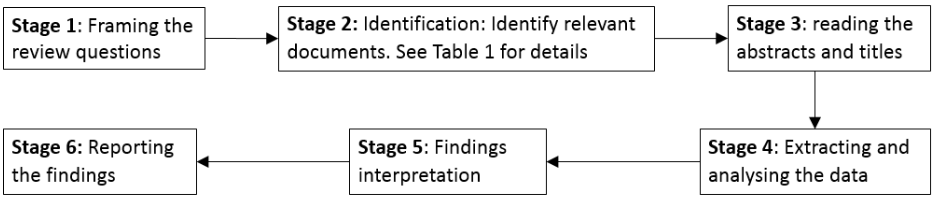

Figure 1: Overall research process

Table 1: Details of the identification section of Figure 1

Date of search	Keywords, Publication year, and location of search on documents	No of docs before limits	Limits: Sources type; Sources type; Language	No of docs after limits
21 March 2023	(TITLE-ABS-KEY (*technology*) AND TITLE-ABS-KEY (*enforcement*) OR TITLE-ABS-KEY (*compliance*) AND TITLE-ABS-KEY (*health* AND *safety*) OR TITLE-ABS-KEY (*wellbeing*) AND TITLE-ABS-KEY (*regulations*) AND TITLE-ABS-KEY (*construction*) OR TITLE-ABS-KEY (*digital* AND *technology*) OR TITLE-ABS-KEY (*digitalisation*)) AND PUBYEAR > *1999* AND PUBYEAR > *1999*	24	Sources type: Conference proceedings, Journal, Trade Journal, book series, book Document type: Conference papers, reviews, articles, book chapter, conference reviews, and short survey Subject areas: Business, Management and Accounting; Computer Science; Energy; Engineering; Environmental Sciences and Decision Sciences Language: English	18
22 March 2023	(TITLE-ABS-KEY (*technology*) AND TITLE-ABS-KEY (*enforcement*) OR TITLE-ABS-KEY (*compliance*) AND TITLE-ABS-KEY (*health* AND *safety*) OR TITLE-ABS-KEY (*wellbeing*) AND TITLE-ABS-KEY (*regulations*) AND TITLE-ABS-KEY (*construction*) OR TITLE-ABS-KEY (*digital* AND *technology*) OR TITLE-ABS-KEY (*digitalisation*)) AND PUBYEAR > *1999* AND PUBYEAR > *1999*	209	Subject areas: Business, Management and Accounting; Computer Science; Energy; Social Science; Engineering; Environmental Sciences; Sources type: Conference proceedings, Journal, book series, book Language: English	24
23 March 2023	(TITLE-ABS-KEY (*emerging* AND *technology*) AND TITLE-ABS-KEY (*enforcement*) OR TITLE-ABS-KEY (*compliance*) AND TITLE-ABS-KEY (*health* AND *safety*) OR TITLE-ABS-KEY (*wellbeing*) AND TITLE-ABS-KEY (*regulations*) AND TITLE-ABS-KEY (*construction*) OR TITLE-ABS-KEY (*emerging* AND *technologies*)) AND PUBYEAR > *1999* AND PUBYEAR > *1999*	20	Subject areas: Computer Science; Energy; Social Science; Engineering Sources type: Conference proceedings, Journal, book series, book Language: English	7
Total		253		49

Table 1, following the keyword search where 253 documents were found, 49 documents were screened for relevance by reading the title and abstract after which 10 (five from the first and second searches each, zero from the third one) were used for the analysis. This was complemented with 20 in the citation approach where the references of materials, e.g. books and journal articles, are searched towards finding relevant materials that can be used [19]. A total of 30 documents were used for the analysis. Umeokafor [1] and Umeokafor and Okoro [19] adopted this approach in the review of literature. The qualitative content analysis was conducted aided by a synthesis matrix [20] which commenced by exploring the preconceptions and experiences of the lead author based on the broad parent themes. The matrix was later expanded by the new ideas from the content analysis.

3 FINDINGS, ANALYSIS AND DISCUSSION

3.1 Description of documents

The 10 documents found in the systematic search consist of 2 journal and 7 conference papers and one book series. Of the 20 analysed from the citation approach, 17 were journal papers, one conference proceeding output, and two reports. Using 30 studies for analysis in a literature review methodology can afford opportunities for reliable findings and conclusions. For example, studies such as Swallow and Zulu [21] have used less 18 for their review and Umeokafor and Okoro [19] is based on 7.

3.2 Barriers to digital technologies implementation in safety, health and well-being compliance checking

The study found 7 themes and 18 subthemes under which the barriers can be categorised, and the summary is presented in Table 2. The themes and selected subthemes are presented and discussed below. There are inter and intra-theme connections between the factors.

3.2.1 Value and cost

This theme consists of three sub-themes, high cost, the perceived value of digital technologies, and the limited understanding of the cost-benefit of the relevant digital technologies (Table 2). The high investment associated with digital technologies for HSW monitoring is covered in studies [4, 9, 14, 22]. For example, Seo et al [23] report the large capital investment for acquiring and maintaining unmanned aircraft systems (UAS). Similarly, installing CCTV cameras on construction sites can be expensive to cover the wide, constantly changing and frequently obstructed work environments [24]. However, when wearable technologies are used, the investment and maintenance of technology can be lower compared to the vision-based ones [17]. Yet, computing is still required to analyse the raw data and generate meaning from HSW information for decision making. The implication of this includes that those small and medium-sized enterprise (SME) contractors who are financially disadvantaged lag behind, and the application is skewed to larger projects. This is consistent with the findings of Andriescu et al. [9] and Gheisari and Esmaeili [22] in the sub-theme titled internal organisational challenges.

In terms of the value of digital technology for HSW compliance, organisations may not find the adoption of the relevant technologies useful for compliance efficiency. Hence, they find little value in taking them on and are sceptical to invest in it (Table 2). For example, Barata and da Cunha [2] found that some companies view that while the current technologies are not ready yet for compliance checking and improvement, they enable the monitoring and alerting of hazards. In one of the interviews, a respondent stated, “sometimes the problem is not in the existence of solutions for OHS; it is in convincing the users of the need to use it, daily”. One of the HSW experts also stated that “we can monitor all the parameters in the world but for regulatory compliance, it is also crucial to proving that the data is reliable and not easily manipulated. It is essential to demonstrate our commitment to safety when dealing with insurance companies and assessors” [2].

3.2.2 Legislation and standards

As noted in Table 2, this study found inadequate standards as a barrier [2, 9, 16]. For example, writing about the lack of certification for standards, Andriescu et al. [9] report how, despite the efforts by the European Committee for Standardisation (CEN-CENELEC), they found smart Personal Protective Equipment (PPE) without certification standards. Further, the reports states that there should be a balance in the certification of standards for OSH monitoring to avoid significant cost increases (ibid). Likewise, inadequate HSW standard issues are consistent with non-technological barriers to H&S in [8]. Another reason is seen when organisations face interoperability challenges. While this belongs in the technological factor theme, the high number of different manufacturers of the technologies results in disconnected solutions rather than following a standard that allows easy integration among the existing systems [9]. The authors also report how the European Union (EU) legislation so far failed in addressing the constant changes in technology for HSW compliance checking. HSW legislation being outdated is consistent with the findings of Umeokafor at al. [8]. However, this challenge might be explained by the fast changing pace of technological advancement which makes it difficult to consolidate isolated efforts. Also, market reach or domination can influence technology adoption, as recently seen in an EU mandate, which requires that all mobile phones must be equipped with a USB Type-C charging port by end of 2024.

3.2.3 Characteristics of construction industry and process

The complex construction environment (Table 2), unlike manufacturing where the product and process may not change as frequently, is unique, the supply chain is fragmented, and the outputs/product and the work environment in which they are constructed are seldom the same. The findings of this study show that they have negative implications for the adoption of digital technologies for compliance checking in HSW (Table 2).

Table 2: Barriers of digital technologies implementation in SHW compliance checking

Theme	Subtheme	Supporting evidence
Value and cost	Cost Value Cost benefit	• High cost of design and adoption of digital technologies [9, 14, 22-25]. • Usefulness: ability of technology, for example, the smart ones to be fit for purpose [2] • A limited understanding of the cost benefit of using technology in OSH compliance [2, 25] • Lack of information for conduction cost benefit analysis of adopting digital technology for H&S monitoring [9]
Legislation and standards	Regulatory limitations	• Limited regulation, for example, on safety distance of UAV to crew, machinery and building during operation [22] • Local regulation limits UAV usage at night [22] • No dynamic legislation – fail to keep up with technological changes [9]
	Inadequate standards	• lack of manufacturing practice/standards or poor quality of technologies [2] • Lack of certification standards [9] • Lack of minimum level of requirements and mandatory informative content [16] • Complex standardisation of smart PPE [9] • Testing and certification by external bodies is complex and lengthy [9]
Charateristics of construction industry and process	Complex construction environment	• Dynamic nature of construction [5, 14, 22] • Non-digitalised construction sites [16] • Complexity and unpredictability of workers movement on sites [14, 15, 23]
	Weather and noise	• Weather challenges e.g. UASs are susceptible to wind [22] • High level of noise [12,15]
	Internal organisational challenges	• Size of organization e.g. SMEs [9] • Complexities in integration of technology [9] • Size of project [22]
People	Collaboration	• Lack of collaboration between H&S coordinators & building designers [16] • Project organization and roles [16] • Exceeding or meeting contractual obligations
	Resistance	• Lack of reliability and acceptability [9] • Dependence on manual methods of monitoring [14] • Oppositions from trade unions against H&S monitoring using technology [9]
Skills, competence, and knowledge	Limited skills competence &experience	• Lack of competence and experience in digital technology for H&S [13,18] • Limited skills and knowledge of usage [22] • Extensive training requirement [22]
	Lack of info. & awareness	• Limited awareness of digital technological in health & safety [26]. • Lack of information on effectiveness of digital technology in compliance checking [9]
	Poor market knowledge	• Poor understanding of market demand for technology [27] • End-user needs not informing the design and development of technology [9]
Technological factors	Technological requirements Inefficient technologies e.g limited algorithm	• Limitations in translating H&S regulations, guidelines, and best practices (normative text) into parametric rule-set which are computable parameters [16] • Errors in outputs as the algorithm and/or types of cameras or other technologies result in inaccuracy [15, 28] • Inaccurate or poor detection [4, 12, 15, 27] • Aspects of technology processes are not automated [5] • High false alarm rate from vision-based ones [14] • Prone to occlusion [14, 28, 29] • Interoperability challenges [9]
	Quality of technology	• Limited durability of sensors [2] • Battery life issues, e.g., from sensor-based ones [4] • Safety concern from usage, e.g., piloting [22] • Heavy monitoring equipment [24]
Liability and legal concerns and damages	Data management	• High data drift with the sensor-based ones [4] • Ethics, data protection, security and privacy [9, 17, 22] • Complex data processing and transmission [17] • Lack of comprehensive dataset [29]
	Personal privacy	• Personal information privacy issues [2, 29, 30-32]

For example, according to Zhang at al. [5], the risk dynamics and real-time representation of unsafe conditions on construction sites may be limited and challenging because of the constantly changing construction environment. Khan et al. [14] and Gheisari and Esmaeili [22] are in support. Further, the study also found that complexity and unpredictability of workers movement on sites is a major barrier [14, 15, 29]. For example, in Anjum et al. [15], see evidence that digital technologies such as vision sensors (cameras) using deep learning to assess the work at height activities for compliance with HSW regulations on site present a risk of less accurate information on unsafe worker behaviours because of the complexity and unpredictability of their movements on site.

Equally important are the internal organisational challenges. Implementing digital technologies can be costly, requiring a higher level of skills to which the larger organisations have more access than the smaller ones. The current study found that some peculiar challenges encountered by small and medium enterprises unlike the larger ones e.g. limited funds and information is a limitation to HSW standards, regulations, and best practices compliance checking [9]. Further, Andriescu et al. [9] demonstrate that employers may be willing to integrate digital technology in HSW compliance due to the associated complexities from the cost, duration of implementation, and non-bespoke solutions or organisational needs. The point here is that every organisation would have an existing HSW management system/procedure, but integrating the digital technology into the system, for example, site inspection systems may be challenging incompatible with some of the activities/procedures of other technologies in use. The technology must be designed and implemented in line. Gheisari et al. [22] also observe that UAS are mainly applied to large and tall projects, putting the smaller ones at disadvantage.

The findings in this theme are consistent with extant studies. For example, Koeleman et al. [30] demonstrate that the characteristics of the construction industry e.g., its fragmented supply chain; the lack of repetitions, e.g., uniqueness of projects; and transience, e.g. inconsistent project teams and constant personnel changes, is the main reason why the construction industry is stuck in the analogue era. Further, Boadu et al. [33] support this argument and offer insight into the negative influence of construction industry (using Ghana as a case study) on health and safety management developing countries, enabling some comparison with the developed ones. According to their findings [33], while the regulatory complexities (for example, the lack of single regulatory authority for HSW in the industry), labour-intensive construction methods, and lack of skilled and educated workforce are the highest-ranking characteristics, the colonial influence and the fragmented practices in the industry are the lowest. Furthermore, the finding of a positive correlation between lack of single regulatory authority and colonial influence (($r = 0.427$, $p \leq 0.01$), means that as one of these increases, the other decreases and vice versa. By implication, there is evidence (based on the view of the respondents) of the colonial influence and absence of a single regulatory authority on health and safety performance of the industry. While some other developed countries experience similar colonial influence, it is unclear the extent to which this applied to HSW compliance checking with digital technology. However, in developed countries such as Nigeria and Ghana, there is an overreliance on colonial influence. Umeokafor [7], Umeokafor et al. [8] and Boadu et al. [33] report how most of the current HSW regulations and standards are adopted from the British ones. Most times, there is little consideration of the intended context of operation hence in most cases, they are not fit for the purpose [7, 8].

In terms of no single regulatory authority, this means that there are distributed occupational safety and health (DOSH) as opposed to the consolidated occupational safety and health (COSH) in developed countries such as Britain [34, 35]. This makes the integration of digital technologies more challenging because of differences in interest and value, skills level, the scope of operations and availability of funds [35]. Umeokafor [35] offer a treatise on the differences between HSW regulatory frameworks of developed and developing countries and why many adopted or transposed regulations or standards from developed countries do not work in developing ones like Nigeria.

3.2.4 People

This theme is made up of two sub-themes, collaboration, and resistance (Table 2). The construction industry has been resistant to technological changes; hence, it is not surprising that there is limited acceptance of HSW compliance technologies in construction as found in our study (Table 2). Equally important is the impact of changes in HSW management systems on the employees and other stakeholders which results in external resistance. Evidence of external resistance was found in the study. For example, in Andriescu et al. [9], trade unions have expressed concerns about the digitalisation of HSW enforcement and compliance checking because the technology-based HSW monitoring systems may result in productivity pressures for workers which will have negative implications for mental health and wellbeing. This finding is consistent with studies such as Watterson [36] where influence of external pressure in the regulation of HSW is well documented. Admitted that there are possible negative mental health and wellbeing implications due to digital technological advancement in HSW regulation enforcement and compliance checking, this is consistent when other changes in organisations. Consequently, should be factored into the risk management of organisational change. It should stimulate innovative ways of organisational change which consider building on external and internal resistance to advance a collaborative environment for HSW management including compliance checking.

3.2.5 Skills, competence and knowledge

Three subthemes are here, limited skills, competence and experience, lack of awareness and information and the poor market knowledge (Table 2). Table 2 shows that poor knowledge of the market, lack of awareness and information, and limited competence and experience were also barriers. For example, [27] found that there is a limited understanding of market demand for digital technologies used in HSW. This is supported by [9] who found that designing and developing digital technologies without understanding the needs of the end-user results in a lack of acceptability. This is consistent with the findings of Boadu et al. [33] in 3.2.3 where the lack of skills and an educated workforce impacts health and safety performance. Our findings show that digital technologies in HSW regulation enforcement and compliance checking are no exception.

In terms of lack of awareness and information, the construction industry is known for its resistance to the adoption and implementation of digital technologies; HSW compliance checking is no exception. The current research found that one of the explanations is the lack of research on the effectiveness of the systems hence adoption is demotivated, according to the findings of extant studies such as Umeokafor et al. [9]. However, the dearth in HSW (including compliance) research is worse in developing countries when compared to the developed one. This also results in the inability to conduct a cost-benefit analysis to justify adoption. This has more negative implications for SMEs than the large contractors (ibid), especially those in developing countries, like Nigeria. All these are possible explanations for the worse compliance with HSW regulations records in developing countries.

3.2.6 Technological factors

Despite the potential of digital technologies to improve HSW, the study found that barriers resulting from them are made up of three subthemes, technological requirements, quality of technology, and inefficient technologies. For inefficient technologies, while the technologies may be effective, evidence shows limitations and inefficiency. The findings of Anjum et al. [15] show that algorithms can be limited, for example, when 2D images from 2D CCTV are used, they identify the workers standing beside ladders as working on them rather than only those working on them. However, stereo-vision cameras can address this. Khan et al. [4] support this finding, reporting the inability of the technology in their study to detect unsafe behaviour, perhaps because of a limited dataset and captured angle of the 2D images. Similar inaccuracy is reported by Ding et al. [28] who also found very long durations of computation, occlusion, and high levels of illumination impact the learning capacity and ability of the technologies to be used in real-life settings. In Habbal et al. [27] inaccurate detections are also found where, for example, there is only 56 percent of shoe or feet detection. Missed or inappropriate detection of hats, e.g., those on the floor not worn by anyone is also found in [12]. Another barrier is that the normative texts of regulations/guidelines/standards/best practices are not translated into a parametric rule set to enable the software to interpret them [16]. The quality of the process of doing this for compliance-checking purposes using digital technologies may be limited and costly (ibid).

3.2.7 Liability and legal concerns and damages

Made up of the two subthemes, data management and personal privacy, the barriers cover the negative implications of data breach or loss. In terms of personal privacy, according to Barata [2] one of the ways that this is a concern is through the level of data that the technologies obtain. For example, wireless and wearable technologies for PPE compliance monitor the performance, heart rate, and even the number of steps of the workers. The personal information here is at a high risk of being breached by fellow employees especially, when medical-related.

Another barrier is ethics, data protection, security, and privacy (Table 2). For example, wearable devices present a high-security threat such as malicious attacks resulting in data theft or corruption [17]. While legislation or trade unions can protect workers, e.g. in Europe [9], this case may not be the same in many developing countries as even when there are legal provisions, the enforcement and ability to protect the workers may be limited. Consequently, Awolusi et al. [17] argue for strong security measures such as proprietary algorithms and secure authentication to protect the data and intellectual property. However, underpinning this with statute in developing countries where regulatory regimes including the instruments are limited may be challenging and take a long time. Even when in place, enforcement is likely to be an issue given the poor legal system in countries like Nigeria with length court cases [7,8].

3.3 Challenges and barriers to implementing digital technologies in the enforcement of construction HSW regulations and standards from the external regulators perspective

The five main barriers found are: multiple types of risk; nature of data analytics; cost; skills, knowledge and experience; and data privacy and security.

3.3.1 Multiple types of risk

While regulators may have more than one Machine Learning (ML) tool, European Agency for Safety and Health at Work [11] found that their dimensions of targeting risks may not match the multiple facets of risks. There are different types of risks so for regulators to develop risk models to capture the varieties is challenging. When possible, it is at a higher cost. Further, when there are political risks and a risk-based approach to enforcement is used, ML algorithms are unable to consider political views [11], a core aspect of this regulatory approach [7].

3.3.2 Nature of data analytics

From the big data perspective, the types of HSW data can be a limitation here [37]. HSW regulators (inspectorates) usually analyse inspection objective data from construction sites and companies. However, they may not be automatically identifiable with unique identifiers as machine learning algorithms depend on unique identifiers to assign predictive values to companies [11]. By implication, this is a prerequisite for application on construction sites but when unavailable using the technology is impossible.

3.3.3 Cost, skills knowledge and experience, and data privacy and security

The high-cost requirement of digital technologies that regulators can use, for example, big data and analytics are covered in literature, by Bilal et al. [38] and Madanayake and Egbu [39] where it is the highest barrier to implementing this technology. This can be a barrier to HSW regulators, especially as the technology is still in its embryonic stage. In many countries, they are constrained by finance [8]. For skills knowledge and experience, and data privacy and security, the same challenges in Table 2 that organisations encounter in compliance checking apply here. The only difference is that regulators may have access to money to tackle the challenges. While some of the challenges and barriers in this Section (3.3) are not unique to HWS regulators, some are. Addressing them is fundamental to integrating digital technologies into the enforcement of construction HSW regulations and standards in multiple project phases, and among other applications, Prevention through Design and Planning (PtD/P) [40-42], proactive safety [43-44], and personalized learning and feedback [45-46]. One consistent implication of the findings in this section is the need for regulators to drive change. Although industry leaders advance their practices regardless, if overlooked, the general industry may not follow swiftly. This happens to be, however, the industry sector that contributes most to the devastating numbers of accidents in the construction industry.

4 CONCLUSIONS

In this study, the barriers to implementing digital technologies in the enforcement and compliance with SHW regulations have been examined using the literature review methodology. The study found that the barriers to HSW compliance checking which aims to meet regulatory requirements can be categorised under 18 subthemes in 7 themes, including technological (e.g., its readiness and reliable use on construction sites), people (e.g., their acceptance, phobia for digital technology, and scepticism), and lack of relevant skills and knowledge. In terms of digital technologies in the enforcement of construction HSW regulations and standards from the external regulators' perspective, while the HSW (or labour) inspectorates also encounter economic, skills, and knowledge shortage barriers, like the regulated, the multiple nature of risks and nature of data analytics are also main barriers.

Digital technology adoption in construction is gradually improving. Its ability to improve the activities of the industry and associated productivity levels is without question. However, it has become evident in the current study that its efficiency in addressing the needs and challenges of HSW regulation enforcement and compliance checking is still a long way away. Hence, this mission continues to encounter challenges that threaten the foundations of HSW improvement, especially in developing countries where the regulatory regime and characteristics of the industry face unique challenges. While overall, the identified barriers seem familiar for any technology adoption in the construction industry, the strategic position of regulation and compliance in HSW make it fundamental to HSW improvement with implications for the performance of the industry. Consequently, practitioners in the role of end user, researchers and developers who initiate or create technology may wish to set a specific focus and clarity in what technologies will aid or transform the state of the practice. As the findings of the study are subject to empirical validation, further study is recommended.

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A MR-BASED DIGITAL TWIN APPROACH TO IMPROVE THE SAFETY OF INTERIOR PAINTING WITH THE HUMAN-ROBOT COLLABORATION SYSTEM

Chung-Wei, Feng [1], Yi-Hsuan, Hsiao [2]

[1]*National Cheng Kung University(Taiwan)*

[2]*National Cheng Kung University(Taiwan)*

ABSTRACT

The working environment of interior painting is usually air polluted, which presents safety concerns and is harmful to construction workers. One of the approaches to improve the safety of interior painting is to use robots to replace human workers. However, employing robots at the construction site depends on the level of automation demanded. Most of the approaches developed still require human workers to operate robots at the construction site. This study proposes an approach of applying digital twin concept to develop the human-robot collaborative (HRC) system that can avoid human workers to work at the construction site for improving the safety and productivity of interior painting. First, the operation of the Interior painting is analyzed to identify the difficulties of employing robots at the construction site and to determine the functional requirements of the HRC system. Then Mixed Reality (MR) technology is employed to build the functions for human workers to plan the tasks for interior painting in a virtual platform. The Building Information Modeling (BIM) which provides the visual 3D model and auxiliary information is also digitally transformed into the virtual platform that integrates with Robot Operating System (ROS) to find the feasible painting trajectory for the robot arm. In addition, the remote connection between the wearable MR device and physical robot control system is established by TCP/IP protocol. As a result, the worker equipped with MR device can intuitively control the robot to plan painting operations according to the information retrieved from BIM in the virtual platform without obstacles. The successful operational sequence is then delivered to the physical robot arm to perform the requested painting tasks in the real construction site. An experimental HRC system is developed to verify the proposed approach. Results shown that, with this digital twin approach, the safety of the interior painting operation can be an improved.

Keywords: Digital Twin, Mixed Reality, BIM, ROS, HRC, Interior Painting

1. INTRODUCTION

Safety of construction workers is one of the most important issues in the construction industry. Taking interior painting as an example, the air-polluted environment is hazardous to laborers. In addition, workers need to constantly go up and down to carry out large-scale painting, which increases the risk of falling. Although employing robots to replace construction workers can improve the safety of 'laborers working in the harsh environment, using robots at the construction site is still difficult. One of the reasons is that the construction site changes according to the scheduled progress, which is not the stable environment for robots usually performing pre-planned and simulated repetitive tasks.

In recent years, the world has entered the era of Industry 4.0, smart manufacturing. The connotation of smart manufacturing includes four major parts: smart equipment and systems, cloud computing systems, human-machine collaborative systems, and the internet of things (IOT). In Industry 4.0, the manufacturing method is made to be intelligent, flexible, and precise. The interactive mechanism of human-machine can cooperate with IOTs to obtain the real-time equipment information to flexibly adjust production method and robot operations. The overall process will be more flexible and adaptable, thereby improve the product manufacturing with high accuracy and high degree of customization.

In the AEC (Architecture, Engineering, and Construction) industry, Building Information Modeling (BIM) is a technology that serves as the foundation for providing and exchanging building information. Under the concept of Industry 4.0, combing BIM with automated robots for construction activities could be the core for developing smart construction. However, the applications of BIM so far are mostly on design review, construction documentation, and construction conflict identifications which are human-oriented tasks. The information within BIM is not oriented for the operations of robots and does not provide detailed control information for robots. At the present development, the human-robot cooperation that human interprets BIM information to instruct robot is a better approach of employing robot at the construction site. A communication tool that can help human cooperate with robots is necessary. Mixed Reality (MR) is an extension of Augmented Reality (AR), a technology that combines virtual and real worlds, which can display digitized virtual objects in the real world.

Through the MR device workers can view the building model at the remote control room to instruct virtual robot to simulate performing construction tasks in the virtual environment, then let real robot perform construction tasks in the actual physical construction site, a digital twin approach. By taking this approach, the safety of human workers can be improving by introducing robot workers to perform construction tasks at the construction site. This study proposes an approach of applying digital twin concept to develop the MR-based human-robot collaborative system that can avoid human workers to work at the construction site for improving the safety and productivity of interior painting. The following sections will describe (1) the past research of robots, BIM, and MR in the construction industry (2) The proposed MR-Based human-robot collaboration framework (3) the experiment conducted based on the proposed approach (4) lesson learned from the experiment.

2. PAST RESEARCH

2.1. Development of Construction Robots

As early as 2004, Kahane et al. [1] proposed an analysis method to evaluate the effectiveness of human-robot collaborative robots in performing site operations. The study also tested the ability of their robot "TAMIR" to perform brick stacking tasks and painting tasks. Construction robot technology brings revolutionary changes to traditional manual construction methods. Gharbia et al. [2] systematically collected and counted the past 52 robotics papers, and pointed out that the construction robot is a growing research field, among which the most studied types are laminate manufacturing, automated installation systems, automated robot assembly systems, etc. And most of them focus on the construction of concrete building components. The study also suggests that improvements in robot hardware, innovations in building materials, and more advanced building designs will improve the benefits of construction automation robots.

In the current practice on the construction field, similar to that construction tasks require different skills of workers, different construction tasks also require corresponding robots. For example, TyBot is an automatic steel bar binding robot, which is suitable for use in bridges, highways, tunnels and other projects that require a large number of repetitive steel bar bindings. SAM100 is a large-scale mobile brick-laying robot composed of gripper manipulator, concrete extrusion pump, and brick conveyor belt. It can grab bricks and automatically smear concrete and stack them into walls. It can stack 2000~3000 bricks a day with only 4~5 people to assist operation [3].

Many researchers focus on interior decoration robots, among them Asadi et al. [4] found that the interior decoration robots studied in the past lacked a high degree of adaptability. And most of the work planning was based on a two-dimensional control system. Therefore, Asadi et al. proposed a human-robot collaborative painting robot "Pictobot". The robot consists of a mobile base, a lifter, and a six-axis robotic arm. It can stably and horizontally perform painting tasks at the height of the building. The detector can obtain 3D information of the building, and the operation mode of human intervention and cooperation makes it more flexible to deal with the painting task of uneven surface. However, the above approach still requires human interaction at the construction site, safety concerns still cannot be lift.

2.2. Employing BIM for construction robots

BIM is an integrated information platform. The architectural geometric and semantic data described by BIM can be used to simulate robot operations on the construction site. However, the authoring tools for building BIM or the file format and levels of detail of BIM are usually not suitable to be used in the robot simulation system. Wong et al. [5] proposed a process of simulating robot operations based on BIM, which are: (1) BIM design and data import; (2) selection of robot system model according to requirements; (3) establish the simulation environment; (4) set the operation steps and control methods; (5) execute the simulation; (6) evaluate the results. They proposed to use the IFC (Industry Foundation Classes) file format as a conversion form for transferring information into the robot simulation system.

In the related research of using BIM and physical robot, Giusti et al. [6] developed a robot "BALTO" to perform indoor disinfection tasks in buildings. BALTO consists of a mobile base and a seven-axis robotic arm. It is also equipped with a lidar sensor, a depth camera, and a disinfection nozzle. This robot uses the Robot Control System (ROS) system to develop the control core, the function nodes that can import the BIM with semantic data. ifcOpenShell, an open source IFC toolkit and geometry engine, is then used to interpret the IFC file of the BIM to build an indoor navigation map and generate object disinfection strategies.

2.3. The development of employing MR with robots

The ability of MR to present virtual three-dimensional information within the physical real environment provides a new way of carry out construction operations. The research on this technology in construction engineering applications is increasing. By converting the BIM information into virtual objects and the associated data from the cloud database, engineers can instantly access on-site construction operation information and further use a series of MR functions. The traditional robot control approach needs to the program the action commands in advance. However, such an approach cannot efficiently and flexibly adapt to the customized manufacturing. Therefore, MR is regarded as an emerging medium for human-machine collaboration. Lotsaris et al. [7] used the MR device to issue action commands to human-robot collaborative mobile robots. This research enables the base of the mobile robot to move autonomously to the position specified by the user, and the MR device will display the current stage of the robot's work task, visualizing the safe range of the robot's work. If an obstacle or a worker enters the working area of the robot, the robot will stop in an emergency and display a warning message in the MR device. This research also demonstrates that using MR technology to remote control robot can provide a better safety to human workers.

From the above discussions, it can be realized that the safety of the human workers can be improved by using robots at the construction site. However, several issues need to be addressed so that robots would be employed to improve the safety of human workers. (1) Taking the approach of cooperating human and robot is currently the better way of employing robots in the construction field. Automatous robots can provide safety measurements since human workers don’t need to get into the harsh environment of the construction filed. However, due to the dynamic nature of the construction project, it is not cost effective to program robots to be automatically operated in the changing construction field. (2) Adopting the digital twin concept that simulates the operation of the robot in the virtual environment and let physical robot perform in the real construction site according to the result of the simulation can provide a reliable performance of robots. BIM is the very important data platform to build the digital twin of the construction robot. BIM can provide necessary and sufficient construction information in the virtual environment to simulate robot operations. However, the associated information with the BIM is not designed for the robot operations, which requires converting information and could present technology difficulties. Human interpretation of BIM information is required. (3) Employing the MR device as a communication tool to instruct robots to carry out construction tasks can provide a more flexible way of retrieving BIM and simulate the operation of robots.

Therefore, this study proposes an approach of applying digital twin concept to develop the human-robot collaborative (HRC) system that can avoid human workers to work at the construction site for improving the safety. An experimental operation of interior painting is conducted to verify the proposed approach. First, the operation of the Interior painting is analyzed to identify the difficulties of employing robots at the construction site and to determine the functional requirements of the HRC system. Then MR technology is employed to build the functions for human workers to plan the tasks for interior painting in a virtual platform. The Building Information Modeling (BIM) which provides the visual 3D model and auxiliary information is also digitally transformed into the virtual platform that integrates with Robot Operating System (ROS) to find the feasible painting trajectory for the robot arm. In addition, the remote connection between the wearable MR device and physical robot control system is established by TCP/IP protocol. As a result, the worker equipped with MR device can intuitively control the robot to plan painting operations according to the information retrieved from BIM in the virtual platform without obstacles. Those successful operational sequence is then delivered to the physical robot arm to perform the requested painting tasks in the real construction site.

3. THE MR-BASED HUMAN-ROBOT COLLABORATION FRAMEWORK

The procedure of the proposed approach explained in the following sections: (1) Analysis of the application requirements of the human-robot collaborative painting robot; (2) BIM and painting point information that meet the needs of the robot operation; (3) The human-robot collaborative painting robot control system (4) MR human-robot collaboration project. Fig. 1 shows the structure of the overall development of the proposed approach.

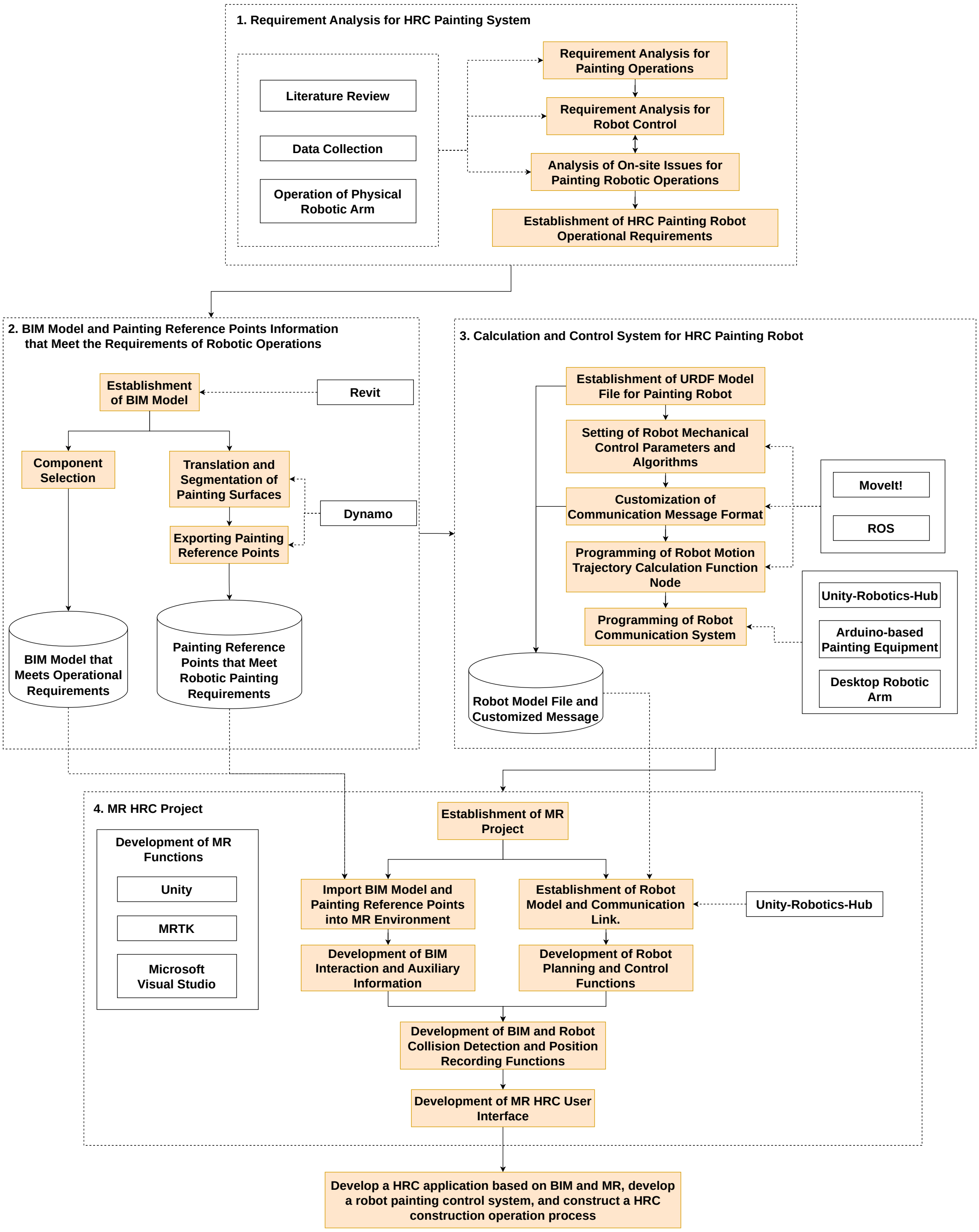

Fig. 1 Overall development structure of the proposed research

3.1. Analysis of the operation requirements of HRC painting robots

Spray gun painting is a stable method which has the advantages of fast operation, saving paints, and producing uniform and smooth painting results. When spraying, it is necessary to keep the spraying direction of the paint perpendicular to the surface and sweep the surface at a constant speed. Although the automatic six-axis robotic arm for spraying is well developed, it is still difficult to directly use a generic spray-painting robot without considering the movement and control of robot arms in terms of angle limit, working range, singularity, and collision with buildings. In addition, the human-robot cooperation requires the simulate the control and movement of the robot arm for spraying paints. The collaborative robot control method also should simulate human actions, such as grasping and dragging the robot for action demonstration. Although he human-robot cooperation increases the flexibility of planning, simulating such human instructions is still inefficient in the virtual environment. Therefore, it is necessary to use MR technology to provide more efficient and intuitive human-robot collaboration.

3.2. BIM construction and painting information export in line with HRC

In this study, LOD300 is used as the standard of level of development to build BIM. Revit is employed to develop BIM and the 3D model is exported by fbx format. The geometric information and appearance of the building model, which provides auxiliary information for spray painting. Users can click on the building objects to generate painting auxiliary information in the BIM environment and input the relevant parameters of the painting equipment to generate the painting reference points. The point information has the geometric position coordinates and the normal vector information perpendicular to the painted surfaces. In addition, according to the specifications of the painting equipment, the painting reference points used as the reference position of the end effector of the robot arm are also produced from the BIM. Consequently, two files are generated to import the Unity to build the MR environment. fbx file that contains the information of the BIM built by Revit and the text file that contains the painting reference points produced by Dynamo, as shown in Fig. 2.

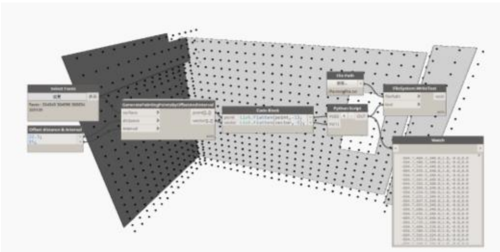

Fig. 2 Export spray painting reference points by Dynamo

3.3. HRC painting robot control system

The Unified Robot Description Format (URDF) file, which is an XML file for representing the robot model, based on physical robots. This study uses URDF to obtain the appearance and physical properties of the robot in the virtual environment. In addition, the robot arm control algorithm is planned through MoveIt, a primary source of the functionality for mobile manipulation in ROS to control and plan robots operations. Furthermore, the Rosserial kit is used to connect with the painting equipment and the physical robot, Arduino is set to control the painting equipment and G-code is used to transmit robot control. As for the MR functions development, the URDF file translates robot information into the Unity through the URDF-Importer provided by Unity-Robotics-Hub. ROS-TCP-Connector is then used to establish a communication mechanism between ROS and Unity to transmit the calculation requirements of robot motion trajectory and the simulated result.

3.4. MR-based human-robot collaboration functions

The functions of the MR-based human-robot collaboration system according to the painting operation is developed and described in this section.

(1) System operation interfaces

The functions of the MR application developed in this research are divided into: the basic function panel of the collaboration system, the robot control panel, the base position selection panel, and the task list planning panel, as shown in Fig. 3.

Fig. 3 The functions of the MR application

(2) Model interaction and reference painting points display functions

The BIM is displayed for user interaction within the MR device. Users can operate the virtual model by gestures through sensors. The reference points of spraying paint generated by Dynamo provide the yellow dot objects in the correct position and direction, which can be used as a reference for users to instruct the robot arm for painting operation, as shown in Fig. 4.

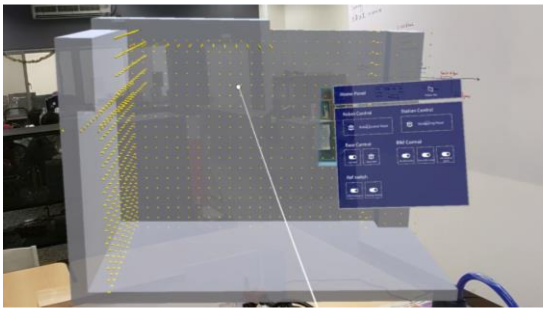

Fig. 4 Model interaction and reference point display function

(3) Feasible working range and painting status display functions

The Feasible working range display function can generate a colored (blue) space in front of the virtual robot arm, which represents the feasible painting working range suitable for the current position of the robot arm. The spraying status display function can generate a continuous spraying cone-shaped example effect in front of the end-effector of the robotic arm. The size is chosen according to the nozzle size of the actual spraying equipment. If the robotic arm collides with the building, the head of robot arm will turn to be red to warn the user, as shown in Fig. 5.

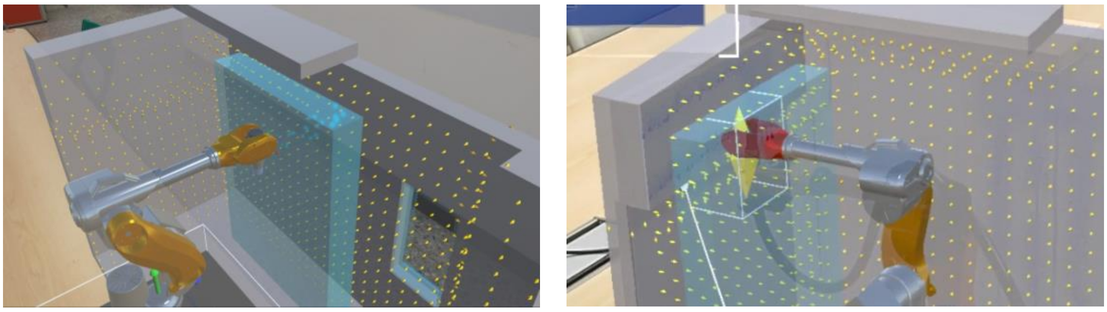

Fig. 5 Feasible working range, paint status display, and arm collision detection

(4) Virtual end effector function

The virtual end-effector is used to indicate the target posture of the robotic arm. The user can arbitrarily move, rotate, zoom, and locate the end-effector in a specified position. As shown in Fig. 6.

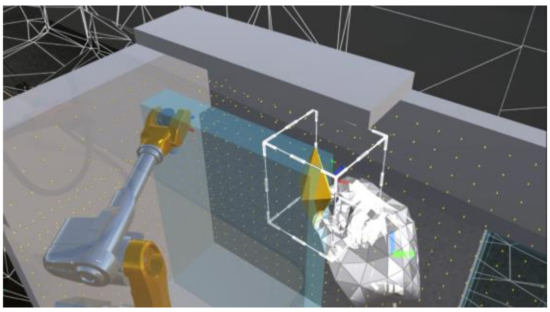

Fig. 6 The virtual end effector

(5) Linear and nonlinear trajectory movement

The trajectory movement function can provide linear movement trajectory and non-linear movement trajectory. The ROS calculates the trajectory from the current robot arm posture to the target end-effector posture, as shown in Fig. 7. After receiving the trajectory, the Unity controls the virtual robot arm to move according to the trajectory, which can visually displayed.

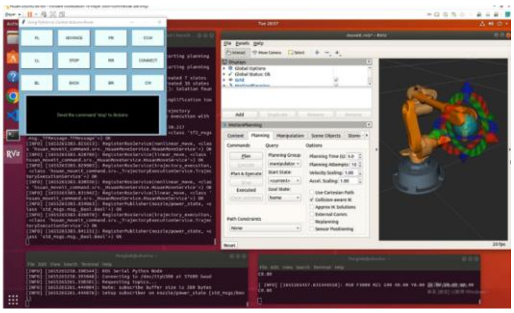

Fig. 7 ROS calculates the trajectory

(6) Virtual base interaction and moving functions

The user can also grab the virtual base and determine its position. After the position is selected, the virtual robotic arm will move to the current position of the virtual base and reconcile with it, as shown in Fig. 8. When the user starts to plan a painting task, the system is set in a situation where the robot base is fixed and does not move, and the position of the painting base is defined as a painting station. While the user starts to plan the painting task, the operation sequence can be recorded for further use.

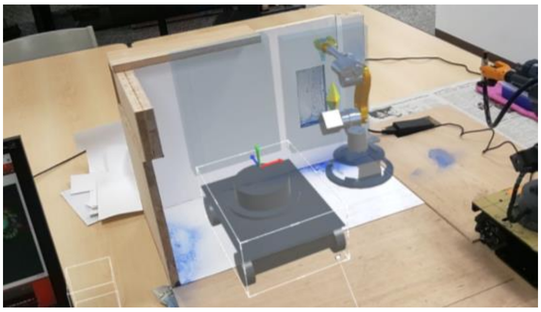

Fig. 8 Virtual base positioning and movement

(7) Task command generation and pose recording functions

The painting task planning panel is for generating painting task instructions. The five parameters are required as follows: (1) initial nozzle state, which can be turned on or off; (2) speed parameters; (3) trajectory type, which can be selected from nonlinear or linear trajectory; (4) second nozzle state; (5) waiting time. When the user touches the "Submit" button in the parameter panel, the current posture of the six-axis robotic arm will be recorded. After the user confirms the planning status of the robot arm through the task list, the painting task can be released to the real robot arm.

4. EXPERIMENT

An experiment is conducted according to the proposed approach. Several experimental settings are selected as follows:

(1) A simple building model is created. This model contains various sections, such as ceiling, column, beam, and windows, which require different types of spraying operations. Both virtual and physical building models are created, as shown in Fig. 9.

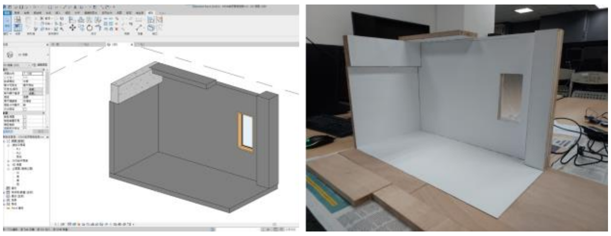

Fig. 9 Experimental building twins Cyber (left) and physical (right)

(2) An experimental physical robot arm with mobile base is employed as the physical spray-painting robot, as shown in Fig. 10. Its virtual representation is also created. In addition, the spray-painting equipment is a simple pomp with nozzle device which use colored water to mimic paint spraying operations. (3) The MR-based HRC system is developed on the HoloLens 2 MR device, as shown in Fig. 10.

Fig. 10 HoloLens2 and physical spray-painting robot

In addition, the scenario of this experiment is developed as: the human worker wearing HoloLens 2 instructs the virtual spray-painting robot in the physical real environment which is physical twin of the the virtual BIM. After the painting instruction is completed, the feasible working sequence and arm trajectory can be determined and will be delivered to the physical spray-painting robot. The physical spray-painting robot then performs the simulation result by itself alone without human worker's involvement. The purpose of this experiment is to verify the proposed approach that human worker can use the MR-based HRC system without physical appearing at the construction site while the physical spray-painting robot performs paint spraying operation in the real environment to increase the safety of the human worker.

4.1. Experiment procedure

(1) Remove obstacles of construction environment, prepare robots and painting equipment

The collaborators need to inspect the on-site construction space to confirm that there are no obstacles that could block the robot's operation or movement. If there are obstacles, they must be removed; after the robot enters the field, the collaborators must also set up the robot and related equipment.

(2) Activate the MR application and the ROS robot system

Human worker puts on the Hololens 2 and activates the collaborative application developed in this research, meanwhile the ROS is activated in the control computer. Then the ROS and the MR glasses are connected through the network after both applications are activated.

(3) Superimpose virtual and physical models

The human worker first open virtual BIM and superimpose it with the physical building model. After the superposition is completed, the BIM is locked, and the reference points for painting can be display for human worker to instruct virtual robot.

(4) Set the virtual robot base position

The human worker then opens the virtual robot base and position it to the location where the painting operation will be initialized. The effective working range space will be displayed in front of the virtual robot base and the painting reference point of the BIM can assist the human worker to select the proper base position. After locating the virtual robot base, the virtual robot arm will be placed on the it for further instructions from the human worker.

(5) Plan painting tasks

The human worker now can use the MR-based HRC system to plan painting tasks. Painting task planning function can help the human worker work with the virtual end effector and control the robot arm. The human worker can plan suitable instructions according to different surface conditions by utilizing the collision detection function, trajectory movement function, and task demonstration function. All those functions can help the human worker know the quality of the planning results in advance and make corrections before delivery, as shown in Fig. 11.

Fig. 11 Human workers instruct virtual robot.

(6) The physical spray-painting robot moves to the designated position

After the planning of the painting task is completed, the self-propelled physical spray-painting robot can move itself to the designated position, which is planned in advance in the virtual environment, as shown in Fig. 12.

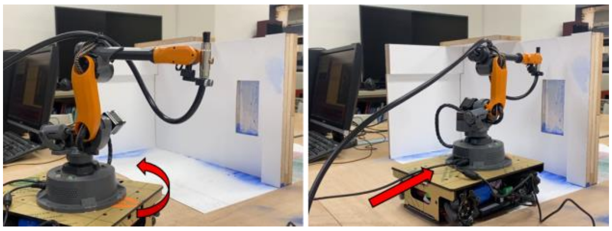

Fig. 12 The physical spray-painting robot moving to the designated location

(7) Delivery operational instructions to the physical spray-painting robot to perform painting tasks

When the physical spray-painting robot arrives at the preplanned location, a series of tasks commands which have been planned and simulated can be delivered to it through TCP/IP protocol. Then the physical spray-painting robot will execute the painting task, as shown in Fig. 13.

Fig. 13 The physical spray-painting robot performing painting tasks

4.2. The results and analyses of the experiment

An experiment based on the proposed approach was successfully conducted. Although a rather small and experimental robot compared to the industrial robot was used in this verification, the proposed approach still showed satisfactory and promising results. In this experiment, the human worker wearing the MR device can instruct the virtual robot to generate feasible task commands according to the superimposition of the BIM and real building model. This approach provides a more flexible and practical method for planning robot operations at the construction site according to the schedule of the construction project. In addition, at the separated time form the presence of the human worker, the physical spray-painting robot can do the painting tasks without the involvement of the human worker, which provides the better safety protection for the human worker since the human worker is not required to physically appear at the construction site while the physical spray-painting robot perform paint spraying tasks. Moreover, compared with the time-consuming approach of importing BIM into the generic robot planning software, the MR technology can BIM more efficiently and effectively. Finally, the developed the MR-based HRC system can help the human worker view BIM auxiliary information in a direct and intuitive manner, which also let human worker train the physical spray-painting robot in a more structural fashion that data about instructions can be collected and analyzed for further uses.

5. CONCLUSION

This study proposed a digital twin approach that goes with the MR-based human-robot collaboration system for interior painting. In addition, an experiment to verify the proposed approach was conducted. Judging from the result of experiment, this proposed approach can improve the safety of the human worker by introducing the physical spray-painting robot. Although the preliminary result is satisfactory and promising, more details should be discovered and improved to make the proposed approach applicable for the industrial robot performing at the construction field. First, the representation of the virtual operational environment needs to be more precise to the actual construction field. A cyber-physical environment that fully integrates the virtual and real environments should be developed. Second the physical spray-painting robot should be more self-guided by introducing more sensors on it. Those sensors could help the physical spray-painting robot adapting to the environment if the planned operational task commands cannot be executed. Finally, providing quick and reliably transferring information from BIM to the robot planning software is crucial to the success of the application. It is expected to develop a more structural and efficiently mechanism to transferring information.

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LESSONS LEARNED FROM THE USE OF VIRTUAL REALITY FOR OCCUPATIONAL SAFETY AND HEALTH TRAINING IN THAMES TIDEWAY TUNNEL

Manuel Tender[1,2], Paul Fuller[4], Alex Vaughan[3], Peter Demian[4], Vivien Chow[4], Firmino Silva[1], João Couto[5], Ricardo Santos[2]

[1] *ISLA-Polytechnic Institute of Management and Technology, School of Technology (PORTUGAL)*
[2] *ISEP-Instituto Superior de Engenharia do Porto (PORTUGAL)*
[3] *Ferrovial / Laing O' Rourke Joint Venture* (UNITED KINGDOM)
[4]*University of Loughborough (UNITED KINGDOM)*
[5]*University of Minho (PORTUGAL)*

Abstract

New Key Technological Developments (KTD) are leading to a challenging paradigm shift in the way Occupational Safety and Health (OSH) is managed in the Architecture, Engineering, Construction, and Operations (AECO) sector. Previous research has shown that these developments have the potential to reduce the risks and costs associated with accidents and occupational diseases at work. This paper reports on a pilot case study covering the implementation of BIM and Virtual Reality for OSH training purposes related to the operation of a Tunnel Boring Machine (TBM). The actors involved included designers, BIM/OSH specialists, construction managers, and training staff. The aim of the research was to identify the benefits, barriers and challenges associated with the implementation of these KTD's in a Joint Venture (JV) organisation delivering part of a complex megaproject in Central London. A tablet-based approach was selected to overcome some of the challenges of implementation identified. The resulting areas of benefits included: better safety in design, improved hazard perception: enhanced risk awareness and increased familiarization prior to working in the hazardous environment of tunnel construction, emergency rescue training, and maintenance training. The main benefits from this are the resulting productivity gains - Tideway estimates that the project could potentially see a 20% reduction in training time, a 10% reduction in accidents and near-misses and significant increases in employee understanding of hazards and risks onsite, which can improve project outcomes significantly. The key lessons learned are the need to keep costs down, the necessity of system portability and ease of access. The results of the study will assist organisations that are interested in the adoption of these KTD's and provide valuable insights to the wider construction industry. This will enable companies to improve how OSH is managed and promote the uptake of KTD for OSH purposes.

Keywords: Virtual Reality, Tunnelling Boring Machine, Health and Safety Management, Lessons learned, Thames Tideway Tunnel

1 INTRODUCTION

1.1 AECO and Key Technological Developments

The Architecture, Engineering, Construction and Operation (AECO) sector has witnessed several key challenges in recent years: low productivity, shortage of qualified staff, insufficient innovation, a lack of consistent processes, standardization and automation, the need tfor a large amount of technical documentation, and an aversion to adopting new technologies [11].

Key Technological Developments (KTD) tools have become increasingly important in providing better integration for the development of Architectural, Structural and Mechanical, Electrical and Plumbing (MEP) Project designs, given their proven advantages to respond to a growing need for optimizing processes, procedures and decision-making throughout the entire construction lifecycle [11].

The AECO sector represents a fundamental driving force in world economy growth and remains a key indicator on a country's prosperity. BIM may be considered today as the methodology that fulfilled the promise of innovation through digitalization of an industry normally reluctant to adopt novel or disruptive solutions need to be found to solve old problems exacerbated by a plethora of new challenges.

Virtual Reality (VR), along with other types of reality substitution, superposition or enhancement, have already proved their worth on several industries but still need to find general acceptance in the AECO industry. In the context of Industry 4.0, it might also be worth mentioning that Augmented Reality (AR) and VR are important components of the emerging concept of the "metaverse”. It can also be said that the correct management of OSH is a critical factor to the success of any construction project and has been widely recognized as one of the most influential aspects in companies’ overall performance [2].

1.2 AECO and OSH

Accidents persist, despite several improvements in construction processes. Factors influencing this, include the increasing complexity of site operations and increasing fragmentation in the supply chain and subcontractors. OSH presents several challenges namely in terms of communication and training:

1) Communications: there is still a lack of collaborative working approaches [3], and it is still done orally [4] and using personal experience [5], and based paper-based two-dimensional drawings, which are error-prone, subjective [6] and sometimes out of date; communication methods tend not to be systematic [7] which hinders the exchange of information between stakeholders;

2) Training: several countries have adopted human-led approaches, both in classroom and in the field [8], to ensure a minimum level of training through lectures, videos, or demonstrations. These traditional training methods often fail to achieve the desired goals due to their significant limitations. For example: indoor static classroom presentations with no hands-on training elements which often fail to engage with the workers leading to a lack of interest, which impedes the retention and retrieval of critical safety concepts [9]. Due to their passive nature traditional training methods such as classroom, on-site presentations, or video-based guides do not necessarily allow a practitioner to test their understanding (as a result they must wait until they physically try to perform what they have been taught before it is known if they have understood the material [10]); the complexities and spatial characteristics of the specific construction site are not properly represented. The transient and temporary nature of the workforce hinders the implementation of new technologies as not all employees are at the same skill levels; there may be a lack of knowledge transfer due to workers not being taught in their native language or have low literacy levels and do not properly understand the training message. In terms of tunnelling activities training, new approaches must be found in order to minimize associated specific risks. Tunnelling risks are as extensive as those involving works above the surface, or even more so. Tunnelling works are prone to several types of emergency situations, particularly collapse, electrification/electrocution, being hit by a vehicle, roadway accidents, intoxication and lack of oxygen.

1.3 OSH through KTD

However, when it comes to OSH, KTD are not yet used as often as is the case in other specialties [12]. The literature indicates that the construction industry, especially larger general contractors and in complex projects, is developing an increased understanding of the application of KTD in real cases of design, construction, and facilities management and are starting to adopt KTD for use in OSH management [14] in order to overcome the challenges identified. The application of KTD to OSH management has the potential to offer innovative and exciting developments in the workplace, and has positive impacts on the optimization of times and costs with an increased production efficiency, and a better connection between production and safety [11]. A number of advantages have been shown to arise from the adoption of KTD for OSH management: more effective sharing of HSW information in a virtual environment and reduced likelihood of losing information; better visualization and interpretation of design through immersive learning environments; a decrease in the amount of time needed to produce outputs; favorable impacts on schedules and costs; savings in HSW practitioners’ time; more focus on greater precision; and more strategic ways to improve safety for everyone in the workplace [11]. Several researchers in the field have identified technical and scientific gaps in terms of research covering the integration of KTD in OSH management systems and have advocated the need for new studies covering:

- the benefits of using digital technologies to improve OSH outcomes [16];
- the theorical validity of the advantages that have been identified using suitable case studies [17];
- the lack of success in technology transition from construction safety research into practice [18].

VR has been widely used for safety training since 2000. In a previous phase of the research [11] the authors evaluated the level of applicability of KTD for each OSH area identified from an analysis of the Council Directive 92/57/EEC [15]. Usage of VR for hazard risk identification and training was evaluated, using a Low/Medium/High level of applicability scale as “High”.

Previous research covering training using VR has indicated that VR training has several advantages over traditional training methods including:

- training is performed in a risk-free and realistic virtual construction site;
- workers' behavior in several unsafe work scenarios can be evaluated;
- a reduction in the time it takes for a learner to become competent and operational in their field of work, and they produce memorable and lasting experiences for trainees;
- a lower required level of language proficiency and literacy and increase the understanding of those in construction who lacks fluency in English removing any language barrier;
- optimization of risk identification (the ability to identify hazardous conditions before starting a task is a valuable tool to promote proactive HSW management);
- simulation of different scenarios;
- on-site construction situations and operations can be modeled;
- aids creation of accident scenarios;
- training can be replayed as often as the trainee chooses;
- conditions of accidents and near-misses can be simulated.

This paper addresses the need for more research with a real case example (pilot study) in Thames Tideway Tunnel (Tideway) project by Ferrovial Agroman UK and Laing O' Rourke Construction Joint Venture (FLO JV) - "Virtual Reality Tunnel Boring Machine" (VR TBM). The case example aimed to retrieve lessons learned from it, analysing the benefits, barriers and challenges, of using VR to transform the way Occupational Safety and Health (OSH) is managed and assessing the benefits, barriers and challenges associated with this approach. This pilot study will have a special focus in areas such as improving hazard perception, awareness, to improve risk assessment, and training during the construction phase and to develop familiarization prior to accessing or working in the hazardous environment of tunnel construction. Affordable and mobile technology to deliver the experience was one of the key aims of the project.

Taking in account the technical and scientific gaps identified in the literature review the following Research Question (RQ) was established: "*What practical lessons and good practices are there to be shared, based on the learning from the Tideway interventions, with wider industry and those involved in fields of OSH development and improvement?"*

Providing construction stakeholders with a list of KTD applicable to improving OSH management along with identifying their key benefits and barriers will facilitate better knowledge and understanding of OSH management. This in turn will encourage increased adoption of KTD solutions, especially amongst smaller contractors who are typically more likely to be resistant to change.

The following section identifies the overall context of the study whilst Section 3 presents the approach to the research methods and methodologies and Section 4 exposes the lessons learned. Section 5 covers the conclusions, explores limitations, and it explains what future studies should focus on.

2 TIDEWAY CASE STUDY

UK was preferred as a suitable location to conduct the research for the following reasons [19]:

- The UK has a large history of mega and complex projects and has several ongoing placing the country in a unique position of global influence [11]. There has been an effort and growing interest in innovation management in megaprojects in UK [20], and there is much to be explored in this area of research [19]. However, innovation on megaprojects remains "surprisingly underexplored in the megaproject management literature" [19]. UK has also played an active role in driving forward KD adoption perhaps leading to interest from professionals in other countries to follow the UK's progress [11];

- The UK adopts the important concept of applying lessons learned from projects both positive and negative. [11]. The lack of learning from projects results in similar errors to occurring and missed opportunities to improve performance;
- The process-based open innovation approach used on the Tideway project provided an opportunity to explore how innovation and learning legacy can be used as a way of transforming the infrastructure industry over time [19].

The Thames Tideway Tunnel Project was selected as it is a from the statistical population of construction project using a convenience sampling strategy. The authors have been carrying out previous research covering the use of OSH on this project which provides a rich understanding of the topic. The project is the biggest infrastructure project (£4.2 billion pounds GBP) ever undertaken by UK water industry and one of largest in Europe. The project has a key objective of pursuing innovative technology as a way of improving cost-effectiveness, productivity and the quality of work delivered. There are some excellent examples how the issues identified are managed and Tideway management have put an emphasis on lessons learned from previous projects.

The Tideway project is being undertaken to renew the Victorian sewerage systems designed by Sir Joseph Bazalgette. Even though the sewer structure is still in good condition, despite its age, it has a shortcoming – due to the increase in population, millions of tonnes of sewage are discharged into the tidal section of the river Thames every year adding to pollution of the river. The Tideway project will provide a new super sewer infrastructure for London that will reduce the current high number of discharges of effluent into the river. This will dramatically improve the water quality of the river and give the city a wastewater system that it can rely on for the next 100 years. The scheme is designed to intercept existing Combined Sewer Outfalls (CSO's) located along or adjacent to the river with the construction of new interception chambers and shaft structures built into the foreshore sites of the existing river wall CSO's. The main transfer tunnel is 25km long and 7.2m internal diameter located predominantly beneath the central section of the Thames and will connect to 34 of the most polluting CSOs. It is being built under London's existing underground infrastructure, deep beneath the London Underground tube lines and utilities, and will pass through a variety of ground conditions. Construction commenced in 2017 with completion scheduled for 2023. The Tideway project has been let as three distinct contracts for three Main Work Contractors comprising Central, East and West. Ferrovial Agroman UK and Laing O' Rourke Construction Joint Venture (FLO) will be undertaking the Central section of the Tideway scheme as Principal Contractor and Designer. This section measures 12.7 kilometers in length, it is the largest of the tunnel's three sections and it is worth 746 million pounds, equivalent to 1,050 million euros. The Central Section of the Thames Tideway Tunnel project has 24 construction sites and is illustrated in Fig. 1.

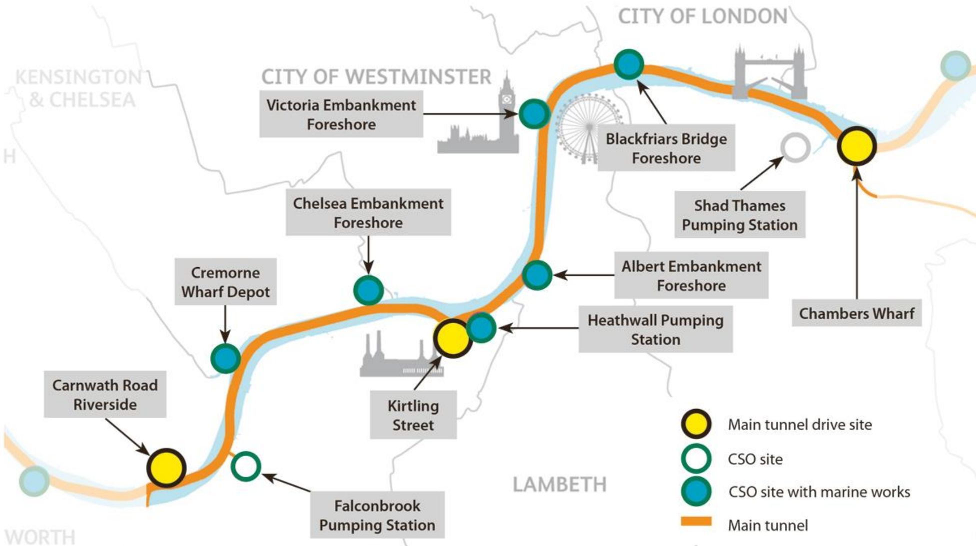

Fig. 1 – Tideway Central Section Map

Occupational risks related to these works include [11]:
- Structural hazards (ground settlements from temporary or definitive structures fragilities or collapse); lifting operations; confined spaces; working at height; flooding; migration of toxic/ explosive ground gases into the tunnel; dealing with services: water, electricity, gas; contact with unexploded ordinance; derailment, roll over and crushing by vehicles; fall of blocks and sprayed concrete fragments; trench collapse; risks related to lifting or moving operations (e.g. Tunnel Boring Machine (TBM) parts, segments, cofferdams); rupture of pipes or temporary structures; fall of person on the same level/to a lower level; fire and explosion onshore or offshore; electrocution; overturning of vessels; hypothermia, drowning; rock mass and sprayed concrete dust inhalation; fumes, diesel gas or fire smoke inhalation; biological risks: leptospirosis and water borne diseases, biological pathogens, live sewers, contaminated land; asbestos; chemical risks: shotcrete, concrete, sprays, petrol, cement, gases from live sewers, gases from soils; terrorist attacks due to site location near and adjacent to government buildings; noise; vibration; hyperbaric interventions; extreme temperatures; radiations; musculoskeletal problems; psychosocial risks e.g. stress and fatigue.

Tideway, as the Project Owner, has the objective of delivering a transformational approach to OSH better than any else currently experienced in construction [21]. This is intended to be achieved through better: leadership; organizational processes and procedures; communications; collaboration; and engagement. These factors have been the key to the successful OSH delivery of the activities carried out. FLO, as a contractor, is taking steps (namely through using new technologies) so that workers finish the project with a good understanding of OSH management and how transformational approaches can be adopted.

3 RESEARCH METHODOLOGY

The Central Section construction sequence provided an opportunity to investigate the advantages and disadvantages of using a VR based approach to OSH. The adopted methodology involves the researcher investigating an activity or process in depth over a period of time using a range of data collection processes (Cresswell 2009). The data collection consisted of interviews, direct observation and archival analysis.

The project was developed by FLO JV in partnership with Hobbs Studios, Thames Tideway Project and knowledgeable Health and Safety professionals within the industry (namely Innovate UK, University of Sheffield – Advanced Manufacturing Research Centre, and Advanced Forming Research Centre – University of Strathclyde). The first stage has been completed and has been used as a trial which took the form of a Virtual Reality (VR) model that could be used by FLO as part of their suite of training tools. A key objective was to improve the technical and logistical understanding of the works normally covered during inductions. The team have retained the industry's naming conventions, where new equipment is named after a saint. This tool has been named after St Barbara, the patron saint of mining, and a virtual St Barbara has been created to sit in the technology.

A proof of concept Induction Training module was developed using funding awarded from the Thames Tideway Innovation fund in June 2017. During the initial demonstration in May 2017, an improvement to the approach was identified which would save £80,000. Additional funding has been awarded by Innovate UK. This will be used to develop the Hyperbaric Interventions / Compressed Air Working and the Refuge Chamber modules. The next step will be to establish modules covering the Refuge Chamber the Build Area and Hyperbaric Interventions / Compressed Air Working.

The VR model was created using a visual support tool using Unreal Engine software (developed by Epic Games) supplied by Hobs 3D. This software allows the user to navigate in a virtual environment to train, explore and modify design of a TBM prior to assembly and delivery to site thus improving hazard perception, awareness and develops familiarization prior to accessing or working in the hazardous environment of tunnel under construction. Hardware medium was a tablet Microsoft Surface Pro 4; a VR Stereographic Projection Optoma 3D Projecto; VR headset Optoma ZD302 3D glasses and a gaming compatible laptop. Usually the virtual TBM is housed in a large cardboard pod – measuring around 6m by 4m, which can be easily transported to exhibitions and workshops. Not only can it be dismantled easily, but the pod can be recycled at the end of its useful life. This is significantly more cost effective than traditional VR pods which can cost between £80-£100k. The cardboard pod cost £4k.

The process was initiated with a working group from the Hobs 3D teams, digital team and the OSH team to create an accurate 3D BIM model. The 3D BIM model was then reviewed by the FLO OSH Lead and Tunnelling OSH Manager to ensure all high-risk areas were captured within the model and the key areas highlighted that need to be reached within the final virtual model. The 3D model was then created using the virtual model using the Unreal Engine software.

Subsequently there was a discussion of the content of the training and key areas and routes of the TBM that they would like to follow in the eventual 360-degree image tour. Digital team then takes the 360-degree camera and follow the agreed upon route and takes the 360-degree photographs at the before specified locations. This tool has various customizable options. Users can adjust the height, add logos and include multisensory features such as 4D sound, changing temperatures, smells and multiple screens, adding an extra level of immersion; ideal for environment simulation.

The VR TBM has been designed with three core principles in mind; Accessibility, Portability and Affordability which differentiates it from anything similar. The instructor can guide viewers, immersed using VR glasses, through the virtual TBM space (Figs. 2 and 3) allowing them to interact with the TBM and environment enabling remote site orientation as well as health and safety training before entering hazardous environments including hyperbaric conditions. This provides the ability to rotate and move around the TBM using the 360-degree imaging from the comfort of a non-TBM environment, allows the inductor to highlight high risk areas, dangerous components, pedestrian walkways, fire points, first aid points, emergency exits, areas of work and more, exactly how they would see it on TBM, without having to go on site.

Fig 2 – Still shot of VR TBM

The TBM construction sequence was complex in terms of the many activities that were occurring and also highlighting to the users the risk of these concurrent works happening at different places. These activities included: the build area of TBM; refuge chamber; hyperbaric interventions; segment magazine area; locomotive training; emergency escape.

Data information about benefits and barriers were collected through participant direct observation (namely site visits), 8 workshops (6 end users each- miners, civil engineers, mechanical engineers, TBM operators, Health and Safety team, fitters, electricians,etc) with verbal feedback and presenting, to take advice and guidance, to industry stakeholders and leaders (4 events with 20 people in each forum) such as Transport for London, London Underground, Thames Water and High Speed 2. Traditionally, similar VR systems would be costly, and the equipment would be difficult or cumbersome to transport. This would also make the equipment inaccessible to many. FLO presented in a Dragon's Den style competition called Tideway's Great Think where they successfully pitched for £20,000 from 4 industry dragons to further develop the concept.

Fig 3 – Still Shot of VR TBM Build Area

4 LESSONS LEARNED

4.1 SUCCESSFUL FACTORS

The pilot study, through feedback from participants' experience with the system, noted that the use of VR for TBM training had the following advantages:

- It provided the opportunity for users to become familiar with the working area/functions and practice interactive scenarios in a safe and controlled environment;
- Users could be assessed on their understanding and knowledge prior to being placed in the environment before workers are required underground and in most cases before the TBM has even been manufactured. Note that some working areas of the TBM are only accessible during high-risk activities such as compressed air working;
- Enhances the user's knowledge of key components and working areas of the actual TBM far in advance of the TBM even being assembled thus reducing the time it takes for real life familiarization training by 30%:
- Within a few minutes the user can become familiar with a TBM configuration by travelling in a VR environment starting at the rear of the TBM and working their way to the front;
- Making the experience interactive encourages questions and all persons present to participate;
- The system is portable (can be transported in a small case on public transport or in a vehicle) and does not require an expert to assemble;
- Designers are able to experience how the TBM will look before it is constructed and how TBM will interact with its environment as well as identifying improvements and the designing out of hazards and risks which is a priority. They will also have the opportunity to identify not only design issues/concerns but also improve the ergonomics related to personnel working on the TBM;
- Allows significant increases in how workers identify safety risks when dealing with problems that are difficult to detect during onsite safety training with real-life hazards;
- Enables better learning (70% of learning is visual), greater reliability and accuracy, understanding and information retention of TBM;
- The cognitive load placed on workers is reduced and retention of information is improved;
- Increases workers' enthusiasm to learn;
- Reduces the time spent analyzing drawings to confirm particularities of TBM;
- Provides the operatives a collective insight of the TBM and a chance for workers to familiarize themselves with their future surroundings and allow them an opportunity to plan how to circulate and work within a TBM;
- Improves the health and safety planning of the works in TBM creating a reduction in risks;
- Better emergency planning e.g. London Fire Brigade can use the tool for training which enables time to be used effectively and prevents them the need to access a working TBM in what is already a tight and congested environment;
- Generates time and cost savings in the form of reduced abortive work and/or wasted time and an increase in production;

t can be used to other functions than training by reducing the need for visits to a busy active site which could have increased risk levels.

There was noticed that this system has also the potential to encourage school children and students into the industry. It demonstrates not only the workplace but also the technology used in the industry. The Tunneling and Underground Construction Academy had expressed interest for using the VR TBM to train apprentices and use it for familiarization training within their courses.

4.2 CHALLENGES

It also was discovered that this tool presents the following challenges:

- It was felt in some quarters, particularly in the tunnelling department that 3D Virtual Reality Training could not replicate real life scenarios however, some working areas of the TBM are only accessible during high-risk activities such as compressed air working. Other areas such as the Refuge Chamber which is a place of sanctuary on the TBM in the event of fire in the tunnel/on the TBM require a sequence for it to operate correctly. It was not intended to replace real life training with a VR solution, it was to enhance real life training.
- There was at the outset a resistance to the traditional methods of communicating information that involve 2D drawings, PowerPoint and historical information. This is usually a one-way method of communication in which the audience is dictated too and can be reluctant to ask questions; This is a traditional challenge that is not unique to VR implementation;

5 CONCLUSIONS

The use of VR in construction has increased over the past few years. The uses of VR for OSH-based TBM training include the following: TBM familiarization, emergency rescue training, maintenance training, STEMET activities, safety in design and creating digital twins. This approach can lead to a paradigm shift in the prevention of work accidents or near-misses through its impact on risk identification, implementation of preventive measures, better communication and use for training.

Applying VR to OSH management has positive impacts by optimizing the time and costs involved in TBM operation. This will increase production efficiency and provide a better connection between production and OSH which will improve financial performance. Lessons learned from this tool may be applied to most civil projects from building bridges to power stations and provide a future legacy for the sector and make the sector act in a more targeted way to improve risk management. It will also help increase the use of VR for OSH training. Each project shall be studied particularly as there is no 'one size fits all' approach. It will also influence decision makers globally e.g. regulatory bodies, standards institutions, etc.

As the TBM starts operating the VR TBM can be twinned digitally so that it will receive real time data and live camera feeds that will enhance the user's experience. Audio can be added to mimic the sounds expected as the user travels along the VR TBM. Although there are variations in the way TBM's are manufactured, the modules and scenarios are similar in most respects. This reduces the costs of further development of the tool. Blue chip clients such as Tideway, High Speed 2 and TfL have expressed interest in the VR TBM concept and are considering the inclusion of the requirement to use immersive technologies in the works information. This builds on the BIM requirements already in place on major projects.

Future studies should focus on:
- developing of further modules in the areas of TBM Familiarization, operation and use of Refuge Chamber, the Build area, Hyperbaric Interventions / Compressed Air Working etc. These modules will cover user interaction as part of hazard/risk perception and learning where users can observe activities and choose the correct options thus learning and becoming more familiar with the operations. As other VR modules are completed, they will be available for the wider industry to use;
- continue exploring lessons learned from major projects and others kind of projects.

A long-term aspiration will be to actually operate a TBM using VR which will reduce or potentially remove workers from the hazardous environment.

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DEVELOPMENT OF A FRAMEWORK INTEGRATING AGENT-BASED MODELLING, BUILDING INFORMATION MODELLING AND IMMERSIVE TECHNOLOGIES FOR CONSTRUCTION TRAINING AND EDUCATION

Akinloluwa Babalola[1], Clara Cheung[1], Patrick Manu[2], Akilu Yunusa-Kaltungo[1]

[1]Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL (UNITED KINGDOM)
[2]School of Architecture and Environment, University of the West of England, Bristol BS16 1QY (UNITED KINGDOM)

Abstract

Effective construction management plays a crucial role in ensuring the successful execution and completion of construction projects. However, the construction industry continues to face numerous challenges, such as time delays and cost overruns, which underscores the need to improve conventional approaches to construction management. As such, training and education are critical components of construction management. Previous research has demonstrated the potential of digital technologies, including Building Information Modelling (BIM) and immersive technologies (ImTs), in facilitating construction training and education. Similarly, agent-based modelling (ABM) has the capacity for visualisation and simulation of scenarios, thereby presenting potential applications in this area. Nonetheless, limited studies have attempted to integrate these tools to augment construction training and education. This study seeks to address this gap by conducting a systematic literature review to establish a framework that integrates the use of ABM, ImTs, and BIM for construction safety training and education. Based on the review, the framework proposes the utilisation of data derived from BIM to simulate and evaluate construction management plans through ABM. Furthermore, the results obtained from ABM could be utilised in educating construction workers through the use of ImTs. The developed framework provides a basis for future studies to examine how its performance could be enhanced through the integration of different simulation techniques, such as ABM and system dynamics (SD). Ultimately, the integration of ABM, ImTs, and BIM in construction training and education could serve as a valuable tool in improving construction management practices and addressing persistent challenges in the industry.

Keywords: Agent-based modelling; Virtual construction site; Building information modelling; Immersive technologies; Training and education

1 INTRODUCTION

It has been observed that delays in construction projects which can be referred to as the elapsed time beyond the stipulated completion date is considered a common problem in the construction industry [2][36]. It has also been observed that productivity in the construction industry has been diminishing for several years [3][36]. This therefore means that the exploration of alternative methods for managing construction projects have become essential to improve the status quo of construction projects. A key method is the application of information computer technology (ICT) tools which has been increasingly useful in the construction industry [47]. An example is the use of simulation modelling and visualisation for the planning of a construction project with the aim of improving the efficiency and performance of the project [47]. Simulation tools are very efficient and risk-free mechanisms for making decisions on construction projects as modellers could conduct virtual construction projects and evaluate their performance under various conditions and settings [35]. The outcomes of actual events or systems can be predicted through the simulation of the model of actual events or systems without spending considerable time, cost, and effort on the events or systems [19]. The different simulation techniques that can be adopted for modelling and decision making include agent-based modelling (ABM), discrete event simulation (DES) and systems dynamics (SD) [35]. Immersive technologies (ImTs) are computer technologies that have been shown to be effective in construction management, especially for training and education [42].A key area of construction management is construction training and education, and this is because it ensures the competence of construction professionals to carry out construction activities [28]. However, it has been observed that the conventional methods of training and education focuses on theories of construction management thereby making it difficult for the knowledge gained to be applied by the trainees when faced with real-world scenarios on construction site [32]. It is therefore necessary for alternative methods for training and education to be proffered in order to address the shortcomings of the conventional method of training and education. Previous studies have however shown that ABM, BIM, and ImTs are digital tools that have the potential for the training and education of construction workers by providing them with practical experience of real-world scenarios of circumstances they will face on construction site thereby addressing the limitation of the conventional methods of training and education.

At the centre of construction digitalisation, BIM generates a lot of management data from different parties in the supply chain. Meanwhile, new techniques such as ABM and ImTs have been widely implemented for construction management. However, the potential integration between ABM and ImTs using BIM data remains arguably unexploited. While it has been observed that there has been an integration of some of these technologies for construction management in literature such as integrating ImTs and BIM or ABM and BIM, the integration of all three technologies for construction management has not been explored in literature. In addition, it has been noticed that every construction project manager faces challenges as regards on-time delivery of projects, within budget, and to a required quality standard [13]. This means that there is an urgent need to develop a framework to address the issues faced by construction project managers to ensure the achievement of crucial performance indicators. With the individual benefits gained from each of ABM, BIM, and ImTs and the benefits also gained through the combination of two of these technologies such as ImTs-BIM, the integration of these three technologies is proposed to obtain enhanced benefits from the technologies as regards construction management. This study therefore conducts a systematic literature review on the applications of ImTs, BIM and ABM for construction management. The findings of the review of relevant literature were then used to develop a related framework for effective construction management through training and education.

1.1 BACKGROUND LITERATURE

ABM refers to a simulation method that is based on individual agents of which their behaviour depends on a set of rules, as well as interactions with other agents, and the environment [36][38][1]. Some software tools that have been identified for ABM are Anylogic, Pathfinder, Evac and STEPS [1]. ABM can also be referred to as agent-based simulation (ABS), agent-based modelling and simulation (ABMS), multiagent simulation (MAS), and multi agent-based simulation (MABS) [25]. The elements of agent-based models are agents (the most significant element) which could be representations of human beings or animals, the environment where the agents operate, and the rules governing the behaviour, communication, the decision-making roles and the interactions between agents and the environment [22].

The features that distinguish ABM from other modelling techniques such as DES and SD are its high regard for the heterogeneity of agents [22] and its lack of specific convention for time progression as it could either follow a continuous, discrete or a combination of both for time progression [10].The heterogeneity of agents enables precise modelling, leading to a more realistic representation of real-world scenarios of the model, especially when compared to other models with homogenous approach for agents [22]. It has also been revealed that the construction industry is characterised by heterogeneity, complexity, and variability of trade performance [31] which makes ABM a useful simulation tool in the construction industry. Overall, users of ABM can get a more realistic model with better prediction accuracy of the outcome of events, thereby offering a very effective way for managing construction projects.

Building Information Modelling (BIM) can be described as an intelligent three-dimensional (3D)-based modelling technique that provides understanding and insights on the development of more efficient building systems to Architecture, Engineering, and Construction (AEC) specialists (Uddin et al., 2021). In addition, BIM can be described as a modern approach for design and management in the construction industry and mostly contains data on all the phases of the lifecycle of a building [20]. A construction project consists of several phases which include the design phase, the construction phase which is the most complex phase and the post-construction phase which is the longest phase of a building lifecycle [34]. Examples of software tools that are used for the creation of BIM models are Autodesk Revit and ArchiCAD, and these tools create models closely approximating the actual building [39]. Other BIM-based platforms used for planning, managing, and updating of construction activities, manage documents, visualise 3D models of construction sites, and monitor the status of construction projects include Autodesk BIM 360, Oracle Latista, Dalux TwinBIM and VisiLean [31]. A 3D computerised representation of building structure containing the geometric and semantic information of the structure can be developed using BIM approach [11]. BIM promotes the effective linkage of the different building lifecycle stages, provides accurate, real-time building information [40]. In addition, BIM can be used to create comprehensive, accessible, replaceable and reliable building information for all stakeholders in an entire building lifecycle [13]. Moreover, not only does BIM maintain building information, it also improves the flow of the building information throughout the lifecycle of the construction project [46] and it can be used to coordinate heavy and fragmented data into a single model [33]. However, there are issues that can be seen as major deterrents to the implementation of BIM for construction projects including BIM versioning, misinformation as regards BIM and BIM authoring [34]. In addition, BIM models are usually developed on devices that do not have sensory components which results in no interaction between the model and the physical environment [33].

Immersive technologies (ImTs) are technologies that are used to induce the feeling of being physically present in a virtual environment through computer-generated images or avatars [7]. ImTs can also be described as the bringing together of virtual reality (VR), augmented reality (AR), mixed reality (MR), and immersive videos [7]. VR can be used to walk through an unbuilt building, test out new building design, and to present to client the exact building space [24]. AR can be described as the overlaying of computer-generated images on real scenarios such as the laying of marks in a televised football match to enhance the understanding of the match by viewers [5]. AR can be used to augment all types of human senses including senses of touch, hearing, and smell [8]. AR can also be used to add virtual objects to real environment and remove real objects from the environment in a process termed diminished or mediated reality [4]. AR are also used for entertainment, robot path planning, medical visualisation, and advertisement [8]. MR is a reality spectrum which ranges from pure reality to pure virtual reality where there is no interaction by users with the real world [27]. MR enhances the accessibility of data for better understanding of projects and for better decision making such as building design check and construction simulation and monitoring [29]. Unlike BIM-based engines, ImTs provide interactions with various construction components and an immersive experience to users [14]. While a real environment is the physical surroundings that people stand in, a virtual environment is an environment that is digitally generated with computers, lasers and light [44].

Each of ABM, BIM and ImTs have been applied for different areas of the management of construction projects in literature. Shehab et al. [36] introduced an agent-based model to act as a decision support system for construction project planners with the aim of addressing delays in construction projects which was effective for the monitoring and control of construction project. The model proved effective for the monitoring and control of construction project, and it can be used to consider unforeseen delays in projects [36]. Another study by Jung et al. [21] simulated an agent-based model to analyse various alternatives of lift systems. The study revealed that the simulation is most useful in comparing the performances of identified alternative lift systems and it is possible to derive countless number of alternatives to lift systems [21]. Ding et al. [13] developed a digital construction framework which demonstrated how project teams could improve on the management of information and organisation in renovation projects using BIM and reserve engineering. The developed framework improved the information utilisation among all the professionals in different phases [13]. Chalhoub and Ayer [9] investigated the influence of MR on the productivity and quality of electrical conduit construction and discovered that MR enabled a significantly higher productivity rate, resulted in fewer errors during the assembly process and increased the number of accurately constructed conduits especially when compared to conduits constructed with traditional paper.

1.2 RESEARCH METHODS

A systematic literature review (SLR) was conducted based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) to obtain articles related to the application of ABM, ImTs, and BIM for construction management. This study reviewed relevant journal articles because these articles are peer-reviewed and they provide a more comprehensive and higher quality information when compared to other types of publications [15][18]. Scopus database which was used to collect the relevant articles used for this study was selected as the database as this database has an extensive coverage of scientific literature [48]. The keywords used for the search were divided into two fields: the first field focused on the digital technologies while the second field focused on the construction industry. Fig. 1 shows a systematic flowchart which displays the SLR process adopted in this study. The set of search strings applied to verify the title, abstract and keyword of the articles obtained from Scopus database is as follow:

(TITLE-ABS-KEY ("Agent-based model*" OR "Building Information Model*" OR "BIM" OR "Virtual Reality" OR "VR" OR "Immersive technolog*" OR "ImT") AND TITLE-ABS-KEY ("Construction" OR "Construction industry")

The initial search retrieved 5,939 articles from the Scopus database. The search strings were then limited to journal publications because they provide more comprehensive information on the field of study. There was no limited timeframe and articles that do not focus on ABM, BIM, and ImTs. The number of journal articles written in English language that was collected was 59 articles.

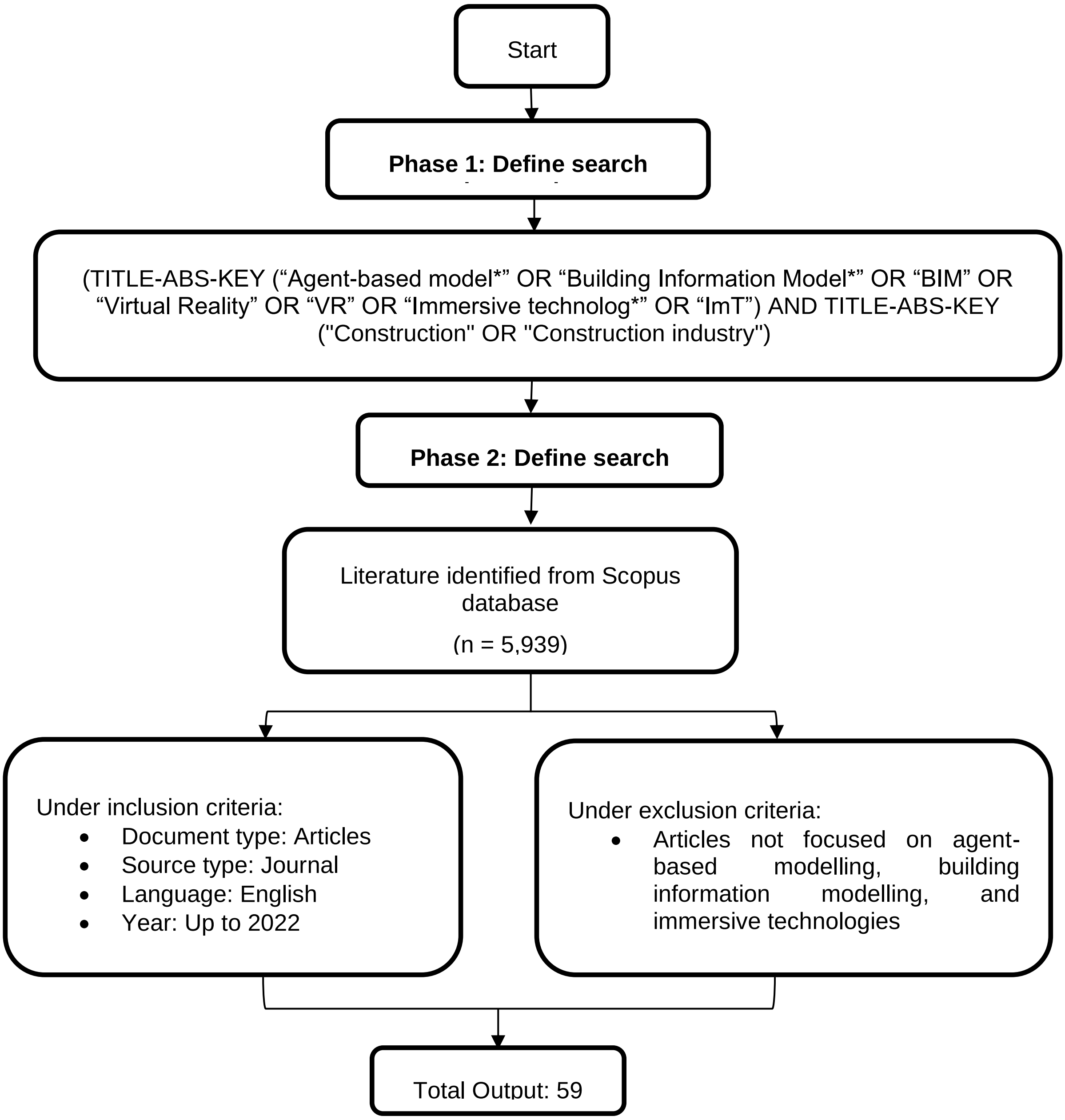

Fig. 1: Systematic literature review flowchart

An example of the many rejected articles due to lack of relevance of its contents obtained from the Scopus database is the article titled 'Virtually authentic: Graduate students' perspective changes toward authentic learning while collaborating in a virtual world' by Han & Resta [17]. The contents of this article were on the perceptions of graduate students of an online teaching and learning course which the authors argued that the construction of new knowledge by participants resulted in authentic learning from the standpoints of social constructivism [17].

1.3 RESULTS AND DISCUSSIONS

1.3.1 Integration between BIM and ImTs

To assist with construction site planning, Singh and Kumar [37] developed an AR-BIM based framework and observed that the AR-BIM improved communication among planners and enabled the understanding of future implications of the layouts proposed. Another study by Wang et al. [41], a BIM-based VR application was developed to minimise the number of assumptions during the determination of quantities from architectural drawings. The BIM-based VR application was proven to be effective in enhancing the understanding of quantity surveyors on the architectural design, efficiency of decision making and the precision in quantity surveying work by navigating the virtual 3D building model [41]. Similarly, Xie et al. [43] implemented a building information model and applied it in a VR environment to assist architects, engineers, and contractors in understanding construction projects and plans in real-time. The real-time VR simulation which was combined with radio frequency identification (RFID) and focused on steel fabrication was useful in differentiating between steel pieces, controlling the schedule of the project and to describe the entire scope of construction [43].

This study also reviewed existing frameworks for the possible combination of ABM, BIM and ImTs. An example is the framework proposed by Kim et al. [23] that integrates BIM and VR for the design phase of construction projects in order to help in making informed decisions by stakeholders. The framework provided consistent results for comprehensive evaluation criteria and metrics in a quantitative and flexible manner [23]. A framework that integrates ABM and Monte Carlo simulation (MCS) was proposed by Seresht and RazaviAlavi [35] to model the performance of construction workers, to determine the performance of a construction project as the aggregated performance of a team and to model the spread of Covid-19 on the construction site. The ABM and MCS model showed that the introduction of a few agents infected with Covid-19 can have a negative impact on the performance of the construction project [35].

1.3.2 Integration between ABM and BIM

Abadi et al. [1] used BIM to extract the spatial and physical properties of the ninth floor of a 17-storey educational building and simulated the fire effect while the evacuation behaviour of occupants was modelled through ABM with the results analysed to obtain the average and maximum required time of safe egress for various renovation alternatives. Abadi et al. [1] then discovered that the presence of fire in renovation work increased the time of evacuation in 60% of cases in fire zone of fire origin and about 40% of cases in the entire building, and it was obvious that the construction schedule with minimum cost or budget will not necessarily be the safest in all cases. As ABM can be used to obtain a realistic model with high prediction accuracy of the outcome of construction activities and BIM used to create comprehensive and reliable building information, these characteristics can be complemented with ImTs by inducing the feeling of being physically present in a construction environment into workers for effective training and education. This study has identified from the review of literature that there have been very limited studies that have focused on maximising the benefits of each of ABM, BIM and ImTs by integrating them for training and education as a strategy to improve the overall performance of construction management. Majority of practical training sessions conducted in a construction site involves oral and video instructions [45], and to a limited degree, on-the-job demonstrations. It has also been observed that the involvement of construction workers in interactive problem solving and decision-making result in higher knowledge transfer [26][30]. Technological advancements which have produced technologies such as ImTs as key interactive tools which provides an immersive experience for workers to interact with various virtual objects under various conditions has proven to be useful for the effective training of people [12][16]. As there is no framework that integrates ABM, BIM, and ImTs for construction management especially around training and education, this study proposes a conceptual framework that combines the functionalities of ABM, BIM and ImTs for construction training and education.

1.3.3 Proposed ABM-BIM-ImTs Framework to model the management of construction projects through training and education

The proposed conceptual framework utilises the combination of ABM, BIM and ImTs to model construction project management through training and education as shown in Fig. 2. Fig. 2 shows a flow diagram that depicts the transfer of data from BIM (e.g., Autodesk Revit) to ABM (e.g., AnyLogic software) via a Dynamo/Microsoft Excel platform.

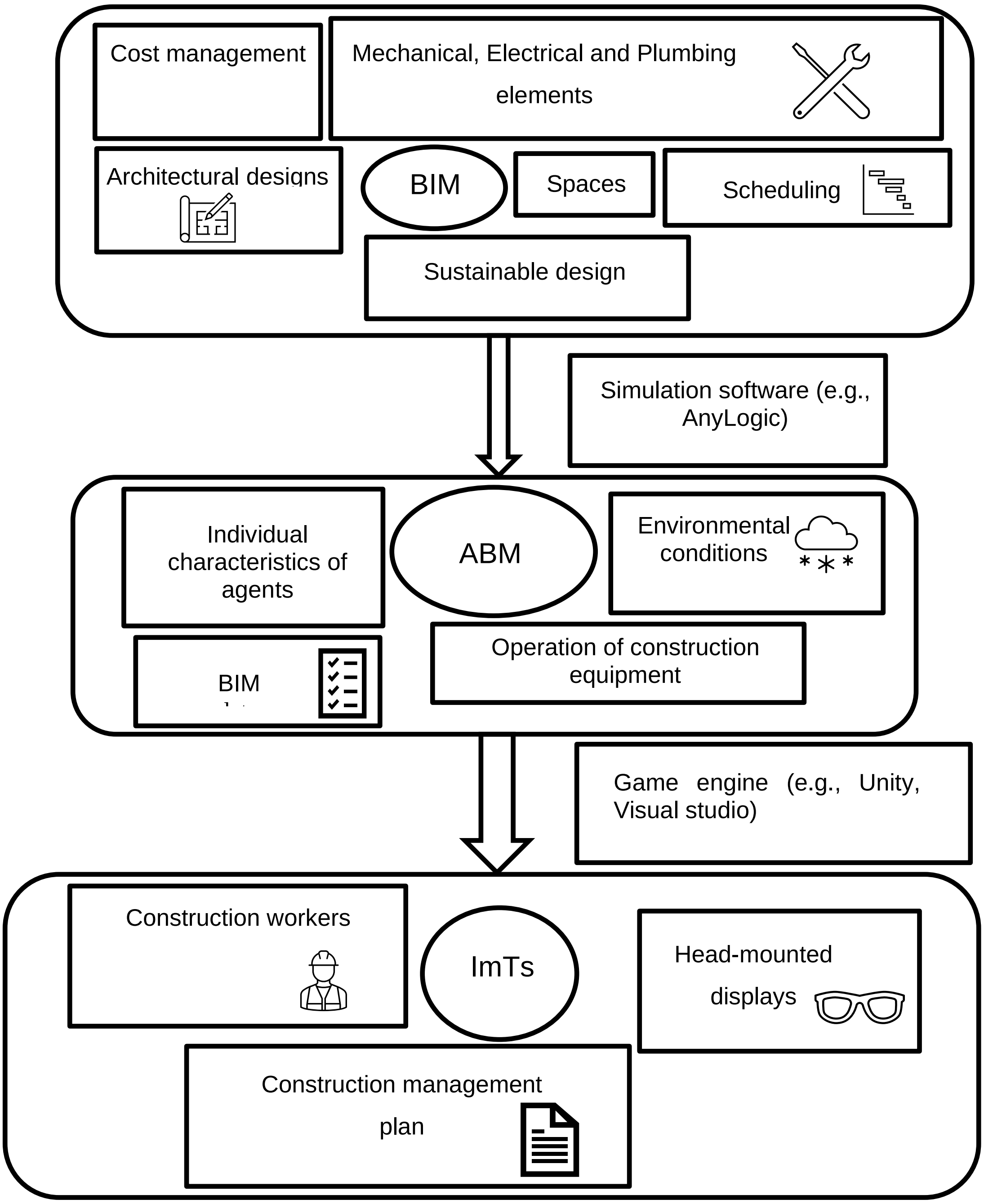

Fig. 2: Construction training and education framework integrating ABM, BIM and ImTs

The data obtained from BIM and transferred to ABM as depicted in Fig. 2 include but not limited to information on cost management, mechanical, electrical, and plumbing elements, architectural designs and scheduling. Consequently, ABM uses the data obtained from BIM for the simulation of a construction site. The simulation augments the data obtained from BIM with agents which represent the different behaviours and responses of construction workers in a construction site. It also includes different environmental conditions such as weather conditions, air quality obtained through various measuring devices such as weather thermometer to measure air temperature and operation of various tools which can affect the behaviour and reactions of agents which are elements of ABM. This is to evaluate the feasibility of the construction project and to assist with the planning of the project's scope, schedule, quality, and safety. The results from the simulation and assessment conducted using ABM is then used to educate construction workers on the planning and execution of construction works on-site with the use of ImTs. Furthermore, ImTs will be used to create the virtual construction site based on the design from BIM that has been transferred to ABM for simulation and assessment. The virtual construction site would be used for the transfer of knowledge about the developed construction management plan to construction workers. The construction workers could be educated on areas such as the various procedures to take to ensure the quality of the different facet of construction activities, the various roles, or tasks each construction works will undertake and occupational safety and health regulations. These are areas that, if not addressed properly, could lead to delay in the completion of construction projects, increase the cost in the execution of construction projects and affect the quality of job done. The construction workers will be immersed in the virtual construction site with the use of head-mounted displays (HMDs) or alternatively with projected screens and controllers in an enclosed environment.

Whilst the integration of BIM, ABM and ImTs may be beneficial for training of construction workers, the integration may come with challenges. As there are many software tools developed for each of these three techniques, the challenges of integrating the tools include the compatibility of all three tools for effective integration. It would therefore require more time and efforts to pick the best tools for each of these techniques for a particular construction project as construction projects are unique. In addition, construction professionals may not have the required skills needed to operate a tool that integrates ABM, BIM and ImTs and as such may need further skills development and training in that regard.

2 CONCLUSION

This study developed a conceptual framework for the planning of construction management to improve the execution of construction projects. The conceptual framework which integrates BIM, ImTs and ABM have a high potential to enhance the construction management through training and education. Information pertaining to the design of the construction project would be transferred to ABM via the Dynamo/Excel platform for simulation and assessment. The outcome of the simulation would drive the training and education of construction workers with the use of ImTs. Potential drawback as regards the developed framework could include the lack of adequately trained experts in the implementation of BIM, ABM and ImTs. In addition, data protection is very essential in the implementation of the framework as data from the BIM model should be protected from misuse or loss.

The study proposes that further work is done to test or validate the conceptual framework on different types of construction projects. Further work can also be done to enhance the performance of the conceptual framework by considering a different simulation technique such as integrating ABM and SD as previous literature revealed that highly dynamic factors such as temperature can be modelled very effectively with SD.

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AN EFFICIENT APPROACH FOR GENERATING TRAINING ENVIRONMENTS IN VIRTUAL REALITY USING A DIGITAL TWIN FOR CONSTRUCTION SAFETY

Kilian Speiser, Jochen Teizer

Dept. of Civil and Mechanical Engineering, Technical University of Denmark (DENMARK)

Abstract

Despite investing many resources into safety planning and control in construction sites, the industry still experiences a significantly higher accident rate than other industries. Recent research introduced serious games based on Virtual Reality (VR), indicating improved safety awareness among workers. However, such scenarios often lack realism and require extensive resources in production. This work proposes a Digital Twin for Construction Safety (DTCS) linking various data sources to generate a Virtual Training Environment (VTE) automatically. The developed VTE framework integrates building information models, construction schedules and safety regulations, and convert it into a VTE prototype in the game engine Unity. The framework then allows data collection of users related to hazards and provide personalized feedback. The prototype is tested with four trainees in a railway infrastructure project with domain-typical hazards. The case study suggests the approach's viability for generating a VTE with little means and human input. The work further suggests utilizing the collected run-time data for purposes beyond safety awareness assessment, like usability studies of safe construction site layouts or machine learning algorithms for hazard prediction.

Keywords: construction safety, digital twins, occupational health and safety, safety training, safe work environment planning, virtual reality.

1 INTRODUCTION

Construction workers have one of the deadliest professions compared to other industries [1]. To address this problem, many organizations invest heavily in safety training programs, which aim to reduce the number of accidents and fatalities by improving worker knowledge and skills. Traditional training methods can be time-consuming, expensive, and not consistently effective. Recent research has introduced extended reality (XR) games as a potential solution for safety training in construction. Still, creating these games is often time-consuming and lacks realism [2]–[4]. Integrating different data sources from IoT devices, laser scans, or Building Information Modeling (BIM) may tackle these issues.

Regarding BIM, an as-planned 4D model defines how a built asset was planned in space (3D) and time (4D), and an as-built model defines how the building was actually constructed. The fourth dimension links the construction schedule to building elements. Digital twins can integrate data from various sources and represent physical assets, systems, and processes in a digital format, allowing for real-time monitoring, analysis, and optimization of their performance. A Digital Twin for Construction (DTC) generates as-performed data based on frequently updated as-built and as-performed states and does, therefore, significantly deviate from BIM models that depict a constructed asset's as-planned and as-designed states [5]. Using the data from various sources such as BIM models, Internet of Things (IoT) sensors, and other relevant information, a DTC provides a holistic view of the construction project and enables more accurate and efficient decision-making throughout its lifecycle.

With the increasing adoption of DTCs in the construction industry, the interest in leveraging them for safety training grows. Recent research introduced a Digital Twin for Construction Safety (DTCS) [6] and conceptually described a dynamic, serious game for construction safety as part of such a DTCS [7]. This paper aims to verify that a DTCS provides the required data to generate realistic virtual training environments (VTEs). Therefore, it first describes the required background knowledge. The study then depicts the method of this work and describes a prototype before discussing the first results of a case study in an infrastructure project. Finally, the authors conclude significant outcomes and propose future work.

2 BACKGROUND

The following sections provide contextual knowledge for the proposed data model. The first part introduces related work regarding novel training methods for construction safety, and the second part explains the underlying concept of close call detection.

2.1 Novel training methods

Effective construction safety training is critical for reducing accidents and improving worker safety. Traditional training methods like classroom instruction and on-the-job training may have limitations that affect their effectiveness. Particularly safety training methods must not expose trainees to hazards. Therefore, virtual training environments have been investigated as a potential solution. Immersive technologies like Virtual Reality (VR) and Augmented Reality (AR) enhance these virtual training environments, providing realistic simulations of construction tasks and hazards that can improve the effectiveness of safety training [2], [8]. Wolf et al. introduced an augmented virtuality (AV) training environment with real construction tools making the experience more realistic [3]. However, the cost and technical complexity of implementing these technologies can be a barrier to widespread adoption. Another issue is that some trainees experience cybersickness during or after immersive experiences, with at least 5% experiencing severe symptoms [4], despite improvements in hardware [9].

Serious games that incorporate elements such as challenges, scorekeeping, and personalized feedback are another approach for more effective learning methods. The term *serious game* implies that the game's primary purpose is beyond mere entertainment [10]. Various studies across domains indicate that gamification enhances the learning experience with more engagement [11]–[13]. Still, the effectiveness of game-based training may depend on the specific design of the game, and concerns about the transferability of skills to real-world construction environments have been raised [14].

For achieving optimal training outcomes, personalized feedback is crucial [15]. High quality should assess the accuracy of performance and provide detailed information on how students can arrive at the correct answer, improve their performance at a higher level, and align their performance with broader objectives [16]. When tailored to the individual, feedback can be more meaningful and relevant, increasing interest and enthusiasm for the task at hand.

2.2 Close calls and protective envelopes

In 2016, the Occupational Safety and Health Administration defined a "close call" or "near miss" as an incident in which an accident was narrowly avoided [17]. While such incidents may involve the risk of death or injury, chance or timely intervention prevents them. Close calls indicate that workplace hazards are not adequately controlled and require further attention to prevent future accidents. Sadly, too few near misses are identified and reported even though collecting in-depth data on close calls is essential for assessing safety planning quality and identifying measures to improve safety design [17].

To address this issue, Golovina et al. introduced a cloud-based framework for automatically detecting and reporting close calls [18]. In earlier work, they proposed weight functions that evaluate the severity of near misses by analyzing factors such as distance, duration, deviation, velocity, and orientation [19]. Their approach applies the Protective Envelopes (PE) concept visualized in Fig. 1. Human workers and construction equipment define a protective envelope based on safety regulations. For instance, ISO 5006 defines a 12 meters minimum distance for workers [20]. Once a worker collides with this sphere, violating the safety regulation is defined as a close call. From this moment, the state of the worker and equipment is stored in so-called "buffer events" every second until the worker leaves the PE of the machine. These buffer events store information about the worker and machine, including the resources' location, direction, and velocity. The previously mentioned weights are computed based on the information given in the buffer events.

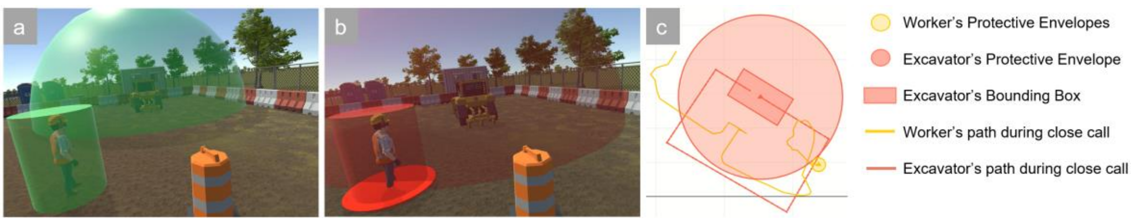

Fig. 1: (a) Worker approaches dozer, (b) close call detected, (c) one buffer event registered, incl. the trajectories of both resources during cloe call event.

3 DIGITAL TWIN FOR GENERATING VIRTUAL TRAINING

The research method includes five steps: literature review, specification, framework development, validation, and identification of further requirements. The literature review revealed that digital twins do not technically implement VTEs for construction safety. The main objective was to utilize the data provided by the DTCS to ease the generation of VTEs. The following requirements specify the goals:

- Automatically generate VTE with a minimum of user interaction.
- Allow the trainer to define parameters for the training scenario.
- Add the most recent BIM model from DTCS to the VTE for a given timestamp.
- Retrieve the construction schedule from DTCS, including tasks, resources, dates, and time.
- Provide personalized feedback based on run-time data collection.

After setting the objectives, the authors created user stories and derived crucial stakeholders. Based on existing ontologies, the authors developed a data model and implemented it into a prototype. The authors created a DTCS comprising the as-planned construction model, scheduled tasks, and involved resources such as workers and machinery. The serious game retrieves the 4D model from the DTCS. Based on a selected task from the DTCS that a player needs to perform, the serious game loads the as-planned status of the project for the specified task. The VTE always loads the latest version from the VTE. Thus, updating the scene according to new developments in the planning phase is automatic.

In the next step, the game retrieves the active resources from the construction schedule at the selected timestamp. The equipment resources, such as excavators, crane loads, or dump trucks, may represent hazards for the player. The VTE tracks the players' commands, trajectories, and close calls and sends the data to the DTCS in run-time for subsequent analyses. Existing methods developed by the authors provide personalized feedback based on the severity of the close calls. In the third phase of the research method, the authors validate the proposed framework in an infrastructure project case study. Lastly, refinements and requirements were identified to make the framework more stable and efficient.

3.1 Digital Twin framework

Based on the defined requirements, the authors created a DTCS providing the 4D BIM model, a construction schedule, and the resources (workers and equipment). Fig. 2 illustrates the implemented framework. The trainer and trainees can operate the web-based user interface (UI) that includes the VTE, personalized feedback for the trainees, and a summary of multiple game results for the trainer. Additionally, it contains a view where the trainer can create game scenarios. The UI accesses a graph-based database via an Application Programming Interface (API). The database supplies the required information from the DTCS to generate the VTE and stores the data collected during playtime.

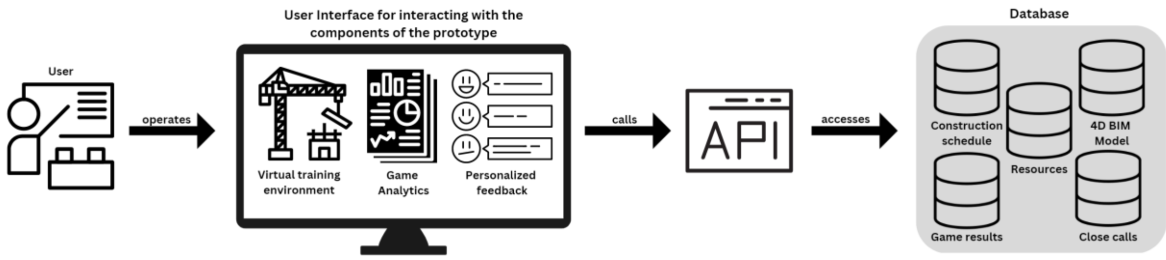

Fig. 2: Framework of the DTCS.

3.2 Game scenario specification

A game scenario defines work tasks that a construction worker should train before performing them on the real construction site. The information stored in the game scenario is input parameters for the VTE to generate the scene. Thus, these scenarios specify the tasks for the players, the date during the as-planned construction schedule, the workers, and the required resources (materials, equipment). Moreover, the trainer can select hazards for the player. Fig. 3 shows the UI and a game scenario exemplarily. In this case, one worker needs to complete three tasks. During the game, there is a dozer and an excavator, and the player is exposed to a malfunctioning generator (electrocution hazard), a missing safety guardrail (fall hazard), and a missing barrier (struck-by hazard). Once the trainer saves the scenario, the information is stored in the database and accessed by the corresponding workers.

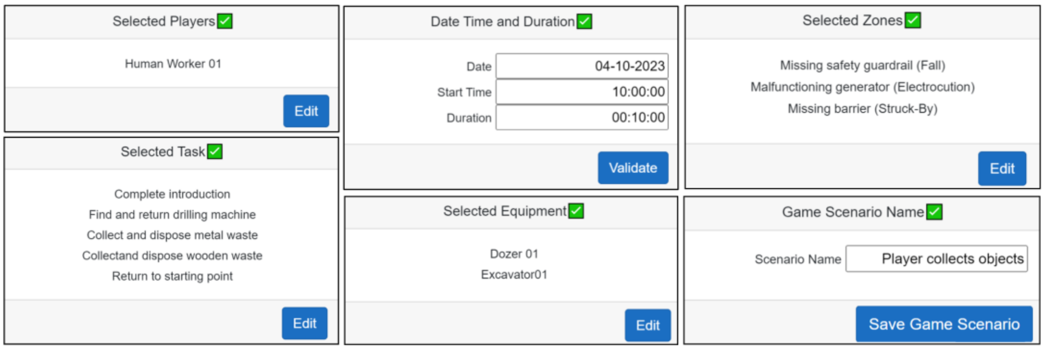

Fig. 3: UI for the trainer to define game scenarios.

3.3 VTE scene generation

This study uses the game engine Unity to visualize the game environment. With the game scenario as input, the game scene loads the as-planned BIM model from the database. Based on the construction schedule, a script filters all active elements at the given timestamp. In this work, IfcConvert converts the provided IFC file into an OBJ, XML, and MTL file [21]. A modified version of the IFC importer asset generates a game object of the model in Unity, which includes objects, attributes, and relationships [22]. The application loads the model in run-time to ensure up-to-date information.

3.3.1 Workers

A script adds an avatar for each player based on the information in the game scenario. The presented framework aims to provide multiplayer training environments eventually. However, this study tests a single-player game. Each human worker represents a resource within the underlying data model. Every resource defines safety parameters for the safety envelope and the protective envelope. A worker's protective envelope is represented by a cylinder. The safety envelope is a bounding box around the avatar. Fig. 4 illustrates the concept of the *safety parameters* for a worker. The VTE triggers a close call once the protective envelope collides with a hazard (compare Fig. 1).

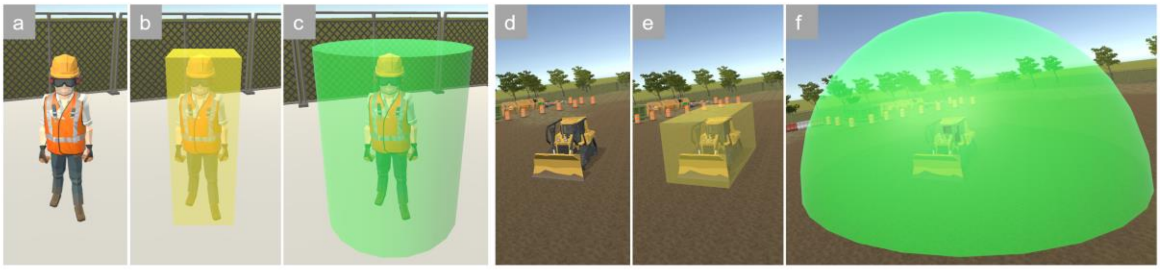

Fig. 4: (a) Worker and (d) dozer with their (b,e) safety envelopes and (c,f) protective envelopes.

3.3.2 Construction equipment

Construction equipment may cause hazard zones. For instance, ISO 5006 defines workers must keep at least 12 meters distance to earth-moving machines [20]. The developed DTCS provides this information for each resource in the form of safety parameters. Similarly to human workers, these parameters define the geometry of the safety and protective envelopes. Fig. 4 illustrates the concept of a dozer. An oriented bounding box around the equipment with an offset of 1m represents the safety envelope, and a sphere with a 12 meters radius represents the protective envelope.

3.3.3 Construction site layout and hazard zones

A successful implementation requires the provided BIM model to contain the site layout and hazard zones like the SafeConDM model describing a domain model for safety design [23] or the latest proposal of a hazard ontology [24]. This work assumes that the DTCS provides a safe 4D BIM model, including safety layout and hazard zones. We define a hazard zone as a space that workers can only enter if they are specifically permitted to. If workers enter the zone, they put themselves in danger and trigger a close call. This work focuses on the four leading hazards in construction: falls from height, electrocution, struck-by, and caught-in-between. Typically, falls from heights and electrocution are static zones, while struck-by and caught-in-between relate to moving construction machines.

The BIM model in this work contains hazards according to the ontology defined by Johansen et al. [24]. Each hazard in the model links to mitigation equipment. Fig. 5 exemplarily illustrates how such hazard zones in a BIM model may appear. As the DTCS provides a safe model with mitigated hazard zones only, a script in Unity removes mitigation equipment according to the trainer's input in the game scenario. This ensures that the player is exposed to hazards during playtime.

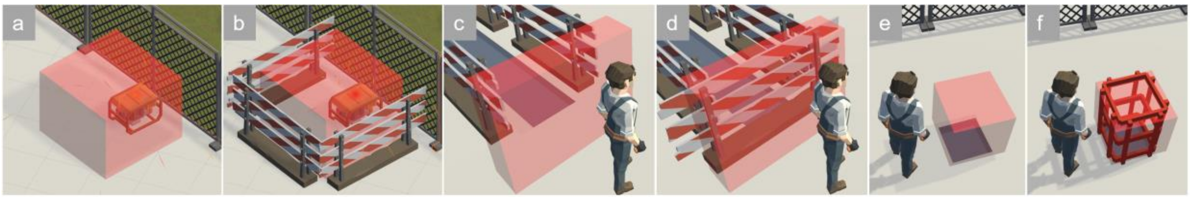

Fig. 5: (a) Malfunctioning power generator (b) with temporary mitigation equipment, (c) unprotected leading edge, (d) mitigated fall hazard, (e) unprotected manhole, and (f) mitigated by guardrails.

3.4 Data collection and analyses

The VTE collects and analyzes data throughout the game experience to evaluate the player's performance and identify behavioural patterns. This section describes the data the VTE collects and sends to the database using the API.

3.4.1 Trajectories

The trajectories of the players are an essential data source for evaluating the player's performance and retrieving valuable behavioural patterns. The implemented game tracks the location of each resource throughout playtime and continuously posts the data to the DTCS. This information allows further analysis to compute indicators such as velocity, walked distance, or proximity to equipment. Fig. 6 visualizes the collected trajectories for the trainer while the trainees play. The green line shows the player's trajectory, and the red lines indicate the player's path during a close call. The VTE also records the trajectories of the machines. In Fig. 6, the excavator in the centre moves forward and projects the trajectory in blue.

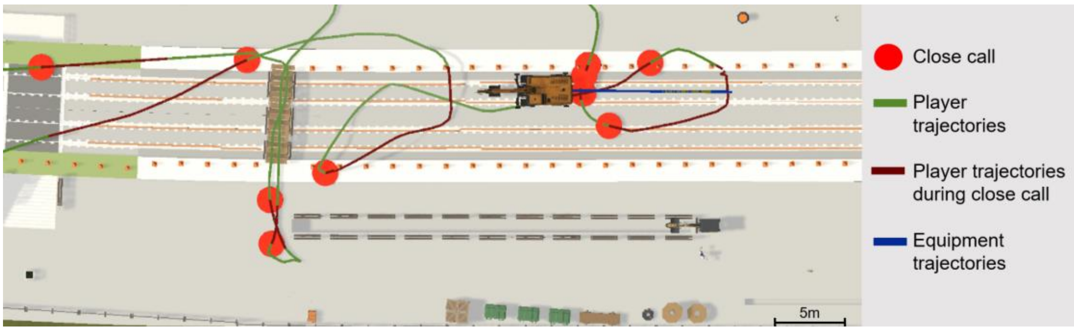

Fig. 6: Trajectories of the player and equipment and the detected close calls during playtime.

3.4.2 Proximity events and close call analysis

As previously described, this work uses a concept of detecting close calls introduced in previous research, where a close call corresponds to a collision between a PE of a human worker and a hazard zone [19]. Therefore, each hazard in the training environment has a script assigned that implements the two methods *OnEnter* and *OnExit*. The following code excerpt shows the methods using pseudo-code:

```
FUNCTION OnEnter(Resource endangered)
        IF endangered.InDanger:
                CloseCall cc = ActiveCloseCalls.Add(endangered)
                StartCoroutine(AddBufferEvent(cc))
        END IF
END FUNCTION
FUNCTION OnExit(Resource endangered)
        CloseCall cc = ActiveCloseCalls.Get(endangered)
        cc.PostProcess()
        ActiveCloseCalls.Remove(cc)
        Http.SendCloseCall(cc,url)
END FUNCTION
```

Once any other geometry collides with the hazard, *OnEnter* checks if the colliding resource is an endangered worker and adds a close call to the collection of active close calls (line 3). The collection is crucial because one hazard can simultaneously experience close calls with multiple resources. Line 4 initiates a coroutine to continuously insert a buffer event. The buffers contain information about the trigger and the hazard, such as their location, velocity, direction, orientation, and time. Once an endangered resource leaves the hazard zone, *OnExit* retrieves the close call with the endangered worker from the active close calls (line 8). A post-process analyzes the severity of the close call using existing methods based on the information in the buffer events (line 9). Finally, the function removes the close call from the active events and dispatches the data to the API in lines 10 and 11, respectively.

3.5 Personalized feedback

As highlighted before, personalized feedback improves the quality of the training experience. The developed prototype implements feedback for the trainee and the trainer. The trainees obtain a feedback card (see Fig. 7) summarizing their performance based on a few indicators. For further insight, a dashboard provides information on a low level. The following chapter explains the collected data for creating feedback based on the first tests. The trainer has the opportunity to overview the results from multiple game experiences and compare individual players (see Section 5).

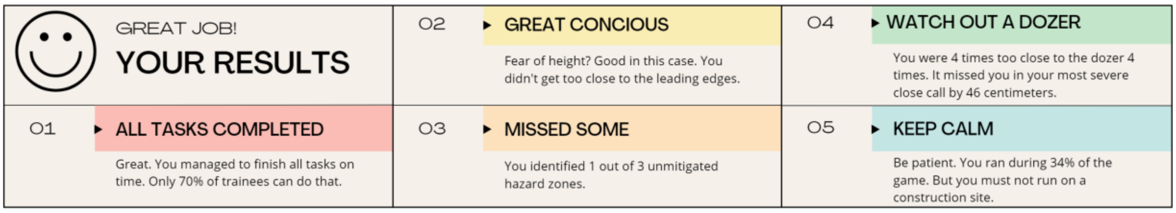

Fig. 7: Feedback card for the trainee.

4 PROTOTYPE VALIDATION

A study with four trainees was conducted based on a railway infrastructure project to validate the proposed approach. In the first game scenario described in Fig. 8, a player needs to perform five tasks: (1) Complete an introduction to the game's objectives and controls (Fig. 9), (2) find a drilling machine and bring it to storage, (3) find a wooden piece and dispose it at the correct recycle container, (4) find a recycle bag and bring it to the correct container, and (5) return to the initial position. Visuals highlight the locations where a player should go, as the game scene is rather large. However, there are different paths a player can choose. The player has the main objective of not exposing themselves to hazards. This game scenario comprises the hazards defined in the game scenario from the previous section: two dynamic hazards in the form of moving machinery and three static hazards: a malfunctioning generator, an unprotected leading edge, and a missing barrier (compare Fig. 5).

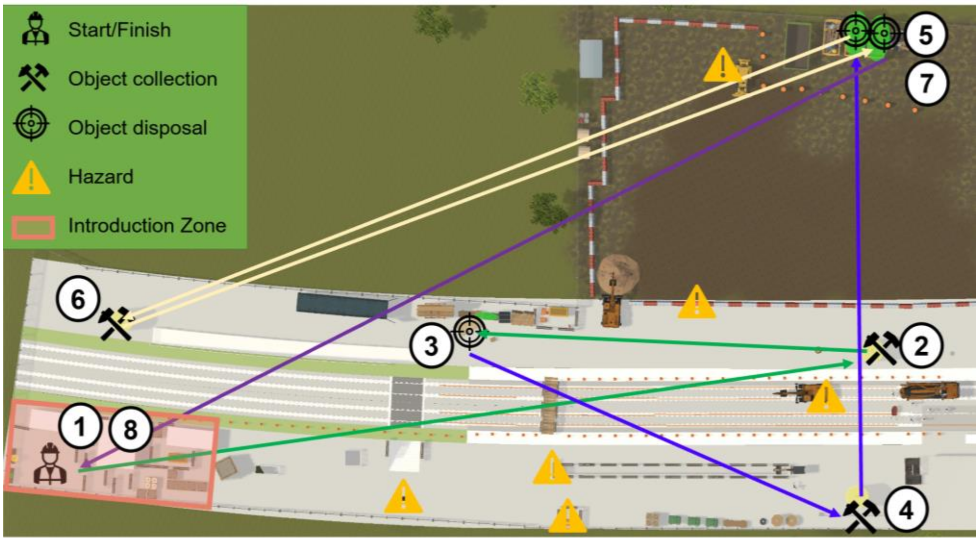

Fig. 8: The players get introduced to the controls (1), handle three objects (from 2 to 3, 3-4-5, and 5-6-7, respectively, shown are the shortest and potentially unsafe pathways), and return to the start (8).

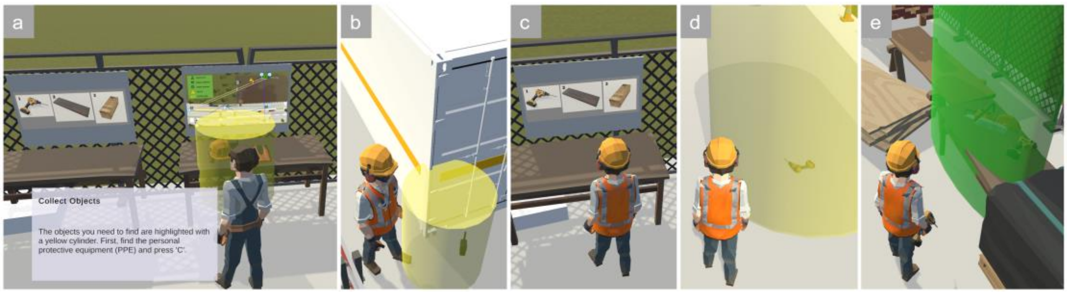

Fig. 9: Entrance of user to VET: (a) Instructions to the game controls by selecting PPE, (b) detecting a pick-up location in form of a transparent yellow cylinder, and (c) task preparation through visuals, (d) in-game pick-up location, and (e) drop-location in form of a transparent green cylinder.

4.1 Instructions

The game first introduces the user to the objectives and the game controls. The worker in this prototype is navigated in a third-person view on a screen. Still, the authors expect the proposed concept also to work with immersive VR solutions. To familiarize players with the game controls, they must first find their personal protective equipment. In the second step, the player must find a walkie-talkie and put it on a desk. This exercise introduces the player to how to collect objects. Before the training starts, the player can see a map of the game environment indicating hazards and objectives (Figure 9a).

4.2 Safe and unsafe paths

The player can freely navigate through the game scene to complete the tasks. The safe construction site layout comes from the BIM model and provides safe paths for the workers. However, the game removes mitigation equipment to expose the player to hazards. Fig. 10 depicts two examples. The trainee should cross the railways using the safe bridge instead of risking proximity with the excavator. In another example, a portion of the barrier has been removed, but a stop sign next to a hole should indicate to the player that they should not enter and instead find a safer path.

Fig. 10: (a) A secure bridge to the left offers a safe path for crossing the railway under construction, (b) a gap between the barrier may lead a user to enter a restricted work zone, and (c) a safe alternative.

4.3 Feedback

After the game, the players get forwarded to a website for in-depth insight into their performance (see Fig. 11). The first element indicates the severity and location of individual close calls. The second element provides an overall grade. The authors have not yet developed the grading as more tests are required. Component 3 provides mean values for each weight of the near misses, and component 4 lists the number of close calls caused related to the different hazards: struck-by, fall, and electrocution.

5 DISCUSSION

Table 1 and Fig. 12 overview the results of the first training experiences in a table and a dashboard, respectively. All four trainees completed the five tasks within the given time limit. Player 3 was the slowest and walked the longest distance, while Player 2 was the fastest. In this context, fast is not necessarily good as it may lead to inattentive behaviour. On average, Player 1 experienced 9 close calls. Despite being the fastest, Player 2 has the lowest value with 5 close calls, and Player 4 has the highest with 16. However, Player 2 has the highest average weight for the close calls. Fig. 12 indicates that Player 4 never used the bridge for crossing the railway and always crossed the work zone of the dozer instead of taking the alternate safe path. Only the third player detected and used the designated path to avoid the hazard of the traversing dozer. As previously stated, this work does not yet implement a holistic method to evaluate the performance quantitively. However, based on the results shown in Table 1 and Fig. 12, Player 3 would probably receive the best grade concerning safety awareness.

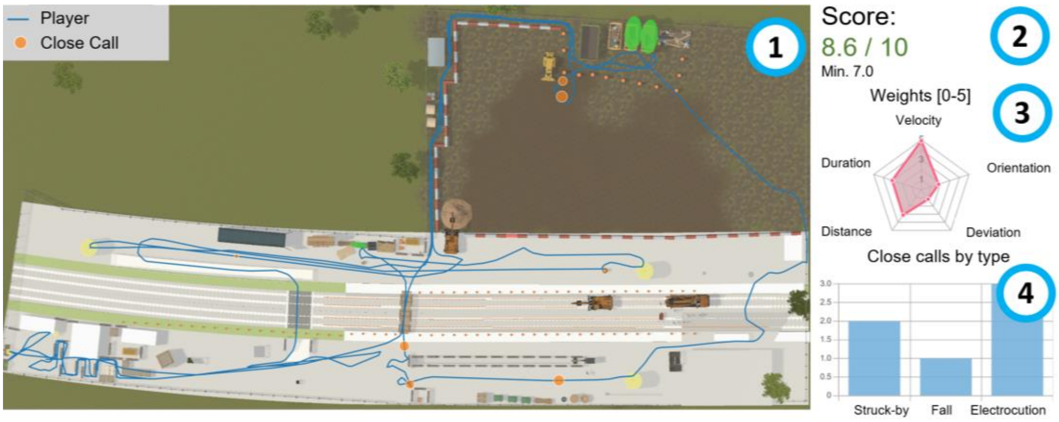

Fig. 11: Web-based dashboard for trainees provide some of their personalized feedback.

Table 1: Comparison of crucial indicators for the performance of the four trainees.

Player	Duration [m:ss]	Distance [m]	No. of close calls [-]	Average weight [-]
1	3:49	703	9	2.79
2	3:40	782	5	2.91
3	5:02	1045	6	2.80
4	4:24	843	16	2.62

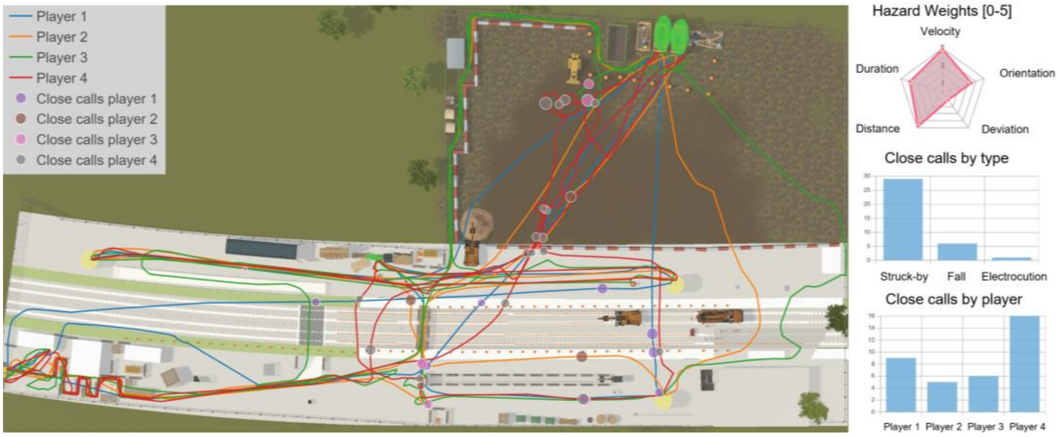

Fig. 12: Dashboard for the trainer overviewing all game results.

The severity of the hazards is rather high. The observed 36 close calls have an average weight of 2.7. While the velocity and the distance weights are high, with 4.9 and 4.8, respectively, the deviation weight has the lowest value (1.1). These results raise the question whether the weight formulas require adjustments. However, most close calls relate to moving machinery, as expexted these are one key concern in railway construction, where the exposure to velocity contributes most to the total weights.

Fig. 12 shows that no trainee solely used the safe paths, perhaps because no signage was provided. All players crossed the railways and the work zone of the dozer at least once. This fact highlights one of the significant advantages of this novel training method. In on-the-job training, the trainer would need to intervene immediately once the worker enters such a hazardous area as the risk of an injury is too high. In the VTE, however, the trainer can expose the workers to such situations and evaluate their behaviour. The VTE allows trainees to learn and experience potential hazards under both safe and controlled conditions, and the safety trainer can collect valuable information about workers' behaviour once they find themselves in a hazardous situation. This information is yet available but primarily in accident reports where the damage already occurred. Another advantage is that decision-makers can retrieve valuable information regarding the usability of their safety design by simulating the tasks in such a VTE. Future work will investigate how the results can contribute to improving the site layout regarding usability and safety in an automatized way. For instance, how can algorithms determine that the players did not use the designated safe paths, and how can these algorithms propose adequate improvements?

6 CONCLUSION

This paper verifies that a DTCS provides the required data to generate realistic VTEs for construction safety with little manual means. We implemented a data framework based on existing ontologies into a prototype for a DTCS. The prototype integrates a VTE in a web application where the trainer can create game scenarios, and the trainees play a serious game to train their safety awareness. The prototype utilizes the 4D BIM model from the DTCS for generating the VTE and storing game results in a database. Algorithms process the results on the DTCS and provide personalized feedback. A dashboard summarizing the game results for all trainees allows the trainer to compare the performances. Based on the first results, we conclude the following three theses that require further investigation.

1. Accurate information about the location of materials and equipment makes VTEs more realistic.
2. The construction schedule requires more detail than current practice provides.
3. VTEs, as part of a DTCS, generate valuable data for purposes beyond pure safety awareness evaluation of construction workers.

First, the construction site in the case study was too tidy. Thus, the DTCS requires more knowledge about materials and the project status to make the VTE more realistic. Otherwise, a specialist must improve the scene with manual effort. Second, the construction schedule for the railway project links elements to tasks. The construction schedule must provide information about as-planned trajectories for the automatic generation of VTEs, purely based on such tasks. The construction industry is not yet at a point where, for instance, a crane follows a predefined path for locating objects. However, using as-performed trajectories of machinery from IoT devices could solve this issue. Lastly, the first results in a test with four trainees indicate that such a game generates valuable information beyond pure awareness evaluation. For instance, decision-makers can identify flaws in the safety design or simulate the usability in such a VTE before the construction starts.

Based on the main conclusions, the authors suggest future work investigating the impact of a DTCS providing advanced information regarding the placement of materials and as-planned trajectories of equipment. Furthermore, future research should study how the collected data in VTEs can contribute to improved safety design. One approach is to develop models that can automatically propose better site layouts regarding productivity and safety. The collected data could also train machine learning models for predicting hazards during construction based on the results from the training. Additionally, future research can integrate real-time sensor data and other data sources to improve the accuracy and relevance of the virtual training environment, resulting in improved safety outcomes.

ACKNOWLEDGEMENT

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CAN HIGHER EDUCATION AND THE FAIRNESS, INCLUSION AND RESPECT AGENDA HELP ACHIEVE SAFE AND HEALTHY WORK ENVIRONMENT AS A FUNDAMENTAL PRINCIPLE AND RIGHT AT WORK IN CONSTRUCTION?

Ani Raiden[1], Craig Thomson[2]

[1]Nottingham Business School, Nottingham Trent University, 50 Shakespeare Street, Nottingham, NG1 4FQ (UK)
[2]School of Computing, Engineering and Built Environment, Glasgow Caledonian University, Cowcaddens Road, Glasgow, G4 0BA (UK)

Abstract

Construction employment numbers are expanding, yet the industry continues to experience growing demand for workers. This is a considerable challenge given that it is skilled people: carpenters, joiners, and construction managers, that are in highest demand. Attracting and retaining diverse talent is one key requirement of the industry skills plan in the UK, and the Construction Leadership Council (CLC) set up task groups to investigate different routes into construction and how national and local organisations could work together across the industry. Fairness, inclusion and respect (FIR) were some of the central themes in the body of work, with a view that inclusive construction sites not only help meet the demand for increasing number of workers by keeping talent in the industry and attracting new entrants; inclusive sites also facilitate the development of a healthy working environment. Research identifies the image of the industry, gender, ethnicity, and disability as of specific concern in the context of construction and the built environment. These issues intersect in complex ways to create an environment that is not attractive to new entrants generally and especially those from underrepresented groups. FIR is an important aspect of ensuring the ILO/ UN declaration about safe and healthy work environment as a fundamental principle and right at work can be met. Thus, one CLC task group set to investigate how Higher Education (HE) providers attract a diverse and inclusive student body so as to enhance the long-term development of the workforce. This paper discusses the long-standing, high-level commitment to the principles of FIR within HE admissions, together with recommendations on developing the experience and learning on FIR so that graduates from construction courses are well equipped to enhancing the work environment in the future.

Keywords: healthy work environment, diversity, fairness, inclusion, respect.

1 INTRODUCTION

As the global construction market continues to grow, it requires an ever-larger workforce, and it is skilled people: carpenters, joiners, and construction managers, that are in highest demand. Increasing technological and social developments also mean that the sector will require workers with new and differing skillsets. While the construction employment numbers are expanding, the industry continues to experience growing demand for workers (Haynes, 2022) as the global construction market faces increasing labour shortages.

Attracting and retaining diverse talent is one key requirement of the industry skills plan in the UK, and the Construction Leadership Council (CLC) set up task groups to investigate how national and local organisations could work together across the industry (see Construction Leadership Council, 2021; 2022). There are four priorities: (i) Culture change: creating an equitable, diverse and inclusive industry, (ii) Routes into industry (Apprenticeships, Further Education / T Levels and Higher Education), (iii) Competence, and (iv) Skills for a modernised industry.

Fairness, inclusion and respect (FIR) are some of the central themes in this body of work, with a view that inclusive construction sites not only help meet the demand for increasing number of workers by keeping talent in the industry and attracting new entrants; inclusive sites also facilitate the development of a healthy working environment. Research identifies the image of the industry, gender, ethnicity, and disability as of specific concern in the context of construction and the built environment. These issues intersect in complex ways to create an environment that is not attractive to new entrants generally and especially those from underrepresented groups (see for example Raiden and King, 2022). Fairness, inclusion and respect are an important aspect of ensuring the ILO/ UN declaration about safe and healthy work environment as a fundamental principle and right at work can be met.

This paper focuses on the CLC priority two: routes into industry – Higher Education (HE) and discusses the commitment to the principles of FIR within HE admissions. The scope of the research entailed examining secondary data on HE statistics and policies on FIR; reviewing University Access Statements in selected institutions; and interviewing selected Admissions Tutors.

2 HE STATISTICS AND POLICIES ON FAIRNESS, INCLUSION AND RESPECT

Three key areas of interest that emerged from the research are (i) how HEs undertake Access and Participation planning, reporting, and monitoring; (ii) the impact of centralised University Admissions on student recruitment and selection; and (iii) the major differences between subject areas.

2.1 HE Access and Participation planning, reporting, and monitoring

There is a long-standing, high-level commitment to the principles of FIR, commonly termed 'Access and Participation' (A&P), within HE. The history of funded activity in this area can be traced back to the first special funding programme for widening participation that was announced in June 1998 (Selby, 2018) which then led to the requirement for institutional Widening Participation strategies. There were also a series of special programmes for regional and later sub-regional collaborative initiatives, and further changes in government policy in 2006, when the initial focus was to encourage fair access, and in 2011 to include widening participation and success for students from disadvantaged backgrounds more generally (ibid). Knowledge about what the issues in widening participation were, how to measure disadvantage, and how to identify good practice in achieving it were rapidly increasing.

Office for Students (OfS) is now the independent regulator of Higher Education in England, with the aim to ensure that "*every student, whatever their background has a fulfilling experience of higher education…*" (OfS, 2022a). It sets long-term targets to eliminate inequalities within an A&P framework for the sector which sets out the expectations from all universities and colleges registered with the OfS in terms of who they consider underrepresented groups to include and the key priorities for access and participation (OfS, 2022b) (see Table 1).

Table 1. the Office for Students access and participation framework (OfS, 2022b)

Underrepresented groups	***Priorities for access and participation***
• students from areas of low HE participation, low household income or low socioeconomic status • some black, Asian and minority ethnic students • mature students • disabled students • care leavers • carers • people estranged from their families • people from Gypsy, Roma, and Traveller communities • refugees • children from military families.	2018, to eliminate: • the gap in entry rates at higher tariff providers between the most and least represented groups • the gap in non-continuation between the most and least represented groups • the gap in degree outcomes between white and black students • the gap in degree outcomes between disabled and non-disabled students. 2022, new priorities, to: • partner with schools and other local organisations to raise the attainment of young people • develop more diverse pathways into and through higher education through more flexible courses • ensure access leads to participation on high quality courses and secures good graduate outcomes • improve the quality and volume of evaluation of access and participation plan activity • make access and participation plans more accessible in a way that prospective students, their parents, and other stakeholders can easily understand.

Universities are required to set A&P plans that show how they will improve equal opportunities for underrepresented groups (OfS, 2022b), including ambitious targets for improvement, and they are held accountable for meeting those targets, in order to achieve the "*shared goal of improving equality of opportunity for disadvantaged and under-represented groups*" (Donelan, 2021).

OfS publishes statistics as part of their specific duties under the Equality Act, as an annual information release about students with protected characteristics: age, disability, gender reassignment, marriage and civil partnership, pregnancy and maternity, race, religion or belief, sex, sexual orientation. Hereon, those marked with an asterisk (*) relate to one of the protected characteristics under the Equality Act (OfS, 2022c). Beyond the duties of the Equality Act, the OfS publishes statistics relating to who they consider underrepresented groups to include: gender identity; parental higher education; free school meals (FSM) eligibility, an indicator of financial disadvantage for Key Stage 4 pupils; participation of local areas (POLAR4), an area-based measure reflecting higher education participation rates; Index of Multiple Deprivation (IMD), an area-based measure of deprivation in England; care experience, indicating whether a student has been in care; Household Residual Income (HRI), a measure of household income after accounting for certain costs; estrangement, indicating whether a student is no longer communicating with their parents; socioeconomic background; tracking underrepresentation by area (TUNDRA), an area-based measure that tracks state-funded mainstream school pupils in England into higher education (both TUNDRA by Lower Super Output Areas (LSOA) and TUNDRA by Middle Super Output Areas (MSOA) are included in this release); and associations between characteristics of students (ABCS) access quintiles, grouping young people with certain combinations of characteristics by the likelihood of access to higher education.

Table 2 shows that whilst progress has been made over the last decade, for the majority of protected characteristics, the gains have been marginal. The key positives are an increase of those with disabilities, improved ethnic diversity and a higher proportion from low HE participation areas. The gender diversity remains challenging.

Table 2. A comparison of figures for undergraduate students for academic years 2010-2011 and 2020-2021 on selected characteristics (for further, full details please see Raiden et al, 2022)

Characteristic	***2020-2021***	***2010-2011***
Disability*	14.8% of full-time entrants report having a disability	8.5% of full-time entrants report having a disability
	10.8% of part-time entrants report having a disability	7.6% of part-time entrants report having a disability
	3.7% of entrants report a mental health condition	0.7% of entrants report a mental health condition
Ethnicity*	70.4% White	78.7% White
	13.2% Asian background	9.5% Asian background
	9.3% Black	7.4% Black
	4.9% Mixed ethnic background	3.3% Mixed ethnic background
	2.3% Other minority ethnic groups	1.1% Other minority ethnic groups
Sex* (engineering, technology and computing)	82.9% male	85.6% male
Parental higher education	48.5% A parent with a higher education qualification	51.5% A parent with a higher education qualification [a]
Associations between characteristics of	40.5% were from quintile 5, with characteristics that were most strongly associated with access to higher education	38.2% were from quintile 5, with characteristics that were most strongly associated with access to higher education

students (ABCS) access quintiles	8.0% were from quintile 1, those least likely to access higher education	7.7% were from quintile 1, those least likely to access higher education

[a] data from 2012-2013; 2010-2011 data not available

[b] data from 2015-2016; 2010-2011 data not available

2.2 The impact of centralised University Admissions on student recruitment and selection

Many universities operate a centralised Admissions Policy to be able to control total student numbers and provide the flexibility to adjust School/ Department student intake depending on the popularity of courses and the outcome of entrance examinations. The University level commitment to A&P translates into Admissions practice in a variety of ways.

Many Universities now explicitly note their welcome to applicants from diverse backgrounds and personal profiles on their web presence, social media, and marketing and recruitment materials. They have made conscious moves to have imagery used of a better balanced and diverse population of students and staff on open days and campus visit days.

University level A&P plans are communicated to the Admissions teams. Admissions tend to be heavily centralised, and focus is on the merit of each application, not FIR data. The Admissions managers and associates that we spoke with evidenced indirectly that the Admissions Code of Practice is implemented. For example, one respondent stated that,

> "*Universities and colleges ensure admissions processes do not disadvantage applicants and actively seek to address any access gaps related to protected characteristics. Admissions form part of broader institutional equality, diversity and inclusion strategies*."

'Contextual admissions' allow for consideration of additional data that is automatically provided on the UCAS form. This may include living in an area of disadvantage or with low progression into higher education; the school or college where the applicant took their GCSEs/ A-level equivalent has performed below the national average over multiple years; having been looked after in care for more than three months; and/ or having a refugee status.

It is important to note some variation in the Admissions practices for different types of courses: they are likely to be highly centralised and regulated for undergraduate courses (commonly managed external to any given university via UCAS), centralised but direct and managed in-house within universities for masters courses, and very close to the lead supervisor for PhD and professional doctorate courses. Degree apprenticeships appointment could be an existing employee of a company, or a person recruited with selection and admission by an employer and higher education provider having equal power on describing position and enrolment.

2.3 Differences between subject areas, and the feasibility of course level considerations

Data at School/ Department/ Course level is not easily or widely accessible as universities regard these as highly confidential. This means that it is very difficult to gather knowledge about how construction courses are faring on A&P or to analyse trends over time. Arguably, the feasibility of School/ Department/ Course level targets or quotas is somewhat questionable. Firstly, the problem is that the dataset will invariably be quite small at course level. Secondly, there are persistent differences in the perceived interest in certain courses, for example, by gender. The HESA classification that covers construction is "Architecture, Building and Planning" and "Engineering and Technology". These subjects tend to be attractive to more men than women, vis-à-vis social sciences and education and teaching, which tend to attract many more female entrants. The OfS figures relating to the differences in the proportions of female and male students within certain subjects are supported by other sector data (HESA, 2022). The publishing of figures at a course level could potentially be dangerous and lead to misinterpretations and bad publicity should they be read out of context. It could create an opportunity for malicious manipulating of figures by not so well intended members of the press for example. The negative reputational effect of such press may be devastating, not only to the institution(s) involved but also for the subject area more widely. Thus, while transparency is desirable and essential, data must be handled carefully so that it is read in the relevant context.

Table 3 shows a comparison of figures for undergraduate students from the academic year 2020-2021 at the HE sector level and on construction courses within one institution. As alluded to above, data like this is difficult to obtain because universities do not make it publicly available. This data that we gained access to is from a post-1992 institution which historically attracts students with a more diverse background. The data illustrates well the industry specific skew on gender. We compared the data available for construction courses with data available on other courses within that institution and all the other measures (age, disability, ethnicity, sex, IMD, care experience) reflect more general trends within that institution, the locality, and student population they attract.

Table 3. OfS 2020-2021 data (OfS, 2022c) on the protected characteristics and OfS defined underrepresented groups at the sector level and on construction courses within one post-1992 institution (data not available on all protected characteristics and OfS defined underrepresented groups)

Characteristic	***Sector (HE)***	***Construction courses at a post-1992 institution***
Age*	Most commonly entrants on full-time courses are under the age of 21 on entry: 68.4%	Most commonly entrants on full-time courses are under the age of 21 on entry: 58%
Disability*	14.8% of full-time entrants report having a disability	11% of full-time entrants report having a disability
Ethnicity*	70.4% White 29.6% BAME	92% White 6% BAME 2% unknown
Sex*	56.5% Female 43.4% Male	19% Female 81% Male
Index of Multiple Deprivation (IMD)	21.8% of entrants were from the most deprived areas	11% of entrants were from the most deprived areas
Care experience	1.1% of full-time entrants had been in care	0% of full-time entrants had been in care

Thus Table 3 shows that, at this diverse, post-1992 institution, the construction courses underperform, by significant margins, on the listed protected characters in comparison to the overall HE sector.

Table 4 shows a comparison of figures in % of applicants and entrants on undergraduate students on construction courses within the same institution.

Table 4. Applicants and entrants on undergraduate students on construction courses in a post-1962 institution

Characteristic	***Applicants***	***Entrants***
Age*	Most commonly applicants on full-time courses are under the age of 21: 57.8%	Most commonly entrants on full-time courses are under the age of 21 on entry: 58%
Disability*	10.9% of applicants for full-time courses report having a disability	11% of full-time entrants report having a disability
Ethnicity*	66.7% White 7.1% BAME 26.2% unknown	92% White 6% BAME 2% unknown
Sex*	20.9% Female 79.1% Male	19% Female 81% Male
Index of Multiple Deprivation (IMD)	10% of applicants for full-time courses were from the most deprived areas	11% of entrants were from the most deprived areas
Care experience	0.7% of applicants for full-time courses had been in care	0% of full-time entrants had been in care

Comparison between Tables 3 and 4 show that both applicants and entrants to construction courses at this post-1992 institution has much lower FIR percentages compared to the HE sector but there is good correlation for conversion from applicants to entrants with the exception of ethnicity. In other words, this institution attracts a much less diverse pool of applicants, across all protected characteristics and it works hard to convert those applicants into entrants.

3 UNIVERSITY ACCESS STATEMENTS

In addition to the sector level data, Universities UK publish a range of good practice case studies and several Universities publish statements about their longitudinal journeys in widening participation, including: The University of Manchester, Nottingham Trent University (NTU), and Loughborough University. Universities' A&P Impact Reports show the progress made against the targets, objectives, and written commitments they had set out in their A&P plan each year. Commonly this includes analysis of longer-term trends

The University of Manchester has operated a number of schemes over several decades now, including a Targeted Access Scheme, Gateways Access Manchester, Manchester Access Programme, contextual admissions, and school-based access initiatives such as Pathways to Law. Numbers of these schemes have grown from 100 students in 2003 to over 600 students in 2020.

NTU has consistently recruited a greater proportion of its full-time undergraduate intake from Low Participation Neighbourhoods than the sector, and they are committed to paying particular attention to the under-representation of disadvantaged males (white and BME) for example through revised outreach and marketing. Black, Asian and other minority ethnic 18-year-olds are well-represented at NTU. For several years they have been strategically improving support for applicants and students with disability/ies, and the number and percentage of NTU's fulltime first-degree entrants with a known disability has increased consistently.

As part of Loughborough University's commitment, they have invested in a range of initiatives designed to reduce the inequalities observed across the student lifecycle. Alongside a suite of aspiration and attainment-raising activities this includes use of contextual data and measures to identify applicants to Loughborough with the greatest potential to succeed with their studies and to ensure that no groups are disadvantaged during the application process.

4 REFLECTIONS ON ACCESS INTO INDUSTRY VIA HE

In terms of the CLC Skills Plan on the routes into industry, specifically HE, we observe several concerns. Firstly, the intentions of the CLC to spring Universities into further action on FIR in ill-advised. Every HE provider, due to the OfS mandate, already reviews, enhances and embeds their plans for FIR within their student recruitment and admissions criteria. This is largely met by the requirement to set and continually report on A&P plans. The HE sector is some way ahead of the construction industry specific planning. Our research has confirmed that the long-standing, high-level commitment to the principles of FIR, is evidenced by institutional level strategy and practices and continuing improvement in the measures relating to the protected characteristics and OfS defined underrepresented groups. To move further would require a careful consideration of the possible unintended consequences of FIR driven recruitment programmes. Concerns over positive discrimination often emerge in response to interventions which are seen to infringe the fundamental principle of meritocracy (Johns et al, 2014; Dobbin and Kalev, 2016). The HE Admissions practice is currently well aligned with both the principles of meritocracy and contextual consideration of specific circumstances. Major effort in this regard is thus not sensible, and instead, focus ought to be on enhancing the experience and learning on FIR within HE, and also enhancing the workplace profile so that diverse entrants into the industry can be retained. The following key issues need to be addressed to ensure the pipeline of construction applicants into HE is much fairer and more inclusive.

Attractiveness of the construction sector:

The data in Tables 4 and 5 shows that Universities are not able to attract diverse applicants to HE construction courses. Broader research identifies the following themes as of specific concern within the context of the construction industry and built environment as a sector: leadership; the image of the industry and career perceptions; gender; ethnicity; and disability. These issues intersect in complex ways to create an environment that is not attractive to new entrants generally and especially those from underrepresented groups (Raiden and King, 2022: 16; Missa and Ahmed, 2010).

Promoting construction to minorities:

People from ethnic minority backgrounds face limited opportunities within the industry and an awareness of construction careers is minimal within this population (Holborough, 2015; Missa and Ahmed, 2010). Newton and Ormerod (2005) also found that employers in construction are unlikely to have specific policies or practices in place to support the employment of people with disabilities and instead tend to rely on broader equality and health and safety information in managing situations where a worker becomes disabled during at work. They largely ignore people with disabilities in the labour market (ibid: 1079).

Promoting construction to female students:

There is a wealth of research on gender in the context of construction and the built environment (see for example Bigelow et al, 2015; Dericks and Phua, 2020; Ginige et al, 2007; Murphy and Ren, 2010; Ness, 2010; Powell et al, 2004; Sang and Powell, 2012; Thevenin and Elliott, 2018) much of which points to problems with the image of the industry, perceptions of poor career options, family influences, gender stereotypes, male domination and lack of female peers. Baker et al (2021) find that leadership level gender diversity and initiatives which support work-life balance enhance both organisational performance and their ability to recruit diverse staff. Wilkes et al (2015) highlight concerns about the lack of visibility of construction careers. They find that it is primarily only students who know someone in the industry that are aware of the degree and other possibilities within the industry. Oo et al (2020) report that once women work in construction their job satisfaction tends to be relatively high, and this is increased when their career expectations are met. Thus, they propose that familiarisation and fulfilment of newcomers' expectations is an important aspect of retention. Other initiatives put forward by researchers include positive industry promotion focussing at pre school-leavers (Murphy and Ren, 2010; Powell et al, 2004) and breaking down gendered socialisation processes so that girls and boys are not biased towards particular career paths (Powell et al, 2004), increasing enrolment of women on construction courses through school careers counselling (Bigelow et al, 2015), the use of mentors and role models to inspire and motivate students on construction courses – this was found particularly effective for female students (Thevenin and Elliott, 2018), and publishing good news to showcase the technology and engineering achievements to society at large (Ginige et al, 2007).

Role of professional bodies:

These are also committing to fairness, inclusion and respect. For example, the CIOB equality, diversity and inclusion campaign recognises that,

> "*When they leave our universities, students face a construction industry which still has a long way to go to become a more equal, diverse, and inclusive. In the UK, women account for about 15%, professionals from Black, Asian, and Minority backgrounds for about 6% of the construction workforce… [and aim] to discuss how change can be brought about which starts at the education level and might transform the industry our graduates will enter to fully embrace the Art of Building*." (CIOB, 2022)

Similarly, the RICS states that,

> "*The surveying profession needs a diverse workforce in order to utilise the innovative skills and technologies required by consumers in the built and natural environments; it is our responsibility to tackle barriers to entry and encourage a more diverse profession.*
>
> *RICS has been committed to raising the awareness of surveying and the ambition for the profession to be more diverse. The Inclusive Employer Equality Mark is a response to the sector striving to move towards a more diverse and inclusive workforce*." (RICS, 2022)

5 WHAT HE CAN DO ON FAIRNESS, INCLUSION AND RESPECT TO HELP ACHIEVE SAFE AND HEALTHY WORK ENVIRONMENT AS A FUNDAMENTAL PRINCIPLE AND RIGHT AT WORK IN CONSTRUCTION

Given that we are satisfied that HE in the UK has embedded the principles of fairness, inclusion and respect in student recruitment and selection for some time now, and our findings support the Skills Report statement: "*HE provision is performing well in terms of encouraging diversity*" (Construction Leadership Council, 2021: 28), there is no need for further action on this point for now. The system seems well equipped for encouraging continual improvement. Therefore, the focus should include how we support a more diverse and inclusive student body. This may mean action on three levels: (i) the School/ Department, (ii) the University, and (iii) External Stakeholders.

5.1 The School level: embedding fairness, inclusion and respect in the curriculum

Action: embed FIR in the curriculum and make it an explicit module/ course learning objective for all construction and related courses curriculum so as to ensure future generations of construction managers, surveyors, architects, etc. have the skills and competencies related to FIR in the workplace.

5.2 The University level: staff diversity, and training and development, and student retention

Action: Assess staff profiles to investigate whether there are the diverse role models within HE and make information about staff diversity visible. Also, evaluate staff training and development requirements with regards to fairness, inclusion and respect, and review how well academic and support staff at course level are equipped for supporting a diverse body of students.

Action: Investigate retention of students from under-represented groups and devise initiatives to support them through their learning journey. Also, trace how fairness, inclusion and respect is currently embedded in a longitudinal manner to follow a student throughout their studies, from application to entry and throughout their learning journey onto successful learning outcomes and achievement of a qualification, and where necessary consider how this could be actioned (some of this may be devolved to school level).

5.3 External Stakeholders: terms of reference

Action: There is a need for common terms of reference. The ‘fairness, inclusion and respect’ agenda (CITB, 2023) does not align well with the OfS and HE policy and practice on A&P. The OfS approach is more specific and comprehensive (see Table 1), thus a consideration is needed to determine whether (a) their definitions and terminology are adopted for construction too; (b) how FIR is defined, i.e., is it a rebranding of equality, diversity and inclusion (EDI), and how are the core principles of fairness expressed and put into action and measured and evaluated. Such an articulation and developing an understanding of fairness is an opportunity for upskilling at HE level also.

Action: Connect the CLC Skills Plan and actions to the UN Sustainable Development Goals (SDGs) to show connections to the wider global agenda, perhaps specifically and directly with reference to SDGs 5: Gender equality, and 10: Reduced inequalities; and indirectly SDGs 3: Good health and well-being, 4: Quality education, 8: Decent work and economic growth, 11: Sustainable cities and communities, 16: Peace, justice and strong institutions, and 17: Partnerships for the goals. HE institutions globally are committed to doing this (see for example EUA, n.d.; University of Manchester, 2022). As part of NTU’s strategic plan they state:

> “*We will align our activities with the United Nations’ Global Sustainable Development Goals, recognising environmental, social and economic sustainability in a triple bottom line and supporting our partners and suppliers to do the same*.” (NTU, 2022).

This allows for integration of the skills plan into the wider organisational strategic planning and enhances the visibility and significance of specific actions, connecting the local to the global.

Action: HE and professional body commitment to A&P and equality, diversity and inclusion need to be better aligned to achieve further improvements in practice. Professional institutions can highlight it as an accreditation requirement at course level and hence bring it additional focus. A joint approach will allow Schools to learn from other Schools' good practice.

6 CONCLUSION

Attracting and retaining diverse talent is one key requirement of the industry skills plan in the UK, and we present findings of research that was set out to investigate the route into construction via HE. We showcase the long-standing, high-level commitment to the principles of fairness, inclusion and respect within HE admissions, and put forward a number of recommendations on developing the experience and learning on FIR so that graduates from construction courses are well equipped to enhancing the work environment in the future.

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