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FUNCTIONAL RESONANCE OF THE SYSTEM IN THE FORMWORK

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Abstract
Introduction: The complexity of the construction sector necessitates a study that aligns with the activities carried out on-site. Resilience engineering provides tools to understand complex socio-technical systems from a novel perspective, to address unforeseen events. The primary objective of this study is to identify the functional resonance of the system in the formwork of a building slab. **Methodology:** The methodology employed in this article is grounded in the Functional Resonance Analysis Method (FRAM), which enables the analysis of the overall system resonance, considering functions, functional couplings, variability, and other factors. **Results and Discussion:** Thirty-four system functions have been identified in the formwork of a building slab. These functions, along with their variability, have been analysed, considering simple time and precision phenotypes, with a priority given to human functions. This analysis aimed to identify the functional resonance and its impact on the system. **Conclusions:** FRAM, as a tool of Resilience Engineering, has enabled the identification of critical points that could disrupt the complex socio-technical system of construction, adapting to the realities of the sector.

Keywords: Functional Resonance, FRAM, Functions, Construction.

Introduction

Modern systems are complex entities where the interaction of their elements is fundamental to their proper functioning. Therefore, a study focused only on their parts would be inefficient. To improve the safety of these systems, it would seem important to adopt a systemic perspective that allows for the analysis of these interrelationships between elements to develop strategies that optimise the overall performance of the system (Hollnagel, 2021).

The construction sector is an example of these complex socio-technical systems, which, despite advances in the sector, are among the most dangerous worldwide. The complexity of its functions, tight deadlines and variable conditions have resulted in a high incidence of fatal occupational accidents (Lozano-Díez *et al*., 2019). In the United States and Europe, one in five work-related deaths occurs in the construction sector (Huang *et al*., 2022), (Mohandes *et al*., 2022).

The construction sector has become an essential pillar for social development, with its infrastructure projects, housing development and large civil works. This sector in Spain in the year 2021 had registered a remarkable growth with more than 395000 active companies, with a turnover that exceeded 149000 million euros. The construction of buildings has been highlighted as the main activity considering the company and employment parameters representing around 38% of the total (Instituto Nacional de Estadística, 2024).

The remarkable complexity of the construction sector, as well as its high rates of occupational accidents worldwide (International Labour Organization - ILO, 2024; Ranasinghe et al., 2020), require the implementation of safety management strategies coupled to reality. Resilience in these complex socio-technical systems is a predominant factor in the occurrence of incidents, therefore, studying it is fundamental to understand how the safety of the system can be guaranteed, identifying critical events and disturbances to manage them appropriately (Pilanawithana *et al*., 2022),

Resilience Engineering allows for an in-depth analysis of the complex socio-technical system of the construction sector. Through the implementation of metrics such as system management and performance, it would allow to identify the elements that contribute to the resilience of the system (Bergström *et al*., 2015; Righi *et al*., 2015), successfully facing unexpected events, and that would probably allow to improve the current situation, strengthening the system (Bragatto et al., 2021; Xu *et al*., 2023).

By integrating the concepts of variability and functional resonance, Resilience Engineering provides a valuable tool for understanding how complex socio-technical systems can adapt to and overcome disturbances. It differs from traditional approaches that focus on errors by considering the possibility of focusing on the positive factors that allow resilience to be generated in the system (Haavik *et al*., 2019; Hollnagel *et al*., 2015). Resilience Engineering has highlighted learning the right lessons from the right experiences (Patriarca et al., 2018), where understanding and learning from daily work could strengthen workers' reactions to deal with unexpected events (Degerman & Wallo, 2024).

One of the Resilience Engineering tools that would allow the assessment of the complex socio-technical system of construction is the Functional Resonance Analysis Method (FRAM) due to its dynamism and versatility (Patriarca *et al*., 2020), (Tierra-Arévalo *et al*., 2023). The application of this new paradigm would allow the development of a holistic understanding of complex socio-technical systems, considering it as the basis for identifying and analysing the functions involved and their interdependencies. After analysing the disturbances, it would seem important to delve deeper into the functional resonance that occurs within the system, to understand its functioning and to propose mechanisms to achieve a resilient system that contributes to the improvement of occupational safety management (Hollnagel, 2021).

The main objective of this study is to identify the functional resonance of the system in the formwork of a building slab. The following research questions will guide the study:

What are the functions of the system in the formwork of a building slab?

What is the variability of system performance in the formwork of a building slab?

How does the functional resonance of the system appear in the formwork of a building slab?

This article is structured in four sections: introduction, methodology, results and discussion, and conclusions.

Methodology

The methodology used to prepare this article is based on the "Functional Resonance Analysis Method" (FRAM). To do so, it was necessary to know the real performance of the system through documentary analysis and fieldwork, which were based on interviews and observations. For the documentary analysis, the legislation and regulations in force, the guides and manuals focused on the construction of structures, the websites of the main suppliers and subcontractors, as well as the safety plans provided by the collaborating companies were required. The fieldwork was carried out in 3 different construction sites of similar characteristics in the same province, where observations of the work were made and documented with photographs and on-site interviews. The 21 people participating in the interviews were selected according to their experience and their availability of time in the company, to collect the information to feed the model. The interviews were conducted using a script with questions that support the model.

FRAM made it possible to evaluate the complex socio-technical system of the construction sector by adjusting it to the reality of the system. An initial step was the definition of the purpose of the study, which had to be clearly defined, and which was related to the following 3 potential applications (Hollnagel, 2012):

a) Retrospective for event analysis.
b) Prospective risk assessment.
c) System variability assessments or system re-design.

FRAM has been applied considering the following steps (Hollnagel, 2012; Melanson & Nadeau, 2019; Patriarca *et al*., 2017):

Step 1: Identification and description of system functions

The initial step was to become familiar with all the functions that were embedded within the complex socio-technical system, which enabled the objective determined by the system to be achieved. These functions were varied and were determined by 6 aspects to be considered for each case: Input, Output, Precondition, Resources, Control and Time.

Step 2: Identification of performance variability.

After the identification of the detailed functions of the system, the characterisation of the potential variability and the actual variability of the system performance was carried out. For the characterisation of variability, simple phenotypes such as time and accuracy were considered. The variability characteristics could be presented according to the type of function. In this case they were performed considering human functions with high frequency and high amplitude. These functions were performed by workers in the workplace.

Step 3: Aggregation of variability.

According to the couplings of the system, the potential variability of a function was identified, which could have had different results than expected, due to upstream and downstream functional couplings, and which could therefore modify the behaviour of the system. The functional resonance analysis allowed for a holistic and realistic approach to the analysis of the system.

Step 4: Managing variability.

In this step, in accordance with the new safety paradigm, the amplification of the positive effects and the minimisation of the negative effects produced by the variability of the system's performance is proposed, with the aim of having a resilient system that allows the expected result to be obtained.

The principles immersed in this methodology were: the principle of equivalence of failures and successes, the principle of approximate adjustments, the principle of emergence and the principle of functional resonance.

Results and Discussion

In accordance with the research questions posed, this section presents the results and discussion. Regarding the first question: What are the functions of the system in the formwork of a building slab?

Thirty-four functions of the formwork system in a building slab have been identified as follows: To enter the site, to dialogue with the manager, to order material from crane operator, to prepare material, to lift material, to move material to be installed, to indicate height, to open props, to position main formwork supports, to fasten main formwork supports, to position the ties, to define the height of the props, to install props, to adjust props, to measure levelling, to level the props, to position trenches, to lay boards, to extend the working platform, to extend main formwork supports, to extend ties, to add tilting supports, to project the layout upwards, to request machinery from a crane operator, to prepare machinery, to lift cutting machine, to cut boards and timbers, to complete areas , to install boards, to seal holes, to check stock, to verify quality, to collect tools, to release the formwork for use.

Of the 34 identified functions of the formwork system in a building slab, 29 primary functions are highlighted in colour and 5 secondary functions are shaded in Figure 1. These functions, which are part of this complex socio-technical system, do not necessarily develop in a linear manner as traditionally assumed. Instead, they adapt to the system's needs to ensure optimal performance and achieve the desired outcome. The functions themselves do not exhibit any defined hierarchy or sequence.

Regarding the second question: What is the variability of the performance of the formwork system in a building slab.

The variability has been determined by considering the simple phenotypes of time and precision. This variability is highlighted in the functions shown in Table 2. As an example, the variability determined in the function “To cut boards and timbers” is shown in Table 1.

Table 1. *Example of the identification of variability in the function "To cut boards and timbers".*
Source: *Authors.*

No	Functions	Description
27	To cut boards and timbers	1. The excessive dimensions of some boards, planks, and timbers can sometimes hinder handling and affect the cutting process, leading to imprecisions. 2. If the cuts do not meet the exact requested dimensions, imprecisions will result. 3. If the dimensions of a cut are larger than required, rework will be necessary, leading to delays. 4. Conversely, if the dimensions are smaller than required, the cutting process will need to be restarted, resulting in delays. Exogenous: 1. These imprecisions, if not properly managed, could lead to accidents. 2. The repetition of these events throughout the workday due to fatigue could lead to imprecisions and, consequently, further delays. 3. Periodic maintenance of the machinery is necessary to guarantee the cut.

The variability in the system's performance during the formwork of a building slab originates from the multiple couplings between functions throughout the entire system, as observed in Figure 1. The function of "To cut boards and timbers" presents the greatest number of options in which variability is embedded. This function also highlights exogenous variability, which is not necessarily present in all functions.

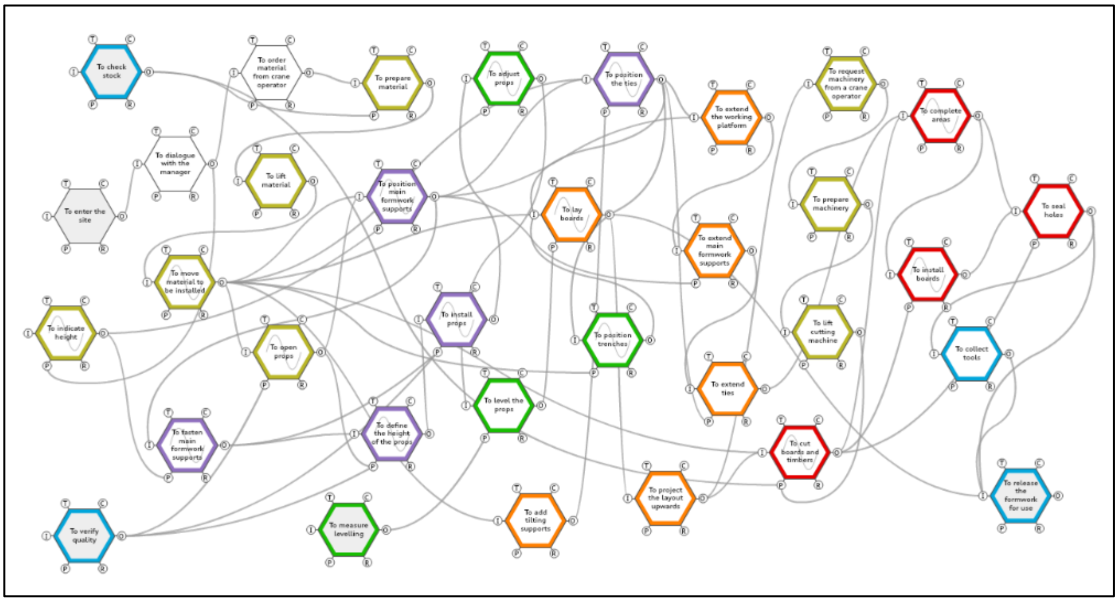

Figure 1.- *Couplings of the system's functions in the formwork of a building slab.*
Source: *Authors.*

Regarding the third question: How is the functional resonance of the system presented in the formwork of a building slab?

Multiple functional couplings upstream and downstream cause resonance in the system which could modify the behaviour of the system (Pardo-Ferreira *et al.*, 2020).

Table 2 presents the functional resonance when analysing the system with a holistic approach.

***Table 2.** Functional resonance of the formwork system in a building slab.*
***Source:** Authors.*

No	Functions	Description
6	To move material to be installed	The material to be used is moved multiple times from its initial point until it reaches the plant. From there, workers will be responsible for transporting it to its installation point. This function of "To move material to be installed" could generate resonance in 7 downstream system functions. On certain occasions, due to the ease of transporting small elements first, an unnecessary wait and inefficiency could be generated in the function of "To position main formwork supports" and in the function of "To open props", since the elements of both functions need to be coupled together to be able to start the shuttering structure. Additionally, resonance could be generated in the function of "To add tilting supports" and in "To position the ties", as they are executed simultaneously, due to the placement of tilting supports on odd ties. Even the final phase of the shuttering, in the functions of "To position trenches", "To lay boards", and "To cut boards and timbers", could be impacted if the necessary corrective measures are not taken in time.
7	To indicate height	The function of 'To indicate height' must be executed with the utmost precision, as any confusion could lead to unnecessary work that would require a disproportionate amount of time to return the worksite to its normal conditions. The downstream function of 'To indicate height' could generate resonance in the functions of 'To position main formwork supports' as well as 'To fasten main formwork supports', which are practically the basis for extending the entire shuttering. The experience of some workers allows them to react favourably to the occurrence of these events, which encourages them to confirm that the marking is consistent with the characteristics of the shuttering to be carried out.
8	To open props	The function of 'To open props' could generate upstream resonance in the function of 'To verify quality' with the aim of reinforcing the parameters established to determine the straightness of the props and ensure they are considered of quality. Downstream, the function of 'To define the height of the props' would be impacted first, since it would not be feasible to manipulate a prop that presents defects. Consequently, in second place, it could generate resonance in the function of 'To position main formwork supports', as without adequate props this function could not be executed, even affecting the development of some downstream functions.
9	To position main formwork supports	Although variability is focused directly on fatigue, the function of 'To position main formwork supports' could generate resonance in the system. For example, upstream, the function of 'To open props' could be affected if the positioning of the main formwork supports is incorrect, and if they fall, the quality of the elements could be compromised. Downstream, this function of 'To position main formwork supports' could affect the function of 'To fasten main formwork supports', if it is not carried out adequately, due to forced fastening because of its incorrect position. Similarly, the function of 'To position the ties' could be directly affected, as they are supported by these main formwork supports. Therefore, a proper positioning of the main formwork supports will impact downstream functions such as 'To extend the working platform' and 'To extend main formwork supports', which, although it can be mitigated by leveling the props, would cause imperfections from the first moment of installation, as they are the initial basic elements.
10	To fasten main formwork supports	The function of 'To fasten main formwork supports' could impact upstream the function of 'To position main formwork supports' due to the instability that could be generated by the movements inherent to the activities that must be carried out and condition a new repositioning of the main formwork supports. Downstream, the function of 'To fasten main formwork supports' could alter the function of 'To install props' due to the initial instability of the system, which would probably prevent the execution of the function of 'To define the height of the props'. Therefore, to fasten main formwork supports could guarantee to a certain extent the initial stability and safety required in the system, which will continue to reproduce according to these initial characteristics.

No	Functions	Description
11	To position the ties	The variability that could be generated in the "To position the ties" function could be essentially due to the placement of the tilting supports on the odd-numbered ties. This omission or alteration of the order of the tilting supports' positioning could directly affect downstream the "To lay boards" function, as the tilting supports will make direct contact with the wooden boards that must be immobilized by nails. In a certain way downstream, if the case warrants it, it could affect the "To position trenches" function, which, although they are not permanently placed, could alter this function. Finally, downstream, if the "To position the ties" function is not performed adequately, it could impede, to the same extent, the execution of the "To extend the working platform" function and the "To extend ties" function. The order of the tilting supports' addition could be corrected, but this would lead to unnecessary reprocessing and the generation of a significant cumulative delay in more than one function.
12	To define the height of the props	The "To define the height of the props" function must be performed using the system's own elements. Using other elements could impact upstream the "To verify quality" function, which would cast doubt on the performance of this function. Downstream, the "To install props" function could be impacted due to the instability that would be generated in the system using elements foreign to the structure with a variable resistance that could be revealed over time.
13	To install props	The "To install props" function could generate some variability when working at heights greater than 3.5 m where sturdier and, therefore, heavier shoring is required, which would affect maneuverability due to fatigue. In some sections, reinforcements and additional elements will be required to place inclined shoring, therefore, the repetition of these activities could cause variability upstream in the "To fasten main formwork supports" function, which if repeated impacts occur in the system could generate a certain degree of instability over time. On the other hand, if the placement of these props is not adequate, it would be difficult to continue with the downstream function of "To adjust props" which could only be performed if the props placement has been adequate. On some occasions, more than one prop can be placed continuously to reinforce a specific point.
14	To adjust props	The adjustment of the props must be performed with the precise number of blows to generate the necessary pressure to stabilize the system. These impacts, if they are abrupt, could generate variability upstream, altering the "To install props" function, since the transmission of movement through the structure could alter the initial location of the shoring. For the same reason, downstream, setbacks could be generated in the "To level the props" function, since the repeated impacts could unlevel the other props that was around, causing rework for its correction.
16	To level the props	When executing the "To level the props" function, the "To adjust props" function upstream could be affected due to the transmission of movement. The threading in the props is a fundamental characteristic to achieve adequate leveling of the props, however, on some occasions, some lifts would be required. This combination of elements could alter the start of the downstream "To lay boards" function if it falls into an adjust and level props loop.
18	To lay boards	The "To lay boards" function could generate a downstream variability that would affect the fulfilment of the "To release the formwork for use" function, due to worker fatigue, which would delay the placement of boards and, if there was no timely relief, these boards could fall and be damaged. The same thing would happen if warped boards arrived, which would make it difficult to fix them to the tilting supports.
22	To add tilting supports	The omission or alteration of the order of tilting supports placement could affect the "To position the ties" function, which in turn would downstream affect the "To lay boards" function, as the tilting supports will make direct contact with the wooden boards that must be immobilized by nails. Ultimately, downstream, if the "To position the ties" function is not performed adequately, it could impede, to the same extent, the execution of the "To extend the working platform" and "To extend ties" functions. The order of tilting supports addition could be corrected, but this would lead to unnecessary rework and a significant cumulative delay in multiple functions.

No	Functions	Description
27	To cut boards and timbers	The 'To cut boards and timbers' function requires a stationary machine with a circular saw, which must be operated exclusively by certified personnel. Worker concentration must be increased due to the movement of the circular saw to obtain wooden elements with the required dimensions. Incorrect cuts could lead to upstream variability in the 'To move material to be installed' function which, if it were to become recurrent, could affect the 'To check stock' function. Downstream, it would prevent the functions of 'To complete areas'; 'To install boards'; and 'To seal holes', the raw material of which is the product of the cutting machine. This function is of high importance in the system, because if it is not fully completed, the process would end, and the completion of the formwork would not be achieved.
28	To complete areas	Difficulties encountered in the 'To complete areas' function could cause variability downstream in the 'To seal holes' function and, in turn, in the 'To install boards' function. Although part of this work could be anticipated, it is recommended to carry it out after the working platform has been completed.
29	To install boards	Battens will support lateral loads during the concrete pouring process. Therefore, the appropriate material, the placement of supports, and the relevant reinforcements will allow for the satisfactory containment of the concrete. Variability in the placement of battens has a direct downstream impact on the 'To seal holes' function, which would be generated between the working platform and the battens. If this is not carried out meticulously, the formwork cannot be delivered.

Conclusions

The analysis of the system's functional resonance in the formwork of a building slab has allowed us to identify several key functions that could alter other functions around them, both upstream and downstream. For instance, the function of “To position main formwork supports”, which could severely affect the extension of the working platform and the extend main formwork supports. In the case of the function of “To cut boards and timbers”, this impacts the system's safety by introducing a cutting machine that requires a high level of concentration from the operator. Apparently, this function has been highlighted using the Resilience Engineering paradigm. Therefore, FRAM has been able to evidence critical points that could alter the complex socio-technical system of construction, adapting to the realities of the sector to propose improvements in safety management.

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