

INTEROPERABILITY BETWEEN BIM AND ROBOTIC FABRICATION PROCESSES: A CASE STUDY APPLIED TO GENERATIVE FACADE DESIGN

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Abstract

This paper investigates the interoperability between Building Information Modelling (BIM) environments and robotic fabrication (RF) workflows applied to generative 3D concrete printing. The study proposes a framework that starts with parametric modelling defined in a BIM environment, incorporates parametric code to structure and export metadata, and translates this information into robot code for extrusion-based fabrication. The workflow integrates geometry, dimensional parameters (height and width), volumetric data, and IFC metadata, automatically organizing and exporting them to ensure consistency between the digital model and the physical prototype. Two BIM-based export strategies were developed and compared through IFC, highlighting differences in geometric fidelity and data representation. The results indicate that, although BIM platforms present limitations in handling complex geometry, they remain effective for managing fabrication-related parameters.

A scaled prototype was produced to validate the full process. The transition from full-scale geometry to a reduced-scale prototype required only minor adjustments to the base geometry, confirming the robustness of the workflow. Issues observed during fabrication were mainly related to extrusion speed, material plasticity, and design choices, rather than to interoperability. Overall, the study demonstrates that BIM workflows can be successfully integrated with RF when geometric complexity and metadata interoperability are properly managed.

1. Introduction

In recent years, the Architecture, Engineering, and Construction (AEC) industry has faced increasing challenges related to efficiency, automation, and the management of complex

information across different project phases. Building Information Modelling (BIM) has been adopted as a central methodology to organize geometric and non-geometric data and to improve coordination between stakeholders. Since the early concept of using computers as a data-based alternative to traditional drawings [1], BIM has evolved into a key environment for design, documentation, and information exchange.

At the same time, advances in digital fabrication and robotic manufacturing have opened new possibilities for automated construction processes. RF, and more specifically 3D concrete printing (3DCP), enables the production of customized components and non-standard geometries that are difficult to achieve with conventional construction methods, while also allowing improvements in productivity and reductions in material consumption [2].

Despite this potential, the development of BIM-based workflows and RF processes have largely progressed in parallel. In many cases, BIM remains primarily a representational or documentation tool, while fabrication workflows are developed independently through computational or fabrication-oriented software environments [3].

One of the main challenges in integrating BIM with RF is interoperability [2]. This challenge involves the translation of geometry, parameters, and metadata from BIM environments into fabrication-ready data while maintaining consistency and control throughout the process. Open standards, such as Industry Foundation Classes (IFC), aim to support this exchange of information; however, practical limitations remain, particularly when BIM models are used to support parametric and fabrication-driven geometries.

2. Related Work

This section presents a review of relevant studies related to BIM interoperability, RF workflows, and 3DCP in construction. The literature review is structured around three main themes that directly support the scope of this study: (i) BIM and data interoperability, (ii) BIM-driven RF workflows, and (iii) robotic 3DCP in architectural applications. The objective is not to provide an exhaustive review, but to position the research within existing approaches and to highlight the specific gap addressed by this study.

2.1 BIM and Interoperability

BIM has been widely adopted as a methodology for managing building information throughout the project lifecycle. The introduction of open data standards, such as IFC, aimed to enable interoperability between different software platforms and disciplines. ISO 16739 [4] defines the IFC data schema, while buildingSMART promotes its implementation as a neutral and open exchange format.

Several studies have shown that BIM platforms are effective for managing structured information, such as dimensions, quantities, and basic parameters. However, limitations arise when BIM is required to handle complex or highly parametric geometries. He et al. [5] demonstrated that BIM-enabled digital fabrication workflows can support industrialized construction, while emphasizing the importance of structuring parameters correctly to ensure consistency across platforms. These findings suggest that interoperability depends not only on the exchange format itself, but also on how data are modelled, structured, and exported.

These limitations become critical when BIM is used as a data source for parametric and fabrication-oriented workflows, where geometric flexibility and parameter control must coexist

with reliable information exchange, which is the focus of this study. Visual programming can act as a bridge between BIM models and digital fabrication workflows implemented in other applications, supporting unidirectional or bidirectional loops.

2.2 BIM-Driven Robotic Fabrication Workflows

The integration of BIM with RF has been explored through different computational and parametric approaches. Braumann and Brell-Cokcan [6] presented parametric workflows connecting architectural design environments to industrial robots, demonstrating the potential of computational design to bridge design intent and fabrication constraints.

More recent studies by Anane et al. [2,7] proposed BIM-driven Design-to-Manufacturing (DtM) workflows for off-site robotic prefabrication. These approaches position BIM as a central information environment, supporting parametric control, data exchange, and coordination between design and fabrication. Davtalab et al. [3] also explored BIM-integrated platforms for robotic construction, expanding BIM beyond visualization and documentation.

Despite these contributions, many BIM-driven robotic workflows focus on modular or regular systems. The integration of BIM with irregular geometries, particularly in robotic 3DCP, remains less explored.

2.3 Robotic 3D Concrete Printing in Construction

Khoshnevis [8] introduced contour crafting as an early approach to automated concrete construction, establishing fundamental principles for layer-based fabrication. More recent off-site extrusion-based approaches using robotic manipulators, commonly known as 3DCP, have been widely adopted to automate construction processes and increase design flexibility [10]. Subsequent studies discussed the opportunities and challenges of digital concrete, including geometric freedom, process control, and system scalability [2]. Several critical parameters influencing fabrication performance, including nozzle height, nozzle width, extrusion velocity and nozzle travel speed have been identified [11–13]. Extrusion stability, layer adhesion, and overall print quality depend strongly on the combined control of rheology and process.

While these contributions significantly advance the understanding of robotic 3DCP processes, they are typically developed outside BIM environments. In most cases, 3DCP workflows rely on standalone computational models, with limited integration of BIM-based information, metadata, or open standards such as IFC. As a result, the potential of BIM to act as an information backbone for managing geometric, parametric and fabrication-related data in robotic 3DCP workflows remains underexplored.

3. Proposed BIM-driven framework

This section presents the proposed framework to integrate BIM, parametric modelling, and RF workflows applied to façade design. The framework is conceived as a DtM approach, in which BIM acts as the central environment for structured information management, while parametric tools support geometry generation and fabrication logic.

Rather than using BIM as a direct modelling tool for fabrication geometry, the framework establishes a controlled data pipeline that connects BIM with parametric modelling environments and RF systems through IFC model. This separation allows BIM to manage

3.2 Software Interoperability and Data Flow

The adopted software configuration is illustrated in Figure 2 and reflects a clear separation of roles between BIM authoring, parametric modelling, and RF environments. Autodesk Revit was used to define the façade element as a parametric family and store project-specific metadata. Grasshopper, operating within a Rhinoceros environment, was employed for parametric geometry generation and fabrication-oriented transformations, while robotic simulation and code generation were carried out using the KUKA|prc plugin.

In this workflow, the process is initiated within the BIM environment, where the façade geometry is structured as a simplified parametric element. This approach ensures consistency with BIM-based information management processes and enables the integration of structured data into downstream computational stages.

Data interoperability between BIM and the parametric model was established through IFC model. In this context, the IFC model was structured using *IfcCovering* elements enriched with custom property sets containing dimensional parameters (height, width, thickness) and identifiers. These parameters were extracted in Grasshopper and used to reconstruct the façade geometry, rather than relying on IFC geometry itself. The IFC model therefore acts as a structured information container, providing non-geometric data to drive the parametric model. Further details on data structuring and geometric reconstruction are discussed in Section 4.

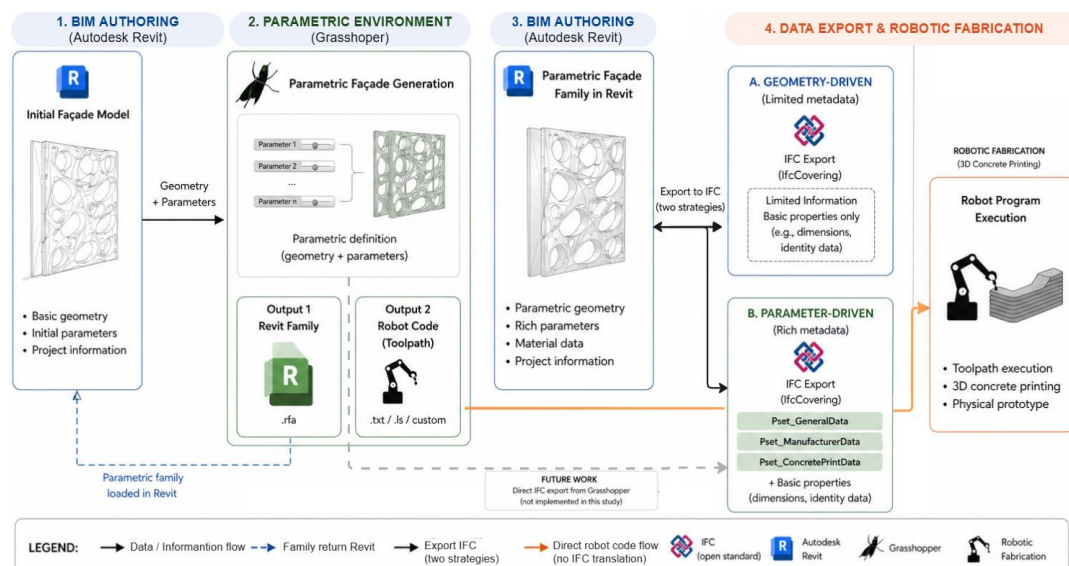


Figure 2: BIM-driven workflow from parametric modelling to IFC export and robotic fabrication. The façade is generated in Grasshopper and returned to Revit, where two IFC export strategies (geometry-driven and parameter-driven) are defined. Robotic toolpaths are generated directly from the parametric model without IFC translation.

4. Implementation

This section presents the implementation of the proposed framework through a case study focused on a generative façade element fabricated using robotic 3DCP. The implementation

demonstrates how BIM-based parameters and metadata are translated into parametric geometry and subsequently into RF data.

The case study was developed based on technical and geometric constraints derived from information provided by Blufab regarding the CREE construction system. These constraints informed the definition of the façade element, which includes an irregular perimeter with two openings, and were used to evaluate how BIM-based information can serve as a reliable input for fabrication-oriented workflows while preserving geometric consistency and metadata.

4.1 Parametric and Computational Model

The façade element is modelled as a parametric family designed to store essential dimensional parameters and metadata. Key parameters include height, width, thickness, reference planes, and volumetric information, which are used as direct inputs for the computational model. The boundary curves extracted from the BIM element, including the window opening, play a central role in defining the parametric logic.

The computational model reconstructs the façade geometry based on this perimeter, generating an irregular surface adapted to continuous extrusion constraints. The surface is subdivided into convex regions, which are sorted to ensure Hamiltonian cycles. These surfaces are further subdivided to generate space-filling curves for 3D printing, considering surface maximal orientation and thread thickness. Robotic limitations such as reach and tool orientation are also considered. As a result, geometric variation is controlled within the parametric environment while remaining dependent on BIM-defined constraints as illustrated in figure 3.

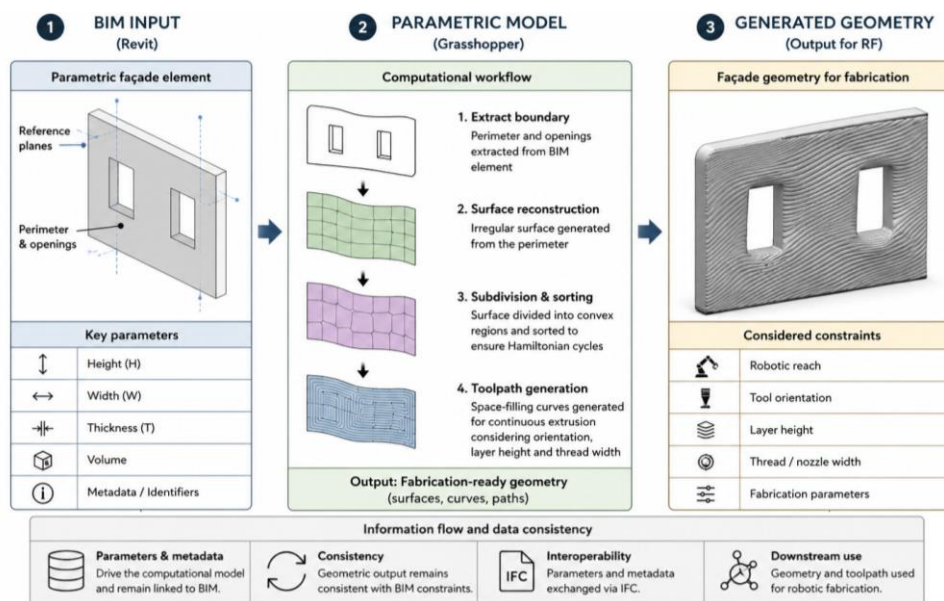


Figure 3: Schematic representation of the BIM-to-RF computational workflow, including parametric modelling, geometry generation, and data flow towards robotic fabrication.

4.2 BIM Integration and Metadata Structuring

The generated geometry and associated parameters were integrated into a BIM environment to support information management and interoperability. Although direct connections between parametric modelling environments and BIM authoring tools are possible through plug-ins such as Rhino.Inside.Revit, this study deliberately adopts an IFC-based exchange strategy. This

choice reflects the objective of evaluating an open, software-independent interoperability workflow, rather than relying on tightly coupled proprietary solutions.

To evaluate interoperability, two different BIM export strategies were tested using the IFC format. Both strategies were applied to the same façade element but differed in how geometry and parameter sets (Psets) were structured prior to export. The first strategy is geometry-driven, resulting in a triangulated surface representation with limited associated metadata. The second strategy is parameter-driven, using IfcCovering elements enriched with custom property sets to preserve semantic information and enable parameter extraction in the parametric environment. In this study, façade elements were exported using IfcCovering entities to better represent non-structural façade components within the IFC schema.

The exported IFC models were analysed using an external BIM viewer to compare geometric representation, parameter availability, and metadata consistency. As illustrated in Figure 4a–b, the comparison shows that the parameter-driven approach preserves the defined Psets and maintains a higher level of associated metadata, whereas the geometry-driven export results in a simplified representation with reduced semantic content. In this context, the IFC model acts primarily as a structured information container, supporting data exchange rather than fabrication-oriented geometry.

Despite limitations in representing highly irregular and fabrication-oriented geometries, the results demonstrate that BIM remains effective for managing fabrication-related parameters and metadata when geometric complexity is controlled and delegated to the parametric environment. The framework also supports the inclusion of editable metadata, enabling adaptation to different projects without restructuring the computational model.

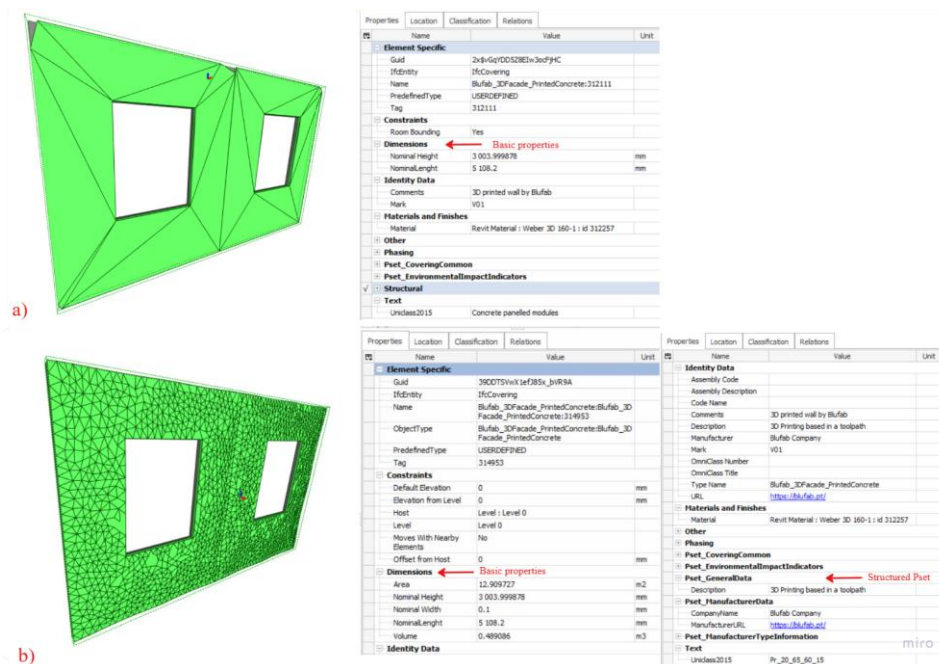


Figure 4a-b: Comparison of two IFC export strategies for the same façade element. (a) Geometry-driven export, showing triangulated geometry with limited metadata. (b) Parameter-driven export using IfcCovering elements with structured property sets (Psets), preserving semantic information and enabling parameter extraction, including Pset_ManufacturerData and Pset_GeneralData. Models were visualized in BIM Vision.

4.3 Robotic Fabrication and Toolpath Generation

Following the generation of the parametric façade geometry, the computational model translates the resulting surfaces and curves into robotic instructions for extrusion-based fabrication. This step is developed within a parametric environment using the *KUKA|prc* plugin (figure 5).

Fabrication parameters such as nozzle speed and layer height are embedded in the robotic instructions, allowing limited adaptation to local geometric conditions and area subdivision. Although alternative toolpath strategies were explored during development, the implementation focuses on validating a single, stable fabrication solution, prioritizing workflow reliability and interoperability over geometric variation. Robotic simulation was used to verify the feasibility of the generated toolpath, thereby confirming consistency between the parametric model and the executable robot instructions prior to fabrication.

Although geometry generation and toolpath definition occur within the same integrated environment, the robotic toolpath remains constrained by BIM-defined parameters, such as global dimensions, reference geometry, and element boundaries.



Figure 5: Robotic toolpath generated from the parametric façade geometry, illustrating the continuous extrusion strategy adopted for 3DCP.

4.4 Prototype Fabrication and Testing

A reduced-scale prototype was produced using the 3DCP setup of the ARENA Lab, at the School of Architecture, Art, and Design of the University of Minho. The reduced façade model was developed by Blufab based on the CREE construction system and adapted for RF. This prototype was used to validate the complete workflow, from BIM-based modelling to parametric geometry generation and RF.

The transition from the full-scale façade geometry to the reduced-scale prototype required only minor adjustments to the base geometry, confirming the robustness of the proposed framework under the tested conditions. The fabrication process was carried out using a KUKA KR120 R2700 robot and completed in under 15 minutes (figure 6).

The prototype was evaluated based on dimensional deviation (measured against the digital model), extrusion continuity, and layer stability during printing. Issues observed during prototyping were primarily related to material behaviour, namely overheating caused by elevated input water temperatures, which affected extrusion stability. These issues were

associated with fabrication and material conditions rather than with the digital workflow or data interoperability, reinforcing the reliability of the proposed BIM-driven framework.



Figure 6: Scaled 3DCP prototype produced to preliminarily validate the proposed BIM-driven RF workflow.

5. Results and Discussion

The results confirm that a BIM-driven workflow can effectively mediate between parametric modelling and robotic fabrication for façade design, when BIM is positioned as an information management layer rather than a fabrication modelling environment. Visual programming proved essential for translating BIM-defined parameters into RF data while maintaining consistency across digital platforms.

Interoperability depends less on the exchange format itself than on upstream modelling decisions. The comparison of IFC export strategies demonstrates that geometric fidelity and metadata preservation are directly influenced by how parameters and reference geometry are structured in the BIM authoring environment. While IFC performs reliably as a neutral carrier of control parameters and semantic information, it remains unsuitable for representing fabrication-oriented geometry or toolpath logic.

The computational model supported irregular geometries and continuous extrusion paths within the tested conditions, highlighting a deliberate trade-off between a simplified BIM model and fabrication-driven geometric freedom in the parametric environment. This separation enables interoperability without constraining robotic design potential.

Prototype fabrication preliminarily validated the workflow and clarified that observed issues—such as extrusion instability and layer deformation—were primarily related to material behaviour and fabrication parameters rather than to data exchange. Overall, the framework proved potentially replicable for similar extrusion-based RF scenarios, although its extension to more complex geometries or alternative fabrication systems would require further refinement of the computational model and more flexible interoperability strategies. Full-scale validation remains a limitation and is identified as future work. A cost-benefit analysis was outside the scope of this study.

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