



BIM integration in prefabricated additive construction projects, case study

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Abstract

A methodological development of a series of scripts created in Dynamo for Revit, aimed at improving workflows in prefabricated additive construction projects, is presented. Through a case study involving the construction of houses using 3D printing, automated solutions were explored to optimize the process from architectural design in BIM to the physical execution of the project. The results highlight how the integration of these digital tools can accelerate the design time in the manufacturing of prefabricated components, thereby demonstrating the potential of BIM for prefabricated additive construction.

Keywords Dynamo · Revit · BIM · 3D printing · Additive construction · Prefabrication · Automation · Workflow optimization

1 Introduction

The construction industry (CI), recognized as one of the key drivers of the global economy, faces a series of challenges that require urgent attention. These challenges range from managing significant volumes of construction and demolition waste, addressing the high energy and natural resource demands inherent in the sector [1], to persistently low productivity rates [2, 3]. The CI exhibits complex and variable dynamics. It is a highly diversified sector that encompasses activities ranging from single-family home construction to the development of offshore oil platforms [4]. Its workflows are often “fragmented,” as planning occurs in temporally phased stages involving multiple companies that participate in projects, each unique from the other. In addition, construction occurs in uncontrolled environments, where on-site activities are subject to variable weather conditions [2, 5].

Various solutions have been proposed to address these challenges, ranging from upskilling the workforce to optimizing processes through methodological and technological

approaches. Among emerging solutions, Industry 4.0—or the Fourth Industrial Revolution has played a pivotal role in transforming industries through the integration of technological and scientific advancements. Within this framework, “Construction 4.0” has emerged as an adoption of digitalization by construction companies [6]. This evolution emphasizes the digitalization of construction processes, with tools such as **Building Information Modeling (BIM)** gaining prominence, as numerous studies have highlighted its benefits throughout the project lifecycle [7]. BIM facilitates more efficient collaboration between teams by centralizing information in a digital model, reducing errors and rework through early conflict detection, and improving time and cost planning by simulating the construction processes [8, 9].

Another disruptive technology gaining traction is **Additive Construction (AC)**, which is characterized by the automated manufacturing of construction elements based on 3D models by depositing the material layer by layer. AC reduces construction times, labor costs, and waste, while increasing design freedom and enabling the use of sustainable materials, among other benefits [10–12]. The adoption of digital technologies is viewed as an opportunity to enhance the efficiency and quality of construction processes and foster business innovation in the sector [13]. The combination of BIM and AC holds promise for significantly transforming construction productivity [5, 14].

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In parallel, **prefabricated construction** (PC) alleviates productivity issues during construction. This system involves the production of structural components in a controlled environment for subsequent onsite assembly [15]. PC improves construction processes by reducing timelines, minimizing waste, and lowering costs owing to standardization, repeatability, and enhanced quality control. These improvements facilitate better planning and coordination among the project stakeholders [16]. However, despite its advantages, automation in PC remains limited because manufacturers achieve satisfactory returns without adopting automated processes. Moreover, the conservative culture of CI fosters skepticism among stakeholders regarding the implementation of new technologies. Additionally, high initial investments and market volatility create uncertainty regarding the returns expected from investing in advanced technologies [17, 18].

In this context, it is necessary to evaluate the simultaneous integration of BIM, PC, and AC. The literature reveals Studies have explored the combined use of at least two of these approaches, such as BIM with PC, BIM with AC, or AC with PC. However, the combination of all three approaches has not been thoroughly studied, thereby preventing a clear understanding of their feasibility in construction projects. Based on this premise, this study presents the outcomes of integrating these three approaches in a case study. It employs BIM methodology as a link between PC and AC, streamlining the workflow from the planning phase in a BIM model to the production of a prefabricated house using AC. BIM automation scripts were utilized for tasks related to the development of the digital model. Although several studies have emphasized the potential of digital tools to reduce costs and increase accuracy, this research focuses primarily on time optimization as a measurable outcome of integrating BIM, PC, and AC. The implementation of automation scripts within BIM and the digital coordination of prefabrication and 3D printing processes allowed for the reduction of task durations in the case study.

This research is part of a project titled “Development of a Sustainable 3D Printing System for Non-conventional Materials to Advance Rural Infrastructure in the Cauca Department”.

2 Literature review

Additive construction, also known as additive manufacturing or 3D printing for construction, represents an evolution of additive manufacturing technologies that were initially applied in sectors such as automotive and manufacturing [19]. Over the past decade, this technology has found significant application in the construction industry

[20]. Additive manufacturing involves transforming three-dimensional digital models into physical objects through a layer-by-layer addition process [21]. In the case of AC, this process involves the creation of buildings through the successive deposition of materials, which requires large-scale equipment such as 3D printers. Robotic arms and gantry systems are among the most commonly used types of equipment [22]. Regardless of the equipment used, this process requires a system to contain the material, a pump to deliver it, and an extrusion mechanism. The material is a critical factor for AC owing to its demanding characteristics it must meet. In its fresh state, it must maintain an optimal balance between fluidity and viscosity (thixotropy) to uniformly flow through the extrusion system and retain its shape after deposition [23, 24]. Key concepts such as buildability, printability, and extrusion capability are essential to ensure that the layers support both their own weight and the weight of the upper layers, avoiding deformations or cold joints. In the solid state, factors such as compression and flexural strength tend to be lower than those of traditionally poured concrete. However, durability continues to be a subject of research, as structures produced using this technology are relatively new and require long-term validation [25–27].

Some researchers have proposed the integration of BIM into AC to facilitate digital construction [28] because both technologies can improve construction workflow performance. In addition, the adoption of BIM is a global concern [29]. Some governments have developed their own standards for the regulated public implementation of BIM in construction projects [30], making it interesting to begin the path of BIM standardization for AC. The application of BIM in AC will contribute to the general progress of the industry. Gradedi and Labonnote in [14] identified the potential of implementing BIM in AC with 12 advantages including: achieving a continuous digital workflow from design (BIM) to production (printing), digitally documenting the life cycle of these structures, and developing new materials based on previously recorded documentation in design, production, and operation phases to propose new improvements, safer construction environments, greater control over finishes, reduced construction process times, new skills and job positions in construction, and coordinated and automated construction.

BIM has been highlighted as a tool that can significantly improve the management of construction projects. BIM is based on the idea of digital construction, generating a 3D model using specialized software that not only accurately represents the project but also contains useful information for design, planning, construction, and operation [9]. It also provides a collaborative environment in which different professionals involved in a project interact, supported by standards that ensure clear and effective information transfer

[31]. A 3D model is essential in BIM because it combines geometric information with data on materials, resources, and equipment. This level of detail allows the inclusion of metadata that are unimaginable in traditional CAD [32]. Furthermore, collaborative design ensures the synchronization of information and allows for timely adjustments by the professionals involved [33]. Interoperability is critical in BIM and refers to the ability to exchange, share, and process information among different platforms throughout the project lifecycle [34]. This aspect is crucial because no single software can model, schedule, budget, or analyze all aspects of a project [35]. Exchange formats, such as the open Industry Foundation Class (IFC) developed by BuildingSMART, allow the export and import of information between programs, ensuring interoperability between BIM processes and reducing costs associated with integration deficiencies [35, 36].

AC shares a key point with BIM: the use of a three-dimensional digital model or 3D model. To better understand this common point, the traditional workflow for 3D printing from a BIM model was described. The traditional 3D printing process begins with the creation of the 3D model; once the 3D model is created, it must be transformed into a standard data transmission file for rapid prototyping, which in most studies consists of an STL file. This step aims to approximate the surface of an object to triangles. The more complex the surface, the more triangles are generated [37]. From the STL file, which is delivered to the slicing software (e.g., Cura Ultimaker, Slic3r, KISSlicer), a digital process known as SLICING begins, where the prototype file is divided into layers. The same slicing software defines the printing path and specifies all parameters to generate the G-code (DIN 66025/ISO 6983 standard), which tells the printer the necessary commands to extrude the material [38]. 3D printers are considered an advanced form of robots because of their ability to perform automated and programmed tasks; [39] they use a GCODE file, which contains the necessary instructions for the hardware to execute precise movements and actions, culminating in the creation of the physical object [40].

With regard to BIM, AC and PC integration, below is a brief review of the experiences found in the literature that have studied this integration.

In [41], the integration of Building Information Modeling (BIM) with 3D printing for prefabricated buildings was proposed, highlighting an algorithm that generates STL files from IFC models as the main innovation. This process allows the extraction of prefabricated components from IFC files and the conversion of BIM data to a format compatible with 3D printers, thereby facilitating the manufacturing of components following specific paths. This advancement highlights progress in overcoming the interoperability

barrier between BIM and 3D printing technologies, contributing to the popularization of 3D printed prefabricated buildings based on BIM.

In [42], a workflow was proposed to use BIM models for 3D printing. As the size of the model elements may exceed the geometric reach of the printing equipment, a segmentation strategy is required, particularly for walls, which are the most commonly used printed elements. The methodology consists of identifying the work quadrant of the printing equipment and consecutively overlaying this area along the model profile (building layout). Subsequently, the printing paths are generated from each segmented module. For this purpose, three types of scripts were developed in Grasshopper: one for straight wall paths, one for curved walls, and one for complex walls requiring temporary support structures. The workflow also includes simulating the printing work with a Kuka-PRC robot using the Grasshopper plugin, which allowed us to obtain preliminary printing instructions in the SRC format. Finally, these paths are adjusted according to the printing nozzle width, element corners, door and window openings, final finish textures, internal lattice of the double-wall structure, joints, MEP systems, reinforcement, and others.

In [43], the authors closely followed a case study of a traditionally prefabricated project and generated a production process map for traditional prefabrication in a plant. They identified how this map would change if the prefabricated components were produced using 3D printing. It was found that costs per occupied area would decrease since the plant layout area would reduce, and the results showed that 3D printed production saves 24% more time than traditional production in the worst-case scenario. In the best scenario, 3D printed production offers up to 53% time savings compared with traditional production.

In [44], they investigated the potentialities in the use of different BIM-based programming tools by testing the interoperability and information exchange capabilities between them. They used OpenSCAD®, Grasshopper®, Rhinoceros®, and Dynamo® of Civil 3D® as design tools that allow the visualization and parameterization of the model and compared the advantages and disadvantages of modeling with each of them a single-track straight-axis railway section. The results report for example that, although OpenSCAD® is free to use, it is limited to geometric modeling. Grasshopper® and Dynamo®, being visual programming languages, are intuitive for the user. Rhinoceros® has a large library of logical nodes, larger than Dynamo's, however, it is not an infrastructure design software, which limits the geometric and information content and also presents errors when exporting the information to IFC. Meanwhile, Dynamo® is a tool with great potential for the automation of model production for applications in BIM environment.

In [45], an integrated framework was proposed for road engineering modeling, based on the Dynamo environment in Revit. This framework includes, on one hand, the linear design of the road alignment defined by a set of control points; and on the other, the structural analysis of the pavement according to the **MEPDG** (Mechanistic-Empirical Pavement Design Guide), by evaluating permanent deformation. The framework was validated through a case study involving the Phnom Penh–Sihanoukville highway in Cambodia, from which system inputs were derived, including design speed, subgrade parameters, and vehicle load. As outputs, a 3D road model was generated, and pavement thicknesses were proposed for different load durations. This study demonstrates the effectiveness of BIM technologies in supporting both geometric design and pavement calculation in road engineering projects.

In [46], an integrated design-to-manufacturing (DtM) framework was proposed to unify the integration of collaborative robots in 3D printing. The proposed framework consists of four main modules: computational design based on BIM; robotic programming assisted by algorithms, which generates paths and control commands directly from BIM models; and cloud collaboration and integration in Off-Site Construction (OSC) environments. Grasshopper 3D is used as the computational design environment because of its robust integration with robotic manufacturing tools and the support provided by Rhinoceros 3D. Grasshopper 3D has a wide range of plugins, such as Robots, HAL, and Machina, and allows an integrated workflow when combined with BIM through Rhino.Inside.Revit (RIR). The results showed a significant improvement in construction efficiency and quality, reducing the need for human intervention and minimizing errors associated with manual reinforcement placement. Additionally, BIM integration allows for more effective project information management and facilitates real-time modifications and updates. This approach represents a significant step toward the full automation of modular construction, combining the advantages of 3D printing, collaborative robotics, and BIM to optimize processes and improve the quality of built structures.

Similar to [41], this research identified a workflow from the BIM model to AC, first identifying related processes within a case study and choosing to focus on those susceptible to automation through tools such as Grasshopper scripts. In this case, the Dynamo for Revit was used. Unlike the research in [41], which focused on on-site modular construction with a KUKA robotic arm, this research considered off-site modular construction with a gantry printer as a case study. Additionally, using [42] as an example, the process map for modular element production before and after automation tools was identified and evaluated in terms of the time differences between both processes. Finally,

taking into account the BIM approach of the research, it was decided to work with the Dynamo interface for Revit over other options, based on the results found in [44].

3 Materials and methods

The research methodology (Fig. 1) consisted of four main stages aimed at optimizing the processes of the case study by identifying deficiencies, developing automation tools, and assessing their impact on the workflow. Each stage is described in detail as follows.

In the **first stage**, an initial mapping of the processes involved in the case study is conducted. This step requires a comprehensive strategy of observation and documentation gathering to understand how activities are carried out, the stakeholders involved, the tools employed, and the execution times. The collected information is organized to generate a process flow map of the initial state, visualizing the sequence and interrelation of activities. Additionally, the development time for each task is measured, providing a detailed view of the current state of the processes, including their efficiency, resource management, and the degree of BIM methodology implementation within the project.

In the **second stage**, deficiencies in the process are identified. The points of friction, bottlenecks, and redundancies within the workflow are examined using the flow map generated in the previous stage. Based on this analysis, a deficiency matrix was developed, detailing the problematic areas, their impact on the overall performance, and the potential causes of inefficiencies. This diagnosis allows for prioritizing processes that are candidates for automation and defining clear objectives for improvement.

In the **third stage**, specific tools were developed to address the identified deficiencies. These tools take the form of customized BIM scripts designed in Dynamo for Revit. These scripts focus on automating repetitive tasks, improving information transfer, and reducing errors. Each script was tailored to address specific issues identified in the previous stage, ensuring that its implementation had a tangible impact on improving the workflow.

Finally, in the **fourth stage**, the developed tools were implemented and evaluated. A new process flow map was generated, which included updated development times for each task and reflected the changes introduced by technological solutions. During this stage, the impact of the tools is monitored in terms of productivity, efficiency, and workflow quality to assess whether the initial bottlenecks have been eliminated or mitigated. Furthermore, a methodological evaluation matrix was created to compare the initial and improved processes, highlighting the reduction in time and

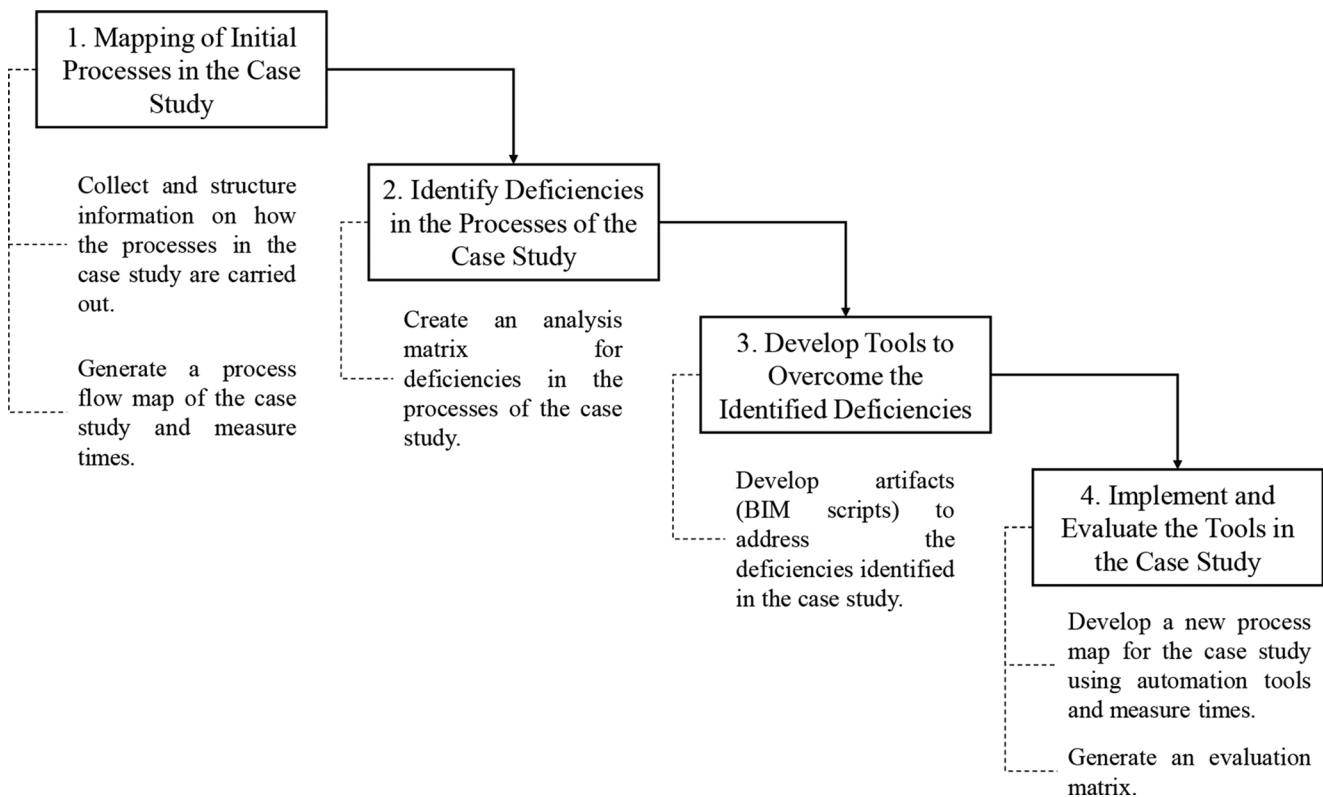


Fig. 1 Phases of the methodological development of the research

increase in efficiency achieved through the implementation of BIM scripts.

4 Results

4.1 Case study context

The main objective of the case study was to develop a housing solution for a rural area in Colombia using Additive Construction (AC) to close the housing deficit gaps in the country, meeting the demand and social requirements of the local population. Considering the logistical and cost challenges involved in building a house in a rural environment using a gantry-type 3D printer, the Construction Process (CP) approach was chosen as the most suitable for the development of the case study. To better understand the case study, the process flow of the project is illustrated in Fig. 2.

1. Identification of requirements.
2. Definition of the Construction Equipment.
3. Definition of Construction System.
4. 3D site model.
5. Design of the 3D printer.
6. *Architectural-structural model*.
7. Prefabrication plant design.

8. *3D printing files*.
9. MEP models.
10. Project scheduling.
11. Production scheduling.
12. 3D printer manufacturing.
13. Plant construction.
14. *Production*.
15. Transport.
16. Construction.

The case study project was developed in three phases: planning, design, and execution. Three main processes are performed during the planning phase. The first was the **identification of requirements**, which involved collecting and analyzing the sociocultural characteristics of the inhabitants of the study area, as well as their preferences in terms of habitat and housing. To achieve this, surveys and interviews were conducted, along with architectural surveys of various traditional houses. The conditions of the public services were evaluated, photographic records were obtained, and climatic factors and other essential characteristics related to the population, homes, and environment were identified. This information served as a key input to begin the design phase processes, which will be detailed later, to ensure that the house design was not only technically suitable but also

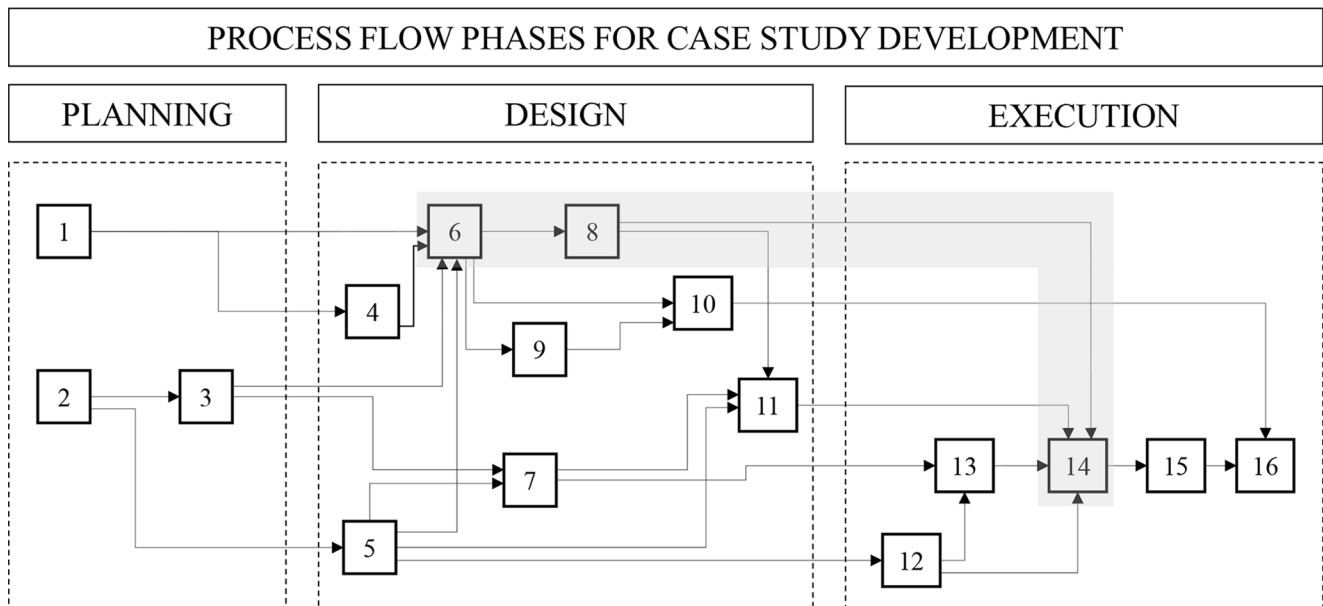


Fig. 2 Process flow for the development of the case study

respectful of the social, cultural, and environmental context of the area.

The second process was the **Definition of the Construction Equipment**, which involved a detailed analysis and subsequent selection of the most suitable 3D printer type for the project. A gantry-type 3D printer was chosen over the robotic arm because of its greater reach in construction applications. Finally, the third process was the **definition of the construction system**, in which a prefabricated construction system was chosen instead of on-site construction. This decision was made considering access limitations in rural areas and the need to continually move printers to construct multiple houses.

In the design phase, the information generated in the planning stage was used. Based on the data collected during the requirements identification, a **3D site model** was developed. At the same time, the construction equipment

definition process began, leading to the **design of the 3D printer**, a gantry-type device whose main features include operational dimensions of 4 m long (X-axis), 3 m wide (Y-axis), and 4 m high (Z-axis); a hopper with a 50-liter capacity to supply material through a screw conveyor to an extrusion nozzle with a diameter of 0.05 m at a speed of 0.3 m per second.

From the printer design, the construction system definition, and the site requirements, the **architectural-structural model** of the house was generated on the site model. Based on these results, **MEP models** of sanitary and electrical networks were developed, and **3D printing files** were generated. Both the MEP models and the architectural-structural model were key inputs for **project scheduling**, which contains guidelines for executing the final construction process

of the house. Simultaneously, the design of the printer and the construction system definition enabled the beginning of the **prefabrication plant design** process, where essential areas were identified and delimited: the printing zone, curing zone, material treatment, pedestrian and vehicular movement areas, and administrative spaces.

Additionally, the necessary resources such as equipment, materials, and personnel were determined, which together defined the production capacity of the plant. Production scheduling began with the information derived from the design of the prefabrication plant, printing files, and printer specifications, **production scheduling** began. This process involved organizing and relating the data from the printing files, which contained detailed information about the geometry of the elements to be manufactured, such as dimensions, areas, and volumes, to define the printing routes, calculate the production times for each element, and consolidate the production schedule. The execution phase begins with the completion of the design phase, in which the models and designs take the physical form. The gantry-type printer is manufactured based on detailed designs. Simultaneously, the prefabrication plant designs are addressed to build the operational space. The printer must be ready to be placed at the designated location according to the prefabrication plant design.

Once the construction of the plant is completed and its optimal functioning certified, it is synchronized with the production schedule. This includes the detailed organization of tasks, resource allocation, and preparation of the printing files in GCODE format, which contains the CNC instructions that guide the printer in manufacturing the modular elements of the house. Subsequently, the series **production**

of the house components begins, strictly following the defined routes and times in the schedule. During this process, each fabricated element undergoes rigorous quality control to ensure that it meets the established standards. The printed elements are organized in batches and **transported** to the construction site, where they are assembled according to the architectural and structural plans. This assembly process concludes with the realization of the house, consolidating the project in its final phase, which corresponds to the **construction**.

The detailed mapping of the process flow of the case study was fundamental to understand how the project was being developed and identifying areas that could be optimized through the implementation of BIM tools. Each process represented in the flow also consists of subprocesses with their own characteristics and particularities that require analysis and definition. However, this study specifically focused on subprocesses 6, 8, and 14, highlighted in Fig. 2, which were identified as the most susceptible to benefiting from these tools. By focusing on the processes of interest, we obtained the graph shown in Fig. 3, as detailed below.

Zona A in Fig. 3 details the three processes considered key for this research. Within this zone, subzone A.1 corresponds to the specific breakdown of process 8, “Printing Files”. This detailed analysis was crucial to understand

the activities involved in creating the printing instructions, which are essential for manufacturing the modular housing elements. This process involves a series of digital format transformations, specific to the prefabricated 3D printing methodology adopted in this case study. It begins with the BIM architectural model, which serves as the basis to develop the prefabrication or modular model. This model is then adjusted to the technical requirements for 3D printing (such as converting traditional walls to double-wall structures), transforming into an STL file, which acts as an intermediary for generating GCODE files. The GCODE files contain the detailed instructions that the 3D printer uses to perform the precise and controlled deposition of material, ensuring the efficient and accurate manufacture of the modular housing components.

Specifically, the process of developing the **architectural model**, as shown in the case study in Fig. 4, involved creating a housing prototype using BIM methodology and integrating both software tools and collaborative strategies. Revit was used for 3D modeling, considering the traditional architectural walls already included in the software families. During this stage, the modeler focused on defining key aspects of the prototype, such as dimensions, area distribution, service spaces, and the orientation of the housing facade, to optimize environmental factors and aesthetic

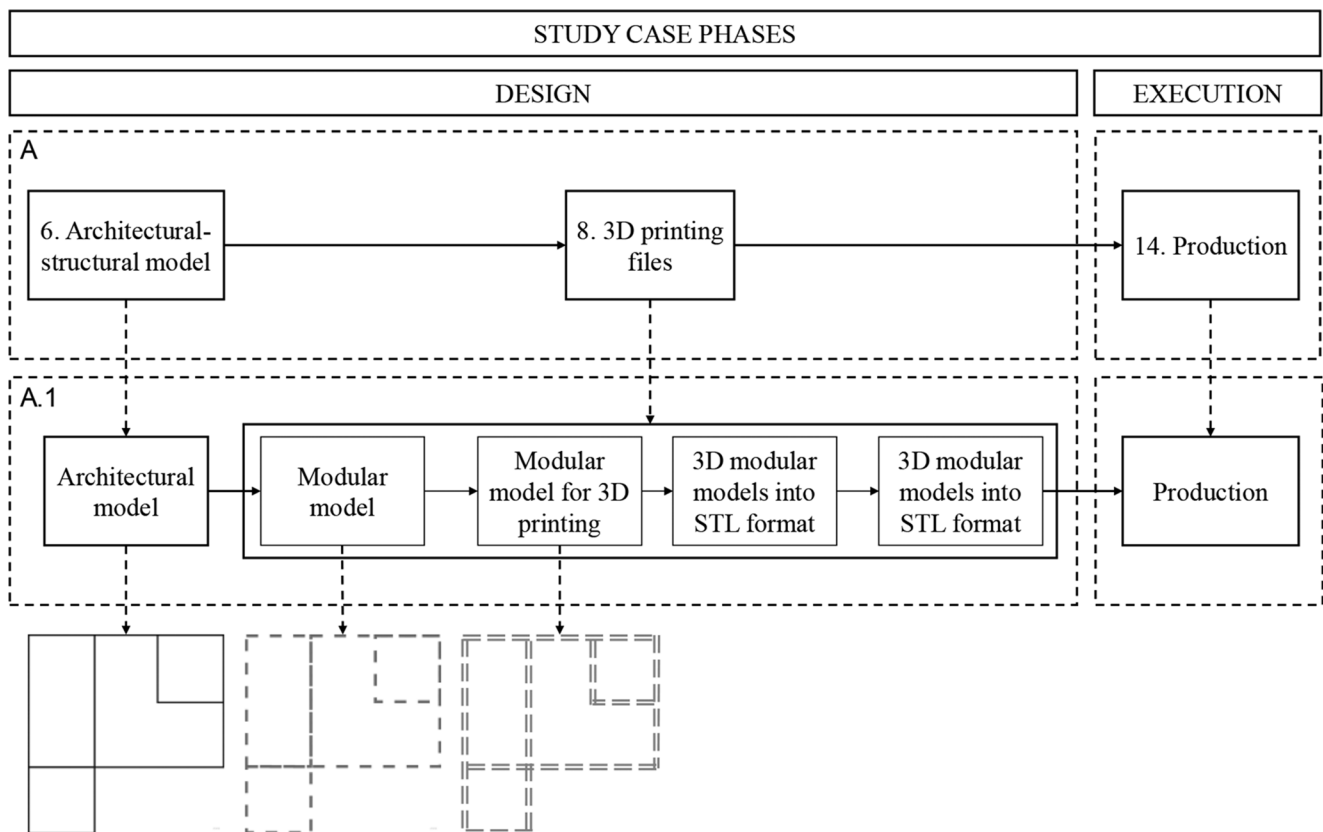


Fig. 3 Key research processes susceptible to the intervention of BIM tools

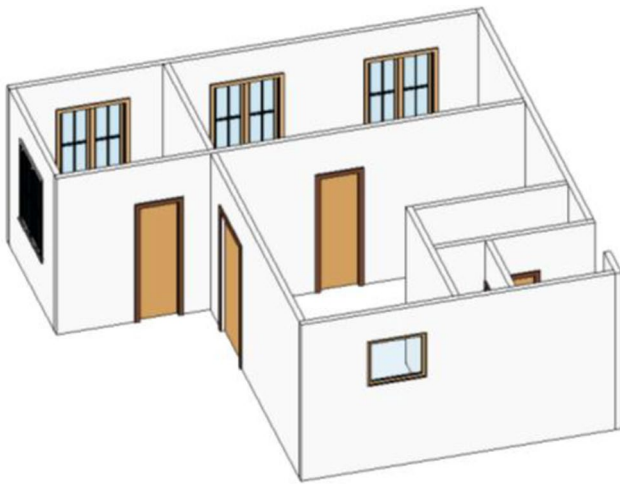


Fig. 4 Architectural model



Fig. 5 Modular model

features that met the needs and preferences previously identified. This approach ensures that the model not only meets technical and construction requirements, but also reflects a comprehensive design aligned with the project's context. Methodologically, an iterative feedback approach was adopted between project participants, allowing the

prototype to be refined and adjusted until it reached its final version.

The next process in the map corresponds to printing files, expanding to study the digital flow of the project, where BIM is a valuable intermediary tool between design and AC. The architectural model (Fig. 4) needs to be broken down into modules for prefabrication; this process is visualized in the diagram as “**modular model**” (Fig. 5). Once the architects deliver the architectural prototype in Revit, the modeler proceeds to segment the continuous walls of the initial model (Fig. 4) into dimensions suitable for 3D printer fabrication (Fig. 5). This is typically done using Revit's “split” tool manually at points on the wall that were previously identified after measuring and placing reference plans, as described in [42].

This segmented model is the basis for generating a **modular model for 3D printing**. In this context, **3D walls** refer to the transformation of traditional walls into double-walled structures, as shown in Fig. 6. This process requires several steps in Revit to configure the walls to be printed appropriately. First, a new wall type called “3DPC 50 mm wall” is created, with the main feature that the thickness of each wall corresponds to the diameter of the nozzle of the 3D printer. The double-wall structures were designed using this wall type, adding the necessary side enclosures. The printing wall was configured as a rectangular wall composed of four assembled components. This modular design ensures that the final wall satisfies the structural and functional requirements of the project. For example, Fig. 7 shows a complete modular model of a housing prototype with 3D walls.

The next objective is to convert each module designed in Revit into printing instructions. This involves transforming the **3D modular models into STL format** and then generating the GCODE files. To export the modules to STL format from Revit, it is essential that each module has an associated 3D view (Fig. 8). The modeler must access each of the views to export the corresponding model in STL format. This procedure is repeated for all the modules in the project.

The exported STL files are loaded into specialized programs, such as CURA or Fusion 360, where the models

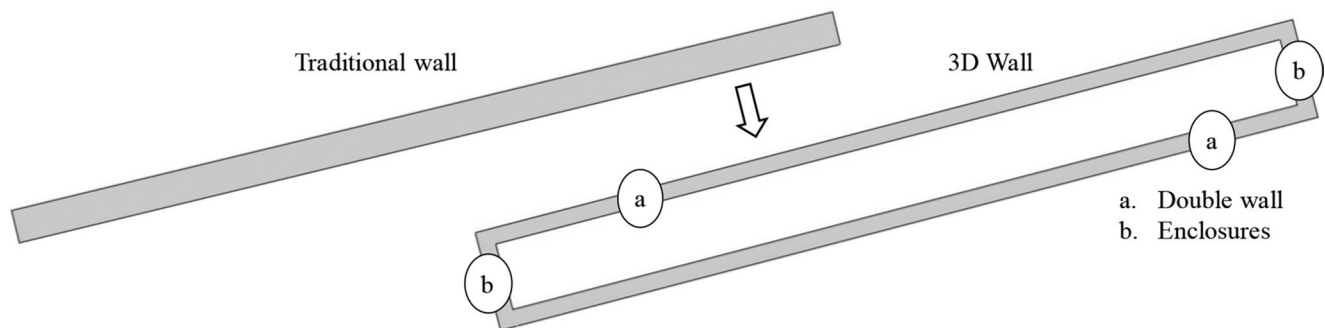


Fig. 6 Differences between the model of a traditional architectural wall and a specific wall for double-wall 3D printing

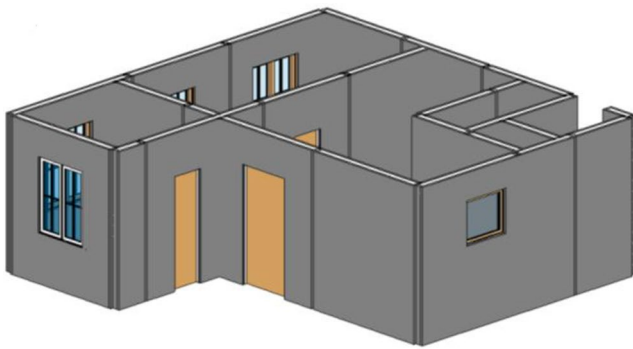


Fig. 7 Modular model with wall for 3D printing

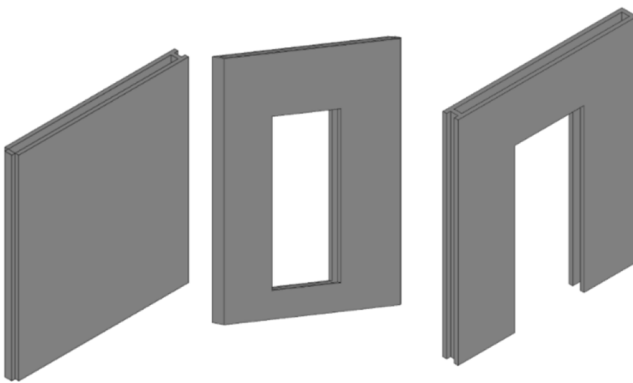


Fig. 8 Examples of modular elements for 3D printing

undergo a process called “slicing.” This process divides the STL triangulated model into horizontal layers, generating printing coordinates layer-by-layer for each element. During slicing, the user defines key parameters, such as the layer height, printing speed, start point, and model scale. These adjustments ensured that the design details were accurately reproduced during printing. The software used for slicing also generates a **GCODE file**, which contains specific instructions for the 3D printer.

This procedure is repeated for each module in the project to ensure the correct preparation of the models for the manufacturing stage. The resulting GCODE files are stored on a USB drive, which is then handed over to the 3D printer to begin prefabrication construction. This workflow integrates architectural design into the digital manufacturing process, ensuring that each modular component is produced with the required quality and precision. This approach optimizes the transition from design to construction, consolidating an efficient system aligned with the standards of prefabricated 3D printing.

Table 1 Identification of activities susceptible to automation through BIM tools

Activity	BIM	Automate
Architectural model		
Information Review	YES	NO
Proposal Development	YES	NO
Socialization	YES	NO
Proposal Correction	YES	NO
Final Proposal	YES	NO
Modular model		
Place Top View	YES	YES
Draw Dimensions	YES	YES
Calculate Divisions	YES	YES
Insert Reference Plans	YES	YES
Apply Wall Cut	YES	YES
Modular model for 3D printing		
Create Wall Type: 3DPC 50 mm	YES	NO
Repeat for each module		
Draw Wall 1 on a Module	YES	YES
Draw Wall 2 on a Module	YES	YES
Draw Wall 3 on a Module	YES	YES
Draw Wall 4 on a Module	YES	YES
Insert Door and Window Openings	YES	YES
Create Assembly for the 4 Newly Created Walls	YES	YES
STL file per element		
Create orthogonal view by module for 3D printing	YES	YES
Export View to STL per Module	YES	YES
GCODE file per element		
Repeat for Each File	YES	NO
In Cura, Configure Printer Information	YES	NO
Import STL File	YES	NO
Position the Model	YES	NO
Configure Printing Parameters	YES	NO
Generate GCODE	YES	NO
Save GCODE	YES	NO
3D printing by element		
Prepare Material	NO	NO
Position Printer at Origin	NO	NO
Load GCODE File	NO	NO
Start printing	NO	NO

4.2 Deficiencies in the case study's process of interest

Considering the automation approach using BIM tools, the key processes and their related activities within the case study were identified. Table 1 lists the specific activities for each process studied, indicating whether each activity involves BIM and whether it is susceptible to automation. The goal was to optimize repetitive and time-consuming activities using BIM tools.

From the previous matrix, it was identified that architectural BIM designs are not always optimized for direct

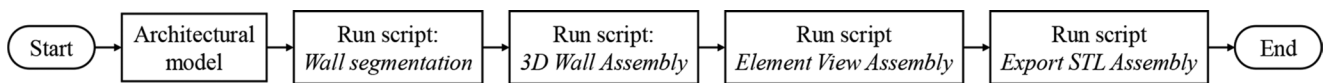


Fig. 9 Recommended execution order of Dynamo scripts

fabrication via 3D printing. Conventional BIM tools require significant manual intervention for adaptation to CP and AC. There is a need to generate scripts to automate repetitive tasks and optimize the workflow from design to construction. It can be analyzed that processes from architectural modeling to obtaining the STL file for each element are carried out in Revit. Fortunately, Revit has a visual programming tool called Dynamo, which is used to automate tasks. For example, in the **modular modeling** process, some activities, such as tracing the four walls and creating the assembly for the generated walls, are repeated for each module. This feature makes the process susceptible to automation.

The process of generating STL files also requires repetitive activities such as creating orthogonal views for each module and exporting each module view to the STL format. This process was also considered susceptible to automation. However, because the transformation from STL files to GCODE files does not occur within Revit, the process of generating **GCODE files per element** was not considered for automation. In the matrix, the activities of the GCODE per element process are classified as related to BIM because, in multiple studies, it has been possible to obtain the GCODE file directly from the BIM model without exporting to STL files, owing to algorithms designed in Dynamo scripts [28, 47]. However, this was not within the scope of the present study.

Finally, because the **3D printing process per element**, which includes activities such as material preparation, printer configuration, loading the GCODE file, and starting the print, does not develop or depend on BIM (as they are physical and manual operations), this process was also not considered for automation in this research.

4.3 Development of tools

Because the project development concept was approached as a CP or modular system, an approach that involves manufacturing building components or modules before installation at the project site, construction is carried out incrementally, working element-by-element. This method implies that the export of the model to the STL format is not performed for the entire house, but for each individual element. This conception in the project's production chain results in an increase in total time from obtaining the model to the complete printing of the house. To optimize this situation, four (4) scripts for Revit were developed through its

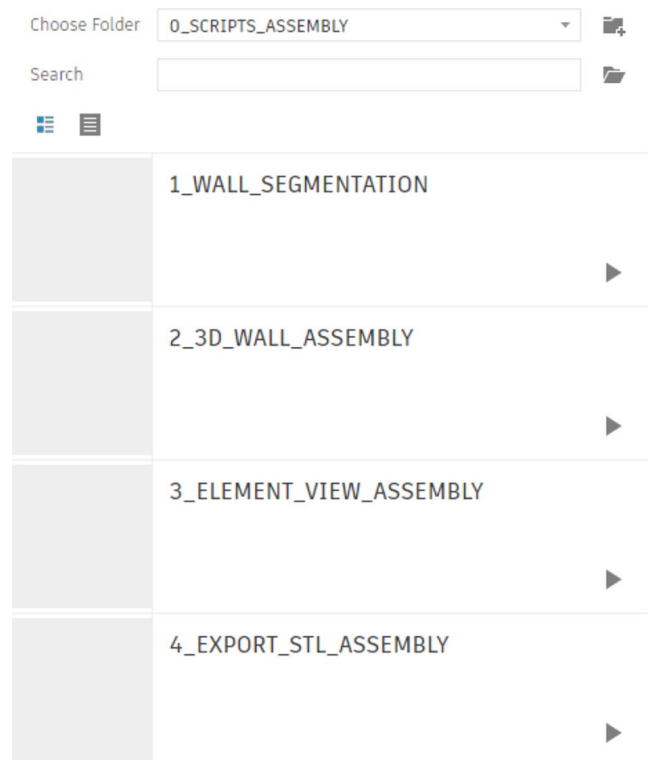


Fig. 10 Dynamo Player View in Revit with Developed Scripts

Dynamo interface. The recommended workflow for using these scripts is presented in Fig. 9.

The workflow begins with the completion of the architectural model of the house in Revit, and this series of scripts will be executed within the same platform. The first to run will be 1_WALL_SEGMENTATION, followed by 2_3D_WALL_ASSEMBLY, then 3_ELEMENT_VIEW_ASSEMBLY, and finally 4_EXPORT_STL_ASSEMBLY, as shown in Fig. 10.

When the last script is executed, a list of STL files will be generated, saved in a directory assigned by the user within their computer's folders, ready to be transferred to the software that will generate the triangulation of each model to obtain the GCODE, which is ultimately the file required by the construction equipment, in this case, the 3D printer.

4.3.1 Script: wall segmentation

Recognizing that the printing equipment imposes dimensional constraints on the construction elements, such as the height of the wall, this script was developed to adjust the dimensions of the walls of any 3D model generated in

Revit. This is done so that these dimensions meet the limitations imposed by the printable width of the gantry-type construction printer. The algorithmic logic of this development is based on addressing two crucial variables that influence the wall segmentation. These include determining the maximum printable width in meters (Cut Length) and the minimum edge value for wall openings, such as windows or doors, in meters (Edge). Figure 11 shows the workflow created by Dynamo for Revit.

The process group *a* is an input block that asks the user for the maximum length in meters that a wall should have, considering the printer's format. It also requests the minimum distance from the edge of an opening, such as a window or door, to the wall's edge. Segmentation will not occur unless this minimum length is met. This information entered by the user will be used as input for groups *c*, *d*, and *e*, as discussed later. Group *b* corresponds to a Python Script module that retrieves all walls present in the model and cancels the joints at the intersections of the corners, ensuring that the walls remain independent at these points. This is useful when avoiding the automatic merging of walls at corners, allowing for better control over the geometry and graphical representation of the construction elements. The output is a list containing the IDs of the wall objects in the project.

Based on the list of project walls (output from group *b*) and printer considerations (output from group *a*), each wall is classified according to its length and the number of openings (doors or windows) it contains, following these four cases: *Major Clean Wall*, *Minor Clean Wall*, *Major Wall with Opening*, *Minor Wall with Opening*. Depending on

the classification of each wall, a segmentation procedure is assigned. Finally, segmentation occurs in groups *d* and *e*. Group *d* contains the algorithm for segmenting walls that have no openings, that is, those classified as Major Clean Walls. Major Walls with Openings are segmented in group *e*. Minor Clean Walls and Minor Walls with Openings are not segmented because they do not meet the minimum dimensions for this process.

When the script that segments the walls of the model is executed, new walls are created over the originals, and each generated element will have a maximum length, as specified. Figure 12 on the left shows the original model, and the figure on the right shows the model with the walls automatically segmented by the script. The printed output shows the list of IDs of the original walls in the model that have been deleted to prevent them from appearing forward. After running the tool, the user can return to the list of all scripts by clicking on the “Back” option at the bottom of the player to run the next script.

4.3.2 Script: 3D wall assembly

Once the modular walls of the prototype are generated according to the physical dimensions allowed by the printer, the traditional walls of the project in Revit must be replaced with walls suitable for 3D printing. Manually converting traditional walls into 3D walls can be a time-consuming process; this script automates the task and improves the overall processing time of the models for printing. The 3D elements are derived from the technical structural specifications of

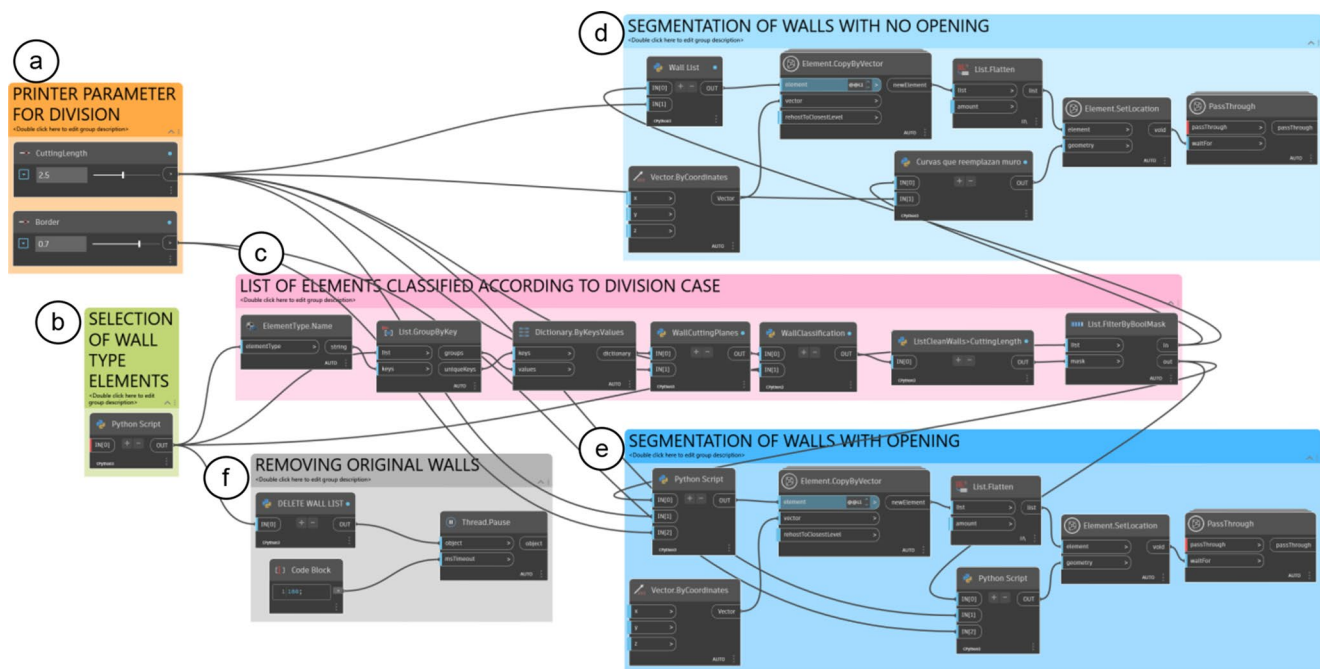


Fig. 11 Visual programming workflow of the “Wall Segmentation” script developed in Dynamo

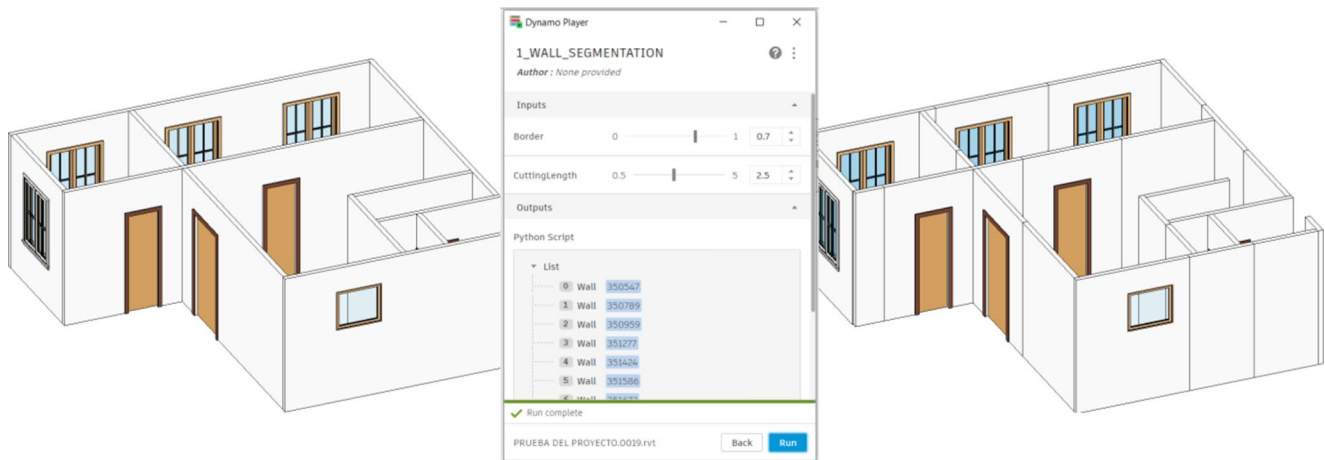


Fig. 12 Execution of the “Wall Segmentation” script using Dynamo Player and the resulting wall divisions in the BIM model

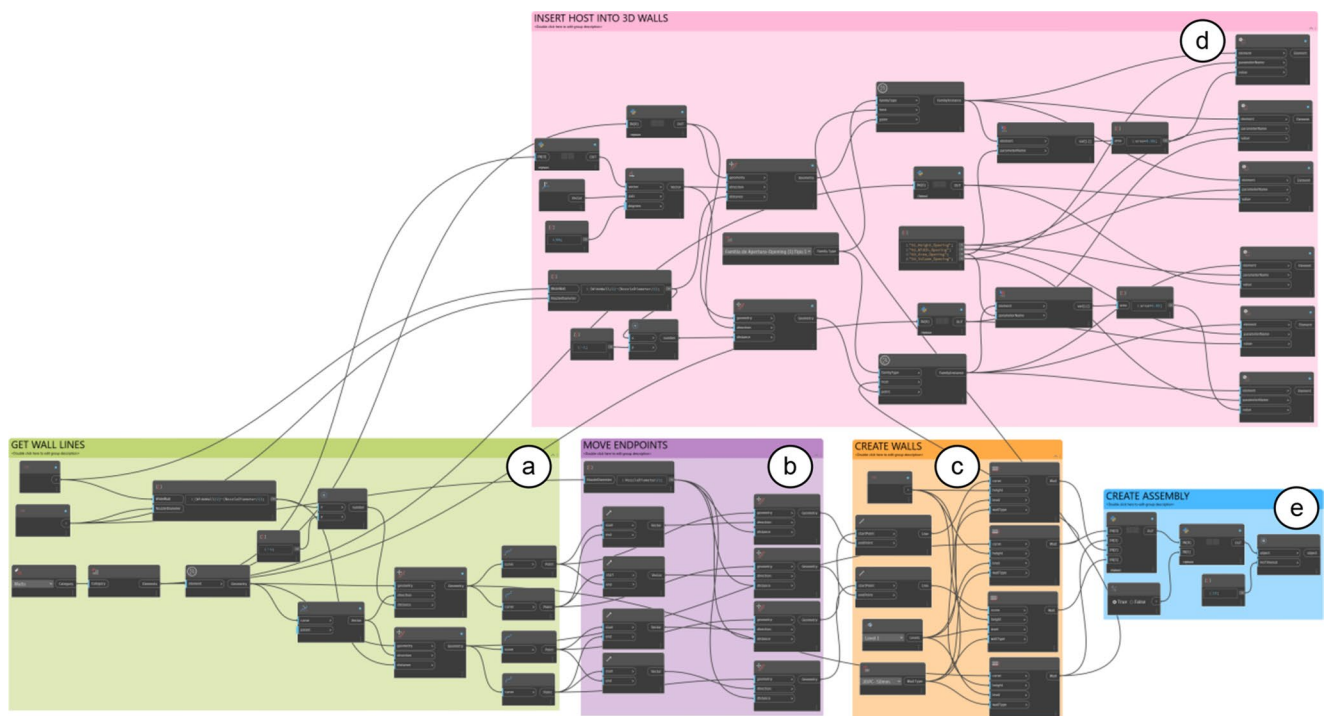


Fig. 13 Visual programming workflow of the “3D Wall Assembly” script developed in Dynamo

the project. These structural guidelines correspond to the total width of the 3D wall and nozzle diameter of the printer. Figure 13 shows the workflow created in Dynamo for Revit for the script.

Group a receives user input for the nozzle diameter and wall width; it reads the location of each wall and draws lines where the double walls will be placed at the floor level. Group b creates the line for the enclosures of the 3D wall, and group c creates the walls over the drawn lines with the thickness corresponding to the nozzle diameter. Once the walls are created, group d automatically creates the window and door openings in the 3D printing walls, and finally,

group e generates an assembly of all the elements that form a single 3D printing wall, repeating the process for each module of the housing prototype.

It is important to mention the actions that the user must take before running this script. First, the user must load a parametric family into the model (OpeningFamily.rfa). This file can be downloaded from the shared public GitHub folder links described in Sect. 5.5. This family allows the script to automatically include the openings for doors and windows in the 3D walls. Second, the user must create a wall type that represents the print cord of the construction equipment. The wall should have a thickness that matches

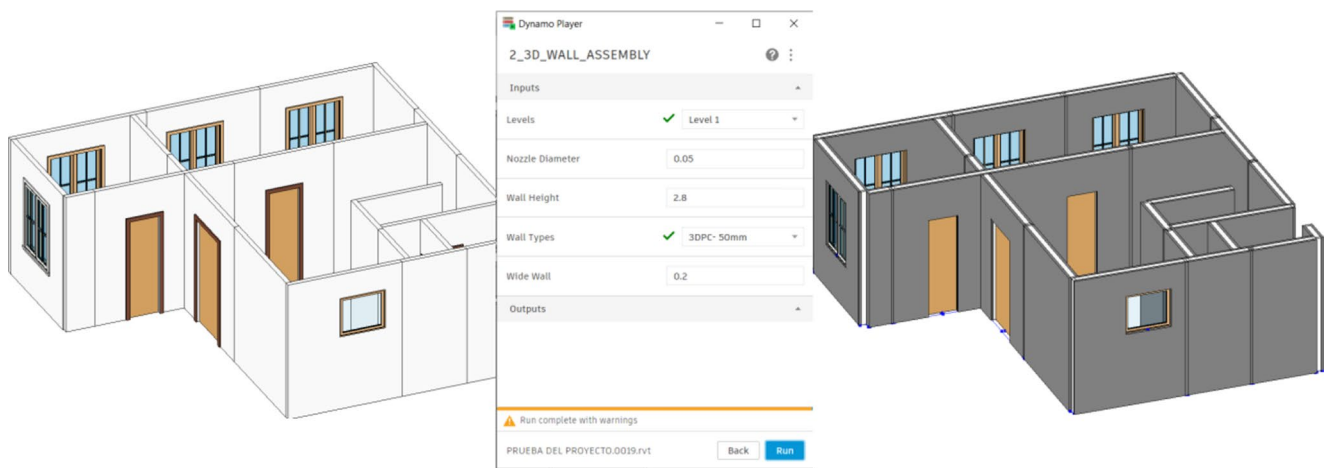


Fig. 14 Execution of the “3D wall assembly” script using Dynamo Player for the generation of 3D-printable wall geometry in Revit

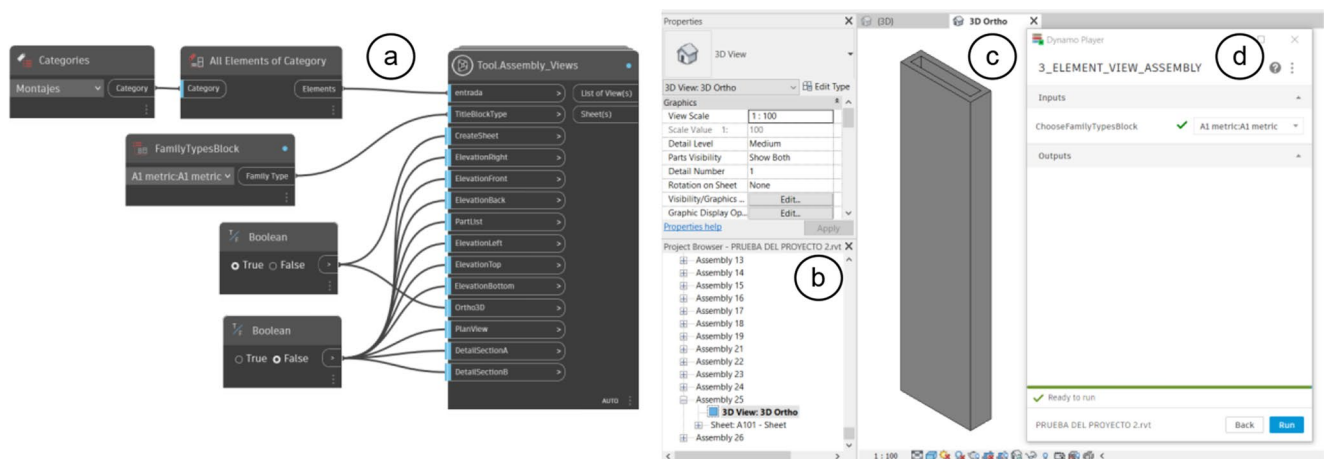


Fig. 15 Visual programming workflow of the “Element View Assembly” script developed in Dynamo and Creating orthogonal views for each assembled element

the diameter of the printer nozzle. For the project, this new type is named “3DPC 50mm” with a thickness of 0.05 m.

Figure 14 shows the segmented model on the left-hand side. At this point, it is time to run the 3D wall-assembly script. The Dynamo player will ask the user for the initial parameters, which correspond exactly to the guidelines previously mentioned: nozzle diameter, wall width, wall height, the project level from which to generate the new walls (note that these 3D walls are created from bottom to top), and which type of wall is used to form the element. The recently created type (“3DPC 50 mm”) should be selected here. When the model is run, a modular 3D printing model is generated, as shown on the right side of Fig. 14.

This process also generates a list of Assembly elements that appear in the navigation panel of Revit, as seen in Fig. 15b.

4.3.3 Script: element view assembly

To export elements from Revit to STL files using Dynamo code, it is essential that the elements to be exported are located in a 3D view or an orthogonal view. Otherwise, empty files would be generated. Therefore, the developed script takes each piece of the model, that is, the previously created assembled elements, and automatically assigns them to a 3D view. The implemented algorithm, shown in Fig. 15a, identifies the categories of the model corresponding to Assemblies. Once located, the script selects all elements in that category and directs them to a 3D view using the Tool.AssemblyView node. As a result, as shown in Fig. 15b, the list of Assemblies now includes an associated 3D view, named “3D View: 3D Ortho.” When this view is opened, the corresponding assembly element can be visualized, as illustrated in Fig. 15c.

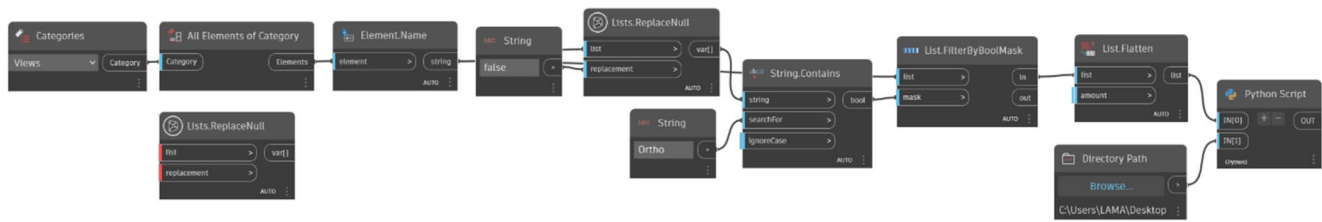


Fig. 16 Visual logic in Dynamo of the “Export STL Assembly”

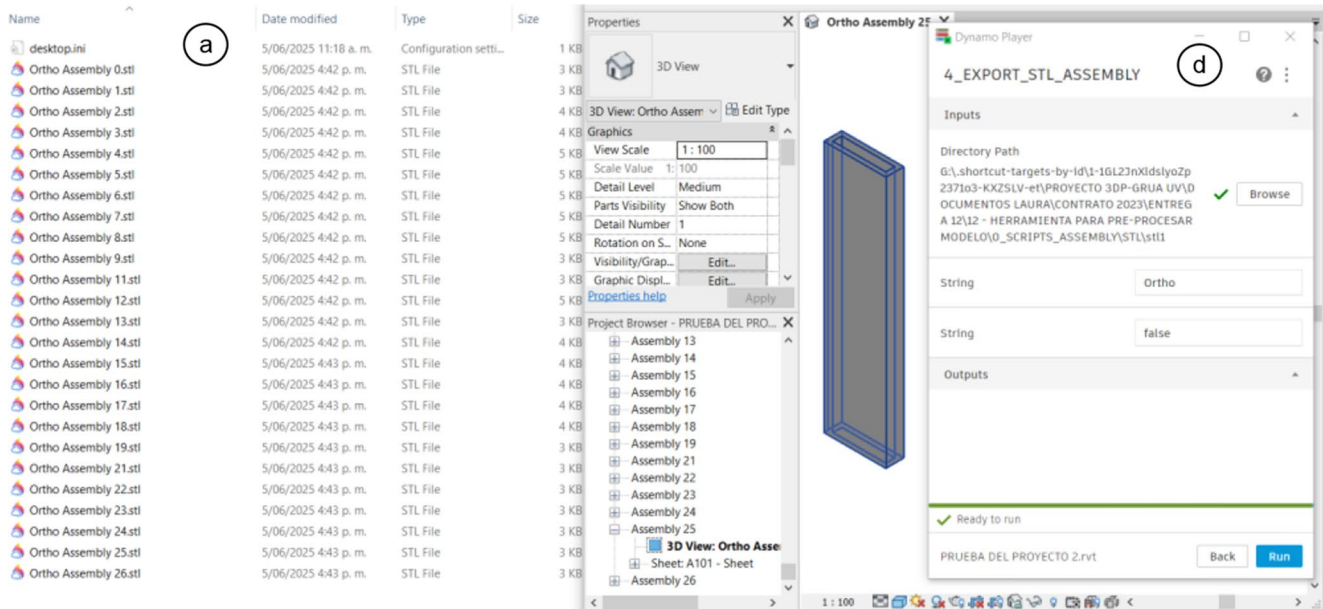


Fig. 17 on the right side of the image is a view of the Dynamo player running the “Export STL Assembly” script. The user selects the folder where all exported STL files will be saved. On the left side of the image, a view of the folder with all the exported files

4.3.4 Script: export to STL of the generated views

When each module of the prototype has its respective orthogonal view, STL files can be automatically generated. The algorithm of the script, illustrated in Fig. 16, selects all the elements from the Views category in Revit. Within this selection, it filters only the views whose names contain the word “Ortho.” These “Ortho” views corresponded to the 3D views associated with the prototype modules. The resulting list is transferred to the final block of the script, which uses a *Python Script* node. This Python code receives two key pieces of data: the list of filtered views and the location of a folder specified by the user, where the generated STL files are saved, as shown in Fig. 17b.

Once the code is executed, the user can verify the correct generation of the files by checking the provided folder, as shown in Fig. 17a. The folder path matches the one specified in the script, and the generated STL files will be available in that location, ready for use in subsequent processes. After the files for each element to be printed are generated, the printing process continues. At this stage, the user loads

each of these elements into a “slicing” software, which calculates the printing path for each element and generates the necessary GCODE file. This type of file is the one that 3D printing equipment can interpret and execute. In summary, once this process is completed, the user is ready to begin printing each of the elements that will form the walls of the house.

4.4 Implementation and evaluation of tools for the case study

It is important to assess the impact of the BIM tools developed for the case study, specifically in terms of the opportunity and efficiency provided. To do this, it was decided to record and compare the execution times of the process flow for the case study in two scenarios.

- case 1: This corresponds to the process flow of the case study in its initial state before the implementation of BIM tools.

- case 2: Process flow of the case study after integration of the developed BIM tools.

Table 2 presents a detailed comparison of the recorded times for each activity in both the process flows. This information allows for an analysis of how BIM tools influence the optimization of tasks and the reduction of time, highlighting their relevance for the development of the project.

The results obtained after comparing the execution times between Case 1 (initial state of the process flow) and Case 2 (process flow with the integration of BIM tools) show a significant improvement in the efficiency of the project development. The data presented in Table 2 is analyzed as follows: In the Modular Model process for Case 1, it required a total of 110 min, while in Case 2 it was reduced to only 13 min. This drastic reduction, equivalent to a time savings of 88%, is similar in the 3D Printing Modular Model process, where the execution time for Case 1 was 113 min, compared to 16 min in Case 2, representing an 85% reduction. For the STL File Generation per Element process, the time decreased from 36 min in Case 1 to only 4 min in Case 2, equating to an 89% reduction. Finally, the execution times for the overall process flow in Case 1 took 258 min, while in Case 2 it was reduced to only 31 min. This represents an 88% improvement in overall process efficiency. These results demonstrate the high level of opportunity provided by the BIM tools implemented in this case

Table 2 Quantification of activity execution times. Comparison between times obtained from case 1 vs. case 2

Activity	Times Case 1 (Min)	Times Case 2 (Min)
Modular model	110	13
Place Top View	12	13
Draw Dimensions	10	
Calculate Divisions	48	
Insert Reference Plans	10	
Apply Wall Cut	30	
Modular model for 3D printing	113	16
Create Wall Type: 3DPC 50 mm	4	4
Repeat for each module		10
Draw Wall 1 on a Module	12	
Draw Wall 2 on a Module	12	
Draw Wall 3 on a Module	12	
Draw Wall 4 on a Module	12	
Insert Door and Window Openings	48	
Create Assembly for the 4 Newly Created Walls	12	
STL file per element	36	4
Repeat for each module		
Create orthogonal view by module for 3D printing	24	4
Export View to STL per Module	12	
Total Minutes	258	31

study. Automation not only significantly optimized execution times, but also reduced the manual effort required to complete the activities. The adoption of these technologies signifies the need to continue to advance the joint development of BIM for prefabricated additive construction projects. Figure 18 summarizes the results mentioned.

4.5 Main contributions to science of this research

In the development of this research, a series of Dynamo scripts for Revit were created, which allow automation of a series of tasks in a workflow from BIM to 3D printing. The scripts are as follows:

1_WALL_SEGMENTATION

2_3D_WALL_ASSEMBLY

3_ELEMENT_VIEW_ASSEMBLY

4_EXPORT_STL_ASSEMBLY

These elements are open for public use and can be downloaded from the GitHub link shared below, where you will also find the base test model and user manual with the necessary configurations for replication.

<https://github.com/LAMAHARI/BIM-Integration-3DConstruction/tree/main>.

5 Conclusions

This study addressed the development of automation tools within the BIM environment to improve the workflows associated with prefabricated additive construction. The main objective was to optimize repetitive processes and save time using scripts designed in Dynamo for Revit, focusing on wall segmentation, generation of 3D models suitable for printing, and STL file export. This study identified deficiencies in the conventional BIM design processes, particularly in the transition to models suitable for direct 3D printing fabrication. Four scripts were developed to automate key activities: **Wall segmentation, 3D wall assembly, Element view assembly and Export stl assembly**.

The implementation of these BIM tools resulted in a significant reduction in the execution time, as evidenced by the comparison of two scenarios: the initial process flow (Case 1) and the optimized process flow with the developed scripts (Case 2). In general, the total time required to complete the process flow was reduced by 88% from 258 min in Case 1 to 31 min in Case 2. This substantial saving was observed in each key stage, with individual reductions of up to 89% in specific activities such as generating STL files.

Finally, this research demonstrated that the integration of BIM-based automation tools not only optimizes execution times and reduces manual effort but also establishes a robust framework for future developments in additive construction

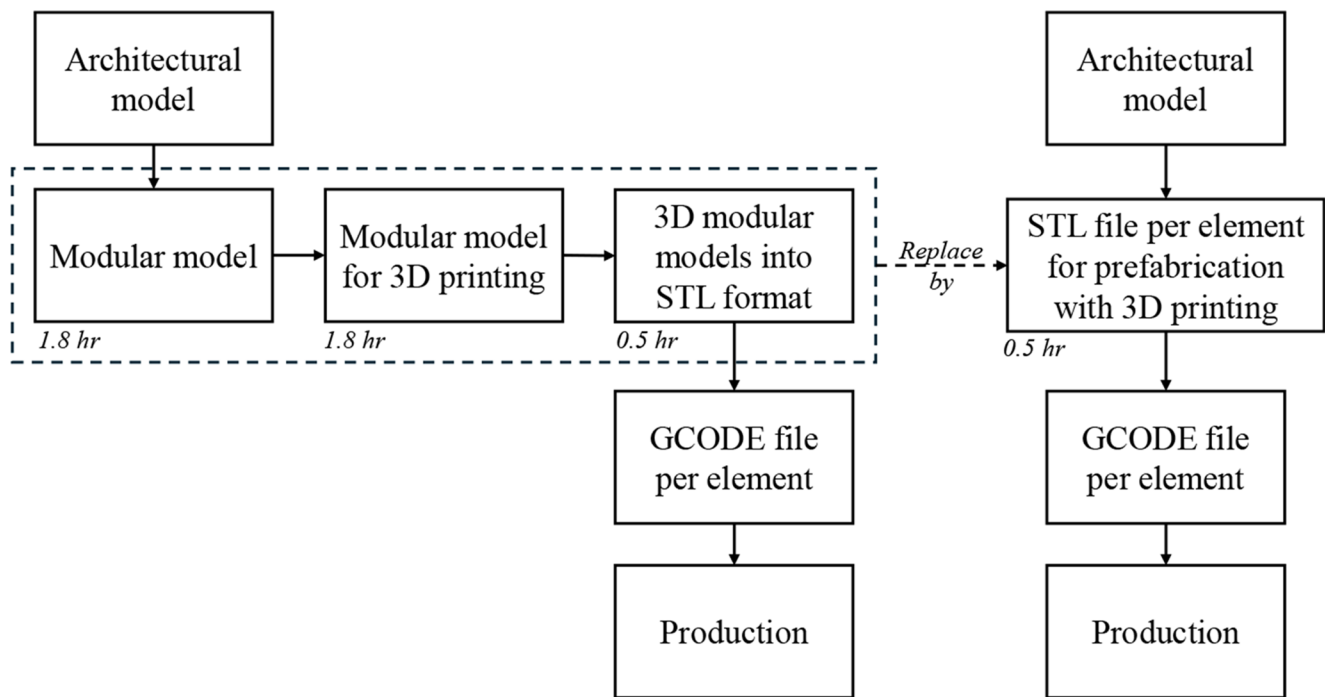


Fig. 18 Results of Task Automation in Revit in Terms of Time

projects. The implementation of such technological solutions highlights the importance of exploring and refining the use of BIM methodologies in the context of 3D printing and prefabricated modular construction.

Finally, this research demonstrated that the integration of BIM-based automation tools not only optimizes execution times and reduces manual effort, but also establishes a solid foundation for future developments in additive construction projects. One promising direction for further work is the direct generation of GCODE files from BIM environments, such as Dynamo, thereby eliminating the need for intermediate formats, such as STL. Although some researchers have already made progress in this area, their solutions have been primarily limited to robotic arms, particularly to KUKA-type systems. Therefore, it would be relevant to broaden this approach to include other types of 3D printing equipment such as gantry-based printers or alternative robotic configurations. In addition, it would be valuable to investigate the application of these tools to more complex architectural geometries, such as curved walls or double-layer walls, incorporating automatically generated internal lattices. These forms pose new challenges in both modeling and print path planning, which can be addressed using advanced scripting and parametric design techniques. The implementation of technological solutions, such as those presented in this study, highlights the growing importance of exploring and refining BIM methodologies in the context of 3D printing and prefabricated modular construction. Finally, future research should also examine the economic

benefits of automation, particularly the relationship between reduced design times and potential decreases in overall project costs.

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Author contributions L.H. wrote the main manuscript text. A.O. and W.C. revised it critically for important intellectual content; A.O. and W.C. approved the version to be published. All authors reviewed the manuscript.

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Data availability The data supporting this research are available in the GitHub repositories at the following link: <https://github.com/LAMAH-ERI/BIM-Integration-3DConstruction/tree/main>.

Declarations

Competing interests The authors declare no competing interests.

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