Implementing BIM Workflows in Prefabricated Modular Construction: From Conceptual Design to Construction

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Abstract

Much research integrating Building Information Modelling (BIM) and prefabricated modular construction (PFMC) only examines BIM implementation in one isolated process, and not its effect on the project's entirety. This hinders the formation of an overview of benefits and disadvantages when implementing BIM on multiple phases of PFMC projects. This paper identifies the benefits, disadvantages, and challenges of implementing BIM workflows in the design, manufacturing, and construction phases of PFMC projects, using an openBIM process with Revit as the main modelling tool and IFC files for interdisciplinary collaboration. Results show that BIM implementation in PFMC increases the productivity and quality of design and manufacturing processes, however costing more time to develop projects and revise geometry in BIM compared to 2D-based workflows. This information can help housing fabricators expand openBIM implementation beyond a single phase, inspiring future research on optimizing the application of openBIM workflows to all phases in PFMC project lifecycles.

Keywords: BIM, Workflows, Prefabrication, Modular, Construction, Automation, Interoperability, openBIM, Revit, Design

1 Introduction

Off-site prefabrication and modular construction is gaining popularity due to six key benefits over conventional on-site construction: (1) rapidly increasing advancements in fabrication technology, (2) increased material, energy, labor, and cost efficiency, (3) decreased environmental impact, (4) increased productivity and reduced production times, (5) safer workplaces, and (6) guaranteed consistency and high quality (McGraw 2011). Many countries worldwide are experiencing social, environmental, and economic challenges related to the built environment. For example, the Netherlands, which is facing an increasing housing shortage (MBZK 2022), environmental crisis (NL Times 2024), and stricter laws related to quality assurance for new building projects (NEA 2024) has clearly demonstrated that conventional building methods alone will not solve these problems. Prefabrication refers to "manufacturing processes generally taking place at a specialized facility, in which various materials are joined to form a component part of a final installation" (McGraw 2011). Modular construction is defined as the "manufacture and remote assembly of major interior or exterior sections of a building (e.g., wall, floor, roof) of one or multiple material types which may include portions of a system (e.g., electrical, plumbing)" (McGraw 2011). The advantages of off-site Prefabricated Modular Construction (referred to as PFMC hereafter) can be amplified when PFMC is combined with Building Information Modelling (BIM), through workflows that integrate all phases of construction projects (Lu & Korman 2010).

1.1 Deficiencies in Existing Research

Research has proven that the benefits of off-site PFMC are amplified when integrated with BIM, and that BIM could help overcome challenges that prevent the implementation of PFMC, such as the requirement of detailed project planning and coordination (Lu & Korman 2010). Benefits of applying BIM workflows to PFMC include but are not limited to: increased labor productivity (Poirier et al 2015), more precise material specification (Abanda et al 2017), and improved communication between stakeholders (Tang et al 2019). There are contradictory findings regarding the amount of time needed to develop BIM projects. Some researchers argue that BIM allows for an increase in scale, amount, and quality of modeled facilities while decreasing modeling time (Ezcan et al 2013), while others find that the development of BIM projects in Revit costs more time than 2D projects in AutoCAD (Pérez-Sánchez 2017). However, studies about impacts of BIM in off-site prefabricated construction (PC) are scarce, with too many focusing on either BIM implemented in traditional construction methods or off-site PC applied to traditional construction methods, but not the application of BIM in off-site PC (Abanda et al 2017). The few studies that exist about BIM in off-site PC focus on the qualitative benefits, with limited research on quantitative benefits when applied to realized projects (Abanda et al 2017).

Furthermore, Zhang et al. (2021) have identified current gaps in research about BIM in PC. There is a lack of research on information exchange and interoperability among heterogeneous BIM software applied in practical PC projects. To exchange information between different stakeholders and BIM software, data created by one BIM software may need many modifications to be processed by another BIM software, weakening the design benefit. OpenBIM, a collaborative process that supports information exchange and interoperability that is vendor neutral, can help overcome these issues (buildingSMART 2024). According to Zhang et al. (2021), "improving the efficiency of information exchange and interoperability between heterogeneous BIM applications and applying the research results to practical projects need further research in the future". Another research gap is the limited research on the integration of BIM with other innovative technologies for PC beyond only the component manufacturing stage. Zhang et al. (2021) state that relevant studies "are experimental research under controlled conditions, which leaves them still a long way from developing practical applications". Most research covers only the component manufacturing stage, rarely involving the field assembly stages, while research examining the entire life cycle remains absent (Zhang et al 2021). The existing literature on BIM in PFMC is insufficient and more quantitative research examining the impact of openBIM in multiple phases of PFMC projects is needed.

1.2 Contribution of Study

To help fill in the gaps in existing research about the impacts of BIM in PFMC, this study identifies the qualitative and quantitative benefits, disadvantages, and challenges of implementing openBIM workflows into multiple phases of PFMC projects manufactured at one of the largest modular housing fabricators in the world. At Daiwa House Modular Europe (DHME), we have recognized the benefits of BIM and have been transitioning from 2D drafting-based workflows to an integrated openBIM workflow applied to PFMC projects, from conceptual design to fabrication and building maintenance, which is implemented completely within the company. Producing over 4600 modules per year, we are the Netherlands' largest modular housing fabricator. We strive to implement openBIM workflows into PFMC processes to help solve the housing shortage by increasing their production capacity and building quality while reducing CO2 emissions by half of that of conventional on-site construction (DHME 2022). The findings of this study can help researchers and housing fabricators expand openBIM implementation beyond a single phase, inspiring future research on optimizing the application of openBIM workflows to all phases in PFMC project lifecycles.

2 Methodology

2.1 Approach

This study investigates the implementation of BIM workflows across multiple phases of PFMC projects, using an openBIM process with Revit as the main modelling tool and IFC files for interdisciplinary collaboration (Figure 1). An iterative experimentation method was taken when developing BIM workflows by testing parts of processes on undergoing projects, receiving feedback, improving, and further developing the processes towards a complete workflow. This iterative approach led to a rapid development and implementation of BIM workflows in comparison to developing entire workflows before applying them to projects and then solving practical problems.

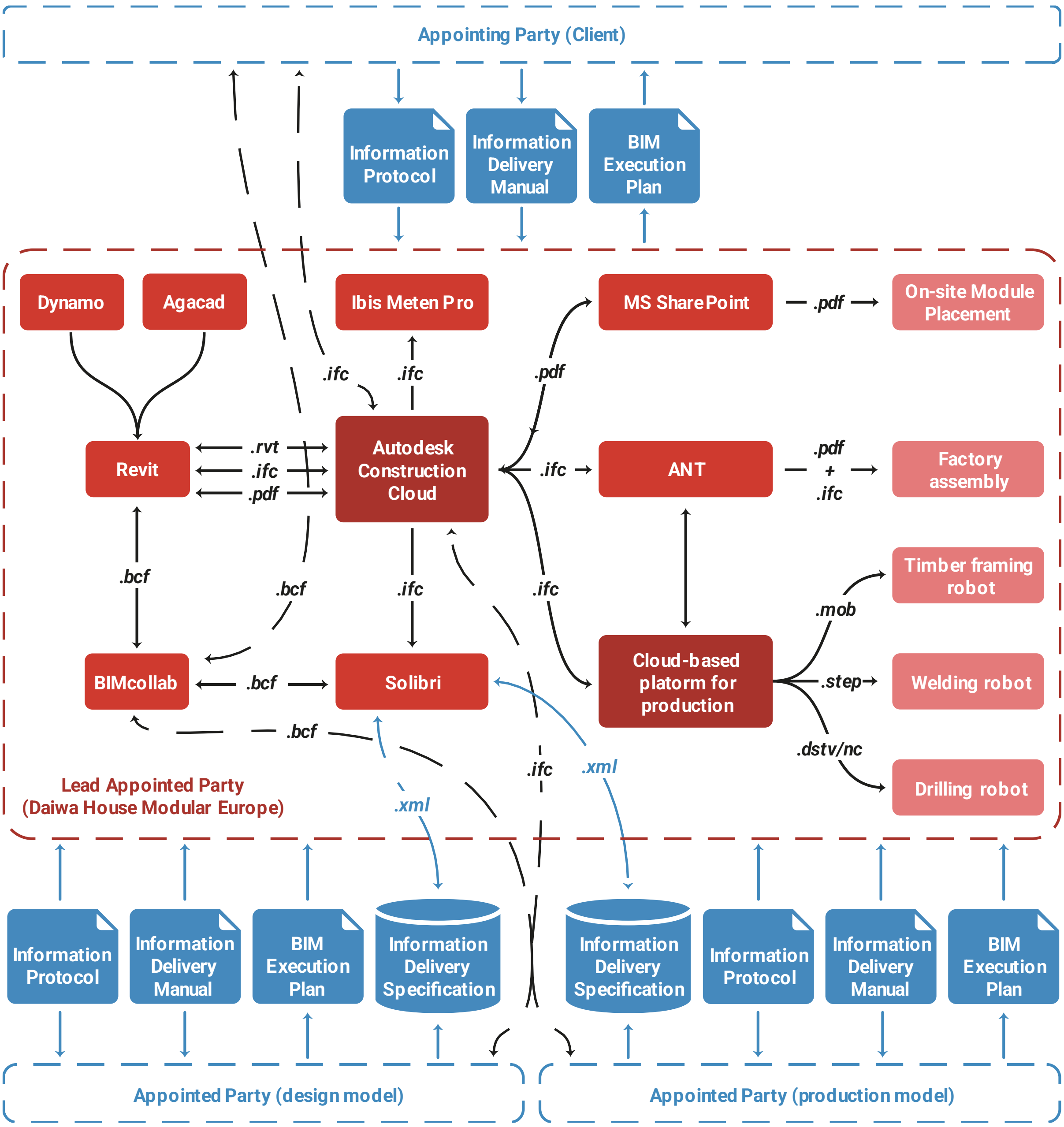


Figure 1. Overview of Daiwa House Modular Europe's openBIM process with Revit as the main modelling tool and interoperable file formats that open up DHME's workflows by facilitating interdisciplinary collaboration and communication between external parties

2.2 Concept Design

In the previous DHME workflow, 3D massing models were created in SketchUp to create visualizations for design proposals. Once the proposals were accepted, draftspeople would begin drawing and developing them in AutoCAD. Switching between two different programs created many inefficiencies, and an integrated workflow using only Revit was developed.

First, Revit is used as a *Concept Design* tool to create design proposals with conceptual massing models that contain useful information to determine the feasibility of a project, such as dwelling types and itemizations of floor areas. This method was inspired by, but not limited to, what in the Netherlands is called “miniBIM” (BIM 2020). This method integrates conceptual building models in the *Concept Design* phase of projects to facilitate objective data-driven decision-making and involve more parties in the design process. 2D floor plans are then embedded into the 3D conceptual masses to not only provide important building information, but to also visualize the modular building and give the client the opportunity to change the design. This methodology allows for ease of modification, which responds to the fast-paced market and our ambition to provide flexibility for the client. Furthermore, this conceptual mass is used throughout the digital design and construction process to attach data to, for example, the construction phasing, construction sequence, and assembly sequence. In this way, information can be tracked for every module from design to the building maintenance and operation phases.

2.3 Spatial Coordination

Next, scripts are used in the *Spatial Coordination* phase to automatically replace conceptual masses with detailed models of modules with production coding within the Revit architectural building model, as seen in Figure 2. A separate model is created for timber-framed elements, and another one for MEP systems. The timber framing and the MEP models are linked into the main Revit architectural building model. Basic geometries of timber-framed walls and roofs are modelled and then numbered and coded. This workflow allows other departments within the company to start working with the quantities of elements and objects within the model. This provides the Estimating Department with the appropriate information to create a detailed cost estimation at an early phase. The design is further developed to be submitted for review against Building Regulations to ensure that the design is compliant.

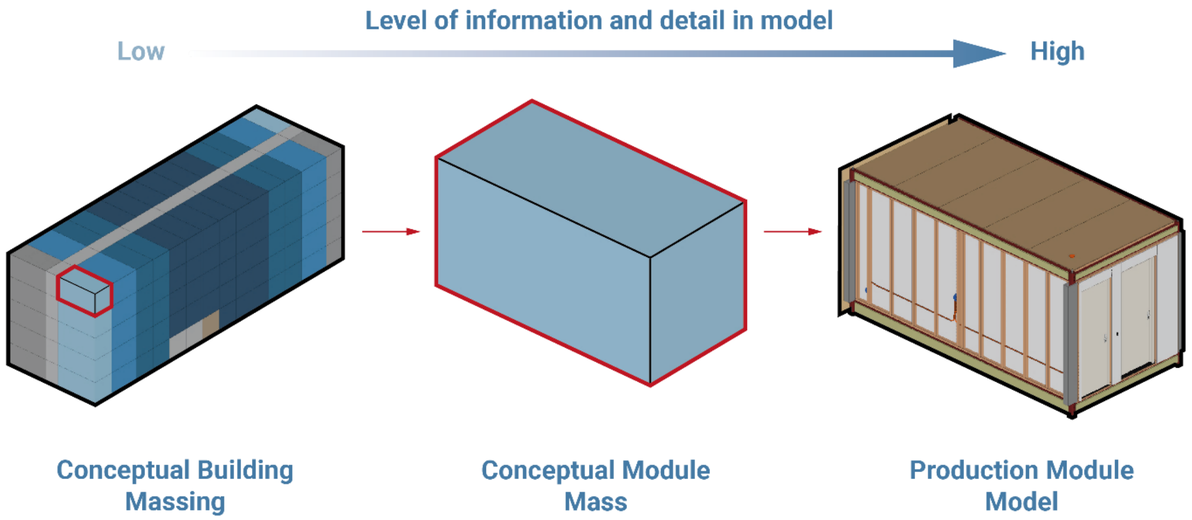


Figure 2. In the *Spatial Coordination* phase, conceptual module 3D massing models with embedded 2D floorplans and basic project information are replaced by production module models that contain more detail and information

2.4 Technical Design

In the *Technical Design* phase, models are developed to a high level of detail and all design outputs required to manufacture and construct the project are produced. For the factory to begin the production of modules, module assembly plan drawings indicating module dimensions, as well as codes and locations of prefabricated steel, concrete, and framed elements are required. A time comparison of the creation of module assembly drawing has been carried out to measure the productivity of 2D-based workflows in AutoCAD against BIM workflows in Revit. Three methods for creating 10 module assembly drawings were tested: (1) a 2D-based workflow using AutoCAD, (2) a 3D-based BIM workflow using default functions in Revit, and (3) a 3D-based BIM workflow using Revit with Dynamo scripts and the Agacad Smart Views add-on to automate the creation of views, sheets, titleblock data entry, overall dimensioning, and tags of codes of prefabricated steel and concrete elements. The starting point of all methods was the same; a developed project, with a complete floor plan of 3 different building levels, without annotations except for codes of framed wall and ceiling elements. As seen in Table 1, the duration of creating the drawings with a 2D-based workflow using AutoCAD was 149 minutes, with the 3D-based BIM workflow using default functions in Revit this was 174 minutes, and with the 3D-based BIM workflow combining Revit with automation was 56 minutes. The 3D-based automated BIM workflow was 68% faster than the BIM workflow with default Revit functions, and 62% faster than the 2D-based workflow in AutoCAD. Not only was the automated BIM workflow in Revit the fastest, it also produced the highest quality drawings with the most consistency and least amount of errors.

Table 1. Comparison of durations for creating 10 module assembly plan drawings using three methods

Working method	Duration in minutes	Comparison to AutoCAD	Comparison to Default Revit Functions
AutoCAD	149	-	14% faster
BIM: Default Revit Functions	174	17% slower	-
BIM: Automated Revit	56	62% faster	68% faster

To create shop and production drawings of prefabricated objects and elements, Revit assemblies are used to group a selection of elements, partially automate the creation of the drawings, and extract valuable building component schedules of those groups of elements. With the use of the Agacad Wood Framing plug-in for Revit, timber-framed elements that were modelled as basic walls and roofs are developed into detailed elements with timber frame components, boarding material layouts, nailing points, and openings. This is done with the use of configurations; user-defined parameters and rules to automatically frame timber elements instead of modelling all elements individually. Due to the high detail level of the timber-framed elements, collaboration with subcontractors has a lower risk of clashes and requires less attention during (BIM) coordination.

Currently there is an excess of proprietary tools available on the market for information exchange between BIM software, such as importing voids, created by subcontractors using various programs, into Revit models. To overcome limitations in information exchange between BIM software, DHME has developed Dynamo scripts that utilize linked IFC models. One script reads the MEP subcontractor's IFC model of the location and size of voids required for mechanical installations, and then, if all parties are in agreement, it automatically cuts these voids in the floor, wall, and roof elements. Another script uses subcontractors' IFC models to automatically load the locations of junction boxes into the timber framing model and place 3D models of the boxes in the production-ready timber-framed elements. These scripts not only reduce the risk of human error, but, with the use of interoperable IFC formats, open up our workflows by facilitating collaboration and communication between external parties.

2.5 Manufacturing and Construction

The drawings, building component schedules, IFC models, and other exports from the Revit models are used in the *Manufacturing and Construction* phase to automate fabrication, coordinate, and track construction.

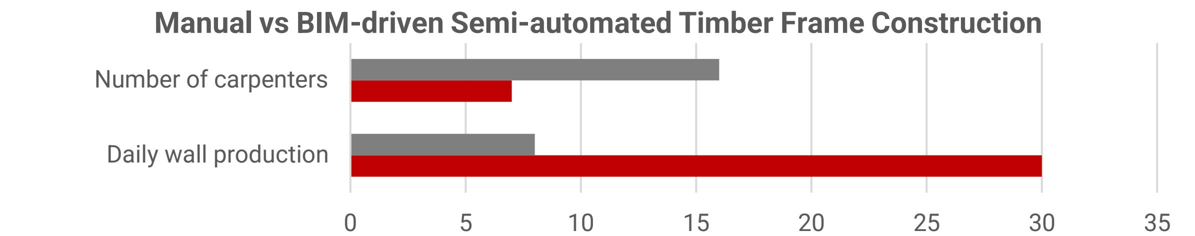
2.5.1 Timber Framing Robot

The timber-framed wall and roof models that were made in Revit using the Agacad Wood Framing plug-in are exported as IFC files. Using a cloud-based platform for production planning and file conversion, the IFC files are converted to the *.mob* file format to control the H&M Mobi-One timber framing robot. The BIM-dependent timber framing robot then automatically downloads panel drawings from design packages, accurately positions and nails timber-frame components, nails or staples the wall sheathing, routs out and trims openings in the sheathing, applies the weather-proofing and vapor membranes, and positions and nails furring strips if needed.

As seen in Table 2, the use of the timber framing robot increases the factory's wall production by 275% and labor productivity by 757%; reducing labor, mistakes, and costs. It takes carpenters approximately one hour to make one timber-framed element by hand. In contrast, the timber framing robot manufactures one timber-framed element every 15-20 minutes. This results in a daily production total of 8-10 timber-framed elements if being manufactured with a team of 16 carpenters by hand, in comparison to approximately 30 timber-framed elements being manufactured with the timber framing robot and a team of 7 carpenters.

Another advantage of producing timber-framed elements using the Mobi-One robot is the consistency of quality and precision; the timber-framed elements that are produced by robot are always square and the size and positions of openings are more precise than those made by hand. In addition to improvements in efficiency and economy, regarding health and safety, the timber framing robot provides a healthier working environment due to improved air quality because of the robot's integrated vacuum system, less strain on workers thanks to ergonomic working heights, integrated timber carriers, clamps, nail- and staple guns, a vacuum lift to place heavy boarding materials, and a butterfly table to safely turn over timber-framed elements (Figure 3).

Table 2. A table comparing the productivity of manual and BIM-driven semi-automated robotized timber framing



	Daily wall production	Number of carpenters
Manual Timber Framing	8	16
Semi-automated Robotized Timber Framing	30	7

2.5.2 Steel Drilling Robot

We have implemented the use of the Voortman drilling machine to drill holes in steel profiles (Figure 3). This has reduced the drilling time from approximately 5 minutes to manually read, measure, mark, and drill one hole, to only a few seconds per hole. In the current workflow, the positions and sizes of the holes have to be manually entered into the Voortman drilling machine software by referencing drawings that were created in Revit or AutoCAD. For every new cage type that has never been produced before, it takes two hours to program all the holes to be drilled. The BIM department at DHME has successfully tested and is implementing a new workflow where Revit models of steel objects are exported as IFC files and then, using a cloud-based platform, converted to the *.nc* file format that automates the data entry into the Voortman drilling machine software that controls the robot, saving hours of manual data entry and potential human errors.

2.5.3 Building Element Tracing and Quality Control

Throughout the manufacturing process at the factory elements, such as walls, are traced using QR codes that are scanned into ANT, a data exchange and management platform. Element tracing will be important for documenting the quality of construction because from January 1st, 2024 the Dutch Building Quality Assurance Act (Wkb) will require building projects to be checked for quality by a Quality Assurance Officer during the design and construction phases (NEA 2024).

2.5.4 New Digitalized Factory Hall Module Assembly Station Operator Task List

To help address the national housing shortage, we are increasing our production capacity with the construction of a new production hall and the implementation of a new industrialized, digitalized, and more efficient production process (MBZK 2022). Furthermore, this way of assembling helps to better secure and demonstrate quality, for the aforementioned legislation as well as our own quality standards. In the former production process, modules would be placed on the factory floor and assembled by teams of specialists who would move from one module to another after completing a task. The weekly production output of the former process was 25 modules with a weekly full-time equivalent (FTE) of 32 workers working a 40-hour workweek.

In contrast, the new production hall process is similar to a conveyor belt. Instead of teams of specialists moving from module to module, modules are placed on automated guided vehicles (AGVs) that move them to dedicated workstations with teams dedicated to carry out specific tasks, as shown in Figure 3. As presented in Table 3, the weekly production output of the new process is 50 modules a week, with a weekly FTE of 40 workers working a full 40-hour workweek. This means that the new production hall and process has increased productivity by 60%, doubling unit production. While this hall can be operated without the use of BIM, a large contribution to this increase in productivity was the integration of BIM with ANT. ANT uses the detailed IFC models that are exported from Revit as input to create production planning, extract building component schedules, determine assembly sequences of manufactured elements, generate task lists for the various workstations in the new assembly hall, display viewable 3D models and visualizations of the assembly order, and provide other drawings and information needed for factory workers to assemble the modules in a safer and easier manner.

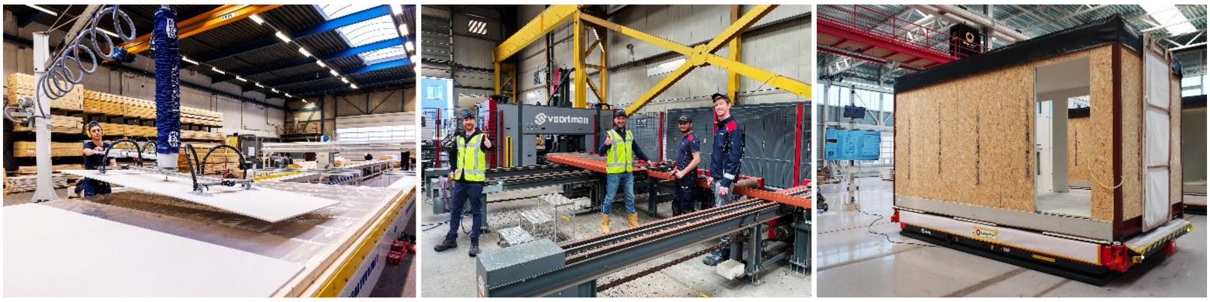
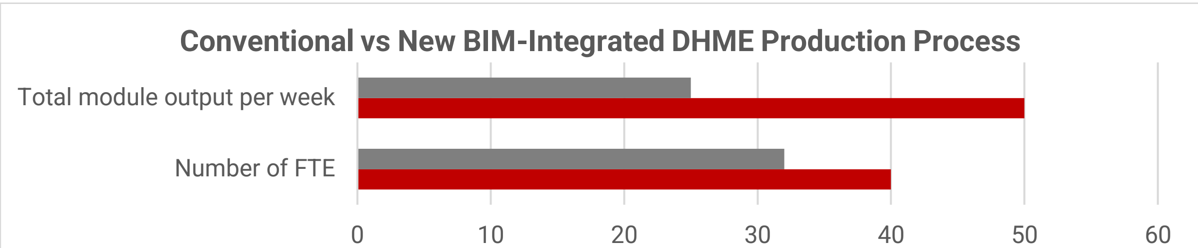


Figure 3. From left: timber framing robot, drilling machine, and a module on an Automated Guided Vehicle (AGV)

Table 3. A table comparing the productivity of processes in the conventional and new BIM-driven production halls



	Number of FTE	Total module output per week
Conventional hall	32	25
New hall	40	50

2.5.5 Yard Management and On-site Module Placement

BIM provides important data and coordination for the construction site. ANT generates module placement sequences based on exported IFC models from Revit. The unified models integrate geometry and data from subcontractors and consultants, accessible for viewing on the construction site. We are creating a workflow to integrate BIM models to facilitate construction and building inspections, and to offer as-built models for clients to enhance building operations and maintenance.

3 Results

Transitioning from a 2D drafting to a 3D BIM workflow that integrated design and fabrication of PFMC projects brought expected benefits and unexpected disadvantages and challenges.

3.1 Benefits of openBIM Implementation into PFMC

3.1.1 Faster Drawing Creation and Revisions of Non-geometric Drawing Information

Although 2D workflows in AutoCAD were faster at developing production-ready projects than 3D-based BIM workflows in Revit, automated BIM workflows outperformed 2D workflows in the creation of drawings. The creation of module assembly plan drawings using an automated 3D-based BIM workflow in Revit was 62% faster than a 2D-based workflow in AutoCAD, and 68% faster than a BIM workflow using only default Revit functions. One benefit of AutoCAD was that annotated drawings of identical unit types could easily be copied, however codes and text had to be checked, entered, and updated manually. Additionally, revisions of non-geometric drawing information in BIM projects were faster due to linked tags and parameter values automatically updating from a single source, avoiding the manual process needed in 2D projects where values were individually entered as text and drawings had to be updated separately.

3.1.2 Improved Coordination and Collaboration with External Parties

OpenBIM processes have helped facilitate information exchange and communication between external parties on PFMC projects, improving collaboration. Dynamo scripts have allowed us to read the subcontractors´ models of openings and improved the coordination, speed, and accuracy of placing 3D void and junction box models in production-ready BIM models. The use of the BIM Collaboration Format (BCF) played an integral role in the development of coordinated models and collaboration with subcontractors who use various BIM applications.

3.1.3 Increase of Productivity and Quality

The use of automated openBIM processes has reduced human errors, increased the productivity and quality of drawing creation, and enhanced information exchange in PFMC design phases while also positively impacting manufacturing and construction phases. BIM-driven robotized manufacturing guided by IFC models exported from Revit projects, like the timber framing robot, has increased production of framed elements by 275% and labor productivity by 757%. Using BIM to control the steel drilling robot saves about two hours per new cage type, eliminating the manual entry of hole sizes and positions by a human operator. By integrating BIM projects with a construction management platform, labor productivity in a new digitalized production hall increased by 60%, doubling unit production. This integration improves quality control and building element traceability from off-site manufacturing to facility management.

3.2 Disadvantages and Challenges of openBIM Implementation into PFMC

3.2.1 High Time Cost to Develop BIM Models and Revise Geometry Compared to AutoCAD

Projects took much longer to develop in BIM compared to those using traditional 2D workflows and existing digital asset libraries. The increase in time was driven by creating new 3D digital asset libraries for Revit projects and maintaining and upgrading existing assets to align with changing client needs and internal information requirements. Our findings contradict those of researchers that found that developing projects in BIM would decrease modelling time (Ezcan et al 2013) and align with the research that has indicated that more time is needed to develop projects in BIM compared to those in 2D (Pérez-Sánchez 2017). Transitioning from producing 2D drawings in multiple AutoCAD files to extracting drawings from a single 3D Revit model was expected to reduce the time needed for design revisions by enabling automatic updates of all drawings based on the 3D model. This would reduce extra work, drawing coordination, and human error when having to manually apply changes to separate AutoCAD drawings. In practice, design changes from external parties (clients, subcontractors, consultants, etc.) and internal parties (Engineering Department, Production Planners, manufacturing halls, etc.) are unforeseeable, yet inevitable. In comparison to applying design changes in the former 2D AutoCAD workflow, revisions to geometry in the BIM workflow in Revit required more time. Changes to geometry in the 3D model often led to extra geometry being added to Revit assemblies or caused disassociation with references, resulting in the loss of dimensions, tags, elements, and even entire assemblies, leading to missing drawings. Changing framed elements late in production made adjusting Agacad Wood Framing configurations time-consuming. This extra geometry significantly slowed down 3D model performance, extending task completion times.

3.2.2 Revit is a Multidisciplinary Design and Coordination Tool, not a Specialized Manufacturing Tool

Revit has showed to be efficient for creating detailed architectural drawings and 3D models, saving time by visualizing and detecting clashes across disciplines, thus preventing construction errors. However, Revit has proved to be an inefficient tool in creating shop drawings for timber, steel, and concrete elements when compared to other specialized tools that are dedicated to creating manufacturing drawings and 3D models.

3.2.3 Limitations of Currently Available Hardware

Despite using a dedicated computer with a high degree of processing power, hardware remains a major limitation for BIM implementation. Scripts on large projects are slower and prone to crashing. The high level of detail required for timber, steel, and concrete manufacturing drawings in Revit frequently causes models to load slowly and impedes navigation due to performance issues. We have experienced instances where Revit's limited multi-core functionality only utilized one core out of a 32-core processor, leaving 31 cores idle.

3.2.4 Employee Hesitancy to Adopt BIM Workflows and Implement a Single Source of Truth

Overcoming the stigma that BIM workflows are inferior to AutoCAD hindered BIM adoption. The main complaints were that creating drawings in BIM takes significantly longer because a 3D model needs to be developed and updated, and that revisions are faster in AutoCAD. Many team members were not familiar with the advantages of BIM or digital collaboration, often comparing BIM against their past experiences with paper-based 2D workflows. Difficulties maintaining a single source of truth stemmed from team members struggling to switch from working individually in separate local files to collaborating in one file. Working in separate files created unnecessary duplicates that had to be managed, such as copies of the same drawing set, but with individual markups by different reviewers. The solution is to increase BIM education and training while emphasizing the benefits of information linked to the model for later project stages, such as cost estimation, production planning, building component schedules, automated robot control, virtual reality yard management, and element tracking in production.

3.3 Conclusion

Off-site prefabrication and modular construction is gaining popularity due to its many benefits over conventional on-site construction. Research has proven that the benefits of off-site PFMC are amplified when integrated with BIM, and that BIM could help overcome challenges that prevent the implementation of PFMC methods. While many benefits of BIM are well known, there are many lesser-known disadvantages and challenges that must be considered when implementing openBIM workflows into PFMC projects in the construction industry.

This paper identified the qualitative and quantitative benefits, disadvantages, and challenges of implementing BIM workflows into the design, manufacturing, and construction phases of PFMC projects, using an openBIM process with Revit as the main modelling tool and IFC files for interdisciplinary collaboration. Our findings highlight the impacts of BIM workflows in PFMC, including: (1) faster drawing creation and revision of non-geometric drawing information, (2) improved coordination and collaboration with external parties (3) increase in productivity and quality of design and manufacturing processes, however (4) developing projects and revising geometry in BIM takes more time than in 2D workflows, (5) Revit is effective for design and coordination tasks but not for manufacturing outputs, (6) current hardware limits the workable size and detail level of BIM projects and the ability to automate BIM workflows, (7) many team members accustomed to 2D workflows were hesitant to adopt BIM workflows and implement a single source of truth because of the stigma that project development takes longer with BIM.

This information can help researchers and fabricators to extend openBIM usage to all phases in PFMC project lifecycles, promoting further research on workflow optimization. This study primarily focused on incorporating BIM workflows in PFMC projects at the design, manufacturing, and on-site construction stages, rather than facility management and operation. Future research should analyze the quantitative and qualitative effects of openBIM workflows in later PFMC project stages. It should also explore the automotive industry for a balance between product flexibility and standardization. Implementing BIM into PFMC offers many benefits compared to traditional construction methods, but their future effectiveness in solving built environment issues depends on how these technologies are developed and implemented today.

Acknowledgements

DHME would like to thank CollaborAll, Arkance Systems, and especially the openBIM community for making it possible to develop and implement a holistic and interoperable BIM workflow.

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