BUILDING INFORMATION MODELLING AND SIMULATION INTEGRATION FOR MODULAR CONSTRUCTION MANUFACTURING PERFORMANCE IMPROVEMENT

Beda Barkokebas[(a)], Youyi Zhang[(b)], Chelsea Ritter[(c)], and Mohamed Al-Hussein[(d)]

[(a),(b),(c),(d)] Hole School of Construction Engineering, University of Alberta, Edmonton, Canada

[(a)]barkokeb@ualberta.ca, [(b)]youyi@ualberta.ca, [(c)]critter1@ualberta.ca, [(d)]malhussein@ualberta.ca

ABSTRACT
Building Information Modelling (BIM) technology and simulation modelling can be successfully integrated to support modular construction manufacturing (MCM). This integration can benefit the MCM project by improving estimation accuracy, production line scheduling, resource allocation, inventory control, and by providing informative shop drawings. This paper demonstrates a case study where BIM technology is implemented to maximize the effective usage of available data and structure information. The extracted information is then stored in a database and used as the input for a simulation model. The material quantity for a product can be generated automatically for different work stations on the production line and will benefit the inventory control. By assigning detailed task durations to the material in the BIM model, the new task duration given by the simulation model can allow for increased accountability, which provides direct improvement to labour resource allocation on the line.

Keywords: BIM, simulation, estimation, modular construction manufacturing

1. INTRODUCTION

Due to the high level of specialization required, construction projects involve multiple disciplines with a high level of interaction and exchange of information among the various stakeholders. For instance, accurate and detailed drawings, developed during the engineering design phase, not only provide support to the estimation department, but also enable an increased level of detail for production scheduling. In light of this, Building Information Modelling (BIM) technology offers significant benefits to the current construction industry due to its capacity to promote effective information exchange while also automating several steps in the design, estimation, and planning phases. During the engineering design phase of the project, accurate and detailed building information not only provides support to the estimation department, but also enables an increased level of detail for production scheduling. This function is especially valuable to modular construction manufacturing (MCM) due to its special requirements in design & drafting for manufacturing (Moghadam, Alwisy and Al-Hussein 2012). Despite its advantages, current MCM remains heavily dependent upon the conventional construction production operation, where there is little innovation regarding industrialization techniques. Accuracy of material and labour estimation is limited due to the amount of manual work required as well as the unpredictable nature of construction. AutoDesk Revit is a key medium for BIM implementation in the industry; however, promoting productivity and improving the construction process on the production line using information from the project model in Revit remains a challenge. Conversely, simulation is a tool that is often used for production line performance assessment, revealing operational barriers as well as offering guidance for improvement; however, regardless of the design of the simulation model, the quality of the input data for the model constrains the quality of data that the simulation can provide to decision makers in the factory. The level of detail and level of accuracy of the collected information using traditional construction methods is not sufficient for MCM.

This paper presents a case study where BIM technology and simulation are integrated and implemented to maximize the effective usage of available data from the model. The collected information, which was previously considered difficult to collect due to the labour-intensive operations in construction manufacturing, can be collected more accurately with the assistance of a BIM application. The simulation model, which uses this data, will provide a reliable production line assessment that will benefit MCM projects.

2. LITERATURE REVIEW

The use of BIM encompasses many benefits to construction processes, including increased productivity, reduced risk, increased sustainability through decreased waste, and increased collaboration, but it is typically used for large-scale projects as the potential for benefits increases as project value increases (Burt and Purver 2014). BIM can be employed in order to obtain and organize information about quantities, and has other benefits, including design validation and worksite cooperation (Ciribiniet, Mastrolembo Ventura and Paneroni 2016), as well as the additional ability to include production line scheduling and inventory control, which results in an increased benefit, possibly making BIM more feasible for smaller projects.

Liu, Al-Hussein and Lu (2015a) utilize outputs from BIM to create a detailed schedule for a panelized construction manufacturer by using BIM information with simulation to create an optimized construction schedule. This study illustrates some of the capabilities of integrated BIM and simulation, and demonstrates that there is an opportunity to bolster the benefits provided by the BIM model by integrating it with simulation and other tools.
Lu and Korman (2010) recognize the potential for BIM to be used in modular construction, and identify the impact of BIM implementation in a modular plant to include: visualization, modelling, code reviews, fabrication/shop drawings, communication, cost estimating, construction sequences, and conflict, interference, and collision detection. Of particular interest is construction sequence, for which it is stated that the BIM model will provide the construction schedule. While this is useful, there is potential for this use of BIM to be expanded further to represent the actual accomplishments of the company in terms of productivity and schedule.
Simulation is another commonly used tool in modular construction. Alvanchi et al. (2012) use discrete event simulation to model the offsite fabrication process for a bridge project, and then to test variations to the fabrication process to achieve a 10% reduction in fabrication time. In their study, the developed simulation model represents constraints, including crane time and construction space, to accurately reflect the conditions in the fabrication plant.
Velarde et al. (2009) use lean tools and simulation to improve production at a modular home construction plant, with the goal of assisting the company to become more competitive. They recognize the importance of simulation as a tool to test different alternatives prior to implementation to help predict the outcome of adapting a new practice. This use of simulation illustrates the opportunity for its use in predicting outcomes and production planning.
In all of the studied cases, a lack of interoperability among software applications is observed as a predominant limitation since a considerable amount of manual work is involved to transfer and prepare the information for analysis. The use of various applications is inherited in the construction industry as observed by Moghadam (2014), which states there is no single tool or application able to perform all the necessary tasks in a construction project. Thus, it can be concluded there is a need to establish a combination of various applications to improve the performance of the design and planning phases of construction projects which can be adapted on a per-project basis. Liu et al. (2015b) integrate BIM and simulation by extracting information from a BIM model and using it as entity properties in the simulation model. By doing this they are able to run a user-defined sequence of panels through a simulation for the pre-existing production line to receive an output representing the predicted process time; however, even in this case, there is significant manual input required to update the simulation model with up to date production times.
This paper proposes applications and workflows to reduce manual work thus allowing more time for analysis in order to improve the informed decision-making process.

3. METHODOLOGY

In order to successfully utilize both BIM and simulation for modular construction production line performance improvement, the following steps, which are described in Figure 1, are critical.

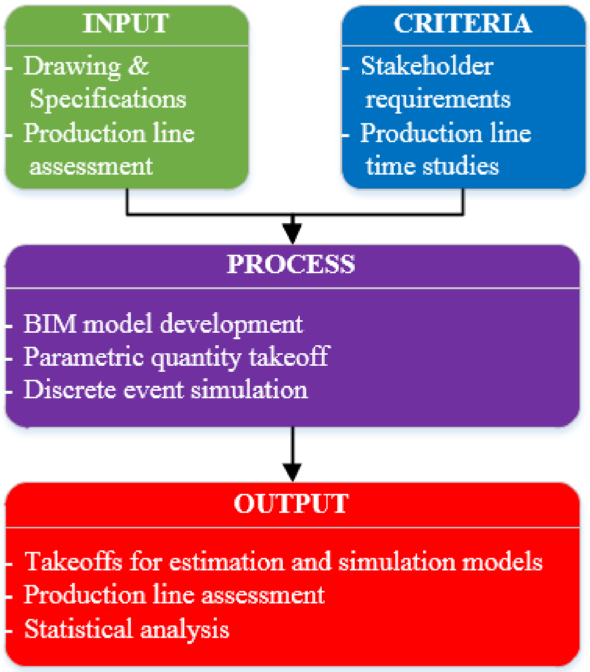

Figure 1: Proposed methodology

First, understanding the current production line operation process and the stakeholder requirements is the key to creating the connection between the drafting/design team, who uses Revit for BIM, and the operation team, who could benefit from simulation analysis. The raw data for either the Revit model or the simulation model needs to be collected during the site observation, but this can be time consuming, and the accuracy is often low. Therefore, with regard to the objectives of data collection, planning the collection method prior to the execution is required.
Second, it is important to know the level of detail required (through the production line time studies) to put into the BIM model and understand the objective for the production line assessment. For example, BIM models in conventional construction are not required to provide detailed information, such as the number of doors and windows per wall panel, due to the lack of simulation models to forecast the uncontrollable and unstandardized work site environment. For modular construction assessment and process improvement, this detailed information could promote a standardized

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working process and make the time duration for each work station more predictable.

The third step is to build the BIM model with the targeted level of detail and generate the database for the simulation model. In addition to providing valuable information for the simulation model, the accuracy of quantity take-off for estimation increases by means of hidden material being revealed. For example, the backings for cabinet installation can be built into the BIM model, whereas previously, these details would not have been included in the drawings at the case study factory.

The next step is to connect the BIM model with the simulation model based on the current production line process and stakeholder requirements. By connecting the database generated from the BIM model to the simulation model, information will be provided as per the stakeholder requirements previously stated.

Finally, a statistical analysis is presented in order to provide more information about the production line and be utilized in decision making, such as inventory control, for each work station on the production line. The work duration at each work station can also assist in the allocation of labour resources on the line.

4. CASE STUDY

The case study factory is a modular home manufacturer whose current production line process is not only manually intensive, but also receives little support from the drafting team to reach a more efficient operation process on the line. The shop drawings appear to be the same type of drawing that is provided to workers on any conventional construction work site. The company is seeking a breakthrough to enhance their production line performance using machines to assist in labour-intensive activities, including a more supportive engineering team and better material and labour resource allocation on the line to increase their productivity.

4.1. Analysis of layout

Due to the scope of this paper, the framework will be applied to the wall framing stations since they comprise the central bottleneck and dictate the overall productivity of the production line. The use of machines is thus proposed to supplement labour-intensive manual framing at these stations. Since the initial investment for the purchase of such machinery is substantial, not to mention the adjustment in company culture, a simulation model is proposed to evaluate the feasibility of such an investment. The information extracted from the BIM model for machine-assisted wall framing will have a greater level of detail than that of traditional manual framing. For example, at the most detailed level, (1) the number of studs in each of the wall panels, and (2) the material used at each work station can be counted from the model. At a lesser level of detail, generally required for traditional manual framing, the total linear length of wall can be calculated instead of using the number of studs to represent the wall panel. At each level of detail, the simulation input database will be different. The algorithms in the simulation will be adjusted accordingly as well.

The primary output from the simulation model is expected to be the total duration for the project and total number of hours required to complete a typical project from the assessed company. This will assist decision makers in their assessment whether to invest in machinery for their production line while enhancing their current design and planning process. The simulated layout is presented in Figure 2 below and includes a total of three workers and one machine.

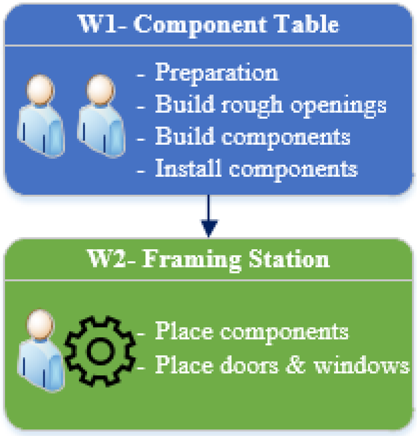

Figure 2: Simulated layout

The feasibility of the investment will be evaluated based on the simulated productivity increase promoted by the use of machinery in the future state. In order to predict the future state of the production line, a time study from another production line using similar machines and production system is used as a benchmark to forecast the system's productivity. Table 1 demonstrates data provided for this study according to each station. While some activities are dependent upon quantities extracted from wall components in the design, the fixed values are presented according to the number of panels. Possible delays are also presented according to the distributions acquired during the time study process.

Table 1: Information collection from performed time studies and input function for simulation model

Time study results		
Station	Task	Variable (minutes)
W1	Preparation	1.00
W1	Build rough openings (ext. walls)	4.75 × No. of windows + 5.60 × No. of doors + 8.00 × Fireplace
W1	Build rough openings (int. walls)	4.75 × No. of windows + 4.00 × No. of doors
W1	Build U-studs	1.00
W1	Build L-studs and triple studs	1.00
W1	Install bracing at openings	0.60 × No. of windows + 0.60 × No. of doors + 0.60 × Fireplace
W2	Place top-bottom plates	1.40
W2	Place singles studs	0.17
W2	Place double/L-studs	0.33
W2	Place multi-studs	0.50
W2	Place large windows (width >1,378mm)	1.33
W2	Place small/regular window (width <= 1,076 mm)	1.17
W2	Place large doors (width >1,134 mm)	1.33
W2	Place regular doors (width <= 1,134 mm)	0.75
W2	Place component	0.58
W2	Delay: Error correction	Triangular (0.08, 4.00, 0.75)
W2	Delay: Machine breakdown	Triangular (1.5, 10.00, 2.2)
W2	Delay: Material supply	Triangular (0.08, 3.75, 0.40)
W2	Delay: Worker away	Triangular (0.08, 1.16, 0.25)
W2	Delay: Other	Triangular (0.2, 1.5, 0.5)

4.2. Simulation model

The sequence of activities is presented in Figure 3 and developed using Simphony.NET to simulate activities observed during the time studies, thus reflecting its inter-dependency and values presented in Table 1. Since most activities involve a simple finish-to-start relationship between them, a discrete event simulation is chosen as the best approach for this problem due to its simplicity to be modelled in Simphony.NET. Delay activities at Station W2, the last station modelled, are modelled at the end since its order has no impact on the results of the model given its objective is to reflect the total manufacturing time of the project. As observed during the time study, each panel is added to the production line and progresses through the simulated stations and tasks. Some tasks are related to the type of panel (internal or external) and are differentiated by its time and sequence, while fixed values are deferred as per each panel regardless of its properties (e.g., preparation and the placement of top-bottom plates).

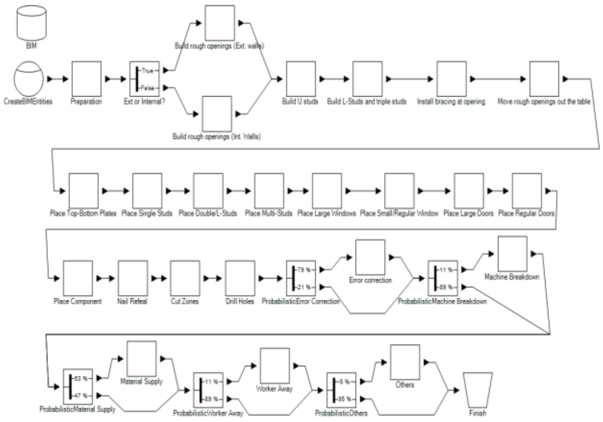

Figure 3: Simulation model

Each panel represents an entity and carries a set of properties imported from the BIM model automatically, thus establishing an interactive inter-dependence between the development of a product and assessment regarding its constructability. The imported data from the BIM model consists of design-related takeoffs addressed by consultants during the product development of the project and corresponds to the information contained in Table 1.

Such information is acquired simply by counting the elements in the model (e.g., number of windows and doors), while others are more time consuming as the number of elements increases such as the number of blockings per panel. Other panel properties must comply with certain logical relationships such as the geometry of each element (large windows > 1,378 mm) or the function of wood elements in the project (e.g., regular studs, corner and intersection components). Although the reasoning is simple, its implementation results in a significant amount of work as demonstrated in Figure 4 below.

Figure 4 describes the work required to transfer the information contained in one panel of the project. Framing components are modelled in Revit, with a total quantity of 46 on the sample panel, and it is sampled according to its use (e.g., single studs and blockings with a quantity of 10 and 28, respectively) by the research engine as properties of the panel entity to be used as inputs to the simulation model in one or more tasks. As projects have a significant number of panels with a large number of framing elements each, the activity to organize and sort the information contained

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in the BIM model becomes time consuming and error-prone, thus jeopardizing the practicality to simulate the production line. The BIM model and its connection with the simulation model are presented in the next section.

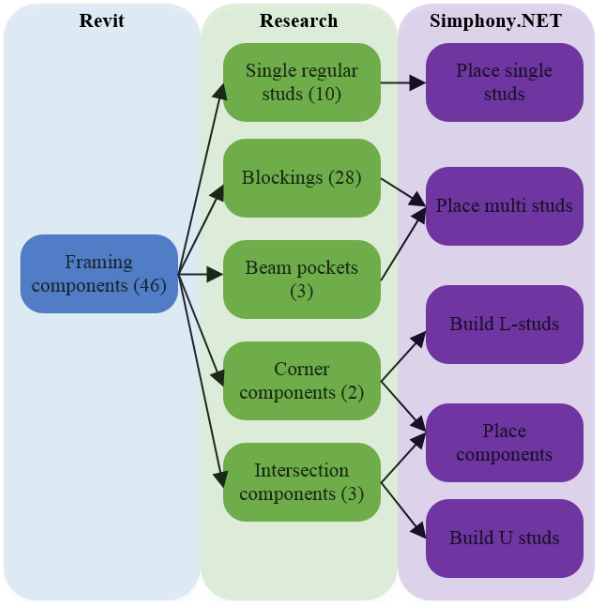

Figure 4: Information transfer required among BIM and simulation models

4.3. BIM model and connection with simulation

The case study project analyzed in this paper is presented in Figure 5 and consists of a modular single-family home with 25 wood-frame panels, one storey, and a total area of 71.64 m^2. The BIM model is developed in the Autodesk Revit environment and—due to the wood frame information required by the simulation model—the framing portion is developed by Framex, a Revit add-on developed by the University of Alberta.

Figure 5: Single-family case study module

Framex defines each framing panel based on existing walls addressed by architects in order to define the desired layout and models all framing components, such as regular studs, opening components, and blockings required for electrical outlets and kitchen cabinets, thus creating the information required to address the developed simulation model. Each panel is then considered an entity for the simulation model and carries distinct properties in order to calculate the total manufacturing time in the simulation model.

Figure 6 presents the workflow proposed in this paper. By using Excel, a software application common to all stakeholders during the development and manufacturing phases, the proposed research engine creates a two-way connection with the BIM model and prepares the information in an adequate format to be imported into Simphony.NET. In Excel, the user defines which parameters are to be extracted from elements (e.g., walls, framing elements, doors, etc.). This file is then imported into Revit generating the automated raw takeoffs, which are sorted as per the time study and formatted into Simphony.NET format through pre-set formulas in excel, comprehensible to all stakeholders for checking. The takeoffs can also be used for estimating, procurement, and inventory forecast according to stakeholder needs.

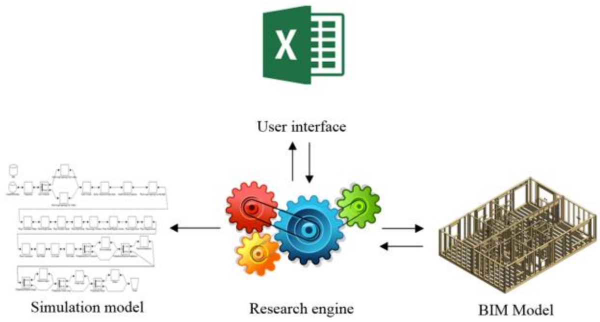

Figure 6: Proposed workflow

The research engine consists of an add-on programmed using Dynamo, an open source graphical programming tool. The development of this add-on is divided into three parts: (1) a stable connection between a pre-set user interface (in Excel) and the BIM model; (2) the import of the Excel file while gathering all required information; and (3) sorting of all gathered data as per the simulation model requirements.

4.4. Simulation results

Using Simphony.NET, the model is simulated 1,000 times, and its data is exported to EasyFit in order to determine an adequate fit for the data. In EasyFit, a histogram with the simulation results is produced while assigning the Log-Logistic distribution as the most adequate distribution as per Figure 7 below. As indicated in Figure 7, there is a variance in results of 8.30 minutes resulting in an approximate 11 % variation over the mean (74.84 minutes).

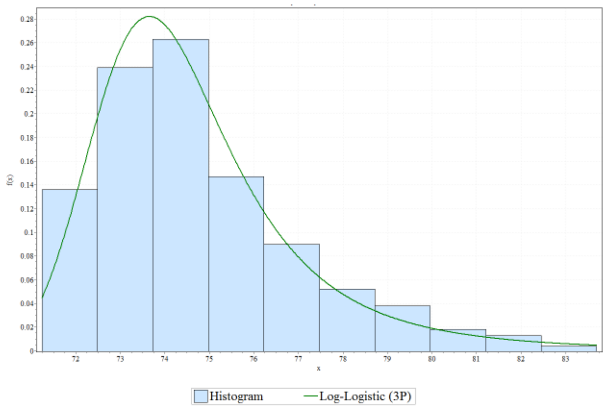

Figure 7: Histogram and fitted distribution on generated data

Moreover, the employment of each task is also addressed in the model. Figure 8 presents a summary of the most employed activities in the simulation model. In this figure, it can be observed that activities involving the manufacturing of components, such as openings, are employed the most on the production line (values of 32.4% and 45.30% for internal and external rough opening components, respectively). Also, the employment of preparation activities for each station are 28.90% and 40.50% for Stations W1 and W2, respectively.
For a better assessment of the production line as a whole it is recommended that the rest of the work stations be included in the model to generate a queue and better reflect a typical day at the manufacturing facility. These are the limitations of this work and will be addressed in future papers.

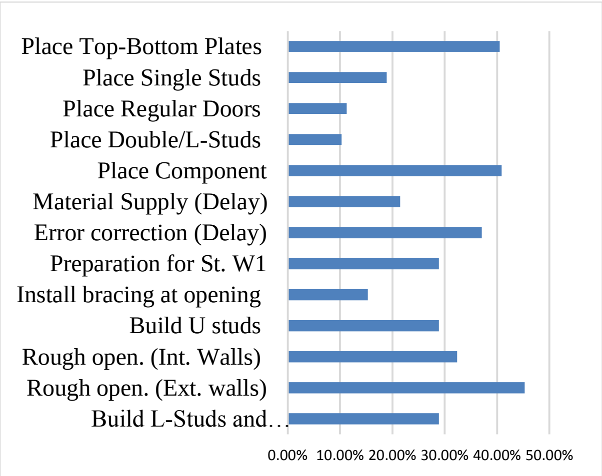

Figure 8: Summary of most employed activities during 1,000 simulation runs

4. CONCLUSION

The proposed methodology provides a solution to connect BIM technology with production line performance improvement using a simulation model. This research can also promote an industrialization transformation for modular manufacturing companies currently utilizing the traditional construction process. Innovated technology can improve the productivity by standardizing and automating the process, which requires support from BIM models.

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ABOUT THE AUTHORS

Beda Barkokebas is a PhD student at the University of Alberta whose current focus is on the pre-panelized construction approach, and the development of innovative building information modelling (BIM) technologies.

Youyi Zhang is a Research Assistant at the University of Alberta, whose focus is on modular construction production line performance improvement, lean production, and simulation application.

Chelsea Ritter is a PhD student at the University of Alberta with a research focus on process improvement and production line layouts.

Mohamed Al-Hussein is a is a professor in the Hole School of Construction Engineering and Director of the Nasseri School of Building Science and Engineering at the University of Alberta, and holds the NSERC Industrial Research Chair in the Industrialization of Building Construction. A highly sought researcher and consultant in the areas of lean manufacturing, construction process improvement, CO_2 emission quantification and reduction, and building information modelling (BIM), Dr. Al-Hussein has successfully applied lean principles to improve work methods and productivity standards for various industries and projects. His research has developed best practices for panelized building systems, lean production, and modular construction, and has been published in approximately 200 peer-reviewed journals and conference proceedings.