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OPTIMIZING MULTI-WALL PANEL CONFIGURATION FOR PANELIZED CONSTRUCTION USING BIM

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With the rise of Building Information Modeling (BIM), off-site construction is gaining momentum in the construction industry. This construction method can benefit the industry through improved productivity and reduced waste. However, it also poses new challenges to building designers and construction practitioners with respect to building design and construction planning. For example, when designing building products and BIM models, designers needs to consider manufacturing process constraints in order to harness the benefits of manufacturing technology. This is in part due to the fact that, in the offsite construction paradigm, building design must be transformed from product-focused to manufacturing process-driven. At present, considerable human involvement and off-site construction knowledge are required to adapt building design (e.g., panelize building objects) for manufacturing processes within BIM environments. In this regard, this research contributes a BIM-based algorithm for panelizing building components. The proposed algorithm is capable of determining the granularity of wall panels and optimizing the configuration of multi-wall panels under engineering constraints, thereby improving productivity. The proposed approach is implemented within an Autodesk Revit environment through application programming interface. A case study of a residential building is used to demonstrate the proposed approach.

Keywords: Building panelization, Multi-wall panel optimization, Productivity improvement, Construction manufacturing, Building information modeling.

1 INTRODUCTION

For decades, the construction industry has been seeking various approaches to improve productivity and to reduce waste. A number of emerging technologies and tools have been applied in industry, such as building information modeling (BIM). However, the industry is yet to see marked improvements in terms of productivity as a result of these emerging tools, this is due in part to the fact that most construction processes remain fundamentally unchanged in spite of the introduction of innovation technologies and tools (Zhang *et al*. 2005). In this context, off-site construction is attracting increasing attention from both industry and academia. In general, off-site construction brings on-site construction works into a climate-controlled facility where advanced machinery can be utilized to manufacture buildings in a standardized and efficient manner. More importantly, off-site construction affords the opportunity for construction methods to be re-engineered in order to take full advantage of manufacturing processes, rather than merely building the product in a conventional manner but under a roof. Off-site construction has the potential to significantly improve productivity and reduce the waste associated with conventional construction processes. At the same time, off-site construction poses new challenges with respect to construction design and planning. One example is the problem of how to balance the production line, given that building panel prefabrication involves a highly variable product mix, in contrast to traditional mass production (Liu *et al.* 2015). (Note that building panel prefabrication is an off-site construction approach in which building components such as walls are prefabricated in the factory as panels.) To address this issue, lean principles such as standardization have been successfully applied to standardize and improve house production processes, including a lean production model for residential home buildings (Yu *et al.* 2009) and a case implementation for lean transformation in a modular building company (Yu *et al.* 2011). In addition to standardization of the building processes themselves, standardization of building design is also essential in building manufacturing (Nawari 2012). Reducing design variability of building objects can decrease the variation of process time during which building objects will stay in one workstation, thus resulting in less waiting time and idle resources, as well as in a better balanced production line. In addition to processes and products, semi-products in the building production line also need to be standardized for certain manufacturing processes in order to maximize the benefits of building manufacturing. For instance, a collection of wall panels of identical height and dimensional lumber type can be framed together as one segment of multi-wall panel to increase utilization of automated framing tables and improve productivity. Nevertheless, existing design and modeling tools are not able to optimize the configuration of wall panels under engineering constraints for building manufacturing. Indeed, standardization of semi-products in current practice has been largely overlooked by both industry and academia.

BIM is an information technology capable of revolutionizing the way various stakeholders operate and interact in delivering projects. With BIM technology, stakeholders in various disciplines can coordinate design information through a unified BIM design model and perform various analyses by leveraging the rich information contained in BIM models. In terms of off-site construction, BIM is often utilized to facilitate processes such as design, modeling, visualization, code reviews, fabrication/shop drawings, and collision detection (Lu and Korman 2010). However, existing BIM systems cannot support building manufacturing in an efficient and effective manner. The reason partially arises from the fact that knowledge of off-site construction process and substantial human involvement are required in order to panelize building for BIM-enabled factory production. Also, generating task-specific BIM models is one of the main challenges faced by the industry in implementing BIM (Ding *et al.* 2014). Particularly for off-site construction projects, construction practitioners need to consider manufacturing process constraints in designing BIM models. Moreover, it is challenging to achieve the optimized building panelization when manually determining the granularity and the configuration of wall panels without a proper optimization formulation or mathematical algorithms.

This research thus contributes a BIM-based algorithm for panelizing building components. The proposed algorithm is able to determine the granularity of wall panels and optimize the configuration of wall panels under engineering constraints with the objective of improving the productivity during the production and is encoded as an add-on to Autodesk Revit via application programming interface (API). Notably, in this study engineering constraints are formalized based on a wall panel prefabrication company, ACQBUILT, Inc., based in Edmonton, Canada. A case study of a residential building is used to demonstrate the proposed approach.

2 MULTI-WALL PANEL

As described above, a multi-wall panel is a combination of panels of identical height and dimensional lumber type that can be framed together. In the example shown in Figure 1, the multi-wall panel consists of three single-wall panels, where the core layers (i.e., framing layers) of the three single-wall panels have identical heights and thicknesses and share the same type of top and bottom plates. Given the common properties of the core layer, these panels can be framed together as one segment of multi-wall panel connected by top and bottom plates composed of single pieces of lumber spanning the entire length of the multi-wall panel. This reduces the setup time for framing activities and to increase utilization of automated framing tables. Once the framing process is completed, the three wall panels can be separated by cutting the top and bottom plates at the designated location. Accordingly, designing based on the combining of compatible single walls to form multi-wall panels can greatly improve productivity.

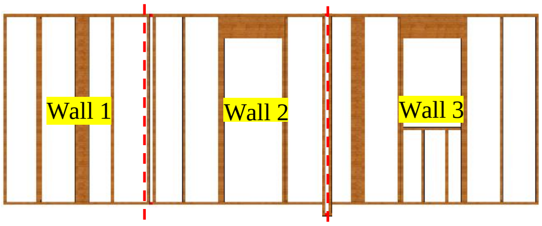


Figure 1. Example of multi-wall panel.

2.1 Optimization Formulation

The objective of this research is to optimize the configuration of multi-wall panels with the purpose of improving productivity. The objective function is expressed as Eq. (1). The mathematical model serves to minimize the difference between the maximum allowable multi-wall panel length and the length of multi-wall panels. In other words, the length of multi-wall panels is maximized in order to attain the maximum allowable length. Maximizing the length of multi-wall panels in turn can reduce the number of multi-wall panels to be manufactured. To solve this mathematical model, the greedy best fit algorithm is selected in this study, as it is capable of providing an optimized solution in an efficient manner (Esparza 2003). In the interest of brevity, detailed explanations of the greedy best fit algorithm can be found in previous studies (Korf 2002, Esparza 2003, Fayzrakhmanov *et al.* 2014). The mathematical model is expressed in the following series of equations (Eqs. (1) to (4)).

$$O.F. = min\ (x \cdot ML_{max} - \sum_{i=1}^{x} \sum_{j=1}^{t} SL_{i,j}) \tag{1}$$

$$\text{St.} \quad SH_{1,i} = SH_{2,i} = SH_{j,i} \tag{2}$$

$$ST_{1,i} = ST_{2,i} = ST_{j,i} \tag{3}$$

$$ML_{min} \leq \sum_{j=1}^{t} SL_{i,j} \leq ML_{max} \tag{4}$$

where *O.F.* represents the objective function; ML_{max} denotes the maximum allowable multi-wall panel length; ML_{min} denotes the minimum allowable multi-wall panel length; $SL_{i,j}$ is the length of single-wall panel j within multi-wall panel i; x denotes the number of multi-wall panel; t represents the number of single-wall panels contained in multi-wall panel i; SH represents the height of single-wall panels; and ST denotes the thickness of a single-wall panel.

2.2 Criteria and Constraints

To build multi-wall panels, there are some important criteria that must be satisfied. These criteria, as expressed in Eq. (2), Eq. (3), and Eq. (4), serve as the constraints for the mathematical model. For example, wall panels within one multi-wall panel must have identical heights and thicknesses so that they can be framed together using the same top and bottom plate. Also, wall panels at different building levels may be mixed into one multi-wall panel under the constraints of production schedule. This criterion is utilized to categorize single-wall panels into different groups; then, single-wall panels in each group are optimized by the aforementioned mathematical in order model to generate multi-wall panels.

3 PROTOTYPE APPLICATION DEVELOPMENT

The automated design system for multi-wall panels is prototyped as an add-on to the Autodesk Revit platform using application programming interface (API). The system architecture is presented in Figure 2. Generally, it includes a model layer and an interface layer. The BIM model is developed using the BIM authoring tool, Autodesk Revit. BIM data is parsed from an Autodesk Revit BIM model using Revit API. The optimization model described above is also coded into the prototyped system, taking BIM data as inputs to optimize the multi-wall panel design. All the system components are integrated through Autodesk Revit API.

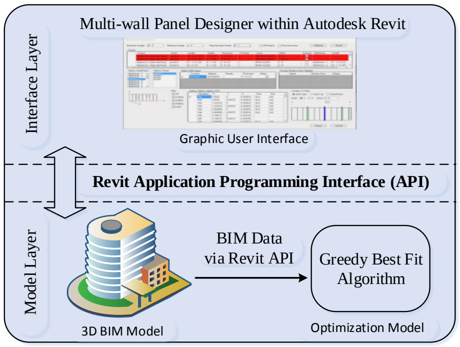
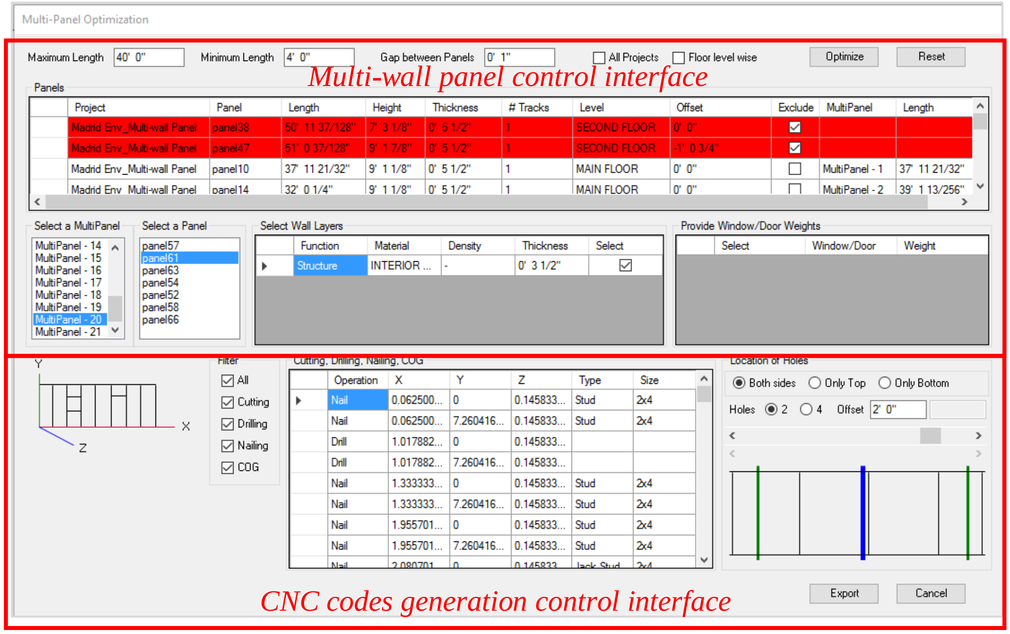


Figure 2. System architecture.

Figure 3 presents the graphic user interface (GUI) of the prototyped system. When the GUI launches, the controls for optimizing multi-wall panels are enabled. The construction practitioner can specify the maximum and minimum length of multi-wall panels, as well as the length of the gap between panels. It is important to note that the maximum length of a multi-wall panel depends on both the length of the framing table and the maximum available length of the top and bottom plate, whereas the minimum length of a multi-wall panel is dependent only on the framing machine length. If the length of a panel exceeds the maximum specified length, it will be highlighted in red in the GUI and flagged as “excluded” (see Figure 3). If “All Projects” is checked, panels will be combined only if they are in the same building project. The interface also allows construction practitioners to optimize multi-wall panel design across multiple building projects. If the “Floor level wise” is checked, panels will be combined only if they are in the same building level. Once panels have been grouped based on the given criteria, the greedy best fit algorithm is triggered to solve the optimization model for each group. The results will be displayed in the GUI, where any multi-wall panels greater than the specified maximum length or shorter than the specified minimum length are highlighted in red. It should be noted that the research presented in this paper illustrates part of a broader ongoing research initiative. As shown in Figure 3, the red box on the GUI highlights the computer numeric control (CNC) codes generated by the prototyped system – the generation of machine-readable CNC codes is out the scope of this paper, and is not illustrated in detail. The output of this system is optimized multi-wall panel design that can be exported and saved into CNC codes.

4 CASE STUDY

To validate the developed prototype system, a wood-framed single-family home from a prefabricated home builder based in Edmonton, Canada, is adopted as a case study. The building shown in Figure 4 consists of three stories and 68 wall panels. The BIM model is first built in Autodesk Revit 2015 (Autodesk Ltd. 2015); then, an in-house Revit add-on is employed to design the framing of the walls. Following this, the developed prototype system is launched in Autodesk Revit to design the multi-wall panels. As shown in Figure 4, the maximum and minimum lengths of multi-wall panels are set as 40 ft and 4 ft, respectively, based on the configuration of the framing table in the industry partner's facility. The GUI as shown in Figure 3 presents the optimization result for the case study. Single-wall panels in the case study are combined into 21 multi-wall panels for the building panel production.



Multi-wall panel control interface

Maximum Length: 40' 0"
Minimum Length: 4' 0"
Gap between Panels: 0' 1"
☐ All Projects
☐ Floor level wise

Panels

	Project	Panel	Length	Height	Thickness	# Tracks	Level	Offset	Exclude	MultiPanel	Length
	Madrid Env_Multi-wall Panel	panel38	50' 11 37/128"	7' 3 1/8"	0' 5 1/2"	1	SECOND FLOOR	0' 0"	☑		
	Madrid Env_Multi-wall Panel	panel47	51' 0 37/128"	9' 1 7/8"	0' 5 1/2"	1	SECOND FLOOR	-1' 0 3/4"	☑		
	Madrid Env_Multi-wall Panel	panel10	37' 11 21/32"	9' 1 1/8"	0' 5 1/2"	1	MAIN FLOOR	0' 0"	☐	MultiPanel - 1	37' 11 21/32"
	Madrid Env_Multi-wall Panel	panel14	32' 0 1/4"	9' 1 1/8"	0' 5 1/2"	1	MAIN FLOOR	0' 0"	☐	MultiPanel - 2	39' 1 13/256"

Select a MultiPanel
MultiPanel - 14
MultiPanel - 15
MultiPanel - 16
MultiPanel - 17
MultiPanel - 18
MultiPanel - 19
MultiPanel - 20
MultiPanel - 21

Select a Panel
panel57
panel61
panel63
panel54
panel52
panel58
panel66

Select Wall Layers

	Function	Material	Density	Thickness	Select
▸	Structure	INTERIOR ...	-	0' 3 1/2"	☑

Provide Window/Door Weights

	Select	Window/Door	Weight

Filter
☑ All
☑ Cutting
☑ Drilling
☑ Nailing
☑ COG

Cutting, Drilling, Nailing, COG

	Operation	X	Y	Z	Type	Size
▸	Nail	0.062500...	0	0.145833...	Stud	2x4
	Nail	0.062500...	7.260416...	0.145833...	Stud	2x4
	Drill	1.017882...	0	0.145833...		
	Drill	1.017882...	7.260416...	0.145833...		
	Nail	1.333333...	0	0.145833...	Stud	2x4
	Nail	1.333333...	7.260416...	0.145833...	Stud	2x4
	Nail	1.955701...	0	0.145833...	Stud	2x4
	Nail	1.955701...	7.260416...	0.145833...	Stud	2x4
	Nail	2.080701	0	0.145833	Jack Stud	2x4

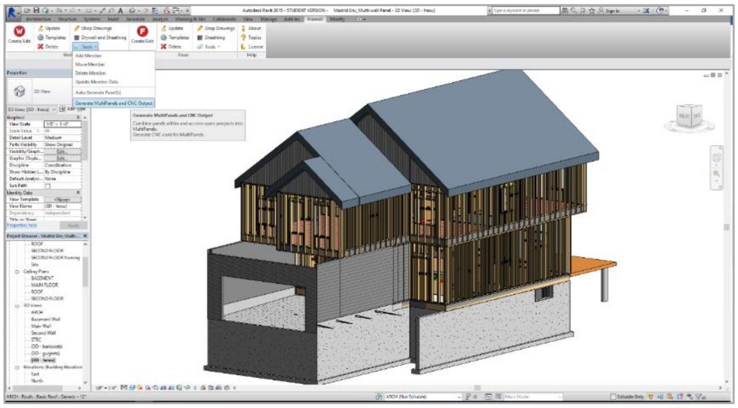
Location of Holes
● Both sides ○ Only Top ○ Only Bottom
Holes ● 2 ○ 4 Offset 2' 0"

CNC codes generation control interface

Figure 3. Graphic user interface of multi-wall panel designer.

5 CONCLUSION

This research targets multi-wall panel design for panelized construction in the light-frame residential building industry. The multi-wall panel design optimization was formulated as a typical one-dimensional cutting-stock optimization, and the greedy best fit algorithm was applied to optimize the configuration of multi-wall panels. BIM technology was utilized to facilitate the design optimization, capitalizing on the benefits of the rich building information in BIM. A prototype design system was developed as an Autodesk Revit add-on. A case study demonstrated that the developed system can produce optimized multi-wall panel design in the form of machine-readable CNC codes. As a result, the prototyped system is able to assist project managers in effectively optimizing multi-wall panel design for building manufacturing. Although the greedy best fit algorithm is able to search for the optimal solution in a short computing time, it should be noted, the optimized solution may be not the global best solution. In order to improve the performance of the prototyped system, other optimization algorithms such as genetic algorithm can be further explored in future research.



Generate MultiPanels and CNC Output
Combine panels within and across open projects into MultiPanels.
Generate CNC code for MultiPanels.

Figure 4. Case study of a wood-framed single-family home.

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