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Automated BIM-Based CNC File Generator for Wood Panel Framing Machines in Construction Manufacturing

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ABSTRACT

Construction manufacturing companies are endeavoring to integrate new technologies and machinery automation throughout the various project phases in the ongoing shift away from traditional stick-built methods. The current practice in constructing manufacturing supports the integration of automated computer numerical control machines, which can undertake various operations and thereby reduce manual work. However, shop drawings need to be obtained from the building information model and imported to third-party software (such as computer-aided design/computer-aided manufacturing software) to generate the corresponding computer numerical control codes. This underscores the need for a fully automated solution for computer numerical control machines in construction manufacturing that reduces the reliance on third-party software, thereby reducing the time, effort, and cost otherwise spent on managing multiple software solutions. As such, the aim of this research is to develop a building information modelling-based automated tool to serve as a direct connection between the building information modelling environment and the automated machine. The tool facilitates the generation of a computer numerical control file directly from the building information model that will serve as an input to an automated wood-wall framing machine. For the wood framing machine under study, a set of rules was developed by which to generate the computer numerical control file directly from the building information model. This included developing an identification system for the main operations that can be performed by the machine and extracting information from the model that may be of relevance to the process. An add-on was then developed in Autodesk Revit to generate the computer numerical control file. The proposed methodology was validated by generating computer numerical control files using the developed add-on and inputting them to the machine. Using the generated computer numerical control files, the machine was found to be capable of properly performing the operations as planned.

KEYWORDS

Construction manufacturing; Automation; Computer Numerical Control (CNC) machinery; Building Information Modelling (BIM)

INTRODUCTION

Industrialized construction (IC) involves producing building components, systems, or structures in a controlled factory setting and then transporting them to the construction site for installation

(Razkenari et al., 2019). This approach reduces construction duration, reduces overall cost, and enhances project quality (Zhang et al., 2016). Indeed, IC has been successfully implemented to satisfy increasing demand within the housing industry in several regions worldwide (Howes, 2002). To capitalize on these inherent benefits of IC, construction manufacturing companies have been moving increasingly away from traditional practices in favour of integrating new and advanced technologies throughout the different manufacturing phases (Kumar et al., 2005). Machine automation allows construction manufacturers to control production flow in such a manner as to minimize the associated fabrication cost, reduce waste generation, and increase the machine's efficiency and utilization (Boucher, 2012). Computer numerical control (CNC) facilitates machine automation as it enables users to communicate with machines using numbers and symbols (Krar et al., 2001). Hence, to further enhance machine automation in construction manufacturing, fully automated computer numerical control (CNC) machines are used given their ability to undertake various operations and thereby reduce manual work (Bock, 2008).

As such, recent research studies have endeavored to automate different tasks related to the operation of machines. For example, Wang et al. (2004) developed a web-based framework to allow for real-time monitoring and control of networked CNC machines. It was developed in a collaborative environment that allows machine operators and production engineers to access up-to-date production data. Moreover, Marriage & Sutherland (2014) presented a digitalized construction approach that uses CNC cutting machines for fabricating cross-laminated timber (CLT) building components. Their aim was to meet the increasing demand for rebuilding houses to recover from the repercussions of the Canterbury earthquakes in a cost-effective manner and within a tight schedule while maintaining a high quality of work. In another study, Li (2016) investigated the development of a modular-based CNC machine for wall framing to increase the level of automation and flexibility. Li developed an algorithm to extract information (i.e., locations of framing operations) from the BIM model. In a follow-up study, Liu et al. (2017) generated geometric locations of the framing operations and exported the information into a CSV file. This file acts as an input file for computer-aided manufacturing (CAM) software in order to generate the CNC codes for the framing machine. Kremer (2018) introduced a new framework for mass timber construction to increase the efficiency of mass customization.

In addition to the framework they proposed, Kremer (2018) suggested that designers can establish a direct linkage between design and manufacturing by translating design drawings into machine-readable drawings and CNC codes. Nevertheless, the current practice for converting drawings into machine-readable CNC codes requires that detailed shop drawings be obtained from the BIM model and imported to third-party CAD/CAM software. Using these software solutions, information relevant to the CNC machines can be coded and used to generate the CNC files. However, this process can be streamlined by reducing the reliance on third-party software as suggested by Kremer (2018), which in turn will support a fully automated solution for the use of CNC machines in construction manufacturing. As such, the aim of this research is to develop a BIM-based automated tool that serves as a connection between the BIM environment and the automated machine. In specific, this connection will allow for the generation of a CNC file directly from the BIM model that can be used as an input for an automated wood-wall framing machine, thereby reducing the reliance on third-party software.

RESEARCH METHODOLOGY

The first step undertaken in the present study consisted of confirming the need for the developed tool. A literature review was conducted to investigate what has been achieved to date with respect to the problem to be addressed. The next step was to conduct a detailed study of the framing machine prototype under investigation in order to gain a thorough understanding of its specifications, its operation, and the structure of the CNC files read by the machine. Then, a set of rules for generating the CNC file from data extracted from the BIM model was devised accordingly. In the following step, an add-on for Autodesk Revit was programmed using C# to generate the CNC file directly from the Revit environment. Finally, the add-on was tested by generating CNC files and feeding them into the machine, which in turn performed the planned operations.

AUTOMATED CNC FILE GENERATOR

Brief overview of the wood framing machine under study

The wood-framing machine under study is a prototype developed by University of Alberta researchers to semi-automate wood-wall framing operations. There are three types of operations performed by the machine: nailing, drilling, and cutting. The machine reads a CNC file to perform these operations and frame wall panels. An operator has to load the machine with the framing elements when prompted by the machine to do so. As framing elements are loaded by the operator, the machine performs the necessary operations based on the CNC file and drags the frame in progress downstream so that more elements can be loaded, and so on. The machine prototype is shown in Figure 1.

Figure 1. Wood-wall framing machine prototype at the University of Alberta lab.

Identification system

The machine's motions are dictated by the operation to be performed. Each operation is identified by a three-character identification code, which consists of the following:

- The first character either indicates whether (1) the machine should perform nailing, cutting, or drilling operations on a framing element or (2) a subassembly (e.g., window opening, door opening) is to be added to the frame. Subassemblies must be distinguished since they require a processing technique that is different from that needed for basic framing elements (e.g., studs). This character is important for helping the machine to understand which operation (i.e., nailing, drilling, or cutting) is needed, and to perform a specific sequence of motions accordingly.
- The second character identifies the operation in more detail as follows:

- Nailing operations: the second character describes the positioning of the frame element on which the operation is to be performed. As shown in Figure 2, the stud could be placed along its shorter edge (i.e., vertically) or along its longer edge (i.e., horizontally, nailed at the top or bottom of the plates) and at different heights.

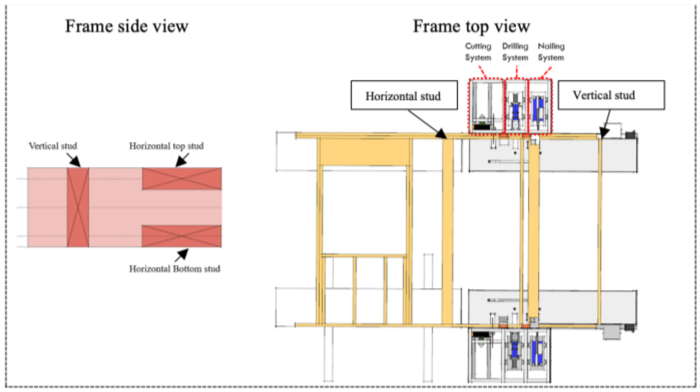

Figure 2. Sample positioning of framing elements.

- Cutting operations: with regard to cutting, the second character specifies whether the cut in the given framing element(s) is to be partial (i.e., cut into the element only to a certain depth) or full (i.e., cut the element into pieces).
- Drilling operations: the second character for drilling is a dummy character and does not provide additional information on the operation.
- Component: here the character denotes the start and end of the component, since the machine performs all framing operations on a component continuously from its start to its end.

- The third character specifies which side of the machine is to perform the operations (i.e., left side, right side, or both sides). For instance, it specifies whether a stud will be nailed only to the top plate of the frame, only to the bottom plate of the frame, or to both sides.

These characters are summarized in Table 1 below. Moreover, Table 2 presents all possible combinations of characters denoting operations that can be accommodated by the machine prototype under study. These combinations of characters are used to represent operations in the CNC file.

Table 1. Machine operations identification system.

First Character	Second Character	Third Character
Nail: ***N***	Vertical: ***V***	Left side: ***L***
	Top: ***T***	
	Bottom: ***B***	
Drill: ***D***	Placeholder: ***R***	Right side: ***R***
Cut: ***C***	Full Cut: ***F***	
	Partial Cut: ***P***	Both sides: ***B***
Component: ***K***	Start: ***S***	
	End: ***E***	

Table 2. Identification codes.

Code	Operation	Code	Operation
NVB:	Nailing Vertical Both sides	NTL:	Nailing Top Left side
NVR:	Nailing Vertical Right side	DRB:	Drilling Both sides
NVL:	Nailing Vertical Left sides	DRR:	Drilling Right side
NBB:	Nailing Bottom Both sides	DRL:	Drilling Left side
NBR:	Nailing Bottom Right side	CPB:	Cutting Partial Both sides
NBL:	Nailing Bottom Left side	CFB:	Cutting Full Both sides
NTB:	Nailing Top Both sides	KSB:	Component Start point
NTR:	Nailing Top Right side	KEB:	Component End point

Transformation of data extracted from the BIM model

The CNC file generator is programmed to extract data relevant to each operation from the BIM model based on the logic proposed by Li (2016) as follows:

- The 3D coordinates corresponding to nailing operations are generated based on intersecting positions between the structural elements (e.g., studs and top/bottom plates) of the panel.
- The number of nails in each nailing position is determined based on construction codes and best practice. For instance, the National Building Code, Alberta Edition (National Research Council of Canada, 2019) indicates that the minimum number of nails required to fasten studs to wall plates is two, with a minimum nail length of 82 mm.
- Drilling positions are defined based on the panel's center of gravity.
- Cutting positions occur at the endpoints of each wall panel.

In addition to this logic, each operation is defined by its 3D coordinates with respect to the panel's starting point, and the sequence of operations is then determined based on the *x*-position of each operation. However, this sequence, which is based solely on the panel's geometry, is not the manufacturing sequence fed into the machine. This is due to the fact that the machine's configuration (e.g., the location of the nailer, the location of the saw) is fixed (Figure 3), and the panel moves in a single direction. This entails that if, when the panel is dragged downstream to perform a nailing operation, a drilling location is pulled past the drill (for the nailing operation) without the hole being drilled, the machine cannot pull back the panel to perform this required drilling operation. As such, the sequence of operations needs to be updated in consideration of the machine's configuration in order to generate the correct manufacturing sequence. This is achieved by computing the *x*-position of each operation relative to the various machine components (i.e., nailer, saw, drill) needed for the operation (Equation 1).

$$x'_{t,n} = x_{t,n} - O_t \qquad n = 1, 2, 3, \dots, i \;\; ; \;\; t \in \{N, D, C, K\} \qquad (1)$$

where $x'_{t,n}$ is the updated *x*-position of operation (*t*) in wall panel (*n*), $x_{t,n}$ is the *x*-position based on the panel's geometry only, and O_t is the offset of the machine component(s) needed for operation (*t*) from the machine's zero position (Figure 3). The machine's zero position, it should be noted, is the machine's operational starting point at which the panel's elements are loaded for framing. Accordingly, the value of $x'_{t,n}$ must be a non-negative real number ($x'_{t,n} \geq 0$) in order for the machine to perform the operation. A negative value of $x'_{t,n}$ would indicate that the location on the panel at which the operation must be performed is downstream from the relevant machine component (nailer, saw, or drill) that is to perform the operation, and therefore must be performed manually rather than by the machine.

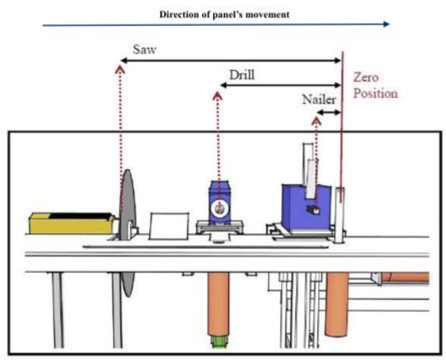

Figure 3. Machine configuration.

Overview of software add-on

The CNC file incorporates various items of information about the required operations, including the 3D coordinates of each operation, the manufacturing sequence of operations, and the type and size of the framing elements for the given panel. An add-on for Autodesk Revit was programmed to automatically extract this information from the BIM environment and generate a CNC file, thereby eliminating the need for any intermediary CAM software. The tool allows the user to set the machine's configuration and then determines the manufacturing sequence in accordance with the logic delineated in the previous section. The current version of the add-on allows the user to enter the nailer offset, the number of drills (if any), the drill offset, the saw offset (if applicable), the location of the panel's top plate with respect to the machine, the maximum height of panels that the machine can frame, and the maximum length of panels. A snapshot of the graphical user interface (GUI) of the add-on is shown in Figure 4.

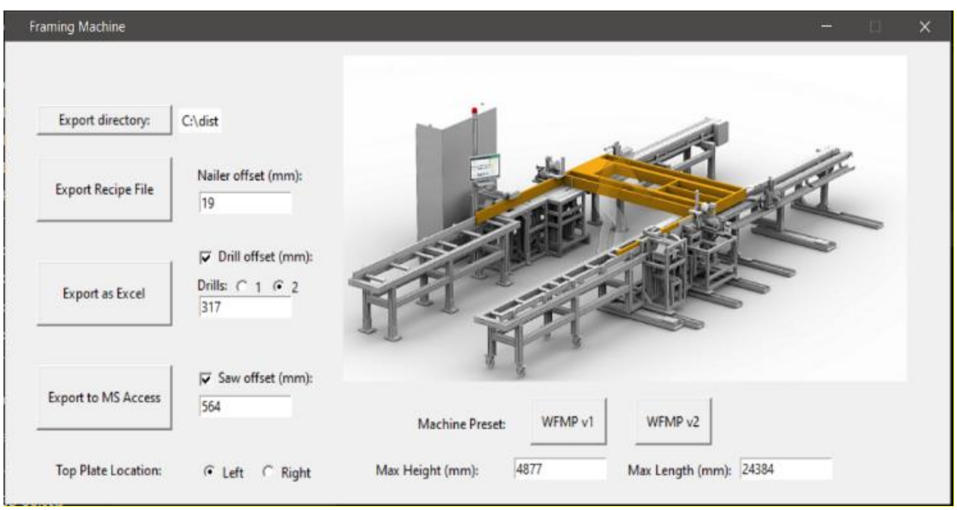

Figure 4. Add-on GUI.

The add-on was deployed to generate CNC files for the Autodesk Revit model displayed in Figure 5. A sample CNC file generated from the add-on is shown in Figure 6. For any panel that cannot be framed using the machine or for any operation that must be manually performed, as previously explained, the tool prompts the user with an error message as shown in Figure 7.

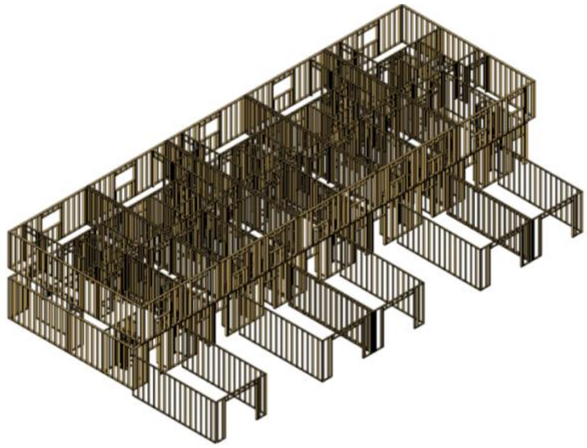

Figure 5. Autodesk Revit model

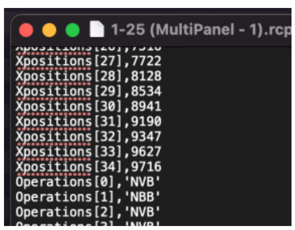

Figure 6. CNC File

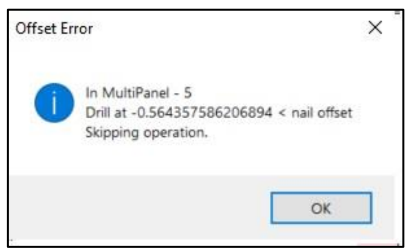

Figure 7. Error message.

The developed add-on also allows the user to extract the operational data into a Microsoft Excel or Microsoft Access format, as shown in Figure 8. These formats clearly structure the data in such a manner that it can be used directly as a point of reference for monitoring the framing process and performing the manual operations.

ID	MultiPanelName	PanelName	Operation	X	Y	Z	Type	Size	Machine	Comp
204	MultiPanel - 6	Panel14	Nail	19	0	70	Stud V	2x6	NVB	
205			Drill	149	0	70			DRB	
206			Nail	375	0	70	Stud V	2x6	NVB	
207			Nail	413	0	70	Stud V	2x6	NVB	KSB
208			Nail	451	0	70	Jack Stud	2x6	NVB	

Figure 8. MS Access file.

CONCLUSIONS AND FUTURE WORK

This research proposed a method to generate CNC files directly from a BIM model, thus reducing the reliance on third-party CAM/CAD tools and facilitating fully automated machine operations in offsite construction. The method was integrated into the Revit environment through a developed add-on for a wood-wall framing machine. The add-on was tested to generate a CNC file for the framing machine under study, wherein the CNC file was fed into the machine, which in turn was able to perform the operations properly based on the CNC file. The main benefits of the developed add-on are that it: (1) saves time and effort by eliminating the need to use separate software solutions to convert design drawings into machine-readable files; and (2) can be customized to match the specifications of a given machine by adjusting the code. Although the current tool allows the user to input some variables concerning the machine's configuration (e.g., nailer offset, per Figure 4), a new version of the tool could be developed that would allow the user to input more variables covering a wider range of CNC machines without needing to adjust the code.

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