Developing a BIM-based Integrated Model for CAD to CAM Building Production Automation

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Abstract –

Modular construction has gained momentum in North America as an emerging construction paradigm in recent years. Modular buildings are assembled from components that are prefabricated in manufacturing plants and transported to the construction site for assembly. The current manual-based approach to modular construction, which typically applies the traditional stick-building-under-a-roof method, is time-consuming and labour-intensive. However, the application of automated prefabrication of components has the potential to significantly advance the productivity, worker safety, and competitiveness of the Canadian construction industry. This research, focusing on the construction of wood-framed panels, presents a methodology which allows intelligent wall panels with different design properties to be analyzed. By integrating external databases with building information modelling (BIM)-based software and generating wall panel combination plans and assembly information, intelligent wall panel prefabrication is achieved. The study of panel prefabrication for a sample house from an Edmonton-based panel manufacturer is presented in order to demonstrate the effectiveness of the proposed methodology.

Keywords –

BIM; Prefabricated wall production; Automation

1 Introduction

Automated construction requires a high level of accuracy in the drafting and design documentation to ensure full compliance with the project pre-planning, project coordination, preliminary design, and transportation plan [3]. However, most design plans do not currently provide complete assembly information. The majority of Canadian homebuilders build without detailed construction drawings since the planning stage is time-consuming and costly. Therefore, they rely on the experience of their carpenters to build homes based on a rough structural design. The introduction of proper construction guidelines to facilitate the shift from the *stick-building-under-a-roof* method to automated manufacturing of wood panels will help to overcome the shortage of skilled carpenters, reduce the high level of timber waste, and improve housing quality, while enabling reduced construction cycle time. Guidelines are proposed for improved panel assembly practice, and the linkage between drafting (i.e., computer-aided design) and manufacturing (i.e., computer-aided manufacturing) is developed.

Facilitated by industrialized construction methods, multi-panel wood wall-framing is applied in place of single-wall framing (as illustrated in Figure 1). A multi-panel arrangement is utilized to reduce the machine set-up time. The multi-panel is partially pre-cut by the wood panel framing assembly to provide easy separation into single-wall panels at a later stage. Autodesk Revit, as one type of building information modelling (BIM) software, provides a means to generate and manage data based on user requirements. After loading the details in order to generate a 3D model, and then extracting information from the structural plan of the BIM model panels, the nailing, drilling, and cutting coordinates are used to analyze and establish a guideline for further BIM-based construction assembly.

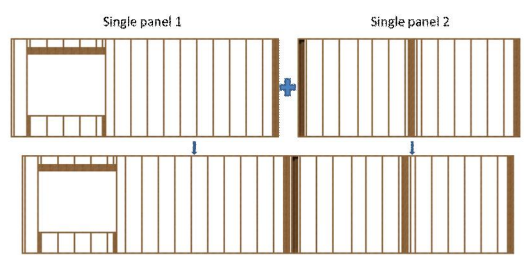

Figure 1. Multi-panel example

2 Review of the State of the Art in Building Production Manufacturing

Factory construction is to be promoted in the homebuilding industry because a controlled environment improves product quality and performance and lowers cost. Since the products are built in a factory, the principles of mass production can be applied to leverage the benefits of a manufacturing-based approach [5]. Mass production of housing components and systems reduces construction duration by half and cost by at least 20% [1]. However, when materials and information are defective or idle, manufacturing-based construction methods can lead to significant waste of resources. The implementation of lean tools to replace mass production involves industrializing home building to improve efficiency [4]. In 2008, approximately 10% of new residential homes were built in factories either as panelized or modular in the United States [7]. However, challenges still remain in making the process more lean, since home building involves a high level of customization and multi-faceted characteristics in the production process. Panels for a specific home possess a diversity of dimensions and design properties which require different amounts of processing time in the production line; the relatively low production volume of specific house models inhibits the full deployment of lean tools [6]. Furthermore, as discussed by Bock [2], the conventional construction methodology has become stagnant and has reached its technical limits. Although efforts toward construction automation are still at the innovation stage, continued research and development targeting automation will propel construction into the growth phase.

3 Mehodology

The key contributions of this methodology are the generation of wood panel framing assembly motion plans, which implement the industrialized manufacturing of intelligent wall panels and are ready for programmers to establish computer numerical control (CNC) code. The BIM model provides rich information for wall assembly such as wall dimensions, stud details, and prefabricated opening component details. As shown in Figure 2, the methodology used to generate operation locations from the BIM model consists of the following three procedures: (1) load framing information into the BIM model; (2) extract framing information from the BIM model to Microsoft Excel; and (3) generate the cutting, drilling, and nailing locations guideline based on real-world on-site experience and construction specifications. Based on the operation coordination and each machine station location, the sequence and interval distance of each operation can be determined.

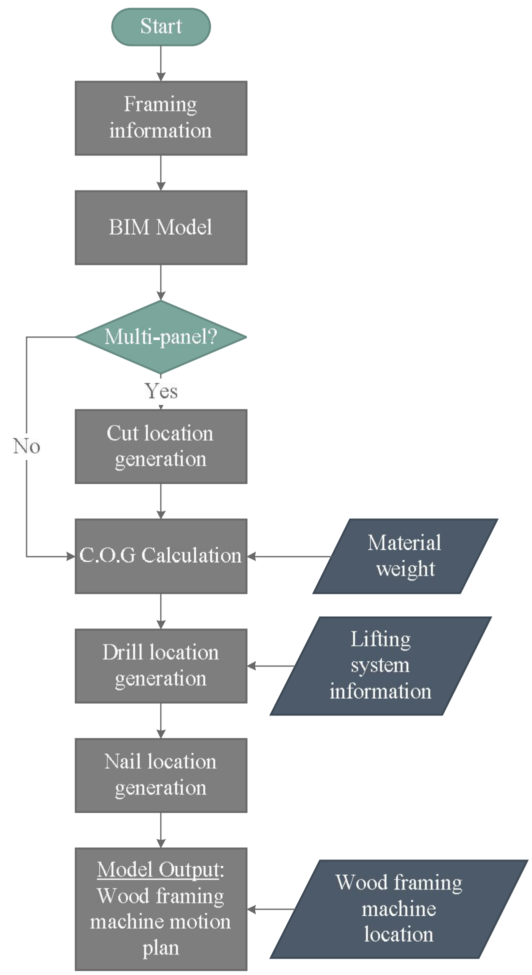

Figure 2. Methodology

4 Operation Sequence Development

Based on current assembly requirements for panels, the assembly process can be subdivided into three parts: (1) treating the stud as a consistent interchangeable part, simplifying the process of loading and attaching them to one another; (2) drill the top- and bottom-plate, which will help facilitate lifting requirements in downstream stations; and (3) after assembly of a given panel is complete, the cut operation should proceed to precut the multi-panel. Based on the operation locations, the sequences of motion for three stations can be determined for the purpose of ensuring that the multi-panel will be manufactured completely and smoothly by the wood panel framing assembly.

4.1 Load framing information

The goal for the automation of wall-framing manufacturing is to build a bridge between the housing wall layouts from the Revit software and the factory panel manufacturing process using BIMSF_Id, which is an identification tag for each wall framing. When generating the wall-framing layout using Revit, each BIMSF_ID is formed automatically for each wall panel using the Revit add-on. The factory plant will identify the BIMSF_ID and will assemble the panel based on the wall-framing layout; the same BIMSF_ID is used to label the finished panel.

4.2 Extract information from BIM model

According to the wood wall-framing table assembly manufacturingrequirements, the information being extracted from the BIM (Revit) model includes: (1) wall properties from the BIM model such as wall details (top- and bottom-plate length (L_{swm}), wall height (H)); (2) sub-wall IDs (m) contained within each multi-panel; and (3) user-defined framing specifications such as number of nails per stud (N), and number of drill holes per wall (D_m). At this point, this data can be used to generate nail, cut, and drill locations, as well as IDs. The drill location must also contain stud location information in order to detect potential collisions, and thus can adjust accordingly.

The coordinates of each stud and each sub-wall belonging to the multi-panel can be extracted based on the origin, as shown in Figure 3. The absolute origin is set as the multi-panel's first stud outside boundary (home position) for $x = 0$; therefore, each stud's absolute x-coordinate is its x-direction centre-point-to-home-position distance. Stud absolute z-coordinates represent each stud z-direction centre-point touching top- or bottom-plate position facing up or down relative to the z-axis. Vertical orientation stud z-coordinate is set to 0, as expressed in Figure 4(a). In this case, the stud orientation and position can be distinguished by the absolute z-coordinates. If the value of z is negative, this stud is horizontal and on the bottom edge of the top-plate, as seen in Figure 4(b). If the value of z is positive, this stud is horizontal and on the top edge of the top-plate as shown in Figure 4(c). The absolute y-coordinate of the bottom-plate outside boundary is set to 0; accordingly, the top-plate outside boundary y-coordinate will be the multi-panel height, h.

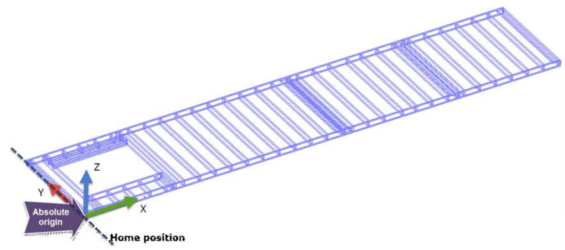

Figure 3. Multi-panel absolute origin and home position

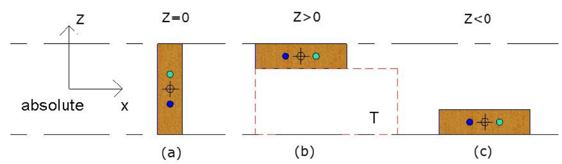

Figure 4. Stud orientation relative to Z coordination

4.3 Generate operation locations

Based on the information obtained from the BIM model, cutting, drilling, and nailing locations for multi-panels can be generated and prepared for the analysis of wood wall-framing operation procedures. If the panel only contains one single panel, which means it is not a multi-panel, the cut location generation step can be skipped.

4.3.1 Generation of cut location and IDs

The first cut location depicted in Figure 5 is located at the end-point of one sub-wall and the second cut location is located at the start-point of the following sub-wall. A ranking of non-zero start and finish sub-wall x-coordinates will be used to obtain the cut locations. All cut locations will be partially cut as expressed in Equation (1) and Equation (2) except the last cut location, since it is coterminous with the multi-panel end-point. At that point, the cutting machine must cut and separate extra top- and bottom-plates completely, as expressed in Equation (3). The cut locations are generated based on the start and finish x-coordinates of sub-walls.

Location of partial cuts:

$$XC_a = XSWS_m - \text{Saw thickness}\,(XSWS_m \neq 0) \quad (1)$$

$$XC_a = XSWF_m\ (XSWF_m \neq L) \quad (2)$$

Location of complete cuts (multi-panel end-point location):

$$XC_a = L \quad (3)$$

where

a: cut ID for multi-panel

m: ID of sub-wall

XC_a: a^th^ cut distance from home position

$XSWS_m$: m^th^ sub-wall start-point x-coordinate

$XSWF_m$: m^th^ sub-wall end-point x-coordinate

L: multi-panel length

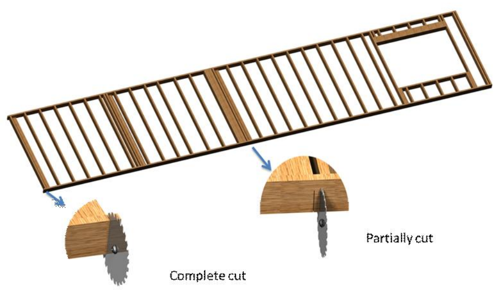

Figure 5. Sample multi-panel cutting location

4.3.2 Generation of drilling locations

There will be drill holes made on each sub-wall to facilitate any necessary lifting actions at further stations, and for transferring to site. The default setting for the number of drill holes on each sub-wall (D_m) is two; however, the user can define the settings to their own requirements. In analyzing the drill hole locations, the location of the centre of gravity (COG) should be considered. If the sling legs are the same length, failure to establish precise COG will create an imbalance in the tension in each sling and cause the load to tilt during lifting. Therefore, the COG should be identified for each single panel first. The drilling points on either side should ensure that the COG is located at the exact midpoint between them to avoid any unplanned movement during lifting due to imbalance (Unirope Slingmax 2015). Since the multi-panel is not symmetrical, the COG may not be located exactly in the middle of the multi-panel. Therefore, in the research, the drill hole location could range anywhere from the COG to the point permitting maximum lift capacity without spreader beam failure, and the optimal drill position will be the spreader beam length, as illustrated in Figure 6. Since the drill machinery has a certain distance to the panel home position, if the drill hole falls within that range then it should be drilled manually. The optimized drill hole locations are determined using Equation (5), with the method summarized in Figure 6.

COG location:

$$COG_m = \sum(m_i \times l_i) / \sum m_i \quad (4)$$

where i = 1,2,3…. total number of members (studs, plates, headers, etc.) in the m^th^ panel.

Optimized drill hole location:

$$XDi = XSWS_m + COG_m + (-1)^i \times L_{sb}/2 \quad (5)$$

where

m_i: i^th^ member mass of the panel

l_i: i^th^ member origin along the panel's x-axis

i: hole ID

L_{sb}: spreader beam length

XD_i: i^th^ hole distance from home position

COG_m: m^th^ sub-wall COG to home position length

$XSWS_m$: m^th^ sub-wall start-point x-coordinate

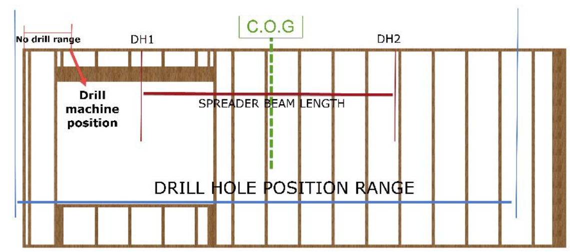

Figure 6. Sample panel of drilling location

4.3.3 Generation of nailing locations

Wall studs and pre-assembled window and door frames are joined with top- and bottom-plates using nails. Depending on the elements belonging to the wall, the top-plate stud number and location may be different from the bottom-plate. Figure 1 depicts an example of a multi-panel with an opening component (window) where the bottom cripples only touch the bottom-plate and do not connect with the top-plate. Therefore, the top- and bottom-plate nailing plans should be analyzed separately.

The default setting for the total number of nails on a stud is two. However, users can specify this setting if necessary, e.g., j^{th} stud on top (T) has N number of nails (NT_j), or k^{th} stud on footer (B) has N number of nails (NB_k). The *y*-coordinates of the bottom-plate nails will be 0 and top-plate nails' *y*-coordinates will be H. Sample nailing *x*- and *z*-coordinates on the horizontal and vertical studs are presented in Figure 4. When the stud is horizontal ($Z \neq 0$), the nails on the *x*-axis position of that stud should be evenly distributed along the stud width. The *z*-coordinates of the nails should be the same as the *z*-coordinates of the stud since they are along the midpoint of the stud thickness. When the stud is vertical ($Z = 0$), the nails on that stud should be evenly distributed across the stud width throughout the *z*-axis. The *x*-coordinates of the nails should be the same as the *x*-coordinates of the stud since they are along the midpoint of the stud thickness. The methodology of nailing coordinate generation is also presented in Figure

4, and expressed in Equations (6) to (17).

Nail locations for horizontal studs at top-plate side ($YT_j \neq 0$):

$$XT_{jn} = [XT_j - (d/2)] + n \times [d / (NT_j + 1)] \quad (6)$$
$$YT_{jn} = H \quad (7)$$
$$ZT_{jn} = ZT_j \quad (8)$$

Nail locations for vertical studs at top-plate side ($YT_j = 0$):

$$XT_{jn} = XT_j \quad (9)$$
$$YT_{jn} = H \quad (10)$$
$$ZT_{jn} = [Z_j - (d/2)] + n \times [d/ (NT_j + 1)] \quad (11)$$

Nail locations for horizontal studs at bottom-plate side ($YB_k \neq 0$):

$$XB_{kn} = [X_k - (d/2)] + \{n \times [d / (NB_k + 1)]\} \quad (12)$$
$$YB_{kn} = 0 \quad (13)$$
$$ZB_{kn} = ZB_k \quad (14)$$

Nail locations for vertical studs at bottom-plate side ($YB_k = 0$):

$$XB_{kn} = XB_k \quad (15)$$
$$YB_{kn} = 0 \quad (16)$$
$$ZB_{kn} = [ZB_k - (d/2)] + \{n \times [d / (NB_k + 1)]\} \quad (17)$$

4.4 Wood framing assembly motion plan

In order to achieve successful operation of the wood panel framing assembly, the nailing, drilling, and cutting operation sequences must be determined based on the multi-panel layout that has been generated from the BIM model. After generating and sorting the manufacturing operations based on the equipment locations, the multi-panel moving distance from pervious task point to next task point are confirmed in order to avoid the omission of any necessary steps or any other conflicts. Therefore, the entire manufacturing plan can be determined.

4.4.1 Calculation of operation locations relative to corresponding machine

Each machine location to multi-panel home position possesses a certain distance. Therefore, operations reaching their corresponding machine distances are the operation locations related to their machine locations (operation locations minus machine locations). The operation locations related to their corresponding machine location can be calculated as per the following equations.

$$D_i = XD_i - D_d \quad (18)$$
$$C_c = X_c - D_c \quad (19)$$
$$NT_n = XTj_n - D_n \quad (20)$$
$$NB_n = XBj_n - D_n \quad (21)$$

where

D_i: i^{th} drilling coordinates
C_c: c^{th} cutting coordinates
NT_n: n^{th} top side nailing coordinates
NB_n: n^{th} bottom side nailing coordinates
D_n: distance from nailing station machine to home position
D_d: distance from drilling station machine to home position
D_c: distance from cutting station machine to home position

5 Results and Discussion

Multi-panel #1, as shown in Figure 7, is selected from an Edmonton-based panel manufacturer as a sample in order to generate operation locations and machine motion sequence.

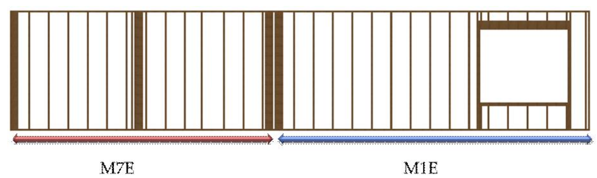

Figure 7. Multi-panel #1 – sample from manufacturer

5.1 Cut locations

The information extracted from multi-panel #1 for cut location calculation is presented in Table 1.

Table 1. Sample multi-panel information (1)

Multi-panel length	39.739	Total number of sub-walls (SW)	2
Sub-wall ID (m)	Sub-wall length (Lsw_m)	Sub-wall start-point *x*-coordinate ($XSWS_m$)	Sub-wall end-point *x*-coordinate ($XSWF_m$)
1	21.604	0.000	21.604
2	18.052	21.687	39.739

Cut locations for a multi-panel are located at the end of the first sub-wall, as well as at the start- and end-points of the remaining sub-walls consecutively; all will be partially cut other than the last point, which is located at the end of the entire panel and will thus be completely cut. The saw thickness for the cutting station is 0.07 ft. The cut location (X_a), which is calculated according to the methodology, is presented in Table 2.

Table 2. Cut location coordinates

Cut type	Cut ID (a)	Cut distance from home position (XC_a)
Partially cut	1	21.604
	2	21.680
Completely cut	3	39.739

5.2 Drilling locations

The COG location calculations for each single panel are as follows:

COG for M1E
Known values:
All member weights and *x*-coordinates are presented in Table 3.

Table 3. Wall member weights and x-coordinates

Name	Function	Multi-panel *x*-coordinate	Weight (lb)
M1E	OC	0.063	3.790
M1E	OC	0.271	3.790
…			
M1E	T3	4.500	2.941
		Total weight	119.252

Center of gravity (COG) location:

$$COG_m = \sum(m_i \times l_i) / \sum m_i \quad (4)$$

where
i = 1,2,3…. total number of members (studs, plates, headers, etc.) in the m^{th} panel
$\sum$ (mj × member x-coordinate li) = 1,201.495 lb•ft
$\sum m_i$ = 119.252 lb
COG_1 = 10.075 ft

The information from multi-panel #1 for drill location calculation is listed in Table 4.

Table 4. Sample multi-panel information (2)

Sub-wall ID (m)	Sub-wall start-point x-coordinate (XSWSm)	COG	Drill number	Spreader beam length
1	0.000	10.075	2	10
2	21.687	8.612	2	10

The drill location (XD_i), which is calculated according to the methodology, is shown as follows:

Drills #1 and #2
Known values:
Sub-wall ID = 1
COG_1 = 10.075 ft

After substituting the known values for the following equations, the result for the optimized drill location *x*-coordinate is accessible.

Optimized drill hole location:

$$XDi = XSWS_m + COG_m + (-1)^i \times L_{sb}/2 \quad (5)$$

$XD_1 = 0 + 10.075 - (-1)^1 \times 10/2$ = 5.075 ft.
$XD_2 = 0 + 10.075 - (-1)^2 \times 10/2$ = 15.075 ft.

The *x*-coordinates for drill holes in multi-panel #1 are listed in Table 5.

Table 5. Drill location coordinates

Drill ID (i)	Drill distance from home position (XDi)
1	5.075
2	15.075
3	25.299
4	35.299

5.3 Nailing locations

The nail locations are determined by the coordinates (*x*, *y*, *z*) and the type of object, which can be extracted from Revit and regarded as known values. The number of nails on each object is set to 2. The information extracted from multi-panel #1 for nail location calculation is listed in Table 6. Stud 1 is used as the example to show the nail location generation.

Table 6. Sample multi-panel information (3)

Name	Type	IsTop	IsBottom	X	Z
M1E	2×6	True	True	0.063	0.000
M1E	2×6	True	True	0.271	0.000
M1E	2×6	True	True	1.318	0.000
M1E	2×6	False	True	1.443	0.000
…					
M1E	2×6	True	True	21.250	–0.167
M1E	2×6	True	True	21.542	0.000

For stud j = k = 1 (Vertical stud)
Known values:
Stud j = 1, k = 1
Stud dimensions (2×6 type) b = 0.125, d = 0.4583
Midpoint coordinates (XT_1, ZT_1) = (XB_1, ZB_1) = (0.063, 0)
User-defined values:
Number of nails on stud NTj = NBk = 2

After substituting the known values in the following equations, the results for nail location (XT_{jn}, YT_{jn}, ZT_{jn}) and (XB_{kn}, YB_{kn}, ZB_{kn}) can be found.

Nail locations for vertical studs on the top-plate side ($YT_j = 0$) can be determined as follows:

$$XT_{jn} = XT_j \quad (9)$$

$$YTj_n = H \quad (10)$$

$$ZTj_n = [Z_j - (d/2)] + n \times [d/ (NT_j + 1)] \quad (11)$$

Nail locations for vertical studs at bottom-plate side ($YB_k = 0$):

$$XBk_n = XB_k \quad (15)$$

$$YBk_n = 0 \quad (16)$$

$$ZBk_n = [ZB_k - (d /2)] + \{n \times [d / (NB_k + 1)]\} \quad (17)$$

$XB1_1 = XT1_1 = 0.063$
$ZB1_1 = ZT1_1 = [0 - (0.4583/2)] + [0.4583 / (2 + 1)] = -0.07638$
$XB1_2 = XT1_2 = 0.063$
$ZB1_2 = ZT1_2 = [0 - (0.4583 / 2)] + 2 \times [0.4583/(2 + 1)] = 0.07638$
$YT1_1 = YT1_2 = 8.03125$
$YB1_1 = YB1_2 = 0$

Nailing point for stud 1: (0.063, 8.03125, −0.07638), (0.063, 0, −0.07638), (0.063, 8.03125, 0.07638), (0.063, 0, 0.07638)

Utilizing the methodology to generate the nail locations, the nail locations for the entire multi-panel are determined. The nail locations for the top-plate are sorted based on the *x*-coordinates of each nail, as presented in Table 7.

Table 7. Sample top-plate nail location coordinates

j	Nail number	No.	X	Y	Z
1	2	1	0.063	8.031	−0.0760
		2	0.063	8.031	0.0760
2	2	1	0.271	8.031	−0.0760
		2	0.271	8.031	0.0760
3	2	1	1.318	8.031	−0.0760
		2	1.318	8.031	0.0760
…					
21	2	1	21.174	8.031	−0.1670
		2	21.326	8.031	−0.1670
22	2	1	21.542	8.031	−0.0760
		2	21.542	8.031	0.076

5.4 Wood framing assembly motion plan

Since all the operation locations are calculated based on the home position of multi-panel #1 from Section 4.3, the operation locations must be subtracted from the wood panel framing assembly location in order to obtain the actual distance from the operation point to the machine location. The first top-plate nail, first drill, and first cut are used as examples to show the operation locations related to their machine location.

$$D_i = XD_i - D_d \quad (18)$$

$$C_c = X_c - D_c \quad (19)$$

$$NT_n = XTj_n - D_n \quad (20)$$

$$NB_n = XBj_n - D_n \quad (21)$$

$D_1 = 5.0375 - 1.75 = 3.2875$ ft
$C_1 = 21.604 - 3.0833 = 18.5210$ ft
$NT_n = 0.0625 - 0.0625 = 0$ ft
$NB_n = 0.0625 - 0.0625 = 0$ ft

All the multi-panel operation distances are generated and sorted from smallest to largest, and are listed in Appendix D.

6 CONCLUSION

This paper provides proper panel assembly guideline information to implement the process of industrialized manufacturing of wood panels. The challenge in improving the home building panel manufacturing system is the high customization level in home models and styles. For completing the panel manufacturing, the process has been broken down into three parts: cutting, drilling, and nailing. The next step is analyzing operation location information from the BIM model using an algorithm to generate a database for automated operation locations. The proposed methodology is tested by an industry partner house model that ensures the algorithms cover different panel manufacturing scenarios. The use of BIM-based integrated panel information such as nail, cut, and drill locations reduces the dependency on skilled carpenters to assemble the panels, and thus will save time and reduce the risk of human error by enabling efficient information exchange between Revit and Microsoft Excel. Therefore, the guideline bridges the gap between manufacturing and drafting, providing a complete solution from the BIM model to manufacturing.

In future research, based on the algorithm of the operation locations, a program can be developed in the .NET API in order to generate computer numerical control (CNC) code in Revit which can be readily input into the assembly.

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