Automatic Sizing of Wood-framing Crews Through BIM for Training and Educational Purposes

Abstract
This paper presents a contribution towards integrating field-level construction knowledge in BIM models. Specifically, the paper presents a simplified formula that allows using BIM information to automatically select the optimal crew size for wood-framing activities. The derivation of this formula consisted of first developing a method to automatically generate a list of tasks such as lumber handling, measuring, cutting, placing, and nailing as well as the list of task precedents. The task precedents were generated by applying geometrical and technological reasoning to the BIM model while the duration for each task was determined based on direct observation of videotaped activities. Second, The optimal crew size was calculated by using each of the available resource leveling rules in Primavera (P6). In each case, the Late Start (LS) leveling priority rule gave the total shortest duration. Based on the findings, a decision matrix for calculating the optimal crew size was created and a step function was derived from it. Third, Autodesk Revit Structure with a particular add-on feature was used to depict how a crew size can be extracted directly from a BIM model. The paper indicates how this approach can be integrated in project management for increasing the productivity and safety of framing operations (training purposes), as well as how sizing the framing crew will be taught in any construction curricula that have a BIM lab component (educational purposes).

Key Words: *crew size, resource leveling, micro-scheduling, BIM, training, education**

1. INTRODUCTION

In construction industry, decisions made on site have a crucial influence on the crew productivity (for a literature review of this point, see Day et.al. 2007, and Styhre and Josephson 2007). These field decisions are largely based on the knowledge and expertise of the foremen. Experienced foremen know instinctively how to size the teams to ensure maximum productivity. Unfortunately, with the aging of the construction workforce, this skill of the foremen is rapidly vanishing. For the purpose of this paper, we will call a "crew" a group managed by a foreman and a "team" the sub-group that is given specific tasks within a crew. For instance, a crew of framers can have five members and may be split up by the foreman into a team of two and a team of three framers. This research focuses on developing calculation to determine the most effective crew size using information readily available in BIM models. We decided to select wood framing as a test case because (1) most BIM programs (such as Revit or ArchiCAD) already have the capability to automatically design and represent all the elementary components (studs and plates) of wall frames; and (2) we had access to jobsites where wood framing was taking place. The term "task" refers to elementary actions, such as lumber handling, measuring, cutting and marking, placing, and nailing. Due to the detailed level of the activity (task) description - lower than level 5 in the CSI work breakdown structure in the CSI Master Format 2010 – the scheduling of the tasks will be referred to as "micro-scheduling". While the study focuses on framers involved in the production of wood frames for partitions and exterior walls, the presented method can be applied to any other construction activity.

2. PROBLEM STATEMENT

Construction crew productivity and its impact on project cost and schedule has been the focus of construction research for a long time (Randolph, Amr, 1995). Liberda et al. 2003, laid lot of emphasis on the importance of external factors affecting labor productivity. However, Richardson's (2003) study concluded that while the idea of craft involvement in solving productivity is not new, it is hardly practiced on construction sites. Prior research has focused on optimization at the level of operations above the whole crew. The focus of the latest research appears to be on newer algorithms for minimizing the duration of repetitive projects with probabilistic activity durations, while achieving continuous resource utilization (Srisuwanrat, 2009). Other authors (Kastor & Sirakoulis, 2009) were concerned with the handling of scarce resources by the various PERT/CPM software packages.

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New concepts, such as "critical sets" and "critical clouds" are proposed by Rivera & Duran (2004). Rivera & Duran provide a consistent and unified treatment of criticality in projects with resource constraints, but the application of their algorithm is still aimed towards the above crew level of the project. While these algorithms are useful for optimizing whole projects, schedulers, field management and crafts people need simpler principles to optimize the productivity of their crews and a quick and automatic way to size them. The case studies presented in this paper compare resource leveling algorithms and priorities in Primavera (P6) to determine the optimal size of crews. The research considers the limitation of resources (number of framers) and the pool of available tasks required to be accomplished for completing wood frames of interior and exterior walls. The reason behind selecting Primavera (P6), as well as using micro scheduling for crew sizing was addressed in a previous paper (Maghiar et. al., 2010).

3. OBJECTIVES

The main objective of this research is to use the information available in BIM models to determine the optimal size of framing crews. This information includes the shape and connections of each component of wooden frames (studs and plates). Specifically, the following four goals were established:

1. Determine an implementation methodology for team and crew sizing to improve on site productivity.
2. Test the possibility of automatically generating tasks from BIM models.
3. Application of the BIM information in the decision matrix to determine crew size for training and educational opportunities.

4. METHODOLOGY

To achieve the objective of this research, the videotapes of four stick build wood framing structures were analyzed. Each lumber element was assigned a specific code based on the observed sequence of their placement in frame. Each task performed on these elements and its duration (in seconds) was then recorded in a table. For instance, the task "cutting" can be applied to any of the studs in the frame. Cutting is preceded by measuring and marking. Three types of constraints were then applied to each task: precedence constraints, resource availability constraints for specific tasks, and resource continuity constraints for specific tasks. To obtain a practical and efficient schedule, it was essential to account for these above mentioned constraints in micro-scheduling. A precedence network was then created for all the tasks of each frame. Each individual task was assigned the resource of one framer, and the duration (in seconds) obtained from the recording. The precedence network was then run on Primavera (P6) program with each of the available resource leveling options, while increasing resource limits until the total duration of the activity (building the frame) stabilized at an absolute minimum value (i.e. adding more framers would not reduce the total time of building the frame). The results were then analyzed and used to create a decision matrix to calculate the exact crew size. Finally BIM software, namely Revit Structure with an add-on component called MWF (Metal Wood Framer), was used to obtain primary components to the level of studs and plates that could easily be inserted in the decision matrix for obtaining crew size.

5. CASE STUDIES

Figures 1 to 4 show the four as-built frames with all the elements represented by a two-digit code (01, 02, 03, etc.). Seven different types of tasks were identified and assigned to each element. The following notation was used to describe each task and element. H XX Handle element XX; T XX Tape measure and Mark element XX, M XX YY Measure and Mark element YY on element XX (Note that measuring and marking are one task, as one has no practical value without the other); C XX Cut element XX; P XX Place element XX; N XX YY Nail element XX to element YY ((either through or toe nailing - the head of the nail is in element XX). For example, the available tasks pertaining to element 6 in Figure 1 (frame 1) are as follows: H 06, T 06, C 06, P 06, M 06 05, M 06 10, M 06 13, M 06 14, M 06 15, M 06 34, M 06 78, N 06 02, N 06 34, N 06 05, N 06 78, N 06 10, N 06 14, N 06 15 and N 06 19. It is worth noting that element 3 and 4, as well as 7 and 8 form two sub-assemblies. Once nailed, they form new elements E 34 and E 78 that are dealt with accordingly. Other forms of sub-assemblies identified were elements 17, 18 and 32 (in frame 2) and elements 29, 30, 31, 32 and 33 (in frame 4).At this stage of the research, we consider these subassemblies a-priority. Further research is needed for the automation of the decision making in regards to these subassemblies. Each task and its associated duration from the videos were then entered in P6 program for each

individual frame. To start with, the level of resource “framer” was set to 1. For instance, if C 15 took 3 seconds and C 18 took 2 seconds (in Figure 1, frame 1), each was introduced with its respective duration.

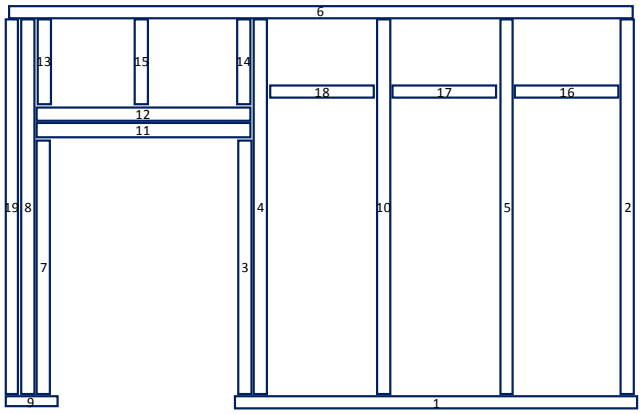

Figure 1. InteriorPartition wall – a wood frame built on-site by framers

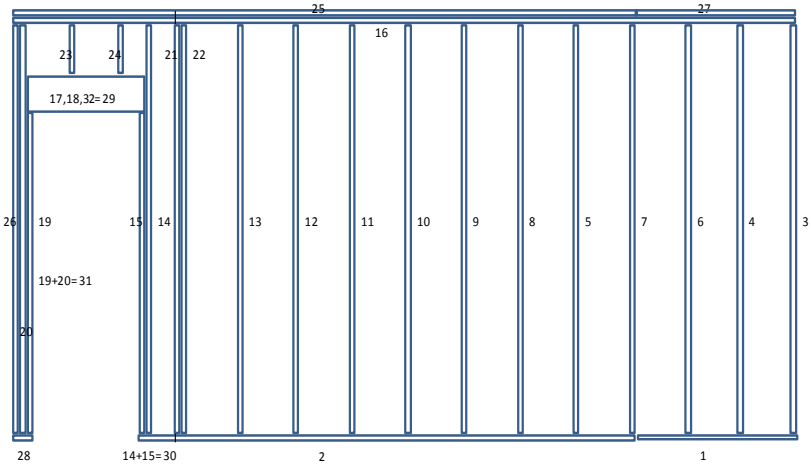

Figure 2. Interior wall with one door opening – wood frame built on-site by framers

Task precedence was determined using elementary geometrical and logical reasoning. These rules consisted of the following precedence chain for every element: Handle, Measure and Mark, Cut, Place and Nail. Note that Nail and Place are both successors of Cut in situations when two elements are nailed together even if they are not yet in their final place. An example is E 03 and E 04 that are nailed together to form element 34. Furthermore, any through nail that is covered by an element (such as N 11 03 covered by 12; figure 1, first frame), will precede the placement of the covering element. The following is an example of the notation: N 11 34 → P 12.Using these rules the precedence table was created semi-automatically using Excel. An excerpt of the precedence table for the first frame is reproduced in table 1. Note how the placing of element 11 and element 12 (i.e. P 11 and P 12) have respectively different types of predecessors. N 11 34 is a through nailing of 11 to 34. Since element 12 covers this nail, P12 is preceded by N 11 34.Special rules were applied for the two existing subassemblies, specifically pertaining to elements 3, 4 and 7, 8 (shown in table 1).

5. RESLUTS OF RESOURCE LEVELING

P6 resource leveling priorities such as Activity ID, Activity Priority, Early Finish (EF), Early Start (ES), Free Float (FF), Late Finish (LF), Late Start (LS), and Total Float (TF) were tested to generate workable schedules. Other priority options, such as Original Duration, by Department, by Phase, by Planned Finished or Planned Start, remaining Duration, and by Responsibility were deemed irrelevant for the purpose of micro-scheduling. The total production time was computed for a matrix of scenarios with constraints on the maximum number of available framers (resources starting from one and going up to a maximum of twenty-six framers for each frame). The result of “Late Start” resource-leveling principle, for the first frame is presented in Table 2.

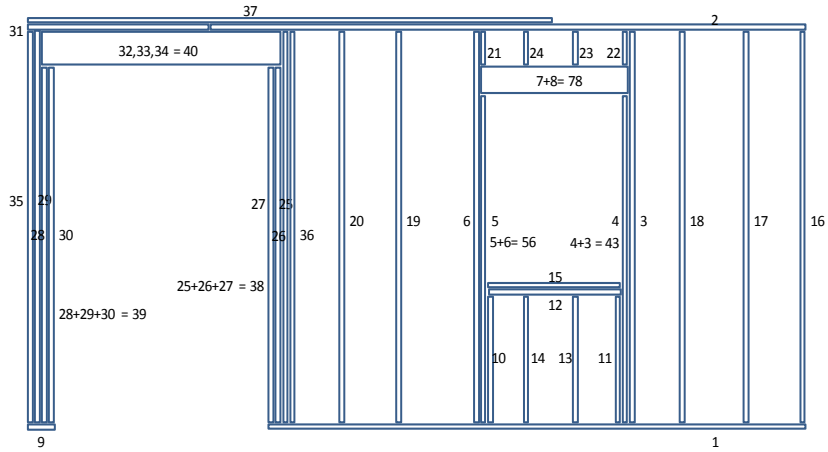

Figure 3. Exterior wall with one door and one window opening– wood frame built on-site by framers

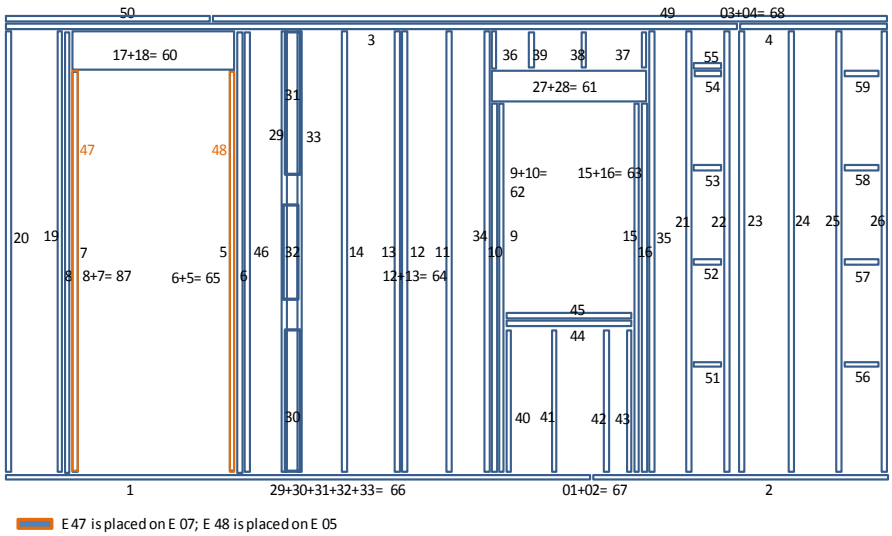

Figure 4. Exterior wall with one door and one window opening– wood frame built on-site by framers

Table 1

Predecessors for elements 11, 12 and predecessors for assemblies 3-4, 7-8

Element	TASKS	Predecessors
E 11	H 11	S
	T 11	H 11
	C 11	T 11
	M 04 11	H 04
	M 08 11	H 08
	P 11	C 11, M 04 11, M 08 11
E 12	H 12	S
	T 12	H 12

Element	TASKS	Predecessors
E12	C 12	T 12
	P 12	C 12, P 11, N 11 34
E 34	M 01 34	H 01
	M 06 34	H 06
	P 34	N 03 04, M 01 34, M 06 34
E 78	M 09 78	H 09
	M 06 78	H 06
	P 78	N 07 08, M 09 78, M 06 78

The productivity of the framers in a team was calculated as the fraction of the total time it took for one framer to complete all the tasks (i.e. a "team" of one framer). Note that in table 2, the total time stabilizes at 76s, with a crew of six framers. Increase in crew size above this limit only reduces the productivity, without any decrease in total production time. The results of the calculations are depicted in the graphs presented in figures5 and 6. Two important trends were observed:

1. Late Start priority rule proved to be the most effective approach for micro-scheduling in all four frames.

2. There is a measurable decrease of productivity when increasing the allocated resources. This decrease is important when deciding to crash a project.

Table 2
Duration and productivity in P6 for Frame 1

No.	Priority rule	Total duration	Resources units	No. People	Total labor (seconds)	Productivity	Crush Duration
1	**Late Start**	384	100%	1	384	100%	100%
		198	200%	2	396	97%	52%
		136	300%	3	408	94%	35%
		104	400%	4	416	92%	27%
		86	500%	5	430	89%	22%
		76	600%	6	456	84%	20%
		76	700%	7	532	72%	20%
		76	800%	8	608	63%	20%

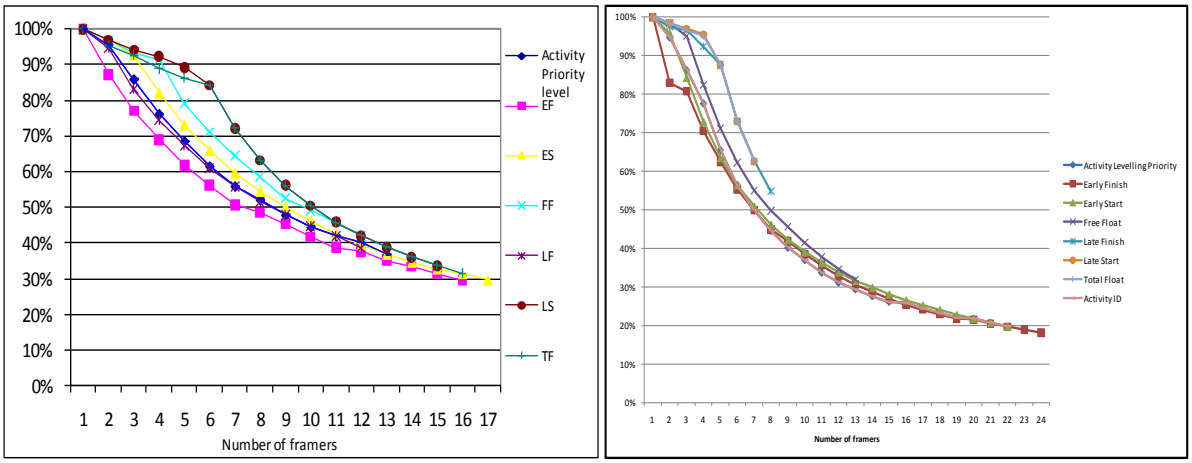

Figure 5. Productivity comparison for different leveling priority rules in P6, first and second frame

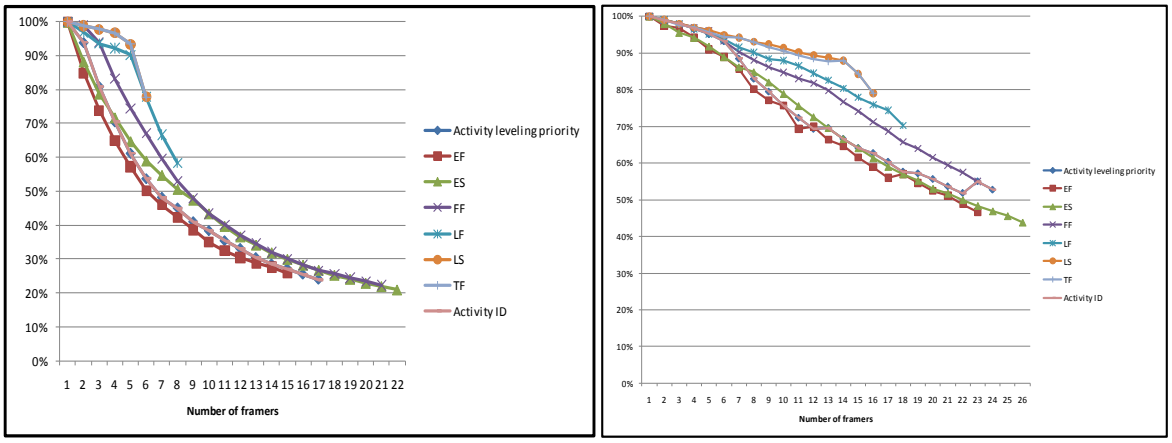

Figure 6. Productivity comparison for different leveling priority rules in P6, for third and respectively fourth frame

Based on the conclusions from the P6 results, the LS priority duration was compared to the Actual execution time as seen in table 3. As expected, in all four studies P6 (LS priority rule) gave shorter execution times when compared to

the actual execution, indicating the scope for productivity improvements (i.e. best possible expected time for the given crew with the given individual skills). .

Table 3
Comparison of Production Time between Actual execution on site and P6

Duration-2 Framers	Frame One	Frame Two	Frame Three	Frame Four
Actual Execution	544 seconds	620 seconds	460 seconds	480 seconds
P6-LS Priority rule	452 seconds	514 seconds	399 seconds	466 seconds

6. DECISION MATRIX FOR DETERMINING OPTIMAL CREW SIZE

Based on the available information and the results from resource leveling (number of framers in the team), the productivity loss dependency matrix was created. The matrix and the three-dimensional graph representing it are depicted in figure 7. A one-framer "team" represents the baseline, as there is no theoretical loss of productivity due to coordination. To ease the reading of the three-dimensional graph, the single-framer "team" was omitted. This matrix allows us to automatically determine the maximum size of a team based on the size of the accepted loss of theoretical productivity. For instance, if a 2% loss of theoretical productivity is accepted, then the maximum number of team members is as follows: Frame 1 – 1 framer, Frame 2 – 2 framers, Frames 3 and 4 – 3 framers).

	Frames			
Framers	**Frame 1 119 Tasks**	**Frame 2 149 Tasks**	**Frame 3 203 Tasks**	**Frame 4 343 Tasks**
1 Framer	0%	0%	0%	0%
2 Framers	3%	**2%**	1%	1%
3 Framers	6%	3%	**2%**	**2%**
4 Framers	8%	5%	3%	3%
5 Framers	11%	12%	7%	4%

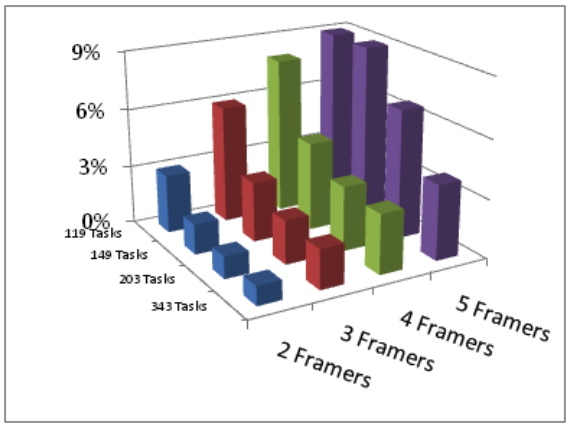

Figure 7. Matrix of different productivity levels and framer availability (with known number of tasks)

An assumption was made that the real-case productivity will be proportional to the calculated productivities. The largest teams we observed had three members which led us believe that the total accepted loss of theoretical productivity is about 2%. Using 2% as a guiding number, the method described above can easily be implemented to size the teams for framing. The guiding principle presented in table 4, is that the number of team members is a step function of the total number of tasks required to build the frame. The critical number of tasks that warrant placing 3 framers on a team (rather than 2) is between 150 (i.e. >149) and 203. We chose the number 200 to compensate for the error in the simplified formula we use in calculating the total number of tasks. A close approximation of the total number of tasks can be obtained by multiplying the number of components by four (each component has Handling, Measuring, Cutting and Placing), adding two more tasks for each point where two components meet (for Marking and Nailing), and then subtracting twice the number of full-length studs. Studs are usually pre-cut, so Measuring and Cutting are not part of the list of tasks. For instance, Frame 1 has a total of 19 components and 32 points where components meet (11 vertical components induce 22 points and 5 horizontal components induce 10 more points). Six (6) of these components are full-length studs. The simplified calculation for the total number of tasks in frame #1 is 19 x 4 + 32 x 2 – 6 x 2 = 128 tasks (compared to the 119 tasks that were observed in the video recording). We tested the team sizing function on Revit Structure with add on component named MWF (Metal Wood Framer). The software correctly generated all the elementary components such as the studs and plates as seen in figure 8. Currently, MWF provides the breakdown of the studs (king studs, jack studs, headers, sole and bottom plates, cripple studs, etc.) which then is added to obtain the total number of studs per frame. This information on the total number of task to be executed in any given frame when used in the production

loss dependency matrix can provide us the optimal crew size. However, further research is needed to determine the exact number of contact points based on the geometry of each frame.

Table 4
Team sizing as function of number of tasks

Number of tasks	<=120	<=200	>200
Maximum Team Size	1	2	3

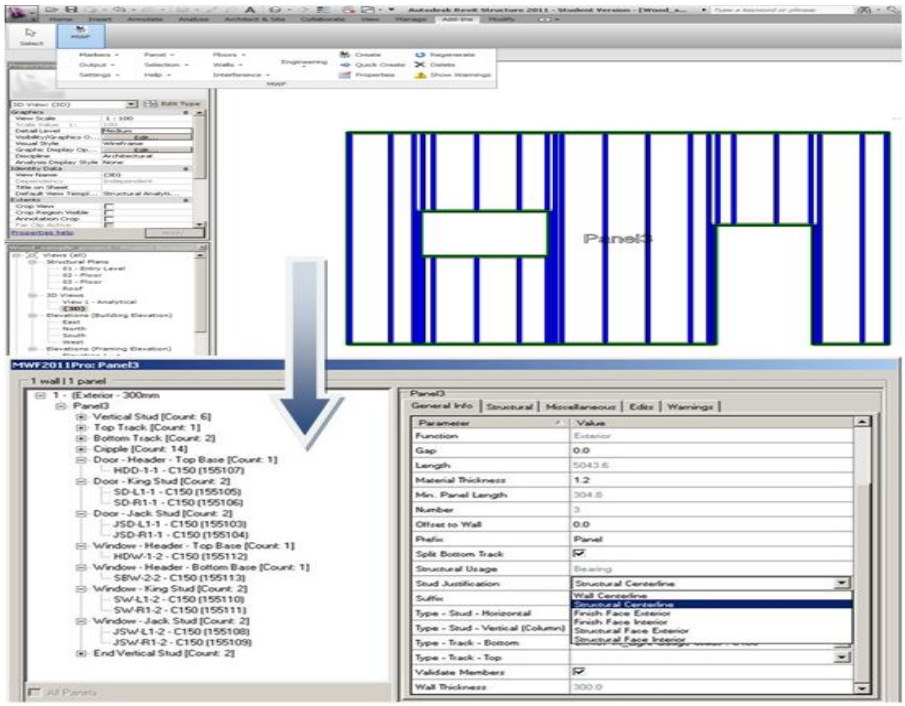

Figure 8. A wood frame BIM model integrating Revit Structure &MWF- generating total studs and plates

7. Discussion and conclusions

The goals of this research and the conclusions are reiterated below:

1. BIM has the capability to build each component of each element (such as studs and plates for wood frames). With relatively simple programming, BIM information can be used for team and crew sizing. An approach similar to the one presented in this paper is probably suitable for crew sizing as well. However, the aggregation of the teams into crews needs further research. The opportunity for research in this paper indicates how this approach can be integrated in project management for increasing the productivity and safety of framing operations (for labor training purposes).
2. Late Start was the most effective criteria for micro-scheduling. However, the sequence of operations on the critical path was haphazard. Our research in this area indicates that certain task sequencing based on simpler, more easily comprehendible for adaptation on site is possible. The results of this research will be published in a follow-up paper.
3. It is possible to calculate the maximum size of the teams without going through the entire process of P6 optimization. Experienced foremen are most likely using a similar approach in a natural, subconscious way. They assign smaller teams (one or two framers) to simpler frames (i.e. fewer components and, hence, fewer tasks) and teams of three framers to more complex frames. The minimum number of tasks for a team of three framers is around 200. The fact that sizing of the framing crews can be taught in any construction curricula that has a BIM lab component represents an educational opportunity to enhance learning in Project Management classes. The learning is enhanced with the hands-on practice of labor crew assignments to various framing jobs.
4. In an academic scenario, students can be taught the principles of this research to develop their understanding of construction on site productivity. They can be given the task of performing videotaped case studies of different

construction activities, generating BIM models in a lab and relating them to the productivity loss decision matrix to determine the crew size. This exercise will help project management students develop BIM knowledge not just as a design tool but as a tool to develop construction field productivity. It will aid in training the new generation while filling the gap on the vanishing skills of the highly experienced foremen.

5. Productivity of framing operations will potentially be increased by using BIM in the pre-planning of the micro-operations. At this stage the possibility to automatically calculate the optimal team size for a frame was proven. More research is needed for the optimization of the crew assignments and the parting of the frame in subassemblies. Furthermore, this research can be used in training construction crews to improve their team productivity while transferring knowledge to the field. Giving each crew member specific tasks, actions to perform will help eliminate errors and improve quality and safety of crew's daily operations.

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