SIMULATION MODEL OF PREFABRICATED HOUSE FROM MANUFACTURING TO ON-SITE INSTALLATION

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ABSTRACT
Prefabricated home building has been becoming a popular construction technique among home builders due to the superior quality, fast production, and design flexibility. Prefabricated home manufacturing is unique from traditional manufacturing industry as every house is somewhat unique due to the customization. This makes it difficult to predict the cycle time of the full production and installation process without a sophisticated model of the entire process. This paper developed a complete simulation model of the prefabricated residential home production process from manufacturing to on-site installation. The simulation model is then utilized for the purpose of calculating required amount of resources such as transportation trucks, cranes and direct labor. Based on the simulation results, different types of house can be scheduled in a way that will provide maximum utilization of different resources. A prefabricated home production facility located in Edmonton, Canada has been used as a case study to develop the simulation model.

Keywords: Prefabricated home production, simulation model

1. INTRODUCTION

Prefabricated building process starts with the virtual creation of the entire house in 3D building information modelling (BIM) software. From the 3D model, all the structural component of the house is verified and then all the materials are ordered and machine files are generated. A typical residential home has mainly three components – wall, floor and roof. All three of these components are manufactured in different areas based on the 3D drawing and then transported to the site for installation. However, the productivity of these three areas is not same and it is important to balance the production of wall, floor and roof components in order to have a smooth flow. After production, wall, floor and roof components/panels are transported and then installed on site using crane. The installation process follows the following sequence – main floor panels, main floor wall panels, 2nd floor panels, 2nd floor wall panels and finally roof panels. Back framing and roof shingling work follows after the completion of the panel installation.

The complete cycle time of a house production depends on the square footage of the house, number of wall panels, floor panels, roof pitch, roof type (gable/hip), number of trailer required, number of windows and doors, distance from manufacturing plant and so on. These different factors contribute towards the productivity of different components, travel time and site installation time. For this reason, it is difficult to predict the total duration of a project and necessary resources required for the job without a detailed model. In order to address this issue, a simulation model has been developed in this study starting from plant production, transportation to on-site installation. ACQBUILT Inc., an Edmonton based prefabricated home builder was partnered with University of Alberta to develop the simulation model of their home production process.

The simulation model has been utilized as a planning tool in various sectors of the construction and manufacturing industry. Its application can improve the understanding of a complex system and can be a useful decision support tool. Many researchers have used simulation models in construction and production planning in order to schedule activities, perform “what-if” analysis, allocate resource, and implement layout optimization. Halpin (1977) has introduced CYCLONE, a simulation environment that created the foundation for the progress of construction simulation. AbouRizk and Hajjar (1998) have proposed a framework for the application of simulation in construction, specifically focusing on construction practitioners. They have presented the concept of special-purpose simulation (SPS), which is a computer-based environment specially built for experts in the area, the advantage of this environment being that the user does not need to have knowledge of simulation. AbouRizk and Mohamed (2000) have introduced Simphony.NET, an integrated environment to model construction activities. This simulation software supports both DES and continuous simulation. It can provide different model outputs, such as standard statistical averages, resource utilization, standard deviation, minima and maxima, and charts such as histograms, cumulative density functions (CDFs), and time graphs. Al-bataineh et al. (2013) have presented a case study in which a simulation model for a tunneling project in Edmonton, Canada was developed in Simphony.NET as a decision support system for the project management team. Alvanchi et al. (2012) have developed a DES model of the steel girder bridge fabrication process for the purpose of providing a solution for the complex process of planning off-site girder bridge construction. Lui et al. (2015) have introduced a Special Purpose Simulation (SPS) template for the panelized construction process and linked the simulation model with building information modelling (BIM). Altaf et al. (2015a) has used the SPS template to build a simulation model of the prefabricated wall panel production process. Lu et al. (2008) have developed an automated resource-constrained critical path analysis using DES and particle swarm optimization (PSO). Based on their study, simulation modelling enables engineers to precisely examine different approaches in order to complete the project. Performing this type of analysis in advance yields reduced costs, improved quality, and improved productivity (AbouRizk 2010). Altaf et al. (2015b) has used simulation and RFID to develop on-line simulation model to get real time feedback from the simulation based on actual production performance. Simulation model have also been in used in prefabricated panelized home production process to resource allocation and optimization of the production schedule. (Altaf et al. 2014a and Altaf et al. 2014b). In the following sections of this paper, the productivity data collection system of wall, floor and roof production area has been presented, followed by simulation input modelling. Then simulation logic and the modeling environment are presented followed by the results and analysis.

2. SIMULATION MODEL

Figure 1 shows the development process of the simulation model. At first, productivity data has been collected from wall, floor and roof production areas as well as transportation time. Based on the collected data, simulation input modeling has been performed to develop mathematical model to estimate production time based on different parameters of the job such as number of wall panel, square feet of floor, roof pitch and type, distance from site, and so on. Then a discrete-event simulation model has been developed using symphony.NET general purpose modeling template. Different parameters of the job are stored in the database which is read by the simulation model to calculate production time, transportation time and number of required trailer per area. The model output will provide total cycle time to complete all the jobs, resource utilization, waiting and bottleneck of the system.

2.1. Process Mapping of the Production Process

The panelized production process starts with drafting the entire house in Building information modeling (BIM) software. Figure 2 shows a wood framed house model drawn in SEMA Software. This model contains all the detail information of the house such as, stud location, nailing pattern, sheathing location, mechanical/HVAC location, crane lift points and so on.

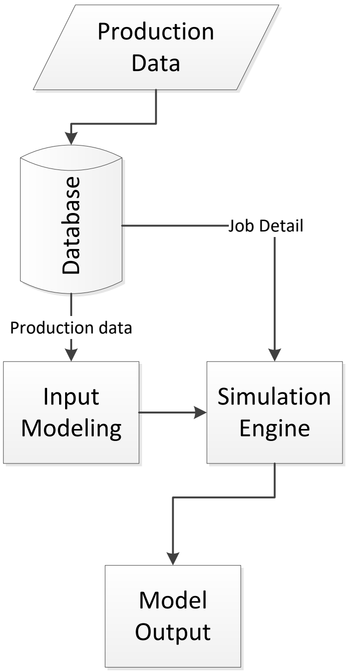

Figure 1: Simulation Model Development Process

After modeling the entire house, machine files are generated from the model, which is read by the CNC machines to pre-cut all the pieces and then build the wall and floor panels in the CNC workstation. Roof panel production is not automated; all the panels are manually built inside the plant in smaller sections and then shipped to the site for installation. After installing the wall, floor and roof panels, back-framing process (installation of the blocking) starts. Figure 3 shows the panelized home building process from manufacturing to on-site installation.

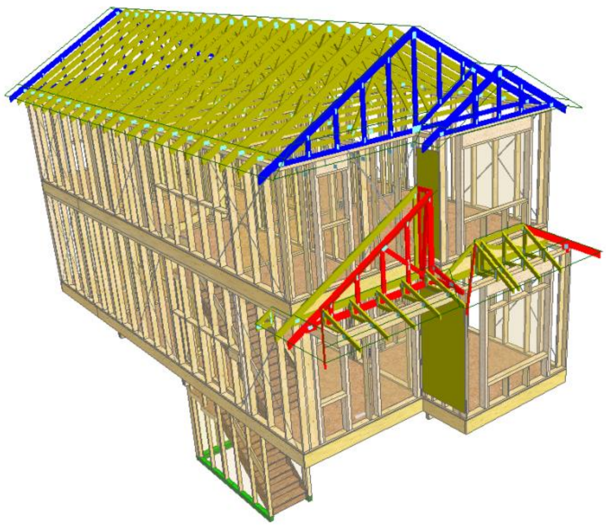

Figure 2: BIM Model drawn in SEMA Software

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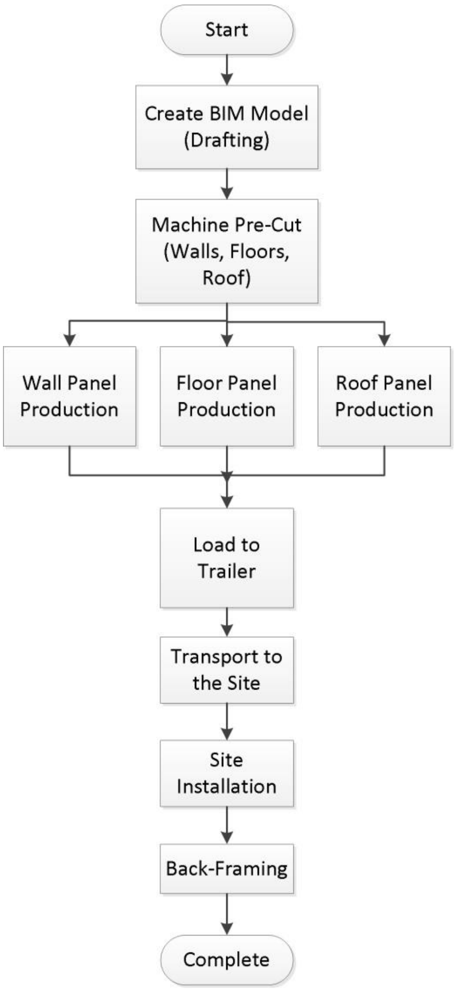

Figure 3: Panelized production process

2.2. Data Collection

Production data has been collected from wall, floor and roof area. The productivity of wall panel production area has been collected using RFID system which automatically collects panel processing time. The floor and roof panel processing time has been collected manually. This data is then used to develop production rate per square feet for each production area. All the transportation vehicles are equipped with GPS tracking device which allows collecting travel time from and to the installation site. Wall productivity is function of wall square footage, floor and productivity is function of floor square footage. The transportation cost is function of number of trailer and travel distance. The field installation time is function of number of panel and square footage of the house.

2.3. Modeling Environment

The simulation model is built in Simphony.NET, a simulation modeling environment, developed by University of Alberta. Simphony's general purpose modeling template has been used to develop the simulation model. The simulation model is linked to a database where all the productivity information as well as job information is stored. After creating the model entity, which represents a job, it read the database to collect number of trailer required for that job for each production area. Then it generates three model entities to represent wall, floor and roof production area. Based on the required number of trailer for each area, duplicate entities are created. Once each entity (now representing one trailer load) is loaded from the factory, transported to the site and lifted with the crane, all the entities marge together into one entity to represent completion of site installation. After that back-framing process starts and then completes the entire job. Figure 4 shows the developed model in Simphony.NET.

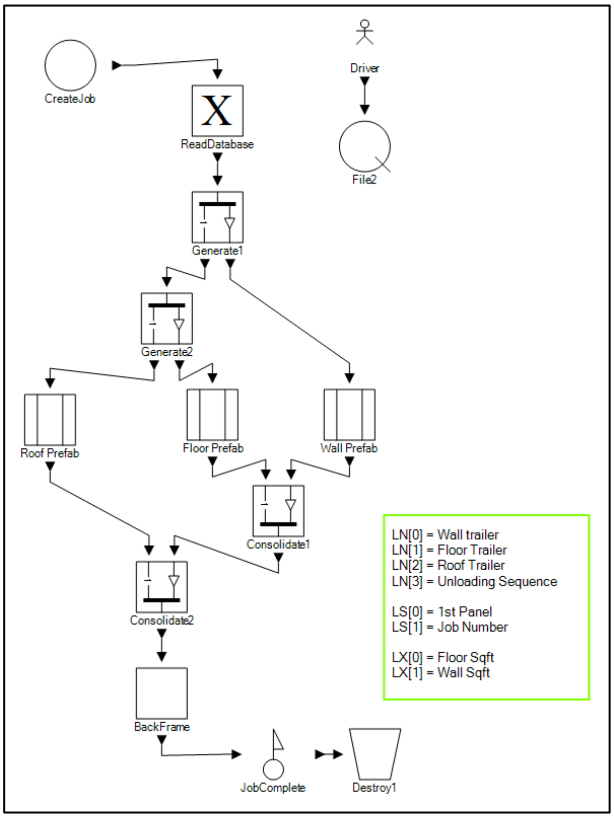

Figure 4: Simulation Model in Simphony.NET

Simphony's general purpose template contains several generic modeling elements which are used to create the model of the panelized production process. These are – *create*, *execute*, *generate*, *task*, *consolidate*, *counter*, *destroy*, *capture*, *resource*, *branch*, *set attribute*, *composite*, and *release* element. *Create* element starts the simulation process by creating entity that passes through different modeling elements. At first the entity goes through the *execute* element which contains the structure query language (SQL) to read the database to get job details. Then using *generate* element multiple entities are created to represent wall, floor and roof panels. In order to keep the model simple, *composite* elements are used to represent wall, floor and roof production process. Each *composite* element contains all the modeling elements required to complete the process. *WallPrefab* composite element is shown in detail in Figure 5 as an example.

At first the entity goes through a *task* element which contains the equation to calculate the panel processing

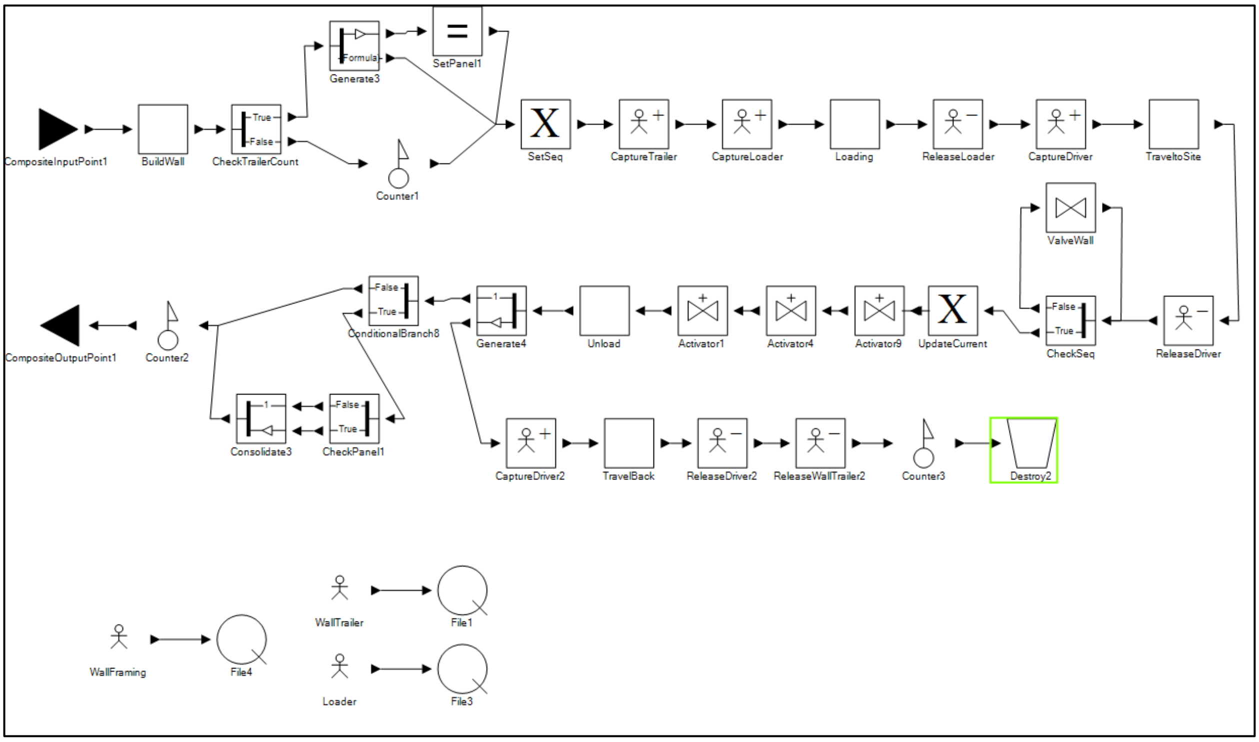

Figure 5: Wall Prefab *composite* element detail in Simphony model

time. The processing time equation is developed based on historical data collected. The model *entity* holds the required square footage information to calculate the processing time. Then another *generate* element is used to generate entities based on the number of trailer required to transport all the panels. This information is also read from the database. Trailer has been set as a *resource* in the model. Based on the availability, the model *entity* captures a trailer and start loading panels into the trailer. This process is simulated using another *task* element which has the loading time equation. In order to complete the loading process, a loader (resource) is required. Once the loading process is completed, the loader is released and any following job can capture the loader. After loading, the entity captures the truck driver (resource) and goes to another *task* element to complete the travel time. After that the drive resource is released and then the entity goes to a *branch* element to check if the current trailer is in order. This is required to simulate the unloading sequence at site. If 2nd floor panel trailer arrives at the site before main floor wall panel trailer, the 2nd floor trailer has to wait until the main floor wall trailer is unloaded and installed. Until the current sequence arrives, the trailer (model entity) will be blocked by a *valve*. All entities will be consolidated into one entity after the completion of the unloading process. Then the entity will go through the final *task* element which represents the back-framing operation. After that, a *counter* is used to collect the model data and the simulation process is terminated.

3. RESULTS AND DISCUSSION

The simulation model of the manufactured home from prefabrication to on site installation has been tested for different house models (attached, detached garage, duplex) and the results are compared with actual performance to validate the model. The simulation model provides the production manager and scheduler the opportunity to plan and schedule the jobs in a most optimize manner. The number of trailer and driver can be adjusted based on the demand which helps to minimize the operation cost. The output from the simulation model is the total time to complete multiple house models, utilization of truck driver and trailer, waiting time for trailer and driver. The simulation model was run for 2 attached garage house and 1 detached garage house model. The square footage of each house and required number of trailers for each work area are summarized in Table 1.

Table 1: House detail for Simulation Modeling

Type	SQFT		No. of Trailer		
	Floor	Wall	Wall	Floor	Roof
Attached Model #1	1656	4263	3	2	2
Attached Model #2	2104	4907	2	2	2
Detached Model #1	1611	3426	1	2	2

Total time required to complete all three houses will be 26 hours from plant production to in site installation and back framing. Numbers of resources inputted in the model are – 7 wall trailers and 10 flat trailers for floors and roof; and 3 truck drivers (Wall trailer is different

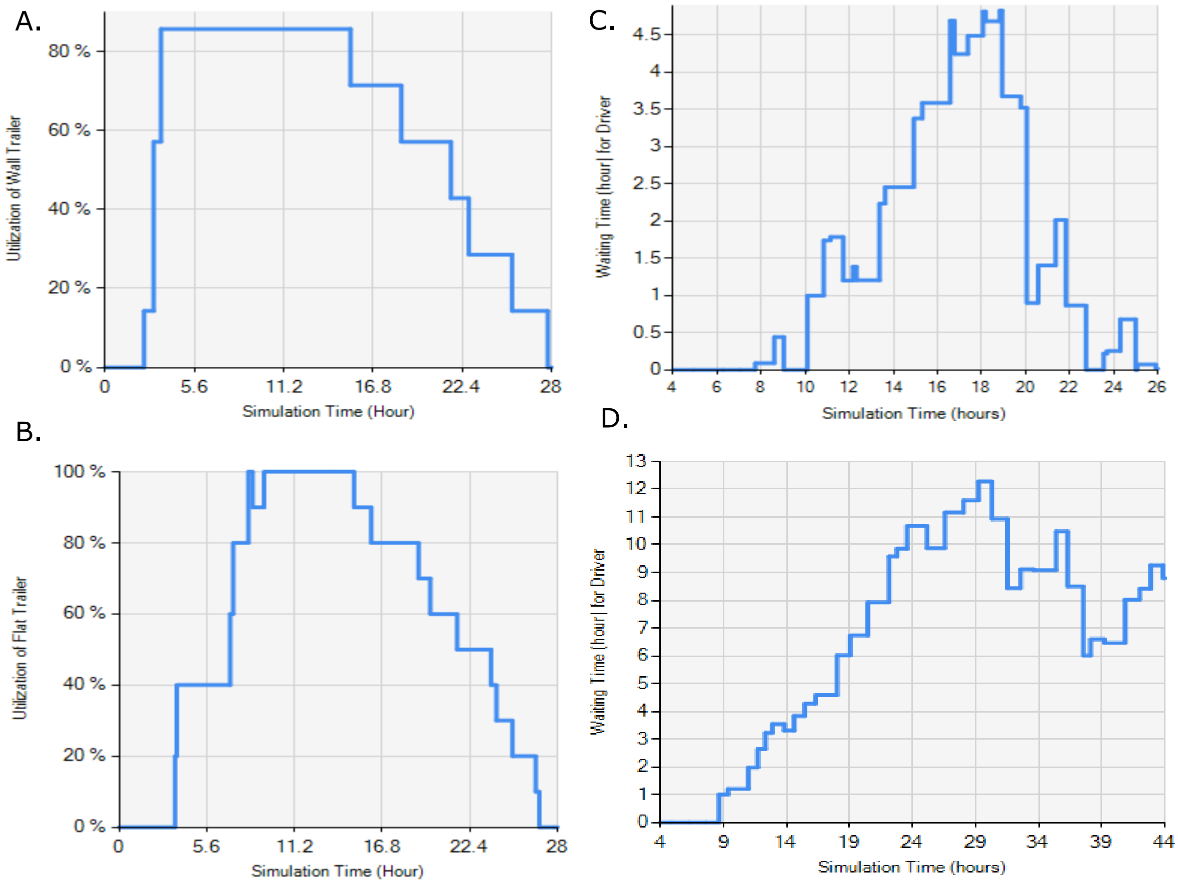

Figure 6: Utilization and waiting time chart from the simulation model – A. Utilization of wall trailer; B. Utilization of Flat trailer; C. Waiting time for driver when 2 driver available; D. Waiting time for driver when 1 driver is available

than floor and roof trailer). Figure 6A and 6B shows the utilization of the wall and flat trailers. The average utilization of the wall and flat trailers are 58% and 56% respectively. If the number of available wall and flat trailers are reduced to 4 and 6 the total time to complete all three houses is also 26 hours. However, the utilization of the wall and flat trailers are 74% and 70%. Similar analysis is done with the number of driver. The result shows that the optimum number of driver is 2 to produce these three homes. If the number of driver is reduced to one, the completion time increases to 37 hours. As shown in the Figure 6C and Figure 6D, the mean waiting time increases from 1.5 hour to 6.5 hour if the number of driver is reduced from 2 to 1. Because of the complex nature of the production process, there are different factors that contribute to the total production time. Even if some panels are waiting for the wall trailer does not always mean that it will delay the entire process as that trailer may need to wait in the site due to the unloading sequence. Thus, it becomes challenging to calculate the required number of resources for a group of house models. A simulation model of the entire process can be a useful tool to determining this critical information for the production planner and scheduler prior to the production date.

4. CONCLUSION

Off-site construction technique has become a popular construction method due to the associated improved quality, reduced waste and environmental impact. Among different off-site construction method, panelized system can accommodate various type of design. However, unlike the traditional manufacturing industry (e.g. car manufacturing), panelized production does not end at the plant; however, a significant amount of work needs to happen on site. Due to this fact, logistics plays an important role in the success of panelized home production. Co-ordination between plant and site activities, optimized use of trucks and trailers, scheduling of different type of jobs based on plant and site capacity – all these factors contributes to the success of the prefabricated home manufacturing process.

In this paper, a simulation model is developed from the prefabricated panel production process to on site installation using simphony.Net modeling environment. This simulation model can act as a decision support tool for the production coordinator by providing utilization of trucks, waiting time, total production time to produce a batch of houses in advance. Without the help of such model, it is challenging to optimize the entire process and obtain maximum plant and site capacity. In future, more elaborate simulation model can be developed for this purpose. This is study, a simplified simulation model is developed where the entire home production is divided into three main areas. All the sub processes in these three areas (wall, floor and roof) are ignored and the average productivity is used to estimate the production time. In future studies, all the individual workstation can be simulated which can be a part of the entire simulation mode.

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