DISCRETE-EVENT SIMULATION MODELLING OF PREFABRICATED WALL PRODUCTION LINE

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ABSTRACT
Simulation is a powerful tool that can be utilized in the production planning and control processes of complex manufacturing and construction facilities. A simulation model can capture complex relationships between different systems and predict possible outcomes in advance. This paper proposes a method to develop a discrete-event simulation (DES) model of a prefabricated wall production line utilizing a special purpose modelling template. Actual production data is collected using a radio frequency identification (RFID) system for the purpose of simulation input modelling. Wall panel information is stored in a database which is connected to the simulation model in order to assign panel attributes to the model entity directly. The proposed method is tested in a wood-framed wall panel production facility and several applications of the simulation model are outlined. The simulation model can be a useful tool to predict total production time, panel sequencing, and performance evaluation.

Keywords: Discrete-event simulation (DES), Prefabricated wall production, Special purpose simulation template.

1. INTRODUCTION

Prefabrication construction is becoming a mainstream construction method due to its superior quality and reduced environmental impact. Simulation models are used as planning tools in various sectors of the prefabrication construction and manufacturing industry. Halpin (1977) created CYCLONE, a simulation environment, which introduced 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 presented the concept of special purpose simulation (SPS), which is a computer-based environment specially built for experts in the area. AbouRizk and Mohamed (2000) 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 in order to provide a solution for the complex process of planning off-site girder bridge construction.

In addition, 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 a project in the most efficient manner. Performing this type of analysis in advance yields reduced costs, improved quality, and improved productivity (AbouRizk 2010). Liu et al. (2015) introduced a special purpose simulation (SPS) template for the panelized construction process and linked the simulation model with building information modelling (BIM).

This paper develops a detailed DES model of the prefabricated wall production line. The paper identifies different modelling elements for the prefabricated wall production line and outlines the detailed methodology of the simulation model development process using a custom-built special purpose simulation template for the production line process. The simulation input model is designed using actual production data collected through a radio frequency identification (RFID) system. Finally, the application of the simulation model as a production planning and control tool is demonstrated.

2. MEHODOLOGY

Figure 1 shows the methodology of the simulation development process for the prefabricated wall production line. Actual production data is collected from the production floor using the RFID system. RFID antennas are installed at each workstation and an RFID tag is placed on each wall panel at the framing station where the prefabrication process begins. The antenna sensors collect data held within the tag when the panel

moves from one station to another and the timestamp is recorded into the database through the RFID reader. Timestamp data collected from the RFID system is utilized in simulation input modelling for each work station.
Wall panel information such as length, type, and number of windows/doors are stored in the database from the 3D model and used by the simulation model to determine the process route of each particular wall panel.

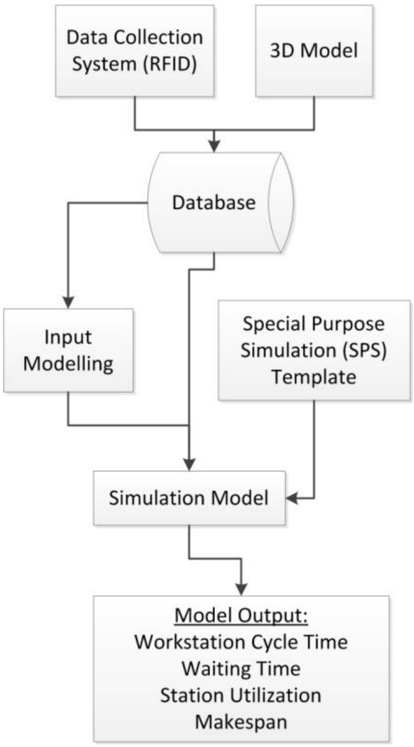

Figure 1: Simulation model development process

A special purpose simulation (SPS) template specifically built for the production line process is used to develop the simulation model. The SPS template contains customized simulation modelling elements such as workstation, storage, and equipment in order to simulate the production line process more efficiently. The simulation model can provide workstation cycle time, waiting time, station utilization, and total makespan for a number of wall panels as model outputs.

3. SIMULATION MODEL DEVELOPMENT

3.1. Production Process

Landmark Group of Builders, a major production homebuilder in Alberta, Canada, has established a production facility in Edmonton where wood-frame wall, floor, and roof sections are prefabricated inside the plant and are then transported to the site for assembly. In this study, the Landmark wall panel production line is simulated using Simphony.NET, a simulation software developed at University of Alberta. Figure 2 shows the prefabrication process of the wall production line. The wall panel production process begins at the framing station where the studs are nailed to the top and bottom plate along with pre-assembled window and door frames by the computer numerical control (CNC) machine. Multiple single-wall panels are built together in order to maximize the framing station capacity. Next, the multi-wall panel is transported to the sheathing station where OSB sheathing is placed manually and then nailed automatically at the bridge table by another CNC machine. The exterior wall is then moved to the spray-booth in order to spray insulation foam. The multi-wall panels are then cut into single-wall panels and transferred to either the window installation station or window bypass line. After installing the window and door (if required), the wall is placed in the storage line before being loaded onto the transport trailer. Interior wall panels are cut into smaller panel components after the bridge station; the shorter interior wall panels (less than 12 ft.) are transferred directly to the interior wall packaging area from the bridge table while the longer interior walls are transferred to the main storage line through the window bypass line. The following two sections of this paper present the simulation input modelling analysis and special purpose simulation template for the production line facility.

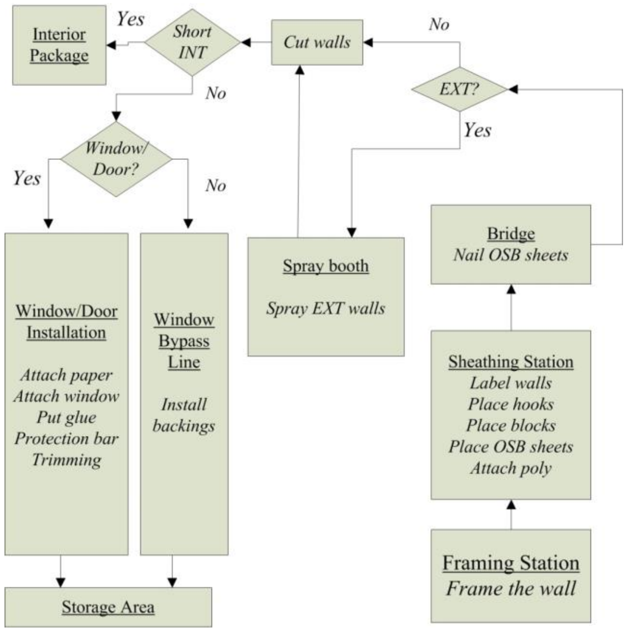

Figure 2: Production process of wood wall panel production line

3.2. Simulation Input Modelling

The RFID system is used in the prefabrication plant to obtain actual production data. Panel processing time at each workstation is collected through the system and stored in the central database. This information is used for distribution fitting using Simphony.NET. Figure 3 shows the probability density function of exterior wall panel processing time at the framing station, which follows a beta distribution.

Similarly, both exterior and interior wall processing time at the sheathing table, nailing station, spray-booth, and window installation line are estimated using actual time data retrieved from the RFID tags. Table 1 summarizes the duration distribution for each workstation.

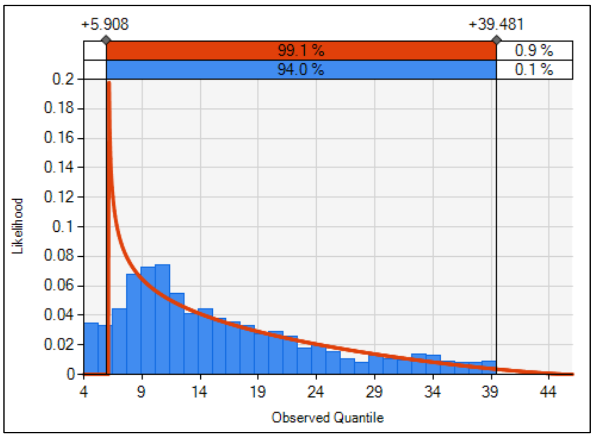

Figure 3: Probability density function of exterior wall processing time at framing station

3.3. Simulation Logic Development using Special Purpose Simulation Template

Simulation models are established using the special purpose simulation template developed by Liu et al. (2015) in Simphony.NET. In the special purpose template, each work station in the production line is represented by a "Station" element; these elements delay the simulation entities that represent building panels for the specific duration of fabrication operations or tasks taking place in each work station. Notably, a work station has a specific capacity limitation and cannot process unlimited building panels simultaneously. As such, the station element provides the user an opportunity to define its capacity in order to control the production flow. Another important element in this new SPS template is the "Entity Router" element. This element routes simulation entities into the correct stations based on the enriched panel information; building panels with various design features, such as IsExteriorOrNot and HasWindowOrNot, will be routed through various work stations that correspond to their specific features. Further, this SPS template provides another element named "Execute" which enables the user to write custom code in order to enhance the flexibility of simulation modelling. The simulation model is demonstrated in Figure 4. Table 2 tabulates the capacity information for each work station. This information is inputted into the developed simulation model in order to simulate the production flow.

It should be noted that the production line studied in this research produces multi-wall panels in order to optimize the use of the framing station capacity, thereby improving the production productivity. A multi-wall panel herein is defined as a wall panel composed of multiple wall panels and whose length is approximately forty feet, which is similar to the length of the framing table. Table 3 lists examples of single-wall panel information, while some multi-wall panel information is tabulated in Table 4. In work stations such as the framing station, sheathing table, bridge, and spray-booth station, operations/activities are performed on the multiple-wall panels. Interior multiple-wall panels are split into individual single-wall panels after the bridge station, whereas exterior multiple-wall panels are separated into individual single-wall panels at the spray-booth station. This indicates that simulation entities should represent the correct wall panels accordingly in order to mimic the production process. In this context, two execute elements are deployed in the developed simulation model, and user-defined codes (as shown in Figure 5) are embedded into those two elements to solve this problem. Once simulation entities representing multi-wall panels enter the SplitEXT and SplitINT element (as show in Figure 4), the user-defined codes release new simulation entities representing single-wall panels that are contained in the corresponding multi-wall panel and the new simulation entities are sent to the connected simulation element.

Table 1: Duration distribution

Work Station	Wall Type	Sample Size	Distribution Type and Parameter
Framing	Exterior	848	Beta (0.73,2.24,45,6.10)
	Interior	1260	Beta (0.72,6.33,67,3.79)
Sheathing	Exterior	930	Beta (1.26,4.79,54.7,5.96)
	Interior	1273	Beta (0.83,6,67.43,2.83)
Bridge	Exterior	909	Lognormal (2.33, 0.615)
Spray-booth	Exterior	240	Triangular (63.14, 0.76, 46.37)
Window/Door	Exterior	815	Triangular (317, 11, 141)
Window Bypass	Both	1058	Gamma (46.84, 1.79)

Table 2: Work station capacity

Work Station	Capacity	Capacity Measurement	Unit
Framing	1	No. of Panel	Count of Multi-wall Panel
Sheathing	24400	Panel Length	mm
Bridge	1	No. of Panel	Count Multi-wall Panel
Spray-booth	37000	Panel Length	mm
Window/Door	47600	Panel Length	mm
Window Bypass	47600	Panel Length	mm

Table 3: Example of single-wall panel information

Multi-wall Panel	Single-wall Panel	Length	Width	Height	Window	Door	Backing	Floor	Type
EW009061	EW009061-00-110	11564	2772	163	0	0	0	1st	EXT
EW009062	EW009062-00-104	9735	2772	163	0	0	0	1st	EXT
EW009062	EW009062-00-105	2124	2772	163	0	1	0	1st	EXT
EW009063	EW009063-00-112	1362	2622	163	0	0	0	1st	GAR
EW009065	EW009065-00-109	2429	2772	163	0	1	0	1st	EXT

Table 4: Example of multi-wall panel information

Multi-wall Panel	Type	Length	Width	Height	Window	Door	Floor	Num Wall
EW009061	EXT	11564	2772	163	0	0	1st	1
EW009062	EXT	11904	2772	163	0	1	1st	2
EW009063	GAR	9043	2622	163	0	0	1st	3
EW009064	GAR	6890	2622	163	0	0	1st	1
EW009065	EXT	12130	2772	163	2	1	1st	4
EW009066	EXT	6755	2772	163	1	1	1st	3
EW009067	EXT	11748	2467	163	1	0	2nd	2

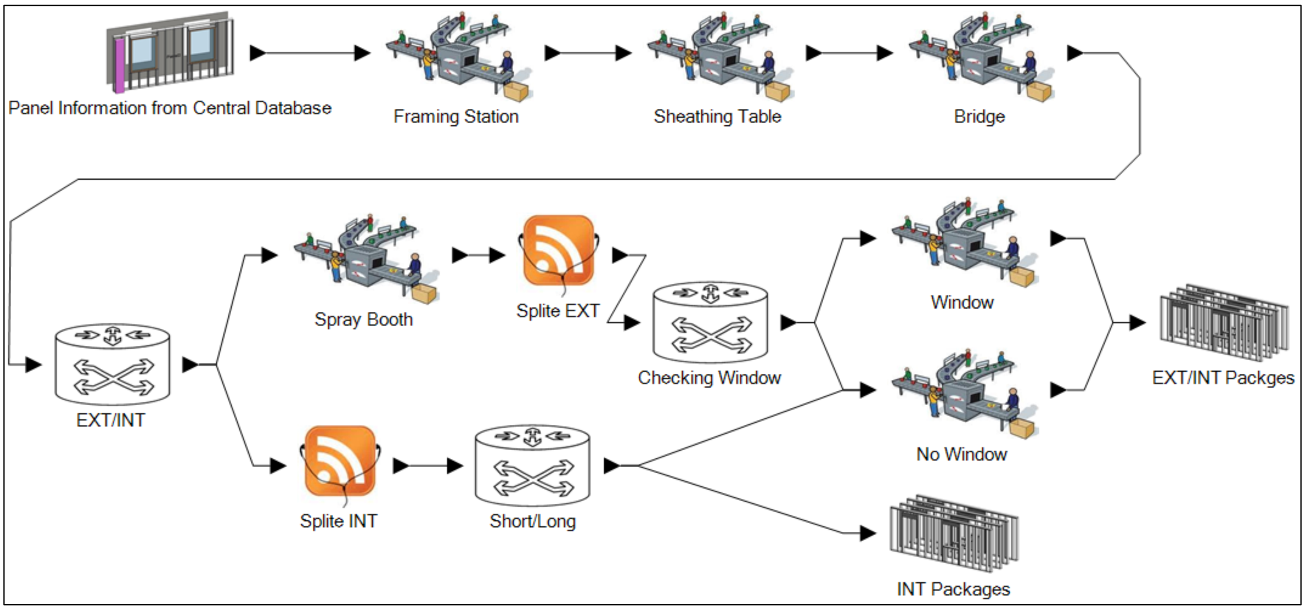

Figure 4: Wall production line simulation model developed in Simphony.NET using SPS template

```
foreach(var newentity in context.CurrentEntity.SubBuildingEntities)
{
    newentity.PreStation = context.CurrentEntity.PreStation;
    newentity.Workpackages.AddRange(context.CurrentEntity.Workpackages);
    windowCheckor.InputPoint.TransferIn(newentity);
}
```

Figure 5: Embedded codes to split multi-wall panel

4. RESULTS AND DISCUSSION

The wall prefabrication process for one single-family home is simulated using the SPS template in Simphony.NET. The house requires 56 wall panels, which are produced as 20 multi-wall panels at the framing station. The house has 33 interior wall panels and 23 exterior wall panels. The details for single- and multi-wall panels are read from the 3D model and stored in the database. The simulation model is run fifty times, and Figure 6 shows the cumulative density function of the total makespan for the house. The mean makespan to produce all 56 wall panels ranges from 397 to 644 minutes with a mean value of 490 minutes. Figure 7 shows the cycle time of the spray-booth workstation. The cycle time ranges from 3 to 61 minutes with a mean value of 37.9 minutes. Average cycle time, waiting time, and station utilization for each workstation is summarized in Table 5.

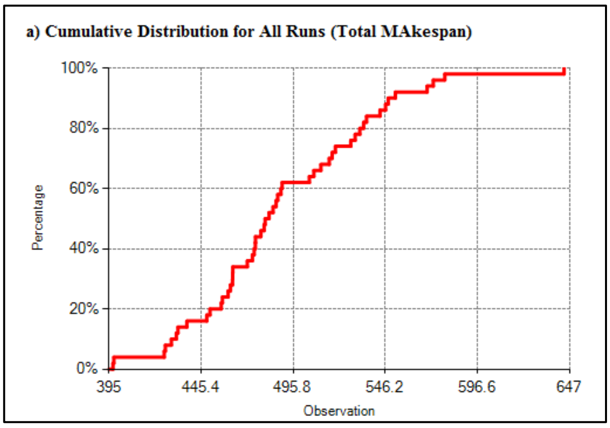

Figure 6: Cumulative distribution function of the makespan

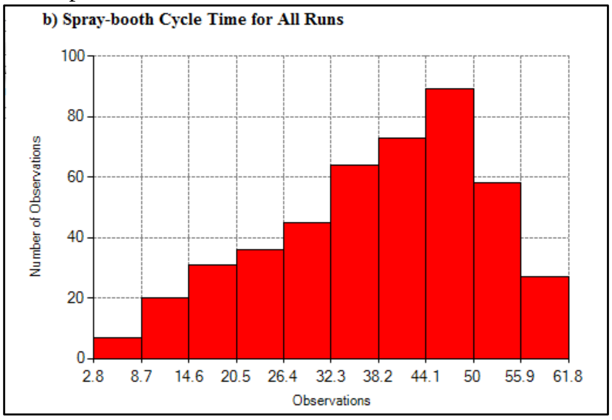

Figure 7: Probability density function of cycle time at Spray-booth

The model results are verified by performing parameter variability-sensitivity analysis and tracing (Sargent 2010). Certain input parameters of the model are adjusted if the model results change based on the expected outcome. For example, if the cycle time of a downstream station increases, the previous station will require a longer waiting time. Also, the number of input wall panels at the framing station should equal the total number of panels in the storage element. The cycle time, utilization, and waiting time values are also verified by comparing the simulation results with manual calculation. Also, the model entities are traced along the simulation time to determine if the model logic is correct.

Table 5: Simulation results

Work Station	Mean Cycle Time (min)	Mean waiting Time (min)	Mean Utilization
Framing	13.78	0.94	87%
Sheathing	13.25	3.9	63%
Bridge	7.13	0.5	77%
Spray-booth	37.91	0	59%
Window/Door	152	-	47%
Window Bypass	84	-	51%

The simulation model can be utilized in advance for the purpose of production planning and control. A production controller can make changes to the model to analyze different production scenarios. The simulation model can be used to optimize panel sequence in order to estimate production time in advance, evaluate performance, minimize the makespan (Altaf et al. 2014a), and allocate resource more efficiently (Altaf et al. 2014b).

5. CONCLUSION

This paper presents the DES modelling process of the prefabricated wall panel production process using an SPS template. Actual panel production time data is collected through the use of a RFID system and stored in the database for simulation input modelling. Also, necessary wall panel information is read from the 3D file to generate simulation entity attributes. The model is developed in Simphony.NET and actual production data is used for input modelling. The proposed methodology is tested by developing a simulation model for Landmark's prefabricated wall production line facility. The model is run for a single-family home and the results are verified through the parameter variability technique. The use of an SPS template simplified the simulation model development process and various simulation parameters can be adjusted more easily. The production manager can utilize the simulation model to analyze different alternatives, estimate production time, and evaluate actual production performance by comparing them with simulation results.

In future research, the simulation results can be validated using the actual production data collected by the RFID system. Also, a dynamic simulation model can be created by connecting the RFID system with the simulation model to provide actual panel locations prior to starting the simulation model. This will provide more realistic simulation results which can be used as a production evaluation tool on a daily basis.

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