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SIMULATION-BASED PRODUCTION RATE FORECAST FOR A PANELIZED CONSTRUCTION PRODUCTION LINE

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Abstract: Panelized building construction has been widely adopted in the construction industry for better productivity and project cost reduction. To maximize the advantages of this type of construction, a production line needs to be improved continuously via planning. However, planning for the production line can be challenging for new panelized construction projects when a production rate of the production line is not accurate or unavailable. In practice, companies still rely on the experience of practitioners to forecast the productivity of the production line for planning. This practice may result in low productivity and increased cost due to unbalanced production line and inefficient resource utilization. To overcome these challenges, this paper proposes a simulation-based method to predict productivity of the production line using a simulation based on captured time study data. Time study was conducted to investigate the current production line process and to identify wall design specifications such as number of studs and door / window area, which affects the cycle time of workstations. As a result, task time formula is developed using multiple linear regression in order to improve prediction accuracy of the cycle time of work stations. The proposed methodology uses the developed task time formula and design specifications as inputs in the simulation model to forecast the production rate. The proposed methodology has been validated in a light gauge steel (LGS) panelized construction project located in Edmonton. The proposed simulation-based method predicts the productivity of the production line as 1.8 panels/hour or 16 panels/day. The comparison between actual and simulated productivity / day demonstrate its accuracy as 72 %.

1 INTRODUCTION

Prefabricated construction is a dominant construction approach as the process can improve construction productivity with reduced environmental effects (Liu 2016). There are various forms of prefabricated construction such as modular construction, panelized construction etc. Among them, the acceptance of panelized construction is increasing in the construction industry as the process provides flexibility in design and also reduces the material wastage (Altaf et al. 2015). However, panelized building includes different types of wall panels such as interior, exterior and bathroom units that vary in size and design specifications (window/doors) depending on the projects. Since these panels are manufactured in the same production line, the cycle times of work stations may vary, which can possibly increase the waiting time between the work stations. The activities in panelized construction are completed in the factory environment, so it is significant for the manufacturers to balance the production line and maximize the productivity (Altaf et al. 2018).

Panelized construction companies strive to enhance the operations of their production line by adopting various disciplines including lean, simulation and building information technologies (BIM). A combination of these technologies have also been tested and implemented by researchers along with industries to improve productivity of the production line. For instance, lean concepts such as pull system and continuous flow was implemented by Shafai (2012) to improve the process of the production line by avoiding overproduction, which was a reason of significant wastage. Yu (2010) implemented the standardized works to remove the cycle time variation at the production line to improve the productivity. However, implementation of new proposed methods requires a great capital investment and without advanced planning tools the potential for failure is high. In regards to advanced planning tools, simulation is an effective tool to facilitate the lean process.

Simulation is defined by AbouRizk and Mohamed (2000) as one of the important techniques developed for decision-making procedure as it accurately models and balance the production process. According to AbouRizk and Shi (1994) simulation can be effectively used to analyze the performance of the construction process. For example, Ritter et al. (2017) applied simulation techniques on the wall panel production line to identify the strategies for implementing the proposed changes, such as effects of different crew size. In their study, the simulation model has used the durations for activities which were determined by the expert opinions instead of conducting time study. This process may reduce the accuracy of planning the production line process. Nevertheless, to improve the accuracy of the production rates systematically, time study is required along with different cycle times of work stations to be used as inputs for the simulation model. Additionally, in the present case study, the modular construction company depends on the experience of practitioners to forecast the productivity of the production line, which is error-prone and leads to unbalanced production line and inefficient manpower utilization.

To address these issues, a simulation-based approach is explored to forecast the productivity of the production line. Time study is conducted to collect the different cycle times of workstations to build the simulation model. Simulation model is developed using a general template in Simphony.NET developed at the University of Alberta (AbouRizk and Mohamed 2000). The proposed methodology is applied into the light gauge steel (LGS) production line as a case study for validation. In the following sections, literature review is conducted, followed by a methodology. Simulation model results are also discussed with future works.

2 LITERATURE REVIEW

The acceptance of panelized construction is increasing as the process reduces the construction waste and cycle time in comparison to the traditional stick-frame construction. Furthermore, to maximise its benefits, lean principles and simulation have been adopted by the construction industry (Altaf et al. 2014). For instance, Zhang et al. (2016) implemented value stream mapping to analyze the current production line process and identified issues such as cycle time variation, which may cause unbalanced production lines. Shewchuk and Guo (2012) used lean principles to optimize the sequencing of wall panels. However, before implementing the lean principles, a comprehensive plan is needed to accomplish an effective lean transformation. Moreover, to increase the confidence of management on the proposed changes, proper planning system should be implemented. Various advanced planning tools such as simulation and BIM have been explored by researchers to improve the efficiency of the production line.

Simulation is a tool that illustrates the real world construction process and provides the platform to evaluate various scenarios before its implementation. In addition to that, simulation models also represent the logic of activities involved in construction process and assist in creating better project plans, which improves the overall construction productivity and reduces the project cost (AbouRizk 2010). The practice of simulation has been tested and recognized by various researchers (Ritter et al. 2017). Cyclone is a simulation tool that was introduced by Halpin (1977) and motivated the advancement of simulation. Graphical representations in cyclone template were used to model the construction related tasks. However, the application was limited to research because of its complex representation (Moghadam et al. 2012). To benefit the construction industry, a customized simulation framework was presented by Abourizk and Hajjar (1998).

Abourizk and Hajjar (1998) presented special purpose simulation (SPS) approach by integrating it with the systems of companies to improve the existing construction practices. Later, Simphony.NET was introduced by AbouRizk and Mohamed (2000) to model the construction activities. The developed integrated system provided outputs such as resource utilisation and charts (time graph, histogram). Moshen et al. (2008) created simulation model by using Simphony and predicted the productivity of the production line. However, in their study, an explanation of duration forecast to build simulation model based on the collected data is not presented. Moreover, in the study presented by Ritter et al. (2017), the duration data of activities is based on expert opinion, which is used as input in the simulation model to evaluate the production line performance. This form of data collection can reduce the accuracy of planning the production line. Therefore, detailed time study should be carried out to increase the accuracy of a simulation model. The next section discusses the proposed framework to achieve the research objectives.

3 PROPOSED METHODOLOGY

As shown in Figure 1, this study proposes a simulation-based method to predict the productivity of the production line based on wall panel components such as dimensions, number of studs, and window space. The proposed methodology is categorized into three phases: 1) conduct time study based on captured time data and wall panel design specification; 2) develop access database and multiple linear regression model; and 3) develop the simulation model. The purpose of time study is to understand the current production line and identify the relationship between components of each wall panel and the cycle times of workstations involved in its production. The relationship is developed in the form of multiple linear regression equation that represents the cycle times of work stations for the different components of wall panels such as wall lengths, widths and heights, number of studs, and window space. At this junction, it should be noted that the wall design components are used as input in the simulation model. The access database is created to store the wall panel information from design specifications. SQL server connection is used to extract the wall panel information automatically from the database into the simulation model. The task time formula for each workstation is used as input in the simulation model to forecast the productivity of the production line. The general template in Simphony.net is used to represent the work flow of the current production line. The simulation output includes the production rate, average interval of wall panels and utilization of resources at each workstation.

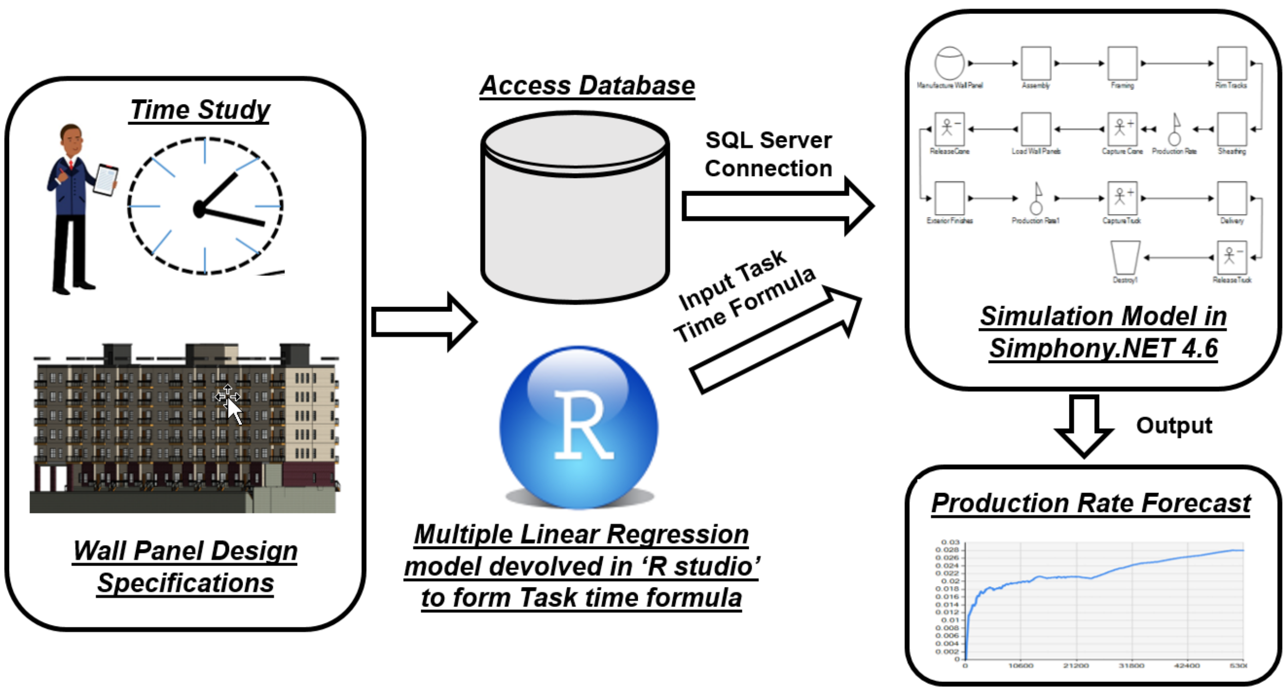

Figure 1: Proposed Methodology

4 IMPLEMENTATION

4.1 Fortis Prefabrication Plant

The case has been developed in the Fortis LGS structures Inc. company, our collaborator in this research. The Edmonton based company specializes in constructing residential buildings using LGS, an environmentally sustainable solution. Presently, building components such as interior and exterior wall panels of different design specifications are pre assembled in the factory and installed on site. Bathroom pods, which consists of 4 wall panels, a ceiling and a floor are also manufactured, but the focus of this research is on the wall panels production. The wall panel production of Fortis LGS involves assembly station, framing station, rim track as substation, sheathing station, exterior finishes and delivery of wall panels as shown in Figure 2a. A typical wall panel frame includes components such as studs, header track, bracings and drywall as shown in Figure 2b. The wall panel production begins with assembly station, where steel studs, tracks, cripples and headers are assembled as per shop drawings regardless of the wall panels type and passed to the framing station. At the framing station, a computer numerical control (CNC) machine is used for pressing studs and tracks to form a rigid frame. The wall panels then moved to substation for rim tracks installation. The interior wall panels are moved to storage area for shipment to site, whereas exterior wall panels which require drywall are moved to the sheathing station. At the sheathing station, drywalls on wall panels are fixed and sent to the panel racks for exterior finishes. The exterior wall panels go through the exterior finishes that includes: waterproofing, door/window installation, foaming, rasping, basecoat and skim coat along with shipment of approved panels to the construction site.

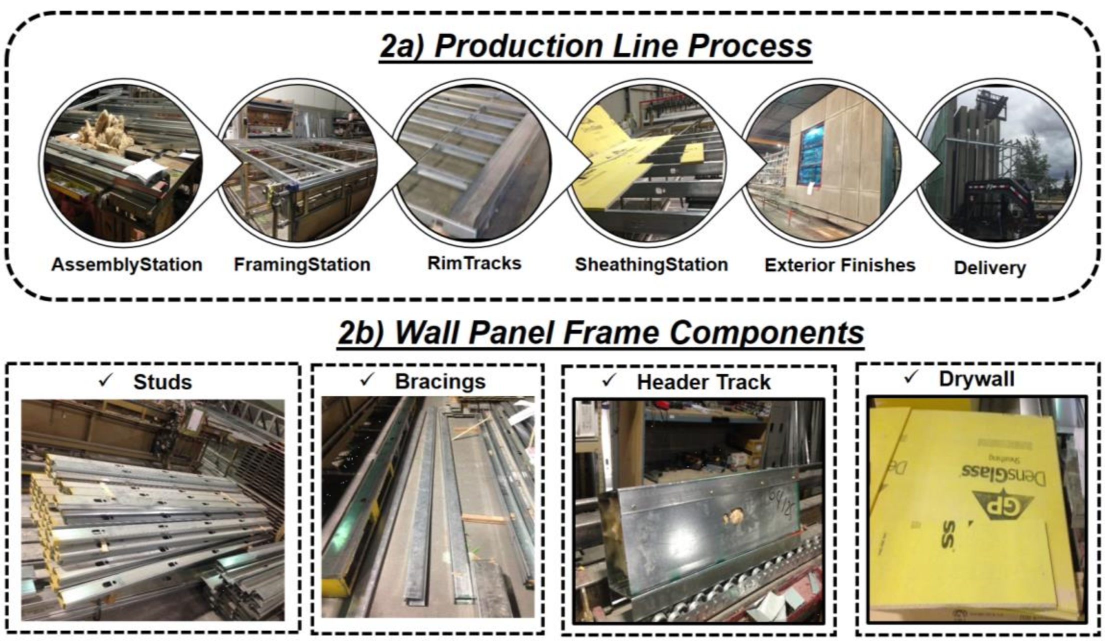

Figure 2: Wall Panel Production Line Process and Frame Components

The developed method is applied to the building project shown in Figure 3. The building is a six storey residential building project. The wall panels of this project are manufactured in the LGS panelized construction company. There a total of 114 units with more than 1430 interior and exterior wall panels. The wall panels height varies from 7.9 feet to 11.9 feet, whereas length is between 2.93 feet and 21.34 feet. The wall panels also have different number of studs, header tracks, bracings, cripples and different size of doors and windows, which affects the cycle time of each work station.

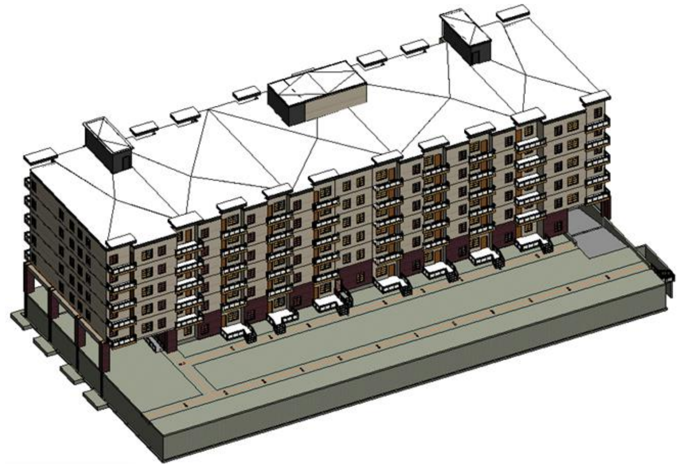

Figure 3: Residential Building Project

4.2 Time Study

The Time study is performed to understand standard operation procedures (SOP) of current production line and to identify the relationship between components of the wall panels, areas of wall spaces and opening spaces, and the cycle times of workstations. Based on the SOP of each workstation, the data collection is implemented by observing the production line. After a brief walkthrough, the cycle times of wall panels at each workstation are recorded. The 150-time data observations were collected for each work station using a stop watch and recorded in minutes on time sheets from June to August 2018. As shown in Table 1, the time sheets include panel name, number of workers, start/finish time, number of studs, surface area (S.A.) of window and Net Area in square feet (sq. ft.). The time collection is implemented from first activity and to final activity at each workstation. For example, at the assembly station, the cycle time is from picking up material to wrapping and moving them to the next station (i.e. framing station).

Table 1: Wall Panel Time Study Sheet

Panel Name	No. of Workers	Start Time	Finish Time	Time (min)	No. of Studs	S.A. Window (sq. ft.)	Net Area (sq. ft.)
I 945	2	13:20	13:45	20	5	-	30.3
I 946	2	15:00	15:44	44	4	20.3	54.1
E532	3	8:30	9:15	45	10	-	143.6
CR 544	3	10:18	11:02	44	14	22.5	115.3
E 1031	4	15:30	16:30	60	20	42.4	123.5
E 1045	4	8:30	9:00	30	16	-	89.8

The number of the design properties, which can affect the cycle time of workstations, are identified based on the SOP and observation of workstations. The cycle time of each workstation is affected by the design specifications of wall panels such as number of studs, door and height of wall panel. Figure 4 shows the identified design factors affecting framing station, such as the net area, number of header, number of bracing and number of studs. Based on the collected time data and design specifications, multiple linear regression models are formulated to predict the cycle time of work station.

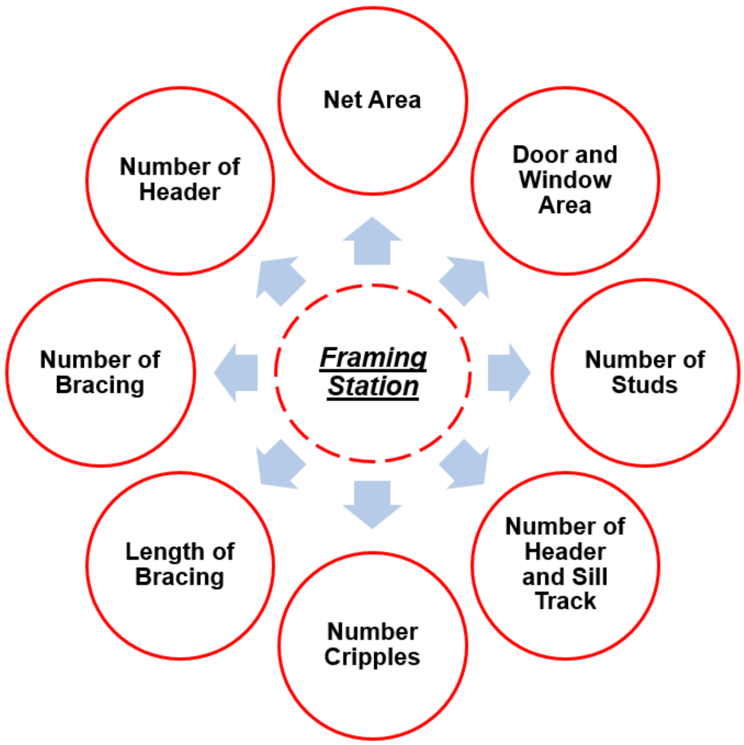

Figure 4: Factors Affecting Framing Station

4.3 Task Time Formula

The wide variations in wall design specifications along the production line pose a challenge to predict the cycle time of work stations. To overcome this challenge, a task time formula is developed using multiple linear regression techniques based on wall panel design specifications to predict the cycle time of workstations. The duration is a dependent variable and design specifications such as number of studs, number of cripples and door/window area are independent variables. The independent variables with P value > 0.05 are least significant and removed from the predictive model. For instance, equation 1 is used to predict the cycle time of the assembly station, where D_A = Duration of assembly station (min); X_S = No. of Studs; X_{HT} =No. of Header Track; X_{ST} = No. of Sill Track; X_{HF} = No. of Header Foam; X_{SF} = No. of Studs Foam; X_C = No. of Clips; X_W = No. of Workers; X_{CR} = No. of Cripples.To interpret equation 1, the coefficients for X_S, X_C and X_{CR} indicate that increase of one more stud, clip and cripple in a wall panel will increase the cycle time for assembly station by 1.61, 0.79 and 2.17 minutes, respectively. The coefficient for X_W is negative which implies that as the number of workers at the station increases by one, the cycle time decreases by 6.16 minutes. The P value for the equation is 2.2e-16 and adjusted R value is 0.765 (76.5%). Table 2 shows examples of task times predicted for different workstations of the production line. In the framing station, the task of installing one bracing can take 1.52 minutes, where as installing cripples can take 0.46 minutes.

$$D_A = 2.17X_S - 3.50X_{HT} - 0.81X_{ST} - 0.07X_{HF} + 3.24X_{SF} + 0.79X_C - 6.16X_W + 1.61X_{CR} + 17.49 \quad \textbf{Eq.1}$$

Table 2**:** Task Time Formula of different tasks at Various Workstations

Task Type	Task Time Formula	Workstation Type
Assemble Stud	2.17* No. of Studs	Assembly
Nail Clips	0.79 * No. of Clips	Assembly
Install Bracings	1.52 * No. of Bracings	Framing
Install Cripples	0.46 * No .of Cripples	Framing
Install Angles	8.45* No. of Angles	Sheathing
Install Headers and sill Track	9.80* No. of Header and Sill Track	Framing
Assemble Tracks	0.71 * No .of Tracks	Assembly

4.4 Simulation Model

General purpose modelling template in Simphony.NET is used to forecast the productivity of the wall panel production line. The simulation model is built based on the workflow of the production line considered in this study. The input information required for the simulation model includes the task time formula, which generate the cycle times of workstations, and design specifications such as height of studs, number of studs, door area and window area are automatically extracted from the access database through the structured query language (SQL) server and used as input into the simulation model. The simulation model is developed for the Fortis LGS structures Inc. Figure 5 shows the wall panel flow at each workstation within simulation model. Modeling elements such as create, task, resource, counter, and destroy are used to mimic the production line process. 'Manufactured wall panel' represents the entity that undergoes through different tasks, for example, assembly, framing, rim tracks, sheathing, exterior finishes, loading and delivery of wall panels to complete the simulation. "Database create" element is used to create entities, whereas task element represents the workstations. Resource elements represent the resources, such as crane, truck and crew size for each workstation. In case of non-availability of resources, the entities waiting time is also recorded. The counter element is used to count the number of entities passed in the given time. The simulation output involves production rate, average interval of wall panels and utilization of resources. The simulation model provides the results of production rate in the form of report and graphs.

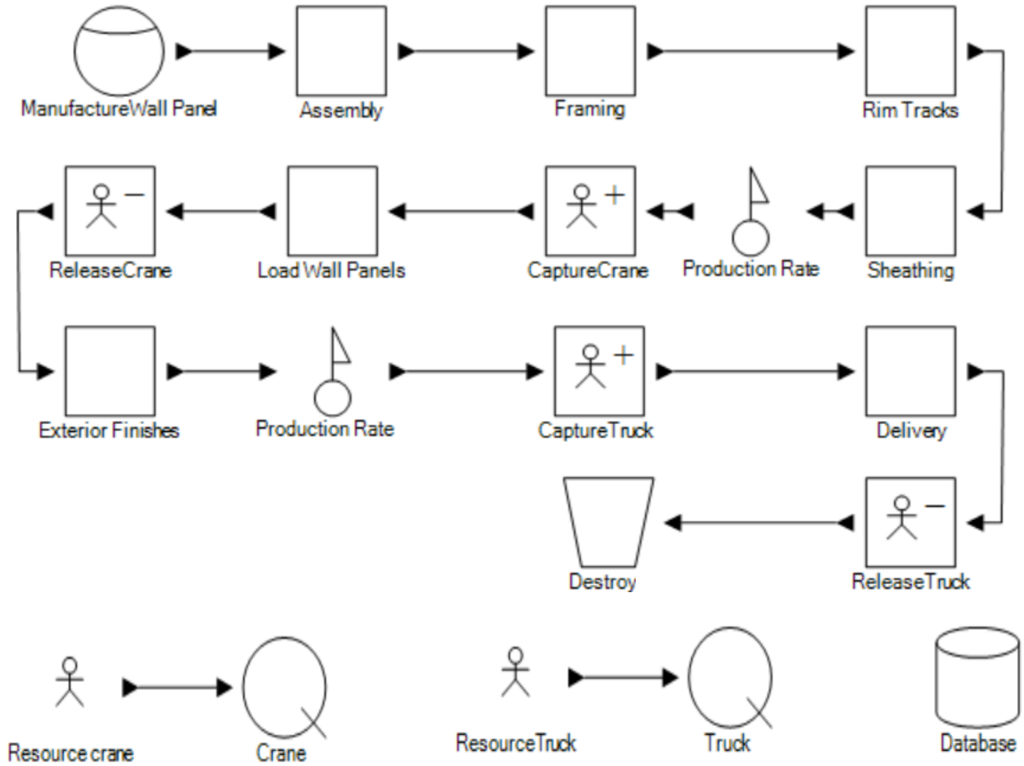

Figure 5: Simulation Model of Wall Panel Production Line

Figure 6 represents the result of the simulation model which is the wall panel production rate. The production rate is 1.8 panels/hour or 0.03 panels/min. Statistics report provides the information about the production line process such as: 1) non - intrinsic statistic report forecast of 89 days as the total production duration to complete 1433 wall panels; and 2) resources statistic report shows that the utilization rates of crane and truck are 22.4 % and 99.7 %, respectively. This utilization rate of the crane is very low because the sheathing workstation takes more time to complete the process of installing drywalls on the wall panel frames, which makes the crane resource idle for more then 75% of the time.

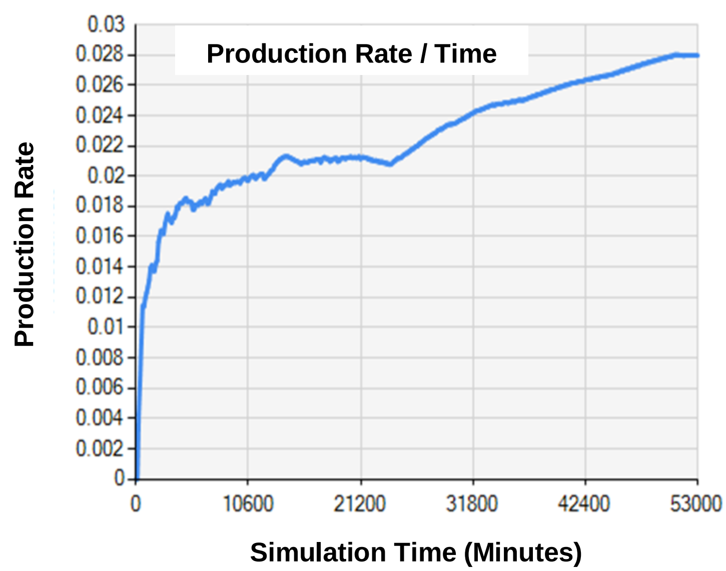

Figure 6: Simulation Wall Panel Production Rate

The actual productivity (11-19 panels / day) of the manufacturing plant is compared with the simulation productivity results (16 panel / day) as shown in Table 3. For example, on June 11th the actual productivity is 14 panels and if compared with the simulated productivity that is 16 panels / day, the accuracy can be interpreted as 86 %. The comparison between actual and simulated productivity / day demonstrate its accuracy that ranges from 55 to 93% (average accuracy 75%). The large variation between the numbers of wall panels produced in simulation model and the actual factory production is because of limited observations used for task time formulas, which reduces the prediction accuracy.

Table 3**:** Comparison of Actual and Simulated Productivity / Day.

Prod. Date	Actual Productivity / Day	Simulated Productivity / Day	Difference = (Simulated Days – Actual Days)	A = Difference /Actual Days	Accuracy = (1-A)
June 11th 2018	14	16	2	14%	86%
June 12th 2018	15	16	1	7%	93%
June 13th 2018	13	16	3	23%	77%
June 14th 2018	11	16	5	45%	55%
June 15th 2018	12	16	4	33%	66%

5 CONCLUSION AND FUTURE WORKS

This paper forecasts the productivity of a production line based on simulation model developed in Simphony.NET. A Time study was performed to understand the current production line and to identify the relationship between components of the wall panels and the cycle times of workstations. Based on the relationship identified, multiple linear regression equations are used to develop the task time formula to accurately predict the cycle times of work stations. The task time formula for each workstation is used as an input for the cycle time of workstations in the simulation model to forecast the productivity of the production line. Additionally, SQL is also used to enhance automation of information transfer into the simulation model. The results show that the simulation model predicts the productivity of the production line such as 1.8 panels/hour or 16 panels/day. The comparison between actual and simulated productivity / day ranges from 55% to 94% and this large variation between the numbers of wall panels produced in simulation model and actual factory production is because of limited observations used with the task time formulas, which reduces the regression model prediction accuracy. Moreover, the cycle time is collected manually, which is slow and imprecise, therefore it is difficult to create a historical database for a company. To address this issues cloud based tracking application will be used in the future to automate the data collection process of each workstation. In the next stage of research, the simulation template will be used to evaluate the sequencing of wall panels that will help in balancing the production line and utilization of workers.

Acknowledgments

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