SIMULATION ANALYSIS OF AUTOMATED FACTORY FABRICATION OPERATIONS FOR STEEL WALL FRAMES

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ABSTRACT

Modular construction an emerging paradigm within North America's building construction sector, is an approach in which building components are prefabricated in factories and transported to the construction site for assembly. Traditional industry practices in prefabrication of structural components are neither efficient nor economical, hence the need for the advancement of factory automated prefabrication in the Canadian industry to meet customer's delivery requirements and to maximize asset utilization. This paper describes the development of simulation models for the automated light gauge steel wall panel fabrication process of different configurations using discrete-event simulation (DES) mimicking real-time machine production capacity and cycle time. These models will aid in providing managers recommendations for efficient resource and machine utilization in wall framing operations to improve factory performance and facilitate material flow.

KEYWORDS:

Modular Construction; Light Gauge Steel; Discrete-Event Simulation; Wall Framing.

INTRODUCTION

The rapid and vast development in building construction requires effectiveness in creating solutions which in turn accelerate construction, lower building costs, and reduce the effort required compared to traditional industry practices. In North America, the preferred construction material for residential and non-residential projects is wood. But wood as a construction material is limited by many constraints such as cost, availability, environmental impact, and building codes. Since many building codes prohibit the use of wood in structures taller than 6-stories, such as commercial and high-rise buildings, the demand for light gauge steel as a construction material is growing. A factory automated light gauge steel panel framing system provides a cost-effective solution where most of the building components are prefabricated off-site in a controlled factory environment. In addition, the automated factory system can optimize the utilization of materials and human resources that are input to the components during fabrication prior to transporting the components to the construction site. To date, the use of virtual simulation models as a decision-making support tool during the conceptual phase of an automated factory production flow system has been limited. With the aim of emphasizing the importance of simulation models in the conceptual phase of factory design and analysis using Simphony.NET, which is a simulation engine developed at the University of Alberta, this paper proposes an automated factory production line simulation model for a light gauge steel wall panel fabrication process. The model maps the procedures of the production line with corresponding machine combinations by using discrete-event simulation (DES) to produce light gauge steel wall panels. The automated production line consists of multiple machines and stations functioning in a successive mode of operation.

LITERATURE REVIEW

The light gauge steel panel framing system allows for a rapid building process without the use of heavy equipment and tools. The fabricated components are relatively light and can easily be handled manually and expeditiously transported to the particular construction site. Efforts have been made in recent years to improve the quality of off-site construction outcomes and formulate a consistent design making process in order to support these outputs. In this regard, Gupta (2011) describes the implementation of prefabricated steel wall frames in several construction projects. Gupta discusses the manner in which frames are assembled together and the placement of a concrete in-fill on site. Other relevant publications have appeared in recent years because of the growing prevalence of multi-storey building projects, with regard to which the challenge is to overcome the inherent structural design load problems. Xuechun et al. (2015) describe a tested design model of a modularized prefabricated steel frame structure with inclined braces, including a detailed explanation of how to implement suitable prefabricated steel frames in high-rise buildings. A study by Prajjwal et al. (2016) discusses prefabricated modular and steel structures and their effectiveness in the structural development process. Their study summarizes the advantages of using prefabricated steel in construction, such as material cost savings, improved safety, labor cost savings, and time savings. They report that the use of prefabrication and preassembly has increased by 86% over the past 15 years, where it now has a significant influence on the cost performance and time performance of a project. Many papers have been published which outline the benefits of prefabrication and preassembly of steel frames. Wajiha et al. (2014) discuss the effects of cost and time savings in construction projects. However, their study indicates that, despite all the benefits of prefabrication, its application is generally limited in the construction industry. The research presented in this paper thus seeks to fill this gap by providing historical data in terms of the effects of cost and time. Based on the study, 77% prefabricated content can result in 100% or greater cost performance, and 74% prefabricated content can result in 100% or greater time performance.

Simphony.NET provides a simulation environment that mimics real-world construction systems and generates statistical data based on the model inputs, thus providing construction managers with a comprehensive representation of construction systems as they evaluate different construction scenarios. Simphony.NET as a tool can be used to obtain an inclusive analysis of productivity, utilization, and repeated processes in construction AbouRizk et al. (2010). The software provides two different environments, cyclone template and general template, but both are utilized to obtain statistical outputs, including production rate, cumulative distributions, resource utilization, cumulative density functions, histograms, time charts and graphs, observation count, standard deviation, and mean values to the input data. The software also enables simulation in two different paradigms, discrete-event simulation (DES) and continuous simulation. Many studies have been developed which apply simulation to improve decision making in construction. Amos et al. (2011) develop a simulation model using DES for general conceptual factory flow design. Altaf et al. (2015) present a methodology integrating simulation with an automated data acquisition system to examine the stored data in a database and compare it with the prefabricated wall panel production using both DES and radio frequency identification. Liu et al. (2015) develop a simulation model which applies a set of simulation elements in Simphony to provide construction practitioners with inclusive insights on the performance appraisal of the light gauge steel panel production line by integrating DES and building information modeling. In light of these studies, this paper aims to study the effectiveness of the steel wall frame production line and to measure its performance in order to address the weak points and improve quality. In this study, the analysis is conducted using DES to mimic the operational processes in prefabrication.

METHODOLOGY

Figure 1 illustrates the factory production line data modeling. A conceptual data model is developed based on the data requirements received from the industry partner, perhaps in the context of an activity model for the factory operations. The data model generally consists of entity types, attributes, relationships, integrity rules, and the definitions of these objects. The model is then used as the starting point for interface or database design. The use of data models has been proven to be successful when observing the original development of a single system in isolation. After collecting the data requirements from the client, the logical data model is created using the activity model and detailed data requirements for the application being developed as an input. This model is then subject to the technical environment and machine performance considerations of the actual factory, such that a physical data model enriched with accurate information can be generated. Accordingly, the physical data model output will indicate the key triggers and the important factors for the stable and improved production rates of each machine in the factory.

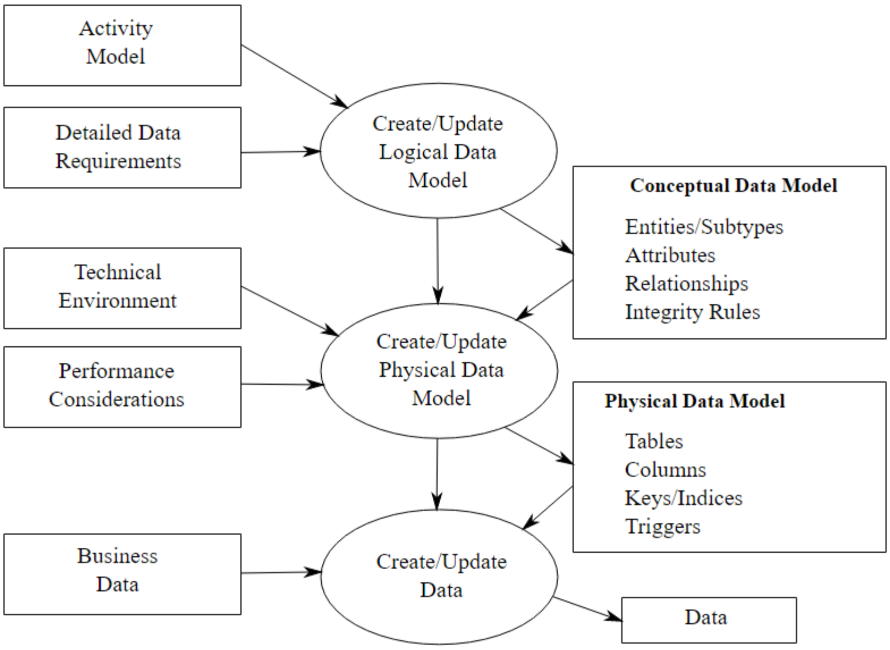


Figure 1: Production Line Data Modelling Overview

SIMULATION MODELING OF LGS PRODUCTION LINE

Light Gauge Steel Wall Panels Fabrication Process

In current practice, in light gauge steel (LGS) production factories some building components such as structural bearing and non-bearing walls are pre-assembled in the factory, then shipped and installed on site. This paper focuses on the wall panel production line in particular. The LGS production line consists of multiple stations, each containing multiple sub-activities and resources. To simplify the simulation model, this study focuses on developing a condensed layout of the LGS production line with a detailed analysis of the automation of the framing station, which involves complex processes. Thus, to streamline the modeling, the detailed processes are encapsulated in multiple “composite” elements that act as folders containing different elements. The framing station simulation model is adapted based on the steel framing prototype machine currently being built at the University of Alberta in Edmonton, Canada (Figure 2).

The following sections describe the sequence of the LGS production line. The production line consists of a series of workstations each with different combinations of machines where specific operations/processes are carried out to produce wall panels. The fabrication process begins with steel decoiler where studs and plates are produced as raw materials with a special feature called dimples. These dimples are punched by the roller former at specific preset positions in the steel components being produced; these locations are extracted from the shop drawings to aid in eliminating the use of measuring tools during the assembly process. The table automatically adjusts its width using an electrical linear actuator depending on the size of the framed panels, where the heights of the manufactured panels vary from 8 ft to 12 ft. These components are then assembled together into panel frames at the framing station, where two major processes take place (Figure 3). The first involves the soft connection process where the worker manually loads and sets the studs into position using a Snap-On technique, which is a locking mechanism used to preliminarily fix the LGS components in place before screws are added to form a permanent connection. The second is the hard connection process where the placed components are fastened together using metal self-drilling screws. The screws are fed automatically into one of four pneumatic screwdrivers from a magazine or strip with a maximum of 50 screws per screwdriver. Each screwdriver is mounted on a movable carriage and a ball screw which enables it to move along the y- and z-axes correspondingly on a stationary gantry. These movements are controlled by an electric motor that is connected to a programmable logic control (PLC) where a computer numerical control (CNC) file has been uploaded to control and direct the carriages and screwdrivers. After screws are in position the panel is dragged slowly using a set of four squares holding the panel from its four corners using electromagnets. The motion between the squares and the screwdrivers is also controlled by the PLC, and the operation execution sequence is predetermined by the extracted CNC file from the panel's shop drawings. Finally, the panel is dragged to the next station as a rigid frame for further work, and the process then is repeated for consecutive panels. Subsequently, framed wall panels are transferred to the sheathing station for placement of MEP components and nailing of sheathing sheets. Panels then pass through the polyshield station, and then to the door and window station for the addition of windows and/or doors before being moved to the vertical panel storage area to be shipped to site.

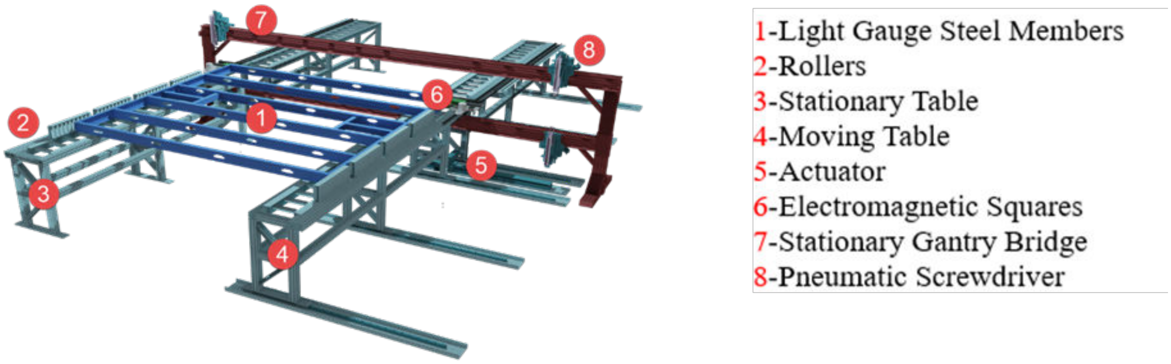


Figure 2. Steel Framing Prototype Machine

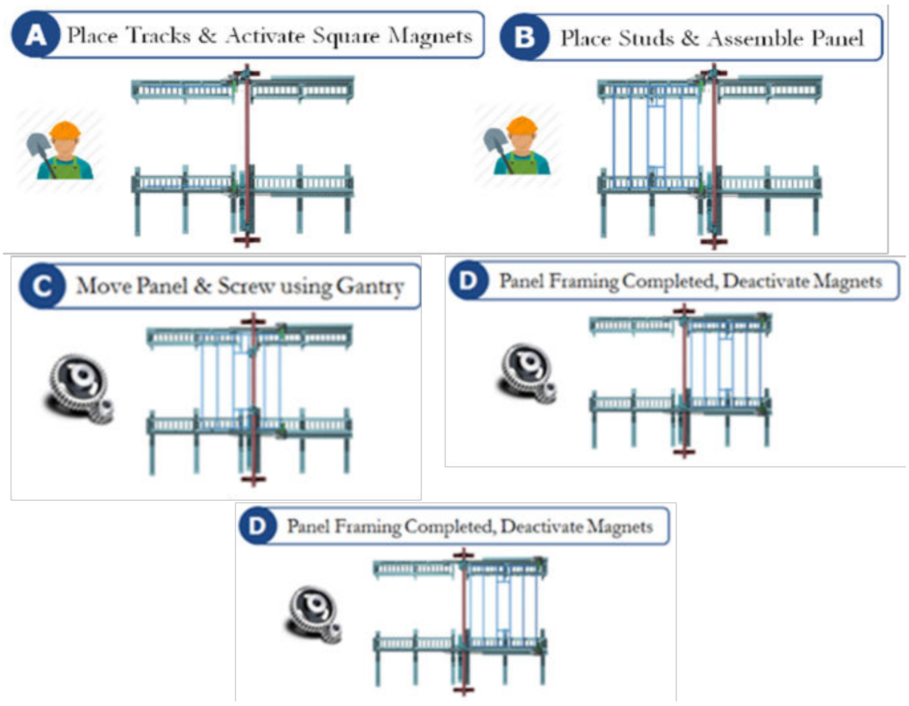


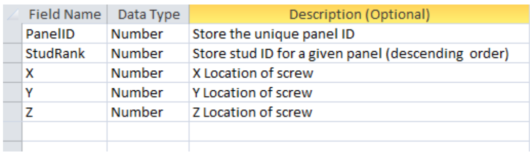
Figure 3. Sequence of Operation in Framing Station

Data Description

Since the size and shape of a given panel can vary considerably, the simulation model is linked to an MS Access database, thereby providing an accurate link between the model and the actual shop drawings. The following sections describe the process of obtaining, converting, and utilizing the shop drawing information to construct a reliable estimate for the production of each steel panel.

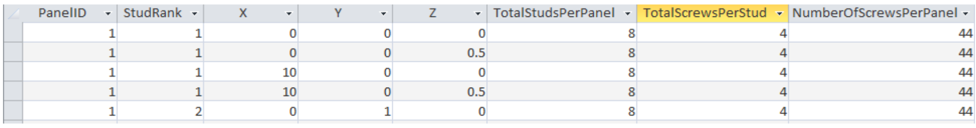
Input Data

The exact location of each screw is required in order to simulate the production of the framing machine. Since each steel panel is a unique structure, it is ideal to construct a comprehensive database with the information of each screw location and the corresponding panel ID and stud ranking (Figure 5). For this study, the data for each panel is manually added based on the industry best practices, Alberta Building Code (ABC) 2020, and Canadian Standards Association (CSA) S136-1963; however, in the future, this information will be directly linked to in-house software that will automatically export the required information for any number of shop drawings.



Field Name	Data Type	Description (Optional)
PanelID	Number	Store the unique panel ID
StudRank	Number	Store stud ID for a given panel (descending order)
X	Number	X Location of screw
Y	Number	Y Location of screw
Z	Number	Z Location of screw

Figure 5. Data Required from Shop Drawings



PanelID	StudRank	X	Y	Z	TotalStudsPerPanel	TotalScrewsPerStud	NumberOfScrewsPerPanel
1	1	0	0	0	8	4	44
1	1	0	0	0.5	8	4	44
1	1	10	0	0	8	4	44
1	1	10	0	0.5	8	4	44
1	2	0	1	0	8	4	44

Figure 6. Final Structure of Simulation Model Database Query

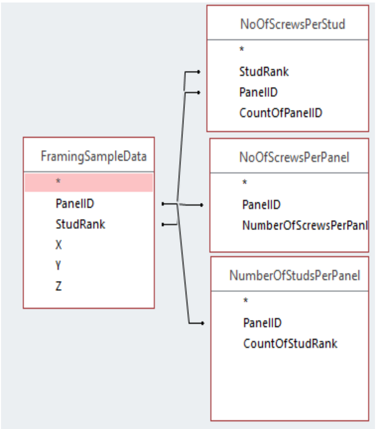


Figure 4. Four Query Design

Converting Data

Given that the database can potentially store information for multiple panels, it is crucial to add a few extra parameters which can dynamically control the flow of entities in the final simulation model. For this purpose, four SQL queries are created to summarize (1) the number of studs per panel, (2) the number of screws per stud, and (3) the number of screws per panel (Figure 6). The final data setup for the simulation model includes five actual and three derived variables (as shown in Figure 4).

Utilizing Data

Since the simulation model only requires screw information for the framing station, the model stores all the screw information in one overarching entity (known as panel "Batch"), representing one frame, that passes through different stations. The batch entity representing the frame splits at the framing station, where the information for each stud is batched and processed accordingly. Upon completion of each stud, the frame is batched again for the final sequence of the production line.

Simulation Modelling of LGS production line

Simulation models are constructed in the general template of Simphony, using a combination of discrete and continuous modeling environments. In Simphony, each activity can be modeled using a "Task" element, which holds an entity for a specified amount of time. This element is used consistently to represent different activities and stations in the production line. The data transformation from screw coordinates to stud or frame entity is accomplished using a "Batch" element, whereas the reverse action is executed using an "Unbatch" element. The data flow between different elements is controlled using "Flow" and "Valve" elements. Finally, for "Task" elements requiring resources, a "Capture" element is utilized to occupy available resources for the specified duration. Since the "Capture" element requires a resource, a task linked to this element must wait until the resource becomes available.

In addition to different elements, Simphony also features two different types of variables, i.e., local and global. Here the local variables represent the attributes of a particular entity, whereas the global variables are used independently from entities. For the simulation models in this study, all the local variables are set using an

Access database, and their information is shared using the global variables. A complete list of all the variables and their descriptions is presented in **Error! Reference source not found.**.

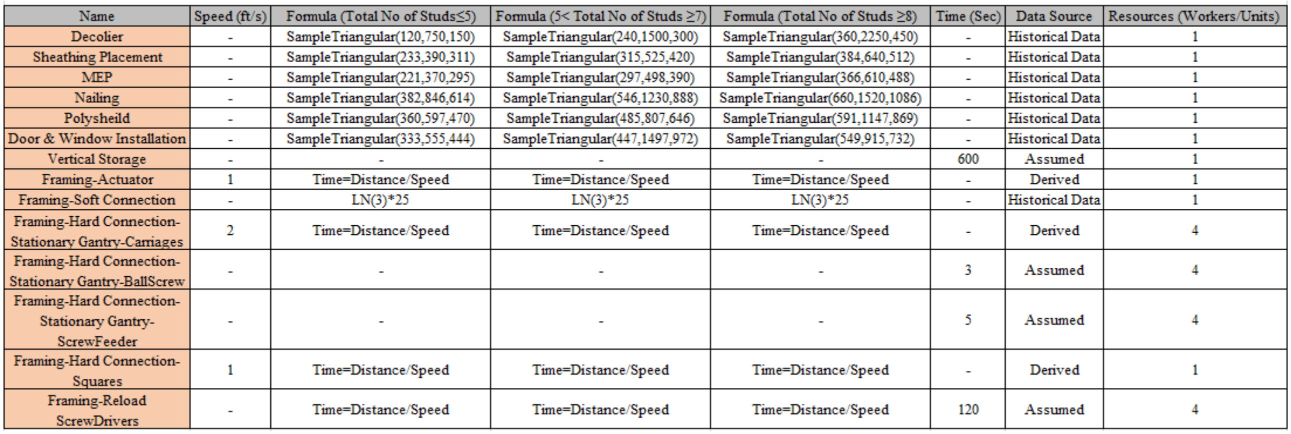
Scenario One: Production line with Semi-Automated Steel Framing Station and Manual Screw Feeding (Strips of 50 Screws)

The production line sequence begins with the creation of all the entities to be stored in the database. This point represents time zero in the simulation environment. At this point, multiple global variables are set with an aim to control the flow and the duration for different "Tasks". Moreover, all screw coordinates are batched into their respective panels with the final batch entity storing the properties of the last screw coordinate (represented as a red line in Figure 8). Here the property of the last screw is used to adjust the height of the framing table. After all the entities are converted to panels, individual decoiling for each panel takes place, after which the batched panel entity flows to the framing station.

After the completion of the soft connection, the panel entity is unbatched, and another conditional branch allows for entities relating to the first stud to enter the "Stationary Gantry" composite. At the same time, GN (4) Boolean is activated, thereby simulating an additional drop in pressure caused by the back pistons. The entities in the "Stationary Gantry" composite are guided to one of four screwdrivers depending on their screw coordinates. The stationary gantry includes four carriages which allow for motion in the y-direction, four Ball screws that allow for z-direction motion, and four screwdrivers that carry out the final hard connections. All of these elements work together to screw the stud at the exact location as specified by LX(1), LX(2), and LX(3). It should be noted that each screwdriver holds only 50 screws. Thus, if all the screws are depleted, all four screwdrivers will stop functioning, and it requires 2 minutes to manually load each screwdriver with another strip of 50 screws.

After all the screws are simulated, the entities for a given stud are batched, and the stud then passes through an activator, which allows for the entities relating to the next stud to pass. The information for the next stud is used to move the "Square" to the correct position, after which another valve is opened that allows for the entities relating to the next stud to reach the "Stationary Gantry" composite. At the same time, the completed stud waits for the whole panel to be completed before batching into the final hard connected panel. After all the studs have passed through the "Stationary Gantry" composite, the final panel (with hard connections) is batched, the "Squares" are reset, and the pressure drop simulation is halted. It should be noted that the compressor must maintain a pressure between 90 psi to 120 psi. As such, if at any stage the pressure drops below 90 psi, the compressor will be turned on (set GX(11) = 1) until it reaches 120 psi (set GX(11) = 0). At this stage, "Lockframe" valve is reopened which allows the entity of the next panel to flow into the "Framing Station" composite (represented by blue line in Figure 7). The process is then repeated for the remaining panels. The completed panels combine with the "MEP Station" and move on to the "Nailing Station", followed by "Polysheild Station", "Door & Window Installation", "Vertical Storage", and "Final Transfer to Site".

Table 1. List of Stations Details Used in Simulation Model



Name	Speed (ft/s)	Formula (Total No of Studs≤5)	Formula (5< Total No of Studs ≥7)	Formula (Total No of Studs ≥8)	Time (Sec)	Data Source	Resources (Workers/Units)
Decolier	-	SampleTriangular(120,750,150)	SampleTriangular(240,1500,300)	SampleTriangular(360,2250,450)	-	Historical Data	1
Sheathing Placement	-	SampleTriangular(233,390,311)	SampleTriangular(315,525,420)	SampleTriangular(384,640,512)	-	Historical Data	1
MEP	-	SampleTriangular(221,370,295)	SampleTriangular(297,498,390)	SampleTriangular(366,610,488)	-	Historical Data	1
Nailing	-	SampleTriangular(382,846,614)	SampleTriangular(546,1230,888)	SampleTriangular(660,1520,1086)	-	Historical Data	1
Polysheild	-	SampleTriangular(360,597,470)	SampleTriangular(485,807,646)	SampleTriangular(591,1147,869)	-	Historical Data	1
Door & Window Installation	-	SampleTriangular(333,555,444)	SampleTriangular(447,1497,972)	SampleTriangular(549,915,732)	-	Historical Data	1
Vertical Storage	-	-	-	-	600	Assumed	1
Framing-Actuator	1	Time=Distance/Speed	Time=Distance/Speed	Time=Distance/Speed	-	Derived	1
Framing-Soft Connection	-	LN(3)*25	LN(3)*25	LN(3)*25	-	Historical Data	1
Framing-Hard Connection-Stationary Gantry-Carriages	2	Time=Distance/Speed	Time=Distance/Speed	Time=Distance/Speed	-	Derived	4
Framing-Hard Connection-Stationary Gantry-BallScrew	-	-	-	-	3	Assumed	4
Framing-Hard Connection-Stationary Gantry-ScrewFeeder	-	-	-	-	5	Assumed	4
Framing-Hard Connection-Squares	1	Time=Distance/Speed	Time=Distance/Speed	Time=Distance/Speed	-	Derived	1
Framing-Reload ScrewDrivers	-	Time=Distance/Speed	Time=Distance/Speed	Time=Distance/Speed	120	Assumed	4

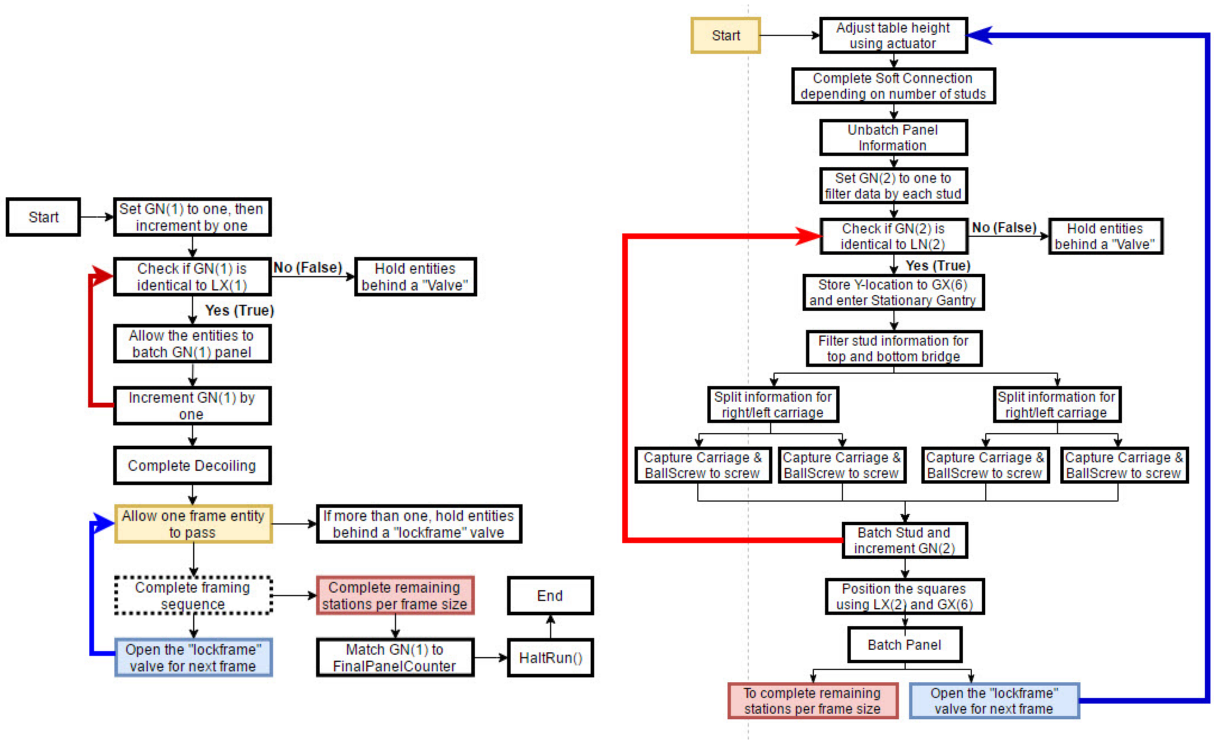


Figure 7. Condense Flow chart for overall simulation model

Scenario Two: Production line with Semi-Automated Steel Framing Station and Auto Screw Feeding (Centralized Distribution System)

The overall production line sequence remains the same in scenario two as in scenario one. However, under scenario two, the screwdrivers are not limited to 50-screw magazines, thereby boosting the productivity of the hard connection process. This change is possible because the steel framing prototype machine has the potential of being upgraded with an auto-feeding system that allows for a capacity of 2,000 screws per two screwdrivers. In short, adding auto-feeding to the framing station results in less downtime, which in turn improves the cycle time of the framing station.

Scenario Three: Production line with Semi-Automated Steel Framing Station using screw dollies (Screw by Screw)

This scenario represents an actual case from an Edmonton-based light gauge steel panel manufacturer. This scenario involves a semi-automated steel framing station that uses a set of two dollies rather than an automated "Stationary Gantry". Using dollies is more labour-intensive work that results in slower production and longer cycle time for a given frame. Rather than a set of complex systems as mentioned previously, this new scenario is modelled using only one "Task" element, where the duration of the hard connections depends on the historical data as provided by the manufacturer. Note: In this case, an additional column was added to MS Access database which summarizes the number of openings in each panel.

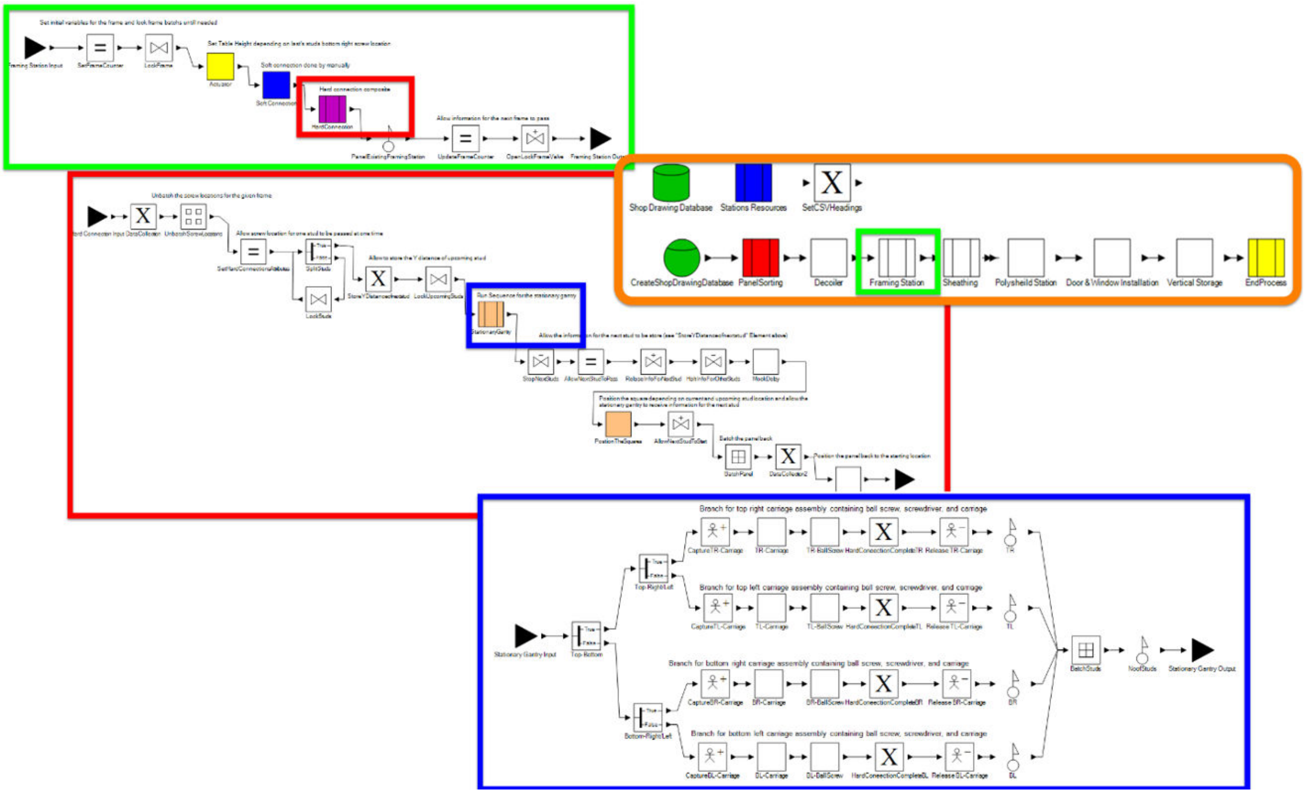


Figure 8. Scenario One: Model for LGS production line with Semi-Automated Framing Station & Manual Screw Feeding (Strips of 50 Screws)

Generation of custom Comma-Separated Values (CSV) file

For the above three scenarios, a custom CSV file is generated for the completion of each model. The custom CSV is designed to output the cycle time of each station for every panel, this CSV file can be used in MS Excel to generate a more accurate forecast for the utilization and the production of panels as highlighted in the MS Access database. The headings included in the CSV files are: Panel ID, Station Name, Time In, and Time Out.

OUTPUT ANALYSIS

To help visualize the simulation results and to produce a useable schedule, a Gantt Chart for scenario one was constructed with an average cycle time of each station for 60 simulation runs. The resulting graphical Gantt Chart can be seen in Appendix A, Figure 1. From the Gantt chart, the Decoiler station has no lag time between the productions of different frames, thereby resulting in a start to finish relationship with zero-lag. The zero-lag relationship means that under the current simulation model, the decoiling station is the first bottleneck in the system because no production can begin unless the studs are ready for the assembly. Nevertheless, after the decoiling station, each frame passes through the assembly station, starting from the Actuator adjustment to the completion of the Hard connections. During, the entire framing process, the time between panels is mostly linked to the availability of the raw material from the decoiling station. However, the extra raw material must wait until the existing panel has clear the framing station, as seen by panel five which had to wait of 5 minutes before the framing could start after the completion of panel 4.

Since the Gantt chart was produced from Scenario one, the increased cycle time for the loading of screw magazines can be observed as two spikes in the cycle time of the fourth and sixth panel. Again, during the loading of magazines the machine must shut down for 2 minutes for the loading of each magazine.

After the completion of framing phase, the Sheathing placement, Nailing, Polysheild, and Door/Window installation stations all follow similar trends, where each frame is processed at the First-come, first-served basis with a short time lag in between every frame. The short time lag between each frame is the result of start to finish relationships between each station. Finally, the Vertical Storage station shows an overlap between different frames, which is the result of having 12 servers. In short, the vertical storage can store up to 12 completed frames concurrently.

The Gantt chart for scenario one was generated using the average cycle times for each station, which ignores the variability of each station due to their stochastic nature. To understand the true cycle time variability for each station with stochastic durations a box plot is shown in Appendix A, Figure 2. Since all stochastic stations are same in all three models, the in-depth comparison between each model was excluded from this paper. Lastly, similar Gantt charts can be produced for other two scenarios; however, this was not done because each model would have a similar flow of panels with only change arising from the framing station.

To understand the changes in the framing station, Figure 9. Comparison of Framing Station for Each of Three Scenarios

shows a comparison between the cycle times for each scenario. Here, the cycle time for the soft connections for the Manual option (scenario three) is higher compared to other two scenarios. This increase in cycle time is the result of adding pre-assembled door and window components. Since scenario one and two follow the same philosophy of soft connections, their timing is exactly the same. Looking at the Hard connection station, the Manual option (scenario three) on average produces higher cycle times when compare to other two scenarios. An exclusion is the loading of screw magazines contributing to the increased cycle time of the fourth and sixth frame in the scenario one. From this analysis, on average having an automatic station for hard connections provides faster cycle times; however, without automatic feeding, the downtime can add extra time to framing cycle which can be seen by fourth and sixth frame. Finally, looking at overall framing station cycle time, scenario one and two will produce same results until the screw magazines require reloading.

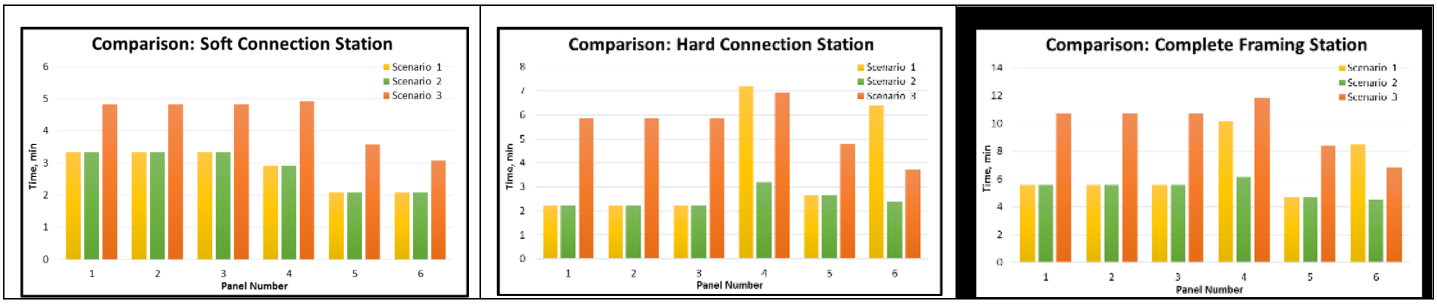


Figure 9. Comparison of Framing Station for Each of Three Scenarios

The increase in frame processing time in the Scenario One can be further investigated by examining the magazine inventory as a continuous process in Simphony. **Error! Reference source not found.** 10 shows an output generated by "Chart" element from Simphony. In this figure, it can be shown that the magazines from the left side were emptied at the fourth frame, which directly correlates to the increase in station time for the fourth frame under Figure 9. Comparison of Framing Station for Each of Three Scenarios

Moreover, the right-side magazines were emptied during the processing of the sixth frame, again, which directly correlates to the increase in processing time seen by the sixth frame in Figure 9.

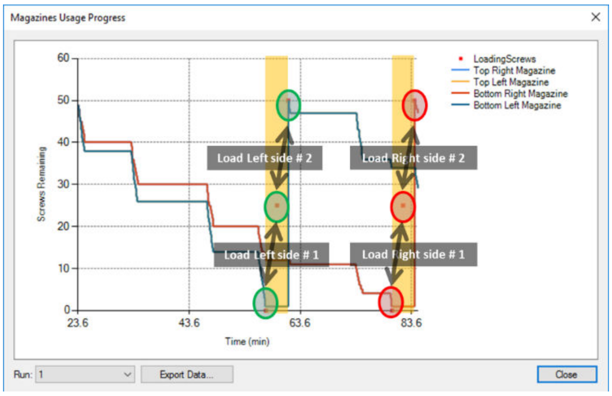


Figure 10. Graphical output from SIMPHONY for magazine usage for every screwdriver in Scenario One

From above comparisons, the Steel Framing Prototype machine provides an advantage over the existing Semi-Automated Steel Framing machine with screw dollies. In fact, the cycle time can be reduced by half thereby resulting in the faster completion of each steel panel. Nevertheless, having to regularly feed screw magazines after 50 screws result in few higher cycle times, which can be avoided by using automatic screw feeding system.

CONCLUSION

To achieve balance between demand and supply in an industrial production line for steel wall frames, factory simulation modelling techniques are employed for estimating the processing cycle times of stations in a production line and their corresponding machines. Furthermore, in order to pinpoint and determine the bottleneck stations/machines, the entire production line is simulated for different sizes of panels using Simphony.NET software. The simulation results provide comprehensive insights pertinent to decision making, informing managers about backward and forward major and minor flows of the stations/machines in the production line. For example, by changing the screw-feeding system from manual to strips of 50 screws to auto-feeding at the hard connection station, the differences and the benefits of each option are observed in improving the production cycle time. Moreover, determining the bottleneck station/machine in the factory production system during the conceptual phase of factory development will limit bottleneck problems across the production line. The results indicate that the simulation of a specific machine operation in a production line is an effective method for production line balancing in real industrial cases, and that simulation can be expected to assist managers in the decision-making process, resulting in more efficient utilization of resources in wall framing operations, thereby improving factory performance and production rates.

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