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ONLINE SIMULATION MODELING OF PREFABRICATED WALL PANEL PRODUCTION USING RFID SYSTEM

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ABSTRACT

The use of discrete-event simulation (DES) in the construction and manufacturing industry has been increasing significantly over the past few decades. However, DES at present is mainly utilized during the construction planning phase as a planning tool, and it still remains a challenge to apply simulation during the execution phase for the purpose of construction control without an automated real-time data acquisition system. This study exploits an approach that involves the integration of a radio frequency identification (RFID) system and DES model in order to capture the real-time production state into the simulation model, thereby enabling real-time, simulation-based performance monitoring. The proposed methodology is implemented at Landmark Building Solutions, a wood-frame panel prefabrication plant in Edmonton, Canada. A simulation model is developed in Simphony.NET and integrated with the RFID system in order to enable the online simulation and to obtain real-time simulation results for the purpose of production control.

1 INTRODUCTION

Prefabricated construction is increasingly adopted in the home building industry due to the fact that it introduces improved quality and reduced cycle time, and allows for higher safety standards to be implemented. In contrast to conventional stick-built construction, prefabrication continuously targets productivity improvement by taking advantage of manufacturing theory and technology, rather than simply implementing field operation in an environment-controlled factory. In this context, construction scholars and practitioners have been implementing various approaches, including DES, to improve the current levels of productivity. It is widely known that DES technology allows construction practitioners to evaluate various construction/production scenarios and investigate different resource allocation strategies; it also provides a powerful tool to perform comprehensive analysis for the purpose of productivity improvements of repetitive processes (AbouRizk et al. 2010). However, to facilitate simulation-based production management and control, the ongoing status of the production line must be captured; then this information must be used as inputs into the simulation model. In turn, the simulation model predicts a meaningful future performance is utilized in planning construction operations. Nevertheless, current data for production lines is primarily collected manually, a practice which is laborious and error-prone and which restricts the application of DES simulation in panel prefabrication management. It is also a challenge to obtain real-time data for simulation without the use of an automated acquisition system. Recently, modern sensor technology (e.g., RFID and barcode) has made it possible to capture real-time construction data in order to improve planning accuracy and efficiency. A real-time data acquisition system could further extend the use of simulation from the construction planning stage to the construction

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control stage. Simply put, real-time data could assist construction practitioners in identifying the performance of the production line in real-time, and further provide timely information about production lines in order to manage and control production. In this regard, this research takes an online simulation-based approach to plan and control building panel prefabrication by means of integrating RFID and DES simulation. The paper provides a review of the literature pertaining to DES, RFID, and construction control. Subsequently, the proposed framework for integrating a data acquisition system and DES with the objective of facilitating real-time production planning and control is illustrated in detail. Following this, detailed implementation of the proposed framework for a building panel production line is presented. A case study of the Landmark Building Solutions wood-panel production plant is also described to demonstrate the effectiveness of the methodology and the prototype system.

2 LITERATURE REVIEW

There has been a considerable amount of research on production planning and control with focus on different types of manufacturing. Researchers have used DES, RFID data, lean principles, and optimization algorithms to develop decision support systems for planning and control. Peters and Smith (1998) presented a simulation control system developed at the Texas A&M Computer Aided Manufacturing Laboratory (TAMCAM). They used this control system to evaluate online simulation for the control process. Online simulation links the information system with the simulation model to provide actual production performance. They concluded that an online simulation-based real-time control system can be very beneficial in terms of adding flexibility to manufacturing systems. Mirdamadi et al. (2005) presented a DES-based real-time shop floor control system taking advantage of online simulation. Azimi et al. (2011) presented an integrated project control and monitoring framework implemented in a steel fabrication project. Their study applied RFID technology to collect real-time data and integrate it into the control system framework on the basis of high level architecture (HLA) simulation, along with DES and visualization, as a decision support system. This system helps the project manager to detect deviations in the production line and to mitigate these problems.

AlDurgham and Barghash (2008) summarized the literature on simulation applications in manufacturing and presented a framework for the application of simulation in different decision areas—manufacturing strategies, material handling, layout, sequencing and scheduling policies, and manufacturing processes and resources. Meyer et al. (2011) presented an intelligent product-based control and monitoring system; they outlined a decentralized control system to deal with all types of disturbances, including small delays that had not been considered in previous studies. The system detects every disturbance from the intelligent products labelled with auto-ID technologies (RFID/barcode), and also proposes solutions to the appropriate person. They validated the framework using simulation experiments, concluding that a centralized system serves better for planning purposes while a decentralized monitoring and control system will provide more robustness. Son et al. (2003) formulated a simulation-based shop floor control system by developing a resource model, a coordination execution model, and a simulation model. Dengiz and Alabas (2000) used a simulation model together with a tabu search to find the optimum number of kanbans in a just-in-time (JIT) system.

Akhavian and Behzadan (2011) presented dynamic data driven application simulation (DDDAS) where real time field data were collected by capturing positional and orientation data. Simulation input parameters were updated automatically from the real time data to create a dynamic simulation model of the construction projects. In another study, they used GPS, accelerometer and gyroscope to capture different construction activities for the purpose of simulation input modelling (Akhavian and Behzadan 2015). However, there has not been any research to date focusing on the development of a planning and control system for the prefabricated home building industry. This study thus seeks to bridge this gap by developing a production control system on the basis of the concept of online simulation outlined in previous studies. The methodology is implemented in a wood-frame panel prefabrication facility in Edmonton, Canada.

3 PROPOSED FRAMEWORK

Figure 1 shows the framework of the proposed simulation-based control system. The core of this framework is the central database that integrates product panel information, the RFID data acquisition system, and the DES simulation model. The building panel information and production schedule are stored in the central database, and production data such as panel location and timestamp are also uploaded to the database from the RFID system in real time. To begin, the simulation model reads the initial panel location from the database as well as the panel information and production sequence. Then, the simulation engine runs the model based on the process map and associated task-time formula (Altaf et al. 2014). Each task in the simulation model has a task-time formula associated with it in order to estimate the task duration. This task-time formula is developed on the basis of time study, and it can also be updated based on the historical data collected from the RFID system.

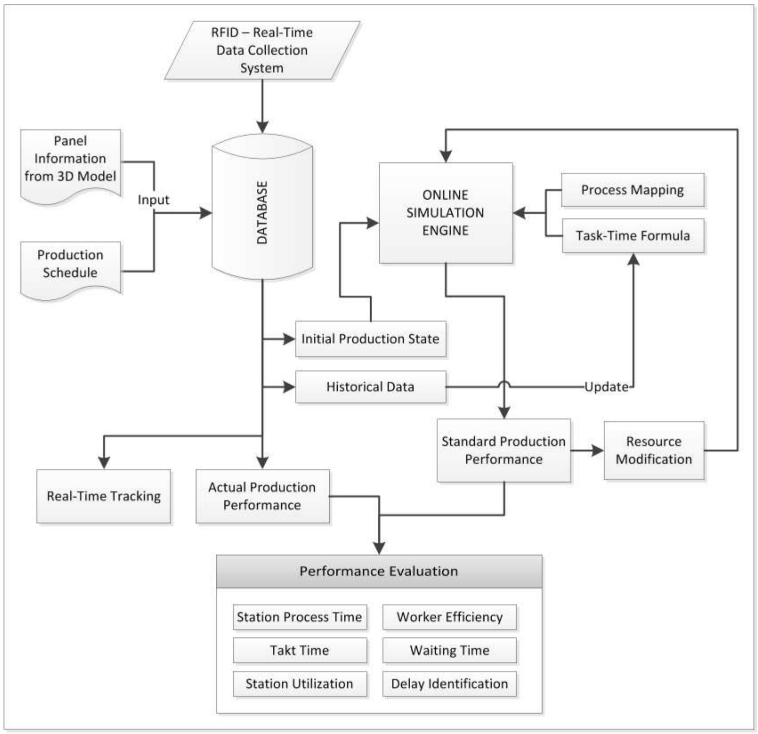


Figure 1: Simulation-based control system framework.

The simulation model provides standard production performance, while the RFID system provides actual production performance and real-time panel location. By comparing the actual and simulation results in real time, the production controller can identify delay, takt-time variation, worker efficiency, and station utilization. The resource allocation strategy can be modified in the simulation model in order to identify the effect of the change in real time and to adjust the process time of specific work stations in accordance with the simulation results. The simulation model also provides the expected makespan for the remaining wall panels at any point in the production,.

4 FRAMEWORK IMPLEMENTATION

4.1 Landmark Prefabrication Plant

Landmark Group of Builders operates a wood-frame panel prefabrication production line in Edmonton, Canada where wall, floor and roof panels are produced through computer numerical control (CNC) machines and then transported to the building site for on-site assembly. Currently the plant produces approximately 3.5 homes per day in two 8-hour shifts. The wall panel production line consists of framing, sheathing, spraying, and window installation stations. The prefabrication process starts at the framing station where the panel frame is built using a CNC machine, and then is moved forward to the sheathing station. Multiple wall panels are assembled together in one multi-wall panel at the framing station in order to leverage the framing station to its full capability. Figure 2 shows different multi-wall panels, which each consist of several single walls. For exterior wall panels, OSB sheathing is placed at the sheathing station by workers and automatically nailed by another CNC machine, which is called a *Multi-Function Bridge*. Afterward, exterior panels move to the spray-booth on a transfer cart where spray-foam insulation is applied. Next, the multi-wall panels are moved back to the transfer cart and cut into single-wall panels, and then transported to the window installation line. From there, all panels are fed into a storage area before loading.

Interior panels are produced during a night shift due to the fact that less work is required to produce them. After the framing station, interior wall panels move to the sheathing station where each single panel within a multi-wall panel is marked and any errors or defects encountered are corrected. The panel then moves through the multi-function bridge and skips the spray-booth. At the transfer cart, all interior multi-wall panels are cut into single-wall panels and shipped directly to the loading trailer as interior wall packages. Only long interior wall panels (longer than 12 ft) go to the storage line via the window installation line, since they are too large to be added to the package and transported directly to trailers.

Figure 2: Multi-wall panel: (A) Exterior multi-wall panel with windows and doors; (B) Garage wall with garage door; (C) Interior multi-wall; (D) Short exterior multi-wall.

4.2 RFID System

A Radio Frequency Identification (RFID) system has been installed in the Landmark's wall panel prefabrication line. Figure 3 illustrates the layout of RFID readers and antennae installed in the wall production line. The RFID system consists of four Motorola FX9500 RFID readers, sixteen Motorola AN440 high performance dual antennas, and one Zebra ZD500R RFID label printer.

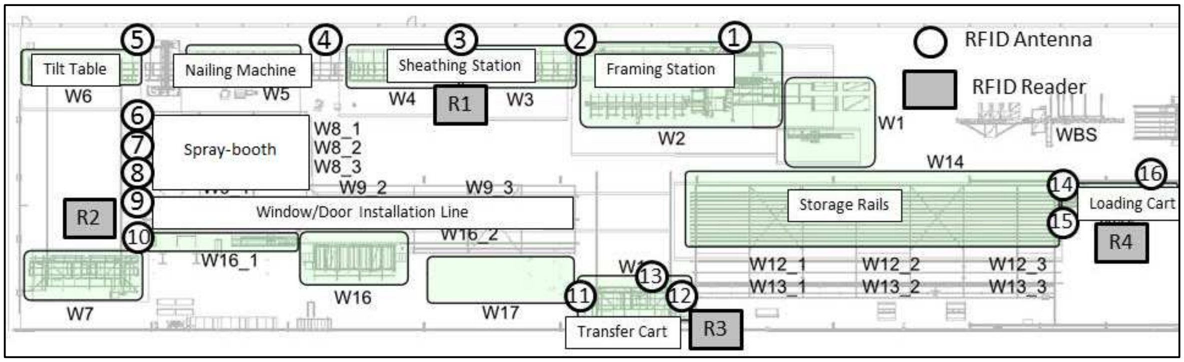


Figure 3: RFID system layout in Landmark's wall panel production line.

The RFID printer assigns the multi-wall panel name, single-wall name, job number, and date to each RFID label at the time of printing and updates the information into the database. The RFID label is glued to each single-wall panel at the framing station. Once the label is read by an antenna, the timestamp is recorded in the database through the RFID reader. Antennae 1 to 5 are placed in a series configuration, while antennae 6 to 8 are located at the entry point of the spray-booth, where the panel is sprayed with insulation foam and then pulled out from the same point once spraying is complete. As the coverage area is considerably large, three antennae have been installed to cover the entire entry point of the spray-booth. Antennae 9 and 10 are located at the beginning of the window/door installation line. Antenna 11 and 12 are located in the transfer cart which transports panels from the window installation area to the panel storage area. Antennae 11 and 12 record the entry and exit times, respectively, of the panel at "Transfer Cart". Both Antenna 14 and 15 record the entry time of the panel into the loading cart. Antenna 13 and 16 are located in "Transfer Cart" and "Loading Cart", respectively, to identify the storage rail. Small permanent RFID tags are installed at both sides of each storage line; Antenna 13 and 16 read these location tags to identify the correct storage rail. In this way, the space availability of each storage rail can be updated into the database.

4.3 Database Design

All panel information, such as panel name, length, width, job number, model name, and number of studs/windows/doors/sheathings, is required in order to calculate the panel processing time at each station. This panel information is extracted from the 3D model and stored in the central database, which is integrated with the simulation model. Additionally, the timestamp of each panel at each workstation is stored in the database in order to calculate the actual panel location and processing time. Figure 4 shows the Entity-Relationship (ER) diagram of the database.

In general, there are six tables in the database linked to one another through the foreign and primary key attributes. These tables are referred to as *Panels*, *ChildPanel*, *ProductionList*, *RFID-Multi*, *RFID* and *StationTime*. The *Panel* and *ChildPanel* tables contain all the information for multi-wall and single-wall panels, and the *ProductionList* table contains the production sequence. The *RFID-Multi* table gathers the multi-wall panel location and the *RFID* table contains single-wall panel location from the RFID system. The *StationTime* table has actual panel processing times for each workstation. The simulation model extracts necessary panel information from the database by means of Structured Query Language (SQL).

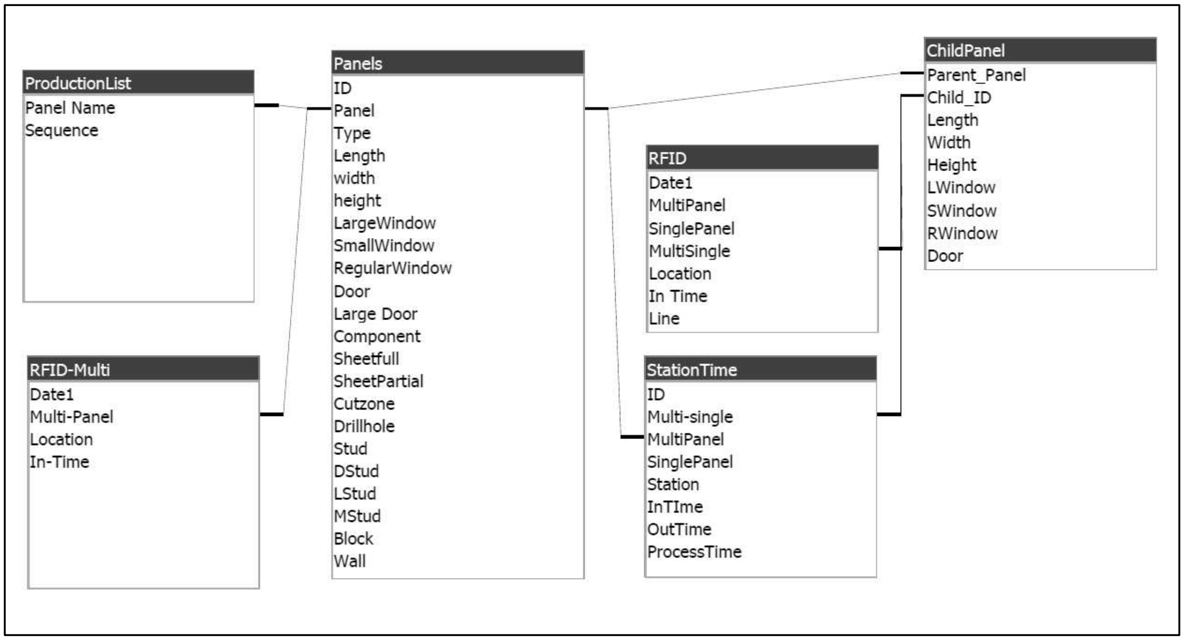


Figure 4: Entity-Relationship diagram in database.

4.4 Online Simulation Model

A detailed simulation model (shown in Figure 5) of the wall panel production line is developed in Simphony.NET, a simulation software developed at the University of Alberta (Mohamed and AbouRizk 2000). Simphony.NET provides various *model elements* in order to mimic real life scenarios. These model elements include *create*, *task*, *resource*, *capture*, *execute*, *counter*, *valve*, *branch*, *composite*, and *statistics*. In the simulation model, wall panels are the simulation *entity*. All the panel attributes, such as panel type and length, number of windows and doors, number of studs and sheets of sheathing, are extracted from the database at the beginning of the simulation model by means of an *execute* element. In order to obtain the current production state, the simulation model reads the *RFID-multi* table from the database in order to identify the number of multi-wall panels that are currently located between the framing table and the transfer cart table stations. Similarly, the model reads the *RFID* table to gain the number of single panels being processed at the window installation station. Based on the data, the model creates the same number of entities and assigns panel attributes accordingly. These entities are then sent to the associated workstation directly.

Each entity goes through a different *task* element on the basis of its attributes. A task element represents a work package in a workstation such as *install backing*, *install window*, or *place and nail OSB sheets*. A workstation can have multiple tasks within itself and requires one or more workers to perform each task. A worker is defined as a *resource* in the model. A workstation is represented by a *composite* element in the model which contains task, *capture*, and other model elements in order to simulate the production logic of that workstation. Framing table, sheathing table, multi-function bridge, transfer table are also each defined as resources, as each of these workstations can process only one multi-wall panel at a time. However, both the spray-booth and window station lines can process multiple wall panels simultaneously and have a maximum capacity defined in linear feet. A *branch* and *valve* element is used before the spray-booth and window installation stations in order to monitor the entry of the wall panel into these stations. At the branch element, the entity checks the current available length of the station using a global variable. If the working space is not sufficient, the entity will be held by a valve, which is looped back to the branch element. Whenever one entity goes out of that station, it opens the valve. The entity that is waiting at the valve, goes back to the branch and checks the availability again. If there is enough space for that wall panel, it enters the station and closes the valve. Figure 6 shows the simulation model section with branch and valve elements. The simulation logic of the branch element is shown below:

```
using Simphony.General;
public static partial class Formulas
{
   public static System.Boolean Formula(Simphony.General.Branch context)
   {
      //get the available length from global variable
      var currentlength = Scenario.Ints[2];
      //get current panel length
      var panellength = CurrentEntity.Ints[1];
      //check if the current panel have enough space in the station
      if (panellength + currentlength < 48768)
      {
         //increase the current available length of the workstation
         Scenario.Ints[2] = Scenario.Ints[2] + CurrentEntity.Ints[1];
         //close the valve
         Simphony.General.Valve valve1 =
         Scenario.GetElement<Simphony.General.Valve>("Valve");
         valve1.State = ValveState.Closed;
         return true;
      }
      else
      {
         //Wait at the valve element
         return false;
      }
   }
}
```

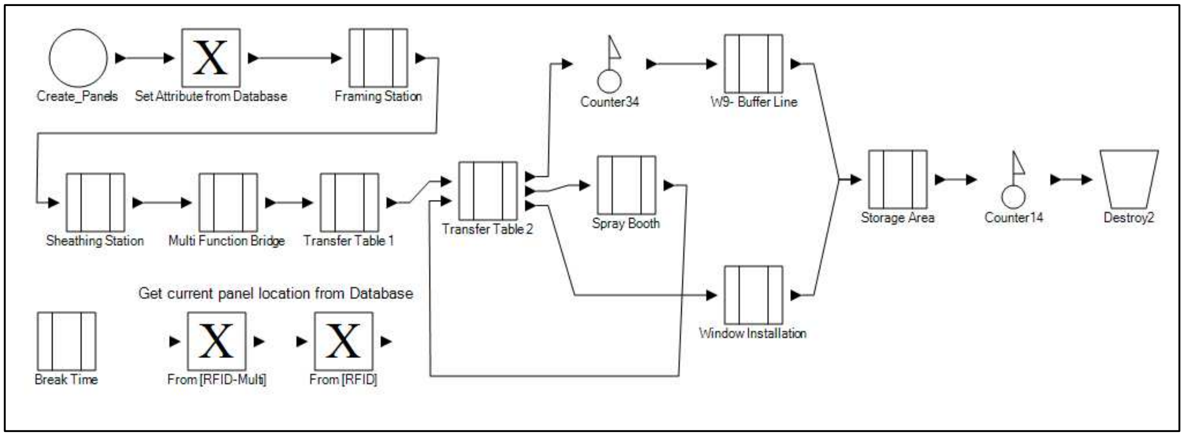


Figure 5: Simulation model of wall production line in Simphony.NET.

Task duration is calculated by means of the task-time formula that is developed based on time study. Each workstation has a delay time which is triangularly distributed. In order to trigger a task, an entity has to first capture the table resource (e.g., framing table, sheathing table), then needs to capture the necessary number of workers resource. The model will then calculate the task processing time based on the entity attributes. For example, if a panel has two windows, at the window installation task the model will multiply window installation time by two to move to the next location at that time. Then the entity will randomly generate the delay value based on triangular distribution. After completing all tasks, the statistics of each workstation are collected and the entity is destroyed using the *destroy* element.

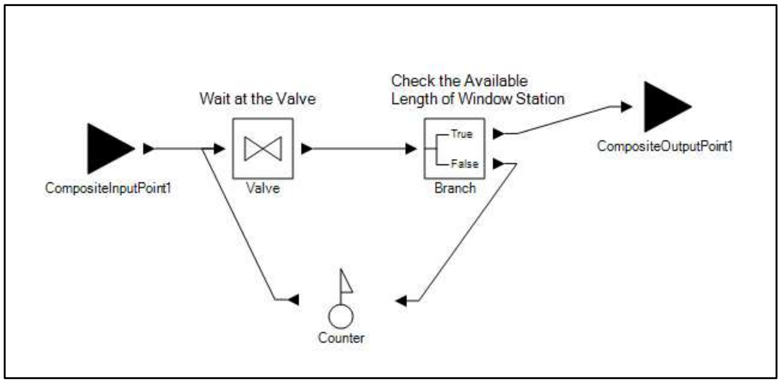
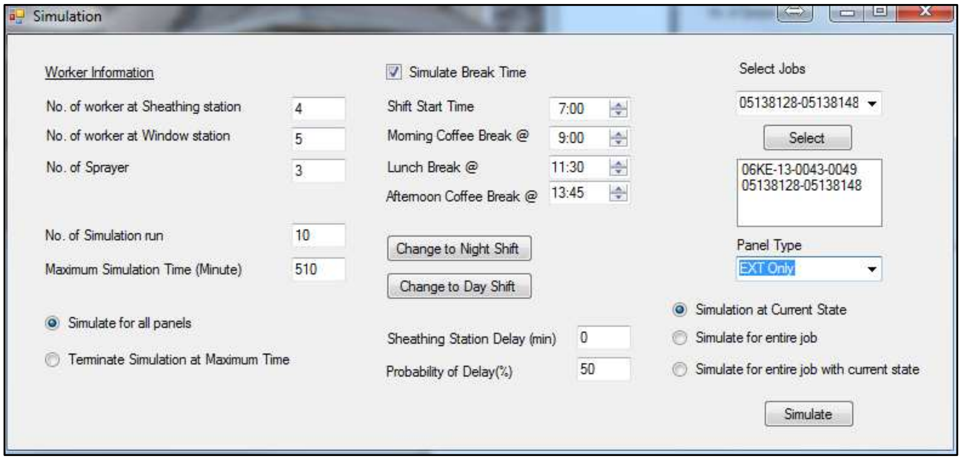


Figure 6: Simulation logic for checking space availability in Simphony.NET.

4.5 Results and Discussion

The simulation model is launched with a user interface developed in a Microsoft.NET framework, as shown in Figure 7. This interface allows users to easily input the job number that needs to be simulated, as well as several simulation parameters such as number of worker at different workstations, number of simulation runs, delay parameter at a given workstation, type of shift, and type of simulation to be performed. The simulation model can run with or without the panels located at different workstations at the time of simulation.



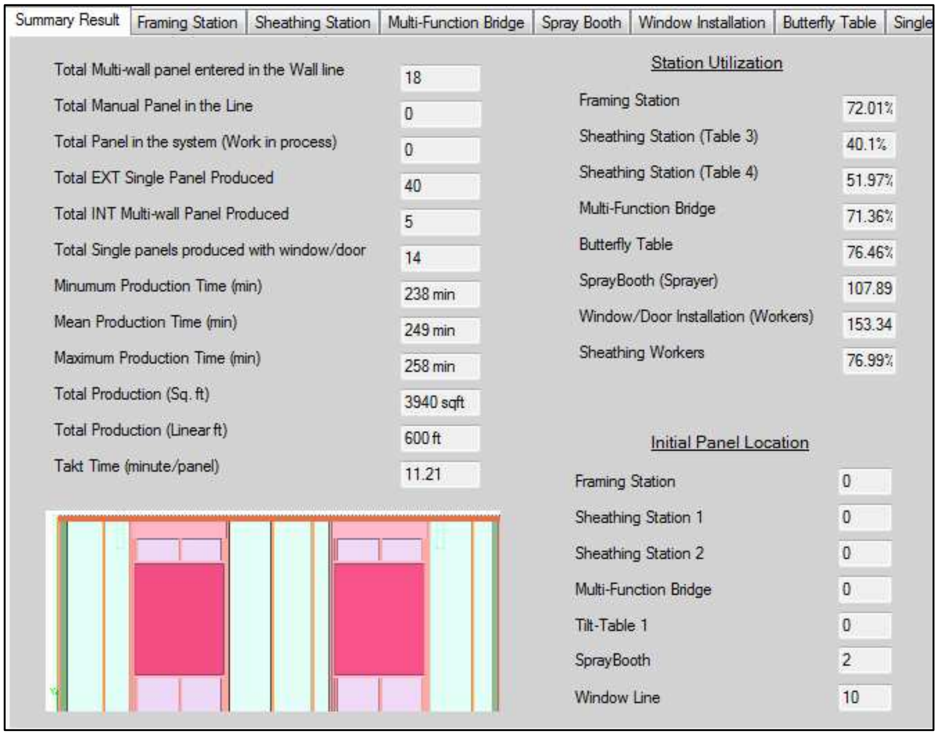
Worker Information
No. of worker at Sheathing station: 4
No. of worker at Window station: 5
No. of Sprayer: 3
No. of Simulation run: 10
Maximum Simulation Time (Minute): 510
● Simulate for all panels
○ Terminate Simulation at Maximum Time

☑ Simulate Break Time
Shift Start Time: 7:00
Morning Coffee Break @: 9:00
Lunch Break @: 11:30
Afternoon Coffee Break @: 13:45
Sheathing Station Delay (min): 0
Probability of Delay(%): 50

Select Jobs: 05138128-05138148
06KE-13-0043-0049
05138128-05138148
Panel Type: EXT Only
● Simulation at Current State
○ Simulate for entire job
○ Simulate for entire job with current state

Figure 7: User interface to select simulation parameter.

The simulation result summary is presented in Figure 8. The simulation is run for 18 exterior multi-wall panels, with 10 single-wall panels at the window installation station and two multi-wall panels at the spray-booth station at the time of simulation. This information is collected from the central database, which is integrated with the RFID data collection system. The simulation model estimates the required production time in order to build these 18 multi-wall panels and the collective workstation utilization. The mean makespan of 18 multi-wall panels and 12 in-process single panels is found to be 249 minutes. The simulation model also provides detailed processing times for each wall panel at different stations. After actual production, the simulation results are compared with actual processing time in order to get simulation-based performance measurements. Currently, the performance measurement indicator mainly includes linear feet or square feet production per day. However, different wall panels require different amounts of work at each station based on criteria such as number of openings, number of studs, spray surface area, and number of sheets of sheathing. For this reason, two wall panels with the same square foot value may need different amounts of time in the same workstation. A simulation model can provide an actual performance evaluation, as it takes into account all the different parameters that contribute to the panel processing time.



Total Multi-wall panel entered in the Wall line	18
Total Manual Panel in the Line	0
Total Panel in the system (Work in process)	0
Total EXT Single Panel Produced	40
Total INT Multi-wall Panel Produced	5
Total Single panels produced with window/door	14
Minumum Production Time (min)	238 min
Mean Production Time (min)	249 min
Maximum Production Time (min)	258 min
Total Production (Sq. ft)	3940 sqft
Total Production (Linear ft)	600 ft
Takt Time (minute/panel)	11.21

Station Utilization

Framing Station	72.01%
Sheathing Station (Table 3)	40.1%
Sheathing Station (Table 4)	51.97%
Multi-Function Bridge	71.36%
Butterfly Table	76.46%
SprayBooth (Sprayer)	107.89
Window/Door Installation (Workers)	153.34
Sheathing Workers	76.99%

Initial Panel Location

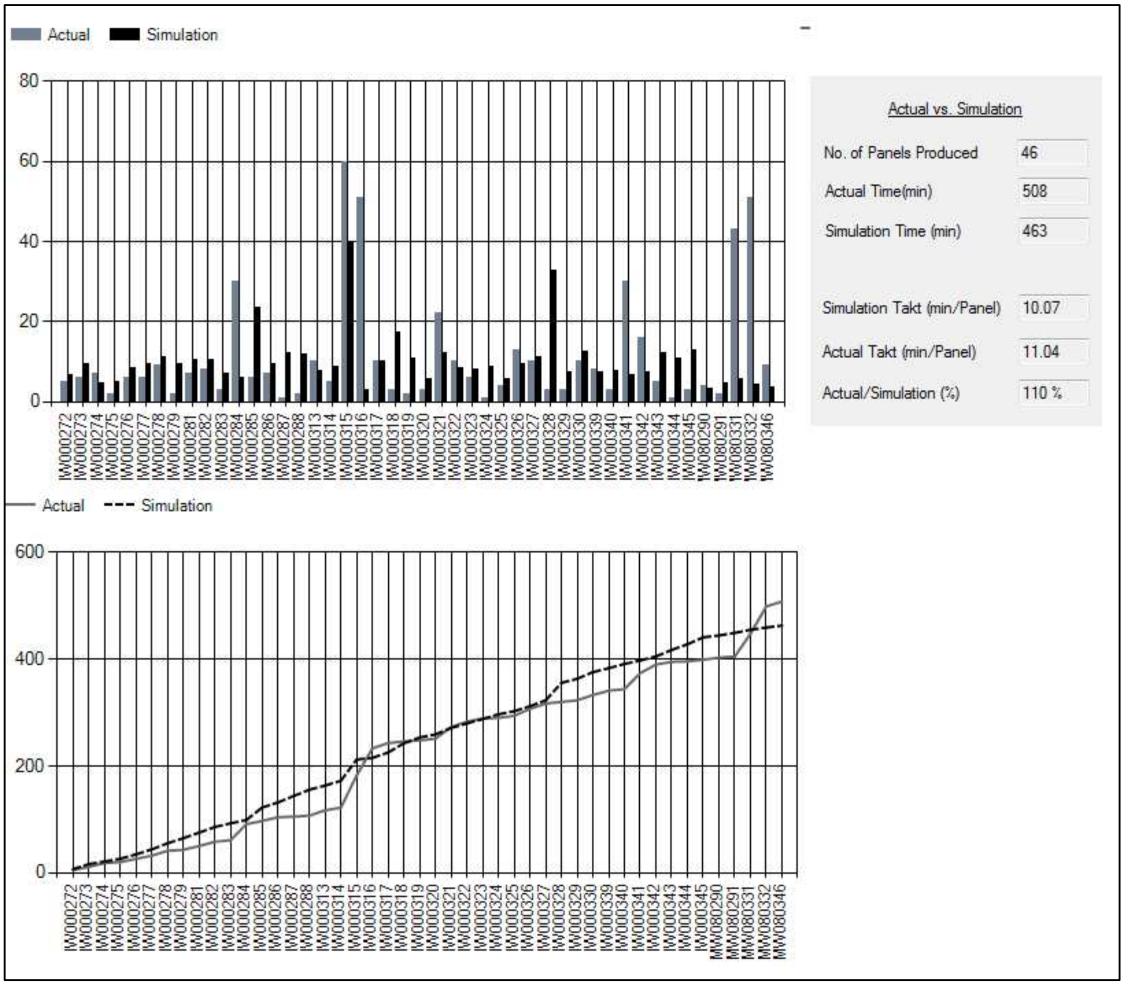
Framing Station	0
Sheathing Station 1	0
Sheathing Station 2	0
Multi-Function Bridge	0
Tilt-Table 1	0
SprayBooth	2
Window Line	10

Figure 8: Simulation result summary.

Figure 9 shows the panel processing time in comparison to actual time at the framing station and the simulation-based performance evaluation. The simulation is run for 46 interior wall panels, and both individual panel processing time and cumulative process time are compared with the actual data. The total time to produce all 46 panels is compared with the actual total production time and, as a result, the actual production time is found to be 10% slower than the simulation time; the panel takt-time is also found to be 1 minute slower than the simulation. These indicators can provide the production manager with detailed insight regarding production performance in real time.

5 CONCLUSION

This paper has presented a methodology to integrate a simulation model with an automated data acquisition system, thereby developing an online simulation-based production control system. The simulation model and automated data acquisition system in this study are integrated through a central database which holds all the required product information and real-time production state data. The simulation model can retrieve the information stored in the central database, and then evaluate the production performance in real-time. MS Access, Simphony.NET 4.0 simulation engine, and a RFID data acquisition system are employed to develop the prototype system based on the proposed methodology. Additionally, a user-friendly graphic interface has been developed in order to easily implement the prototype system in the current industry. The prototype system has been tested in Landmark’s wall panel prefabrication line. The successful implementation of the system demonstrates the utility of the online simulation model as a production control tool. The traditional production control methods are slow and prone to human error. With simulation based control system, most of the information are generated automatically to help make the efficient decision quickly and enable the controller to compare different production options in real time. Furthermore, the online simulation-based production control system provides construction practitioners with insights into the functionality of the production line and further assists practitioners in controlling the production line. This research has also demonstrated the effectiveness of the RFID system as a real-time data collection system in prefabricated panel production.



Actual vs. Simulation

No. of Panels Produced	46
Actual Time(min)	508
Simulation Time (min)	463
Simulation Takt (min/Panel)	10.07
Actual Takt (min/Panel)	11.04
Actual/Simulation (%)	110 %

Figure 9. Comparison of actual and simulation results.

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