AUTOMATED PRODUCTION PLANNING IN PANELIZED CONSTRUCTION ENABLED BY INTEGRATING DISCRETE-EVENT SIMULATION AND BIM

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Abstract: Panelization, a form of off-site construction with origins in the manufacturing industry, has emerged as a popular, more efficient approach to constructing residential projects. This approach transfers some of the construction activities traditionally carried out on site into factory production tasks, and divides construction management into factory production management and on-site assembly management. This change poses some challenges to construction practitioners with respect to project planning and management, such as how to efficiently create work flow, balance the production line, and satisfy various panel requirements to ensure smooth on-site operations. This paper thus explores an automated approach for construction planning in the production plant with the objective of improving productivity and balancing the production line, which achieves a seamless integration of building information modelling (BIM) and discrete-event simulation (DES). Specifically, a BIM-based special-purpose simulation (SPS) template for the production line is developed in Simphony.NET in order to facilitate more efficient modelling of the production line. The new simulation template provides a BIM-based interface which permits enriched information exchange between the BIM model and the simulation model. A case study of a production line for light gauge steel panels is presented to demonstrate the methodology. The simulation results show that proper production sequencing improves production performance, and that the newly developed simulation template is a useful planning tool for the panelized construction system.

1 INTRODUCTION

The light gauge steel (LGS) panel system provides a cost-effective building solution for mid-rise multifamily residential buildings. In this panelized construction method, most building components, such as the walls and bathrooms, are prefabricated in the factory and then delivered to the site for on-site assembly. Compared with conventional construction systems or methods whereby the majority of construction tasks take place on site, the on-site work involved in LGS construction is limited to the assembly of factory-built building components, such as wall panels and floor joists. This process thus has the potential to minimize the waste involved in the construction process and enhance efficiency. Nevertheless, due to the large number of components (panels) involved, the success of such projects relies on accurate and reasonable scheduling for the production, shipping, and installation of the panels, and delays in panel delivery or overproduction in the factory can result in project delays and increased inventory costs. More importantly, prefabricated panels are unique and vary in product design features (e.g., length, having windows or doors, having various connections). Panel fabrication is recognized as a low-volume and high-variety product mix production process. Consequently, it is a challenge for construction practitioners to formulate
production plans which can balance the production line, and satisfy various panel requirements to ensure smooth on-site operations. Still, in current practice construction plans are typically planned manually based on practitioners’ experience and intuition, a practice which can be subjective, tedious and error-prone.

Building information modelling (BIM) is an information technology that has the ability to change the Architecture, Engineering, and Construction (AEC) industry in terms of boosting productivity and enhancing communication. Since BIM hosts enriched product information, which is required for planning analysis, it is capable of supporting the automatic generation of construction plans. Meanwhile, a simulation-based approach can be utilized to perform operation-level construction planning due to the fact that discrete-event simulation (DES) can mimic the construction operation logic and investigate the allocation of available resources among activities. Nevertheless, simulation-based planning at present only utilizes limited building information (e.g., quantity take-offs) for planning analysis, and it has yet to take full advantage of the rich product information in BIM models in order to automate construction plan generation. It necessitates a large amount of human judgment and intervention for simulation model development and information exchanges between BIM modeling tools and planning tools. In this case, both BIM and DES in current practice have not yet been leveraged to their full capabilities with regard to construction planning. To address these issues, this paper thus explores an automated approach which achieves a seamless integration of BIM and DES for construction planning in the production plant, with the objective of improving productivity and balancing the production line. More specifically, a BIM-based special-purpose simulation (SPS) template for building panel production lines is developed in Simphony.NET, a simulation engine developed at the University of Alberta (AbouRizk and Mohamed 2000). The new simulation template provides a BIM-based interface which permits enriched information exchange between BIM and DES, and customized simulation elements with specific simulation behaviour that are helpful and more efficient in simulation modelling of the panel production facility. A case study of a production line for LGS panels is presented to demonstrate the methodology. Various production scenarios with respect to panel production sequence are evaluated in the simulation model. The results show that proper production sequencing improves production performance, and that the newly developed simulation template is a useful planning tool for panelized construction. Finally, conclusions are summarized and limitations of the present research are identified with respect to future research.

2 LITERATURE REVIEW

BIM is increasingly being embraced within the architecture, engineering, and construction (AEC) industry to support various tasks, including design/drafting, quantity takeoff, cost estimation, and communication among project stakeholders. Efforts have also been made in recent years to formulate construction plans by leveraging the benefits of BIM. For instance, Kim et al. (2013) developed a prototype for the purpose of automating construction scheduling by parsing an Industry Foundation Classes (IFC)-based BIM model. Liu et al. (2014) proposed an approach to generating on-site scheduling under the constraints of structural support and topological relationships among building elements. Later, Liu et al. (2015) further developed a BIM-based integrated approach of detailed construction scheduling under resource constraints, which achieves an in-depth integration of BIM models with work package information, process simulations, and optimization algorithms. Chen et al. (2013) also proposed a CAD-based framework to yield the near-optimum schedule. The 3D CAD model in their framework, however, only provided quantity take-offs for the process simulation model, with a large amount of human effort and simulation knowledge required to develop the simulation model. Moon et al. (2013) developed a BIM-based construction scheduling method with the objective of reducing activity overlaps. Their main focus with respect to BIM was on visualization and did not support construction plan generation.

DES is able to mimic real-world construction systems based on elaborate computer programming and statistical analysis, and could provide construction managers with insight on construction systems by evaluating various construction scenarios. It thus provides a powerful tool to perform comprehensive analysis for the purpose of productivity improvement of repetitive processes (AbouRizk et al. 2010). Halpin (1977) introduced CYCLONE, a simulation environment, which has created the foundation for the advancement of construction simulation. AbouRizk and Hajjar (1998) proposed a framework for the application of simulation in construction, specifically focusing on construction practitioners.
presented the concept of special-purpose simulation (SPS), which is a computer-based environment specially built for experts in the area, the advantage of this environment being that the user does not need to have prior knowledge of simulation. AbouRizk and Mohamed (2000) introduced Simphony.NET, an integrated environment to model construction activities. This simulation software supports both DES and continuous simulation and 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. There also have been several studies encompassing the use of DES in various fields of construction, such as bridge construction (Alvanchi et al. 2012), tunneling projects (Al-Bataineh et al. 2013; Ruwanpura et al. 2001), simulation-based production line optimization (Altaf et al. 2014), and SPS for industrial fabrication (Sadeghi and Fayek 2008; Song et al. 2006). Based on these studies, simulation modelling provides a promising means enabling engineers to precisely examine different approaches in order to complete the project. Most of the existing research related to BIM and DES-based planning, it should be noted, has focused on building information extraction from the given BIM model or simulation tool/application. However, the development of a BIM-based simulation tool for construction planning which enhances both enriched information exchanges between BIM and DES and simulation network (construction logic) modelling has not yet drawn much attention within the construction industry. This study thus aims to address these limitations in the existing research.

3 FABRICATION PROCESS OF LIGHT GAUGE STEEL WALL PANELS

Presently, in LGS construction practice, some building components, such as structural bearing walls and staircases, are pre-assembled in the factory and installed on site as panels. Washroom modules each consisting of four wall panels, a floor, and a ceiling (which serves as the floor for the level above), are also prefabricated in the factory, with all other components in the washroom, such as the tub, being pre-installed prior to shipment to the site. This research focuses on the wall panel production line in particular. The production line consists of a series of workstations (as shown in Figure 10) where specific operations/processes are carried out to produce the aforementioned building components. The fabrication process begins with steel studs and plates being assembled together into panel frames at the assembly station, regardless of panel category (exterior, interior, or washroom panel). The assembled panels are then moved to the framing station where a pressing process is carried out by a computer numerical control (CNC) machine in order to form the panel into a rigid frame. Subsequently, framed exterior wall panels are transferred to the sheathing station and nailing bridge for placement and nailing of sheathings; interior wall panels, meanwhile, are moved directly to the vertical panel storage area for shipment to the construction site, whereas washroom panels advance to a modular production line where they are assembled into modules. The exterior wall panels, following sheathing and nailing, go through the polyshield station and the polybase and mesh station, sequentially, in order for polyshield, polybase, and mesh to be applied. Finally, exterior wall panels without windows and doors are sent to the vertical panel storage area, while exterior wall panels which are to include windows and/or doors are transferred to the window and door installation station before they are moved to the vertical panel storage area. The prefabricated washroom modules are transferred to the modular storage area for shipment once they are completed.

4 METHODOLOGY

As described by AbouRizk and Hajjar (1998) special-purpose simulation (SPS) is defined as “a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself.” Hence, a BIM-based SPS template is developed in this research and is utilized to more efficiently build the DES model of the production line, thereby assisting production managers in planning and managing factory production. In general, the developed simulation template can reduce the manual data entry required and enhance information exchange (e.g., quantity takeoff and building design features) from the BIM authoring tool to the SPS model, capitalizing on the developed BIM model parser and the new simulation element “Input” in the proposed simulation template (see Figure 1 and Figure 4). The developed BIM model parser can extract
enriched building information from the BIM model and generate simulation entities in an XML file, while the “Input” simulation element can automatically take the enriched and detailed product design information extracted in the form of an XML file as inputs for the simulation model. In addition, other parameters for the production line, such as Capacity of Station (see Figure 6 and Figure 7), are customized as inputs of simulation elements. Icons of the simulation elements match the production line icons with similar functionality for the purpose of facilitating understanding of the simulation models built from this template among construction practitioners. Furthermore, even construction practitioners who do not have a strong familiarity with simulation can develop DES models of production lines in order to mimic the production processes and to perform “What-If” analyses before actual implementation. More detailed explanations with respect to modelling elements are presented in the following sections.

Figure 1: Overview of proposed methodology

5 SPECIAL-PURPOSE SIMULATION TEMPLATE ELEMENTS

Simphony.Net (AbouRizk and Mohamed 2000) is selected as the simulation platform to build the proposed SPS tool. Six simulation elements—task, input, station, equipment, entity router, and storage—are developed to mimic the factory production processes for panelized building projects.

5.1 Simulation Entity

In the production line, product features (i.e., design parameters) of building components such as length, height, number of studs, number of windows, number of doors, and sheets of sheathing affect the processing time at each station. The functionality of building components such as exterior, interior, structural, non-structural and partition of building components determines the construction processes these components go through. Rich building information, including the aforementioned information, is embedded into building components (parametric objects) as their attributes or parameters in the BIM model (an assembly of pre-defined 3D building objects). Similar to parametric objects in a BIM model, the object-oriented concept can also be adopted to design simulation entities in the new SPS template. (Simulation entities used in most DES engines, including Simphony are capable of representing semi-products or materials traversing the simulation model.)

In order to mimic the fabrication process, simulation entities in the newly developed simulation template are customized to represent building components (parametric objects in the BIM model) that carry detailed design information from the BIM model as attributes, and move through the DES simulation model. These entities will be processed and guided in the simulation model in accordance with detailed design information. For instance, simulation entities will go through different stations based on panel functionality (e.g., exterior or interior). As such, the integration of a BIM product model and a DES model is realized by enriched information entities, which extract rich building product information of building components from BIM and traverse through the simulation model. Figure 2 shows the entity relation diagram of simulation entities representing building components. As depicted in the figure, all the information denoted by solid circles in Figure 2 is extracted from the BIM product model, while the attributes in the dashed-circles are generated by the simulation model. It should be noted that “opening” information and “panel framing” information (in relation to number of windows and number of studs) are listed under the “SubComponents” attribute.
The BIM model in this research is developed in Autodesk Revit. The in-house Revit add-on is developed to parse BIM models, to extract the enriched building information, and to assign it to the simulation entities. Simulation entities with enriched product information are then stored in an XML file, which is the input for the developed simulation model. Figure 3 shows a screenshot of a sample XML file.

![XML Corel file](image)

**Figure 3:** Sample of simulation entities with building information in XML

### 5.2 Input

The input element reads enriched building information and regenerates simulation entities (building panels) in the simulation model. One property of this element is "BIMXMLAddress", which enables users to specify the address of the XML file generated from Autodesk Revit. Once the simulation is triggered, the input element will read this XML file and release simulation entities into the developed simulation model. Figure 4 shows properties of the input element. As noted in the figure, the input has another property, "SequenceRule", which allows users to specify the sequence rule of simulation entities being released in order to determine the panel production sequence by writing their own scripts. Simulation entities carrying enriched building element information are transferred out from this element sequentially and traverse through the simulation model to mimic the panel fabrication processes.
5.3 Atomic task

A task element is the most basic simulation element, and it is utilized to simulate an atomic operation or process in construction. It is designed based on the process modelling ontological concept, which refers to the actors involved in the various processes of a project (El-Diraby et al. 2003). As a result, simulation entities representing building products request construction resources to trigger the task/operation, and these entities are held for a specific duration. Upon completion of the operation being simulated, simulation entities are transferred out from this element. The inputs for this element, as shown in Figure 5, include duration and required resources. Notably, a task element can be connected to multiple task elements in order to mimic the operations being executed concurrently (see Figure 10).

5.4 Station

As described above, the production line consists of several workstations where specific fabrication operations or tasks take place. In this context, a station element is developed to represent each work station. A station essentially represents a process which can be divided into more detailed sub-processes or sub-tasks. Consequently, the station element is designed as a “Composite” element, which allows users to place as many task elements as desired inside the station element. To start the operation in a station element, simulation entities (building product elements) need to be granted their requested construction resources (e.g., stationary machines). Once the requested resources are available, and provided the station’s capacity is sufficient to accommodate the coming simulation entities, these simulation entities are transferred into the element and kept inside until specific operations/tasks are completed. It is important to note that a work station has capacity limitations and cannot process unlimited simulation entities simultaneously. In addition, various stations have different measurements (e.g., panel length or height) for a given production capacity. In this regard, the station element shown in Figure 6 is customized to provide users an opportunity to define capacity and capacity units in order to mimic the production flow. This element can also collect the statistics data of cycle time, utilization, and waiting time for work stations. These statistics are shown graphically and can be used to assist production managers to manage and to balance the production line, and to improve productivity using lean principles.

5.5 Equipment

In addition to stations, various equipment (e.g., overhead crane) is commonly adopted in the prefabrication production line. Similar with work stations, equipment also has capacity limitations and is utilized to perform defined operations and tasks; however, the capacity works differently for equipment. The work stations process panels or semi-products immediately as long as panels arrive at the station provided that the station has sufficient remaining capacity to perform the operation. When the station reaches its full capacity, panels cannot enter the work station and must wait until some panels are released from the station. In this respect, crane operation differs in that it usually does not carry out its operation (e.g., lifting) until it reaches its full capacity. Furthermore, the operation of the crane is performed on batched semi-products (simulation entities). Once the specific operation is completed, the batched semi-products are un-batched and transferred out to the next operation. Another
interesting scenario is when the crane cannot reach its full capacity even if it takes all semi-products in queue. In this scenario, the crane can start the lifting operation without attaining its full capacity. In order to simulate the crane operation, the equipment element is developed. In addition to capacity and unit properties, the element has another two properties—"HavetoBeFull" and "WaitingTime". If "HavetoBeFull" is set to true, the equipment cannot start the operation until the full capacity is attained. If "HavetoBeFull" is set to false, "WaitingTime" can be further specified to determine the amount of time the equipment waits for the coming simulation entities before the operation is triggered. Figure 7 presents the inputs of the equipment element.

5.6 Entity router

Due to the fact that panels vary in design features, such as IsExterior and HasWindow, they will go through various work stations. Simulation entities thus need to be routed into the correct stations based on the enriched design information they carry. An entity router element is thus developed to solve the simulation entity routing problem. Figure 8 shows the inputs of this element. In this simulation element, the user can specify the routing rules in "RoutingConditionList", which is a collection of the next stations or tasks to which the simulation entity should be transferred, along with the condition that should be satisfied in order to send the simulation entity to the station. It should be noted that this element routes simulation entities in accordance with the routing conditions list, rather than connecting them with other simulation elements using directional arrows (as shown in Figure 10). This simplifies the graphical representation of a simulation model for the case in which simulation entities require various unique routes through the production line.

5.7 Storage

The storage element represents the storage area where finished panel products are stored for shipment to site. All simulation entities are finally transferred into the storage element in the simulation model. The main purpose of this element is to collect the statistical data for the total cycle times of the panels. The simulation result recorded into simulation entities as shown in Figure 2 is also written into the XML file by this element.

6 CASE STUDY

The newly developed SPS template was tested in an LGS wall panel production facility for residential buildings. The building shown in Figure 9 is composed of two storeys, each comprising four apartment units, one staircase, and two washrooms. In addition, there are 182 panels, including 60 non-bearing walls and 122 bearing walls. The building rests on 29 concrete footings. The building model is initially built in Autodesk Revit 2014, the building design information is extracted into simulation entities using an in-house Revit add-on, and then the simulation entities with enriched product design information are stored in an XML file. The simulation model can subsequently parse the XML file directly and release all simulation entities into a simulation network via the “Input” simulation element. This template significantly
reduces the effort required compared to preparing the simulation input manually, due to the enhanced information exchange between the BIM model and SPS model. Meanwhile, the simulation template speeds up simulation modelling of the panelized building production line by using customized simulation elements. Figure 10 presents the simulation model of the panel production line described in the previous section. As shown in the figure, the prefabrication process for the Window and Door Station can be further divided into several sub-tasks. In this case, a few task elements are placed inside the Station element in order to simulate the window and door installation process. Also, it should be noted that there are two parallel branches for window and door installation. This exemplifies the fact that some sub-tasks can be executed concurrently, as long as the required labour resources are available. Windows and doors can be installed simultaneously, and their respective processing times are different.

Figure 10: The simulation model of the panelized building production line

6.1 Processing Time Prediction

As described earlier, the process time is affected by the detailed design information about the panels. In the simulation model, process equations are inputted into the Task element (inside the “Station” element) in order to calculate the process time. For instance, the below equation is used to calculate the process time of the panel assembly operation (Altaf et al. 2014; Shafai 2012).

\[ T_A = \sum_{i=1}^{N_{ST}} T_{ST} + \frac{T_{BP}}{N_{BP}} + \frac{T_{TP}}{N_{TP}} + \frac{T_{W}}{N_{W}} + \frac{T_{D}}{N_{D}} + V \]  

Where \( T_A \) is the process time of the assembly station; \( T_{BP} \) and \( T_{TP} \) are the times, in seconds (s), needed to place each top and bottom plate, respectively; \( T_{ST} \) is the time needed to place a single stud; \( T_{W} \) is the time needed to assemble studs for each window; \( T_{D} \) is the time needed to assemble studs for each door, \( N_{BP}, N_{TP}, N_{ST}, N_{W}, \) and \( N_{D} \) are the numbers of subcomponents in the framing component, and \( V \) denotes variation for the assembly process and is assumed in this research to be a triangular distribution.

6.2 Simulation results

The simulation template and developed simulation model are verified by tracking the chronological list and observing the panel cycle time. Figure 11 presents cycle times of wall panels, denoted as “observation”. As shown in Figure 11.a, there are eight peak values for the cycle time, since the test project has eight similar units and wall panels are produced unit-by-unit. For each unit, wall panels are produced in descending order of panel length. In this sequence, the total production duration is 697.98 minutes. Alternative production sequences, such as level-by-level, are also evaluated in the simulation model, and all the production durations are found to be approximately 700 minutes, with the exception of the scenario in which all panels are produced in ascending order of panel length, in which case the duration is found to be 826.63 minutes. This is due to the fact that in this scenario exterior walls are started later than interior walls because they have a greater average length; however, exterior walls also take more time to produce (as demonstrated in Figure 11.a and Figure 11.b). As a result, the concurrent execution of assembly and framing station of Interior wall panels with sheathing and succeeding workstations of exterior wall panels leads to reducing overall production duration.
7 CONCLUSIONS AND FUTURE WORK

This research focuses on a BIM-based SPS template for a panel production line. A set of new simulation elements in Simphony.Net 4.0 is developed to speed up simulation modelling of the panel production line. This new simulation template can enhance simulation modelling in two aspects: (1) enhanced information exchange via object-oriented simulation entities, which mitigates the need for massive manual inputting; and (2) customized simulation elements with specific simulation behaviour, which are helpful and more efficient in simulating the production facility and mimicking the prefabrication process. This new simulation template thus enables construction practitioners who do not have a strong familiarity with simulation to develop DES models of production lines in order to perform “What-If” analyses before actual production. The simulation template has been tested using a case study of a production line for LGS panels. Various production sequences have been evaluated in the developed simulation model. The statistical data of cycle time, utilization, and waiting time for work stations are represented graphically and provide construction practitioners insights on production performance. On this basis, construction practitioners can plan and manage the production line using lean principles. The developed tool is demonstrated to be
helpful for assisting in the planning and management of the production line. In the next stage of research, the template will be further validated and applied to other building panel production lines. Also, data mining technology such as Artificial Neural Network (ANN) will be integrated into the proposed simulation template in order to predict operation process time based on historical data.

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