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SIMULATION BASED MULTI-OBJECTIVE COST-TIME TRADE-OFF FOR MULTI-FAMILY RESIDENTIAL OFF-SITE CONSTRUCTION

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ABSTRACT

Off-site construction is a shift toward a more efficient building process in terms of minimizing cost and decreasing duration of projects. However, since off-site construction consists of two separate phases, a comprehensive cost-time trade-off is essential. It gives control for the overall process where the direct and indirect effect of work performed on an individual task can be measured and evaluated with respect to the final project performance factors. The research presented in this paper develops a simulation model to study the dynamic relationship between off-site manufacturing and cost-time trade-off . A multi-objective analysis for two main indirect costs and inventory cost of the manufactured building components are proposed in order to provide a decision support system tool to clarify any ambiguity in the dynamic relationship between the project's two stages, and assist the manager to improve project planning and control.

1 INTRODUCTION

Planning and control draw different features of supply and demand together to ensure that the project's tasks run effectively and efficiently and deliver products and services as intended by the management team. In construction, planning and control cover many aspects, such as inventory management, supply chain management, enterprise resource planning (ERP), and material requirements planning (MRP) (Slack et al. 2010). The management team makes plans concerning what they aim to do, what resources they need in order to achieve their goals, and what intentions they desire to accomplish (Slack et al. 2010). Planning does not guarantee tasks will be done by the scheduled time and within the targeted budget. For instance, suppliers may not always deliver on time, or resources might not be available at the required time. Therefore, the control phase seeks to deal with changes that may occur when the scheduled tasks do not meet certain objectives, such as the projected timeline, product quality, targeted budget, or safe working conditions.

Additional cost can be incurred when a project's duration is shortened due to expediting some of its activities, such as by increasing crew size above the normal level, allowing overtime, or using unconventional construction methods (Sonmez and Bettemir 2012). Therefore, it is important to provide an optimal schedule based on defined sets of time-cost trade-off. Managers seek to solve trade-off problems by scheduling activities in such a way as to obtain an agreeable balance between cost, time, and quality, considering multiple objectives. Solving trade-off problems is a difficult task among the conflicting objectives in project scheduling. However, a customized, dynamic, and self-adaptive version of a multi-objective model can assist in solving the scheduling problems (Tavana et al. 2013). Normally, the intended multi-objectives consider minimizing the total project cost, project duration, and environmental impact (Xu et al. 2012). In projects, each task depends on its precedence relationship and resource availability. Therefore, resource allocation and leveling affects the project's time and associated cost (Ghoddousi et al. 2012).

Simulation analysis has been used in construction management and decision support systems, and it is considered a significant factor in project planning and control; as described by AbouRizk et al. (2011), "construction simulation, a fast-growing field, is the science of developing and experimenting with computer-based representations of construction systems to understand their underlying behavior." Simulation can be used as a decision making tool for analyzing different supply chain scenarios based on defining multiple objectives and input parameters (Longo and Mirabelli 2007). For supply chain and construction projects, discrete-event simulation (DES) and system dynamics (SD) are common modeling tools which aid decision support systems (DSS) (Tako and Robinson 2011; Alzraiee et al. 2012). Using simulation provides solutions to resolve issues at the strategic, tactical, and operational levels (Tako and Robinson 2011). Normally, a simulation-based approach integrates a DES model with database and spreadsheet applications to afford an appropriate and easy-to-use tool for meeting management objectives (Mohamed et al. 2007).

Integration of planning and scheduling throughout the supply chain remains a major challenge despite long-standing and ongoing research efforts (Samaranyake et al. 2014). On the other hand, trade-off between project time and cost is essential to decrease both project duration and cost and to maintain operations in today's competitive environment (Ghoddousi et al. 2012). Consequently, developing a model to support the integration velocity diagram (VC) and time-cost trade-off is important and relevant to planning and scheduling. This paper thus establishes a unique simulation model based on VC, and time-cost trade-off to ensure that the planned objectives will be achieved, as discussed further through a case study.

2 METHODOLGY

The objective of the proposed research is to develop a DSS to help managers understand the relationship between the off-site and on-site stages of a project and determine the lead time required to start the off-site manufacturing process; this serves to minimize the indirect cost associated with the managerial and overhead cost and inventory cost, according to a desired outcome or required conditions.

A company's policy in regards to project prioritization accounts for the desired conditions. Market conditions, project location, client demand, and the global economic status play key roles in shaping the company policy, which in turn defines the sequence of project initiation and completion. Consequently, it provides guidelines by which to assess project cost throughout a project's construction life cycle. Required conditions are related to uncontrolled incidents that entail a change in the overall plan: resource availability for a specific task, weather conditions, contracting arrangements (which could be defined as a preferable contracting arrangement if a continuous workflow is guaranteed to a sub-contractor), and delays. The cost-time trade-off guidelines are defined by both the desired and required conditions. Once the guidelines are defined, a comprehensive cost-time trade off analysis is performed to specify project cost versus time.

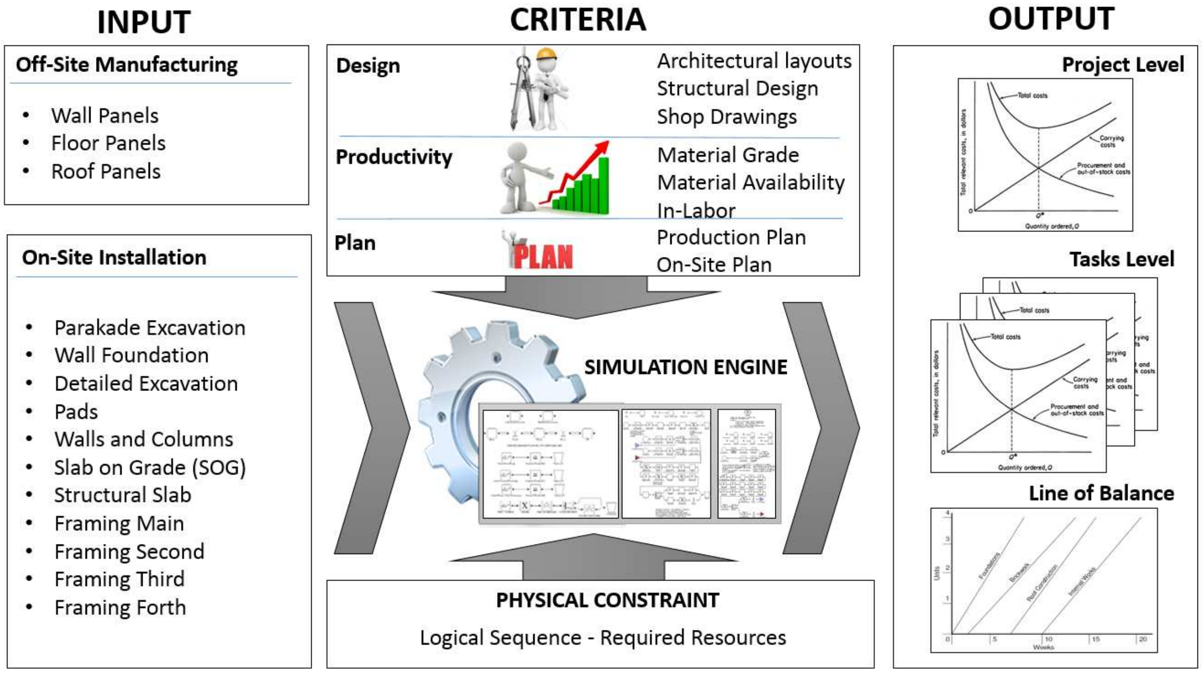


Figure 1: Proposed methodology.

The proposed simulation model captures the overall off-site construction process, which produces project cost and time using Velocity Diagram (VD) as output. It provides the managerial and overhead cost and inventory cost as well. Cost-time trade-off analysis is related to the lead time the off-site stage starts compared to the starting point of the on-site stage. Physical constraints related to the logical sequence of on-site activities are applied. Figure 1 illustrates the overall proposed methodology.

For the purpose of simplifying the simulation model, a three-level work breakdown structure (WBS) is proposed for the on-site activities, project level, task level, and sub-task level. Two levels of cost-time trade-off are proposed: project level, and tasks level. The scenario generation is based on time and work fixed-increment. At the project level, the off-site stage start date and end date define the project duration, and time-fixed-increment scenarios are generated at 10% of the overall duration, 20%, 30%, etc. The physical constraints are respected in regards to not allowing an on-site task to start until the off-site needed resources are available. On the task level, the quantity of work generated in each off-site task is measured, and work-fixed-increment scenarios are generated. These scenarios are represented time-wise, similar to at the project level, through the translation of work quantity performed into time according to the chosen duration distribution for each task in the simulation model.

The simulation model focuses on modeling and analyzing multi-storey residential projects, built utilizing the off-site manufacturing process. Off-site construction comprises two main stages, (1) off-site manufacturing and (2) on-site installation. During the manufacturing stage, the superstructure of the project is being prefabricated. For this stage, inputs include architectural layouts, structural design, shop drawings (design wise), and material availability, material grade and quality, in-factory labor (in-factory productivity wise), production plan, and on-site project plan (plan wise), as illustrated in Figure 1. The on-site installation stage in the illustrated project is divided into eleven tasks.

2.1 Architecture of the Simulation Model

Simphony.NET 4.0 is used to build the simulation model. Given that the main purpose of this model is to emulate the physical process followed in the construction industry to deliver a project, it is important to develop a generic model that adapts to the different cases of off-site construction. In order to achieve this, the model does not consider detailed activities, but combines different tasks into one representative task that captures the time needed to deliver a certain physical component of the building. That being said, tasks appearing in the model are directly related to finishing major project phases in the real-life project.

The simulation model consists of 5 sub-models. Three of these sub-models simulate physical activities, while the others are for monitoring and controlling purposes. Figure 2 shows the sub-models.

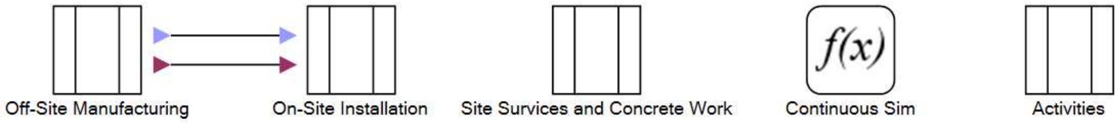


Figure 2: The simulation sub-model models.

The sub-models are outlined below.

- **Off-site manufacturing sub-model**: in this sub-model, the manufacturing process is simulated. It emulates the work to be performed at the plant where building components are manufactured. Since each manufacturer has their own unique floor layout, it is important to generalize this layout so that the model can serve different production line arrangement scenarios. Therefore, the production line is simplified into three stations: assembly, framing, and sheathing. Each of these stations is an abstraction of a group of physical stations. This gives the model the flexibility to capture the production flow of a wide range of manufacturing facilities while maintaining its accuracy. This sub-model is concerned with activities' durations; it captures the time needed to perform the tasks. Therefore, any further optimization using the results of the sub-model should be based on this time information. Figure 3 shows the off-site manufacturing sub-model layout.

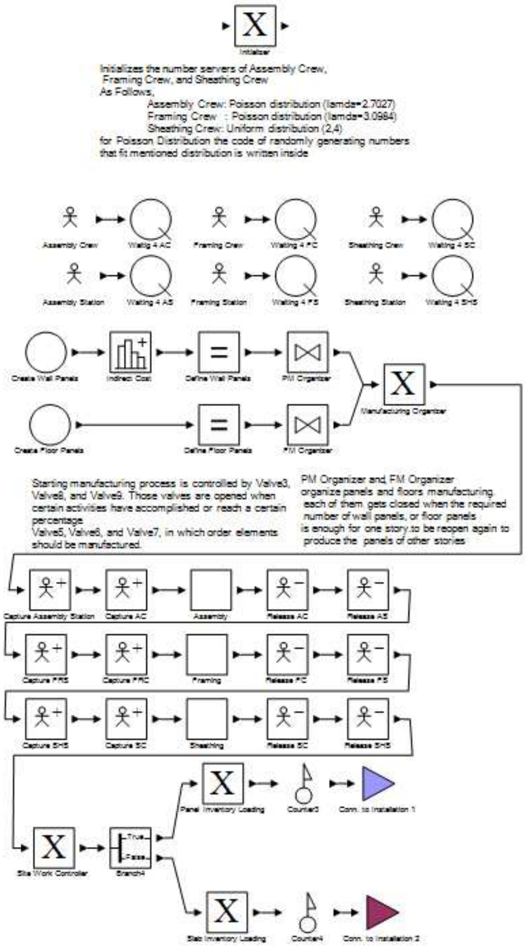
For each of the stations, duration is estimated according to the component type (i.e., wall panels). This duration satisfies the following:

$$Duration\ (hour) = \frac{1}{N \times P}$$

Where:

- N is the number of workers working on that station on a specific day. This number can be a constant, or follow a random variable from a statistical distribution.
- P is the hourly productivity of one worker, and it can be either a constant or randomly generated from a distribution.

Productivity is specified as a random number generated throughout a distribution, as researchers prefer to consider the random nature of productivity. However, inputting the number of crew members is subject to the purpose of the model. If the researcher is interested in optimizing the number of crew members needed on a specific station then it would be better to consider using non-probabilistic input (i.e., a constant number); otherwise, to better capture the production behavior, probabilistic input is recommended.

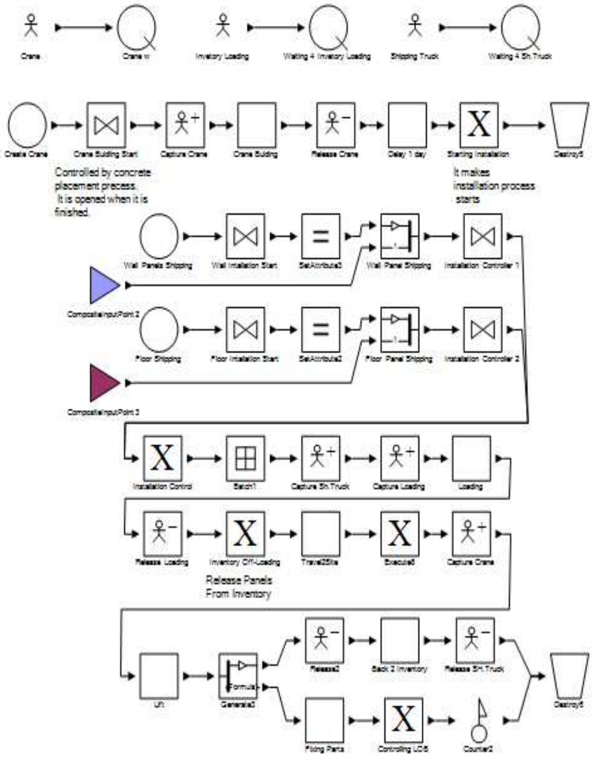


Initializes the number servers of Assembly Crew,
Framing Crew, and Sheathing Crew
As Follows,
Assembly Crew: Poisson distribution (lamda=2.7027)
Framing Crew : Poisson distribution (lamda=3.0984)
Sheathing Crew: Uniform distribution (2,4)
for Poisson Distribution the code of randomly generating numbers
that fit mentioned distribution is written inside

Starting manufacturing process is controlled by Valve3, Valve8, and Valve9. Those valves are opened when certain activities have accomplished or reach a certain percentage
Valve5, Valve6, and Valve7, in which order elements should be manufactured.

PM Organizer and FM Organizer organize panels and floors manufacturing each of them gets closed when the required number of wall panels, or floor panels is enough for one story.to be reopen again to produce the panels of other stories

Figure 3: Off-site manufacturing sub-model layout.



Controlled by concrete
placement process.
It is opened when it is
finished.

It makes
installation process
starts

Release Panels
From Inventory

Installation Controller 1, and Installation Controller 2 are opened according to assembly process.
After the required number of panels have passed through Installation Controller 1, Installation Controller 2 is opened to for floor panels to pass through

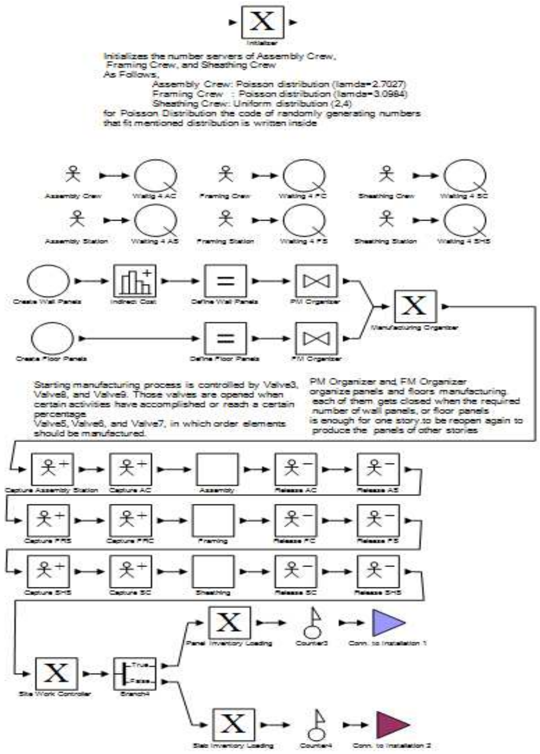
Figure 4: On-site manufacturing sub-model layout.

For the scope of this paper, crew size optimization and resource leveling are not considered. Therefore, crew size is generated automatically through a distribution.

- **On-site installation sub-model**: this sub-model simulates the panel/module installation on site. It controls the assembly process, material release from inventory, material shipping, and crane operation, as indicated in Figure 4.

In this context, material could be any manufactured component, e.g., panels or modules. This extends the capabilities of the model to serve both the off-site and on-site construction methods with the same level of efficiency.

- **Site services and concrete work sub-model**: before installing the manufactured components, the construction site must be prepared. The simulation model considers this technological constraint through the sub-model, “Site Services and Concrete work.” This sub-model runs all activities that precede component installation. It simulates excavation, formwork and rebar placement, and concrete pouring such that the main floor slab is ready for panels or module assembly. All the activities except concrete pouring are simulated using DES. Due to the physical nature of concrete pouring, it is simulated using continuous simulation. Figure 5 shows the simulation abstraction of site preparation activities.



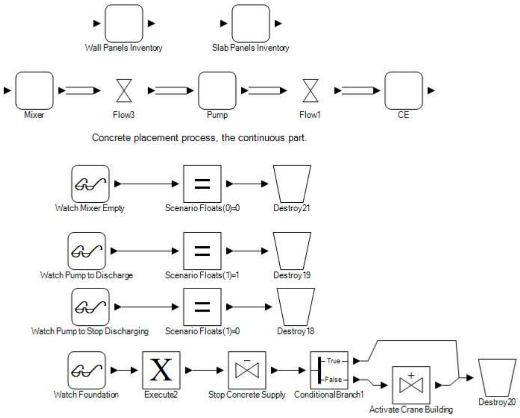


Figure 5: Site services and concrete work sub-model layout.

Figure 6: The components of continuous simulation sub-model layout.

- **Continuous simulation sub-model**: as mentioned above, this sub-model controls and monitors the running of the other sub-models. Its function can be divided into two separate tasks:
  - Inventory watch, where it tracks the status of manufactured components' inventories. It records the changes in the number of pieces stored in the inventory. It is linked to the off-site manufacturing and on-site installation sub-models. While the first provides information about components entering inventories, the second sends information pertaining to materials' release.
  - Concrete pouring, which is modeled using two simulation techniques: discrete-event for concrete supply to site, and continuous for concrete pouring. The DES is part of the site services and concrete work sub-model, while the continuous simulation for concrete pouring is controlled and monitored in this sub-model.
- **Activities sub-model:** this sub-model links the abstracted activities with scheduled tasks. It captures task duration from all the other sub-models and feeds it to the schedule in order to generate different outputs to be used later for assessment purposes. It generates two main graphs: a Velocity Diagram to assess time performance of the project, and indirect cost changes during the project construction cycle.

As mentioned above, the schedule used in this model is not detailed, as it is meant to be generic and applicable to different projects with only minimal changes. Therefore, only the following tasks are considered: parkade excavation, wall foundation, detailed excavation, pads, walls and columns, slab on grade (SOG), structural slab, framing main floor, framing second floor, framing third floor, and framing fourth floor. However, the model is flexible, permitting the addition of a more detailed breakdown for these activities. Figure 7 shows the abstraction of the project schedule.

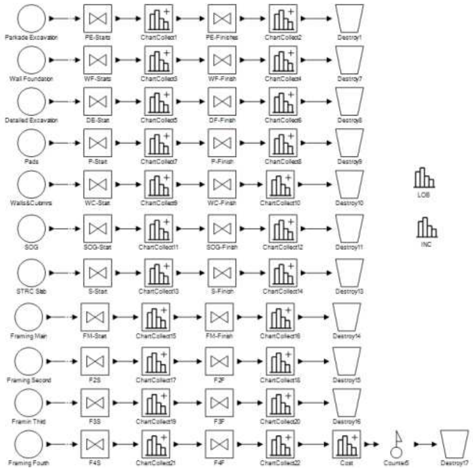


Figure 7: Abstracted activities of the project schedule sub-model layout.

3 COST-TIME TRADE-OFF

Off-site construction poses different challenges due to the separated nature of its stages. This requires extra planning effort to find a feasible schedule that reduces costs while delivering the project in a timely manner. In the context of this study, it should be noted, project cost is the direct cost of material, labor, and equipment needed to perform project tasks. Indirect cost accounts for all the expenses related to logistics activities (e.g., transportation of fabricated components to site, storage security, etc.). The relationship between the project duration and indirect cost is proportional. In off-site construction, inventory has a major effect on the total cost; therefore, its influence has to be considered. Thus, time-cost trade-off analysis will focus on the effect of indirect cost changes over the project duration for each scenario. These indirect costs are managerial and overhead costs and inventory costs measured against project duration to develop a selection tool. The purpose of the selection tool is to assist the planning team in exploring different execution patterns in order to determine the optimal time-cost trade-off. It is important to mention, that this study assesses different scenarios for the combination of off-site/on-site. Therefore, it doesn’t aim to optimize the process, but evaluate the consequences of the decision. This leads to the fact that there is no optimal balancing state that falls under Pareto optimal condition, as the scenarios are always based on the practical configuration rather than ideal cases that could be optimized.

4 IMPLEMENTATION OF SIMULATION MODEL: CASE STUDY

For this study a condominium building is used to test the model. The building uses pre-fabricated panels for the walls and floor. It requires 3,000 wall panels and 400 floor panels. By observing the production process, the research team can identify productivities (crew size distributions are shown in Table 1).

Table 1: Productivity and crew size distributions used in the model.

Station	Productivity Distribution	Crew size distribution
Assembly	Weibull (2.3996,0.88122,0)	Poisson distribution (λ=2.7027)
Framing	Gamma (9.9844,0.0734))	Poisson distribution (λ=3.0984)
Sheathing	Gamma (3.8488,0.1264)	Uniform Distribution (2,4)

To include inventory costs, the researchers consider inventory cost as follows:

$$\mathrm{IC}^{\mathrm{t}} = \mathrm{N}^{\mathrm{t}} \times \mathrm{SPC}^{\mathrm{t}}$$

Where:

- IC^t is the inventory cost at time, t.
- N^t is the number of pieces physically existing in the inventory at time, t.
- SPC^t is the cost of storing one piece at time t. This includes all costs related to keeping this piece in the inventory, such as inventory rent, power supplies, and security services.

Indirect cost is assessed as ($85/day) for the entire project construction cycle.

The following scenarios are fed into the model:

- S1: Site preparation work starts concurrently when manufacturing starts.
- S2: Site preparation work starts after 10% completion of manufacturing.
- S3: Site preparation work starts after 20% completion of manufacturing.
- S4: Site preparation work starts after 30% completion of manufacturing.
- S5: Site preparation work starts after 40% completion of manufacturing.
- S6: Site preparation work starts after 50% completion of manufacturing.
- S7: Site preparation work starts after 60% completion of manufacturing.
- S8: Site preparation work starts after 70% completion of manufacturing.
- S9: Site preparation work starts after 80% completion of manufacturing.
- S10: Site preparation work starts after 90% completion of manufacturing.
- S11: Site preparation work starts after completion of manufacturing.
- S12: Manufacturing starts after completion of excavation.

By running the model for each of the mentioned scenarios, the planning team can obtain visual aids useful in optimizing the planning process. Figure 8 shows the VD of S6, and Figure 9 shows panel inventory repletion during the project construction lifecycle in S9.

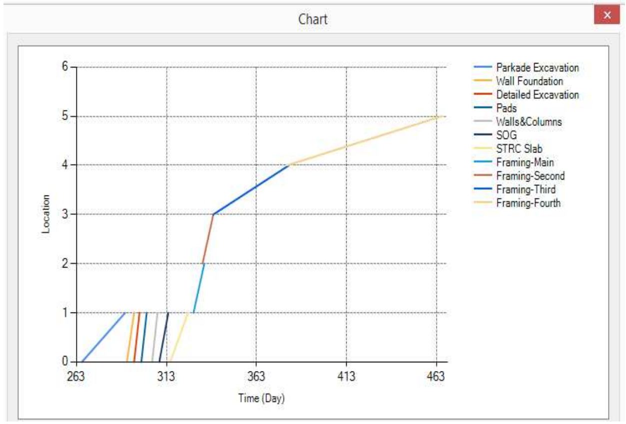


Figure 8: Velocity Diagram of S6.

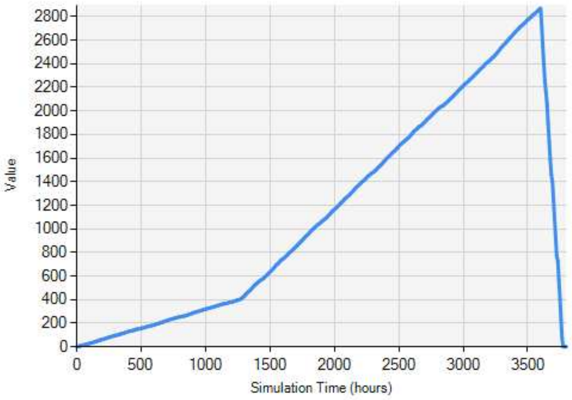


Figure 9: Panel inventory changes during project construction in S9.

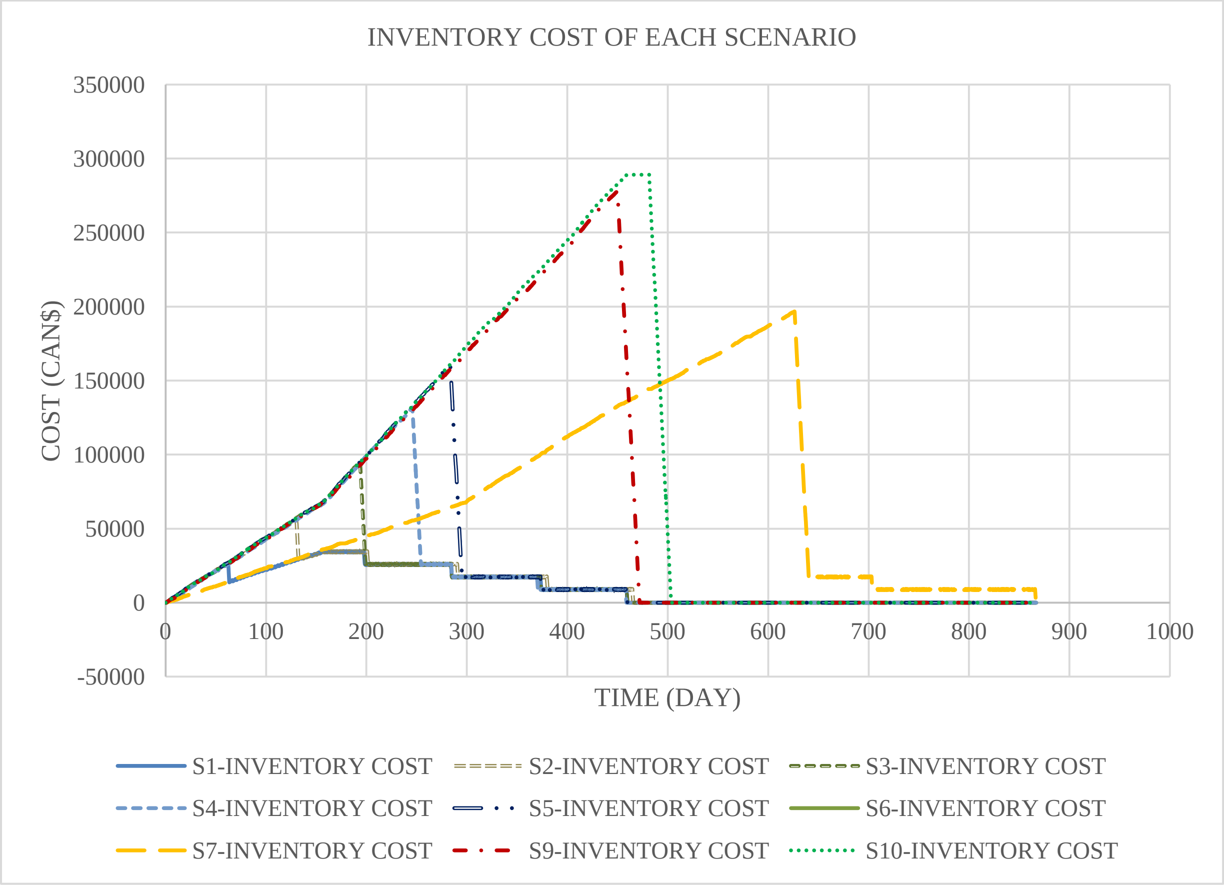


Figure 10: Inventory cost of all scenarios.

4.1 Discussion

As Figure 10 shows, as the difference between the start time of site preparation and the start time of manufacturing becomes larger, the inventory cost becomes larger. This also increases the indirect cost, as it leads to a longer project duration. It is thus important to begin manufacturing of off-site components concurrently with parkade and site operations. This will decrease inventory cost and indirect cost and provide continuous workflow, with minimal delays caused by delivery of off-site components.

However, it is important to mention that this analysis is specific to the case study used in this paper, which is directly related to the manufacturer's data and project size. As the conclusion my differ based on the project size and manufacturer capability, it is up to the project management team to identify different patterns to combine off-site operation with on-site ones, so they can determine which pattern meets the project goals in terms of time and cost.

Moreover, since the model uses stochastic simulation, then it wouldn't be possible to determine a targeted production rate for both off-site, and on-site operation. However, it provide more realistic representation of reality, where there are no crisp deterministic values for production rates. Nevertheless, with minor adjustments, the model could be utilized to determine targeted production rates based on projects goals.

5 CONCLUSION

Along with the advantages of off-site construction methods in terms of the time savings and increased quality it provides, it also presents challenges to which construction personnel are not accustomed. The geographical distance between the plant where building components are being manufactured and the assembly location requires a dynamic approach to planning and scheduling. Moreover, the planning team must consider the increment in cost associated with planning deficiencies, such as installation delays or inventory over-cost. Therefore, this research presents a simulation-based model to assess time-cost trade-off, in order to help planning teams test different alternatives in a timely manner and at a lower cost. It is a generic model that can be used for the two most well-known methods in off-site construction: modular and panelized. Additionally, since it captures the main phases of project delivery, it can be adjusted to handle a wide range of projects that involve off-site manufactured components, as long as it considers the unique nature of work sequences and dependence on the manufacturer's performance.

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