Proceedings of the 2025 Winter Simulation Conference
E. Azar, A. Djanatliev, A. Harper, C. Kogler, V. Ramamohan, A. Anagnostou, and S. J. E. Taylor, eds.

OPTIMIZING PRECAST CONCRETE PRODUCTION: A DISCRETE-EVENT SIMULATION APPROACH WITH SIMPHONY

Julie Munoz[1], Mohamad Itani[1], Mohammad Elahi[1], Anas Itani[1], and Yasser Mohamed[1]

[1]Dept. of Civil and Environmental Eng., University of Alberta, Edmonton, AB, CANADA

ABSTRACT

Precast concrete manufacturers increasingly face throughput bottlenecks as market demand rises and curing-area capacity reaches its limit. This paper develops a validated discrete-event simulation (DES) model of a Canadian precast panel plant using the Simphony platform. Field observations, time studies, and staff interviews supply task durations, resource data, and variability distributions. After verification and validation against production logs, two improvement scenarios are tested: (1) doubling curing beds and (2) halving curing time with steam curing. Scenario A reduces total cycle time by 26 %, while Scenario B achieves a 24 % reduction and lowers curing-bed utilization by 5 %. Both scenarios cut crane waiting and queue lengths, demonstrating that relieving the curing bottleneck drives system-wide gains. The study confirms DES as an effective, low-risk decision-support tool for off-site construction, offering plant managers clear, data-driven guidance for investment planning and lean implementation.

1 INTRODUCTION

Project delivery timelines and overall costs are directly influenced by the sequential efficiency and operational performance of precast concrete manufacturing. Traditional production methods at many precast facilities are increasingly unable to meet evolving industry demands for faster delivery and greater output capacity (Chen et al., 2016). At a precast manufacturing plant specializing in the production of concrete panels located in Edmonton, Canada, the manufacturing process consists of multiple interdependent stages—from material preparation and casting to final finishing. As market expectations continue to rise, throughput demands are pushing the facility's existing system to its operational limits. This situation highlights the urgent need for holistic, system-wide optimization strategies to increase productivity while maintaining consistent quality standards.

To evaluate and improve such processes, virtual modeling through discrete-event simulation (DES) offers a powerful analytical framework as DES enables the identification of dynamic relationships among production tasks, available capacities, resource utilization rates, and operational variability (AbouRizk and Hajjar, 1998). Moreover, decision-makers use DES to simulate proposed changes and assess their potential impacts on system performance prior to physical implementation. Prior research consistently demonstrates the value of simulation-based approaches for enhancing construction process efficiency (AbouRizk and Hajjar, 1998).

In this study, the Simphony DES platform—a specialized simulation tool developed at the University of Alberta for modeling complex construction processes (AbouRizk and Hajjar, 1998) —is used to replicate and evaluate the current production workflow at a local precast concrete facility. Simphony allows for the creation of detailed, customizable models that incorporate resource constraints, task durations, and operational variability, making it a valuable tool for identifying inefficiencies and testing improvement strategies within construction and manufacturing environments. The developed simulation model not only captures the existing operational structure of the fabrication process but also allows for experimentation with potential improvements. Simphony's ability to generate performance statistics supports informed decision-making aimed at boosting production throughput, reducing lead times, and optimizing resource allocation (Itani et al., 2020). Project delivery times, together with costs, depend directly on the sequential efficiency and operation of precast concrete manufacturing. The increasing industry requirements are not manageable by traditional production methods at many precast manufacturing plants (Chen et al., 2016). While discrete-event simulation (DES) has been applied to precast operations for more than two decades (e.g., AbouRizk and Hajjar 1998; Chen et al. 2016), most published models focus on idealized or single-shift workflows and rarely quantify how curing-area constraints interact with resource availability in a high-volume Canadian context. In addition, few studies translate simulation findings into actionable, plant-level key performance indicators such as return on investment (ROI) or payback period. Here, ROI is measured as the net financial benefit of a scenario divided by its direct implementation cost, expressed as a percentage. To bridge these gaps, this paper pursues three specific objectives:

1. Map and validate the full end-to-end workflow of a local precast panel plant, capturing actual task durations, resource pools, and stochastic variability.
2. Identify and quantify the dominant bottleneck(s) through baseline DES runs and verification against production data.
3. Evaluate improvement scenarios (added curing beds, reduced curing time) and express the projected gains both in throughput and simple ROI terms to support management decision-making.

2 LITERATURE REVIEW

Simulation has emerged as a primary tool in construction production systems, driven by the increasing complexity and dynamic nature of operations. Unlike traditional planning tools such as Critical Path Method (CPM) or Gantt charts, DES provides a more robust approach by accounting for system randomness and resource constraints. Simulation also enables practitioners to observe how entities—such as precast panels—interact with processes and resources over time, offering valuable insights into the effects of real-world variability (AbouRizk and Hajjar, 1998).

Foundational research by AbouRizk and Hajjar (1998) laid the groundwork for applying DES to construction workflows. Their work establishes a comprehensive framework for modeling and analyzing construction processes, evaluating alternative sequencing, and assessing resource capacities. This foundational research led to the development of Simphony, a DES platform purpose-built for construction operation modeling (Itani et al., 2020). Simphony supports two primary template types—General and Cyclone—and effectively represents process dependencies and resource constraints, making it well-suited for precast production environments.

Although Simphony gained popularity in the 2000s, earlier generations of construction DES were built on other engines. Halpin (1977) developed CYCLone, a network-based simulator that modeled earth-moving operations and inspired many later extensions. Martinez (1996) introduced STROBOSCOPE, which offered greater flexibility in resource-interaction logic and remains widely cited. These systems collectively demonstrated that discrete-event methods could capture the stochastic, resource-constrained nature of field operations, paving the way for more specialized tools such as Simphony.

Numerous studies further demonstrate the value of simulation in offsite and precast construction. For instance, Liu et al. (2015) integrate Building Information Modeling (BIM) with Simphony to simulate light-gauge steel panel fabrication. Their approach enables optimization of production stations while visualizing the impact of delays and resource constraints. Similarly, Altaf et al. (2015) combine DES with data tracking, representing a significant advancement toward integrating Internet of Things (IoT) systems with simulation platforms.

To align with Lean Construction principles, Abdel-Jaber et al. (2022) integrate Value Stream Mapping (VSM) with DES. While traditional VSM offers a static overview of processes, it lacks the ability to reflect system variability. The hybrid model they propose is tested in a window production case, using Simphony to identify inefficiencies and evaluate future-state scenarios, ultimately leading to improved throughput and reduced waste.

In a different approach, Badreddine et al. (2022) employ Fuzzy-Analytic Hierarchy Process (AHP) and House of Quality (HoQ) to prioritize lean tools based on the needs of offsite construction organizations.

Although their primary focus is lean implementation rather than simulation, their study underscores the complexities of factory workflows—highlighting scenarios where simulation could enhance operational decision-making.

Further to this, Chen et al. (2016) utilize the Arena simulation platform to streamline precast production by consolidating sequential tasks into unified steps, achieving a 24% reduction in production time. While Arena is a general-purpose simulation tool, it shares core DES principles with Simphony, further validating DES's applicability across platforms. Additionally, Yusuf (2019) demonstrate how mathematical optimization methods can manage delivery schedule uncertainty in flow-shop environments, while simulation complements such methods by enabling "what-if" scenario analysis.

Collectively, this body of research affirms the role of simulation as a cornerstone in modern construction production optimization. Beyond simple modeling, DES provides critical decision support capabilities, offering visibility into dynamic system behaviors, proactive scheduling, and strategic resource management. As a result, construction organizations can evolve toward leaner, more agile, and resilient operations.

3 METHODOLOGY

This section outlines the systematic methodology used to develop a production simulation model and conduct performance analysis and optimization within a precast concrete manufacturing facility, using the Simphony DES platform. The research process is structured into four key stages, as follows:

1. Data Collection – capturing real-world process data through site observations, time studies, and staff interviews.
2. Model Development and Verification – constructing a detailed simulation model based on collected data and ensuring logical consistency and operational accuracy.
3. Model Validation – comparing simulated outputs with actual performance metrics to confirm the model's reliability.
4. Experimental Simulation and Optimization – running multiple scenario-based simulations to test alternative strategies and identify performance improvements.

This structured approach ensures that the simulation accurately represents current operations and provides actionable insights for enhancing throughput, reducing delays, and optimizing resource utilization.

3.1 Process Mapping and Data Collection

At the precast production facility, the operational workflow is systematically documented through a comprehensive process mapping session, as shown in Figure 1. To evaluate the fabrication process of precast concrete panels, a mixed-methods approach is employed, combining direct observation, interviews with production staff, and the review of existing documentation. This approach enables the development of an accurate and detailed representation of the production process.

The process mapping identifies the following key stages:

- Material Procurement and Delivery: The process begins with the procurement of raw materials such as wood, rebar, and thermal insulation. Timely delivery is critical to ensure that essential inputs are available for downstream production tasks.
- Material Preparation and Pre-Assembly: Raw materials are cut and prepared using standardized techniques. This stage typically takes 10–15 minutes per material type. Simultaneously, formwork preparation is carried out as part of the pre-assembly stage, usually completed within a 30-minute batch window.
- Assembly of Reinforcement Components: In this stage, rebar cages are assembled, and embedded inserts or connection components are accurately positioned and secured. Each unit requires approximately 15 minutes to assemble using a two-person team.

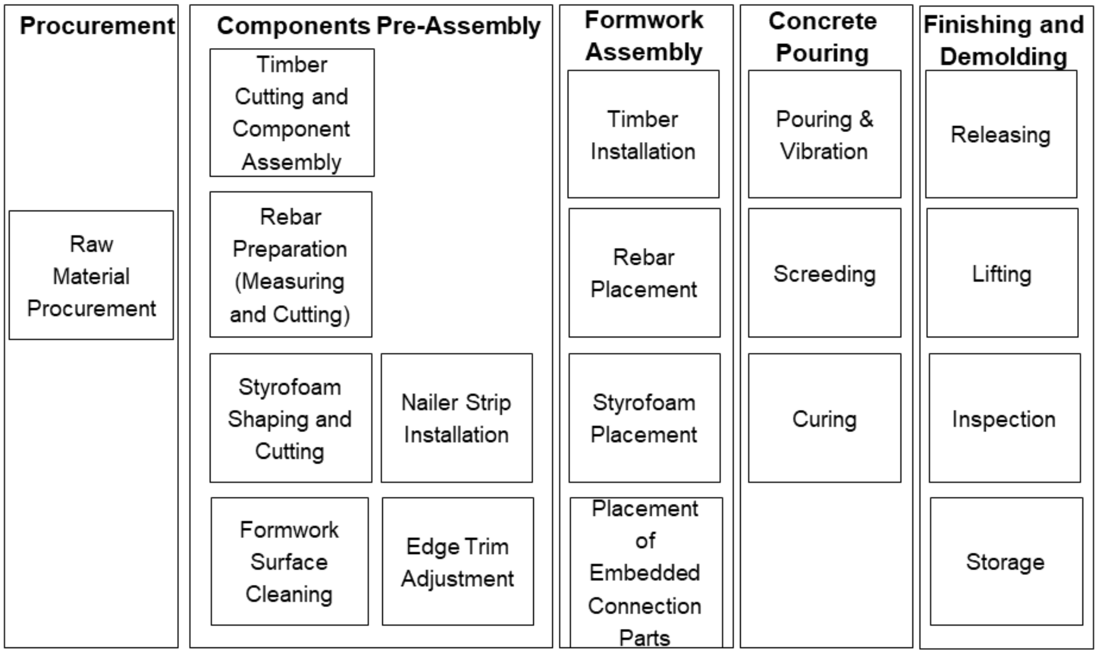

Figure 1. Process description.

- Concrete Pouring and Finishing: The pouring of concrete is conducted by the operations crew, with a daily output rate of approximately 10 units. This stage includes the placement, leveling, and finishing of concrete to meet quality standards.

This structured breakdown provides a clear foundation for simulation modeling and supports a data-driven understanding of time requirements, resource demands, and potential process bottlenecks.

Task documentation also captures a range of essential production details, including basic operational requirements, average task durations, labor assignments, equipment utilization, and operating frequencies. Additionally, key process dependencies—such as concrete curing times, which directly impact mold turnaround and replenishment cycles—are identified and incorporated into the simulation framework.

3.2 Simulation Model Development in Simphony

All the data collected is then utilized to develop a DES model using Simphony.NET, as illustrated in Figure 2. The General Template within Simphony is selected to enable full customization of task logic, queuing behavior, and resource dynamics. The simulation model incorporates several key features, including the following:

- Task Representation: Each activity within the precast production workflow is modeled as an individual Task element, reflecting the sequential nature of operations.
- Task Durations: Activity durations are defined using statistical distributions to account for process variability. For example, curing time is modeled using a Beta distribution ranging from 24 to 48 hours (simulated as 510 to 1,020 minutes of shift time), to more accurately reflect variability observed during field data collection.
- Resource Modeling: Labor and equipment resources are represented using Resource Pools, which include cranes (10-ton and 20-ton capacities) and specialized teams such as cutting crews, pouring crews, riggers, and inspectors—modeled collectively as a six-member crew. Additionally, critical production assets, like curing beds and the concrete bucket, used during pouring, are treated as limited-capacity resources.

- Capture and Release Logic: This logic is applied to ensure that each task can proceed only when all required resources are available, effectively simulating real-world delays caused by resource constraints or scheduling conflicts.
- Conditional Branching: Steps involving conditional logic—for instance, queueing the pouring task if a curing bed is occupied—are modeled using branching elements to simulate alternative pathways or constrained scenarios.
- Daily Production Scheduling: Batch and Unbatched elements are used to replicate daily production routines. For example, all panels poured on a given day are queued for release only after meeting the minimum curing requirement of 24 hours. The simulation is configured to operate in minutes, reflecting a standard 8.5-hour shift per day across 22 working days per month.

This modeling approach enables an accurate representation of production system behavior and reveals how resource availability, task dependencies, and variability impact overall process performance. The completed Simphony model is presented in Figure 2, while simulation results and system logic are further discussed in the following sections.

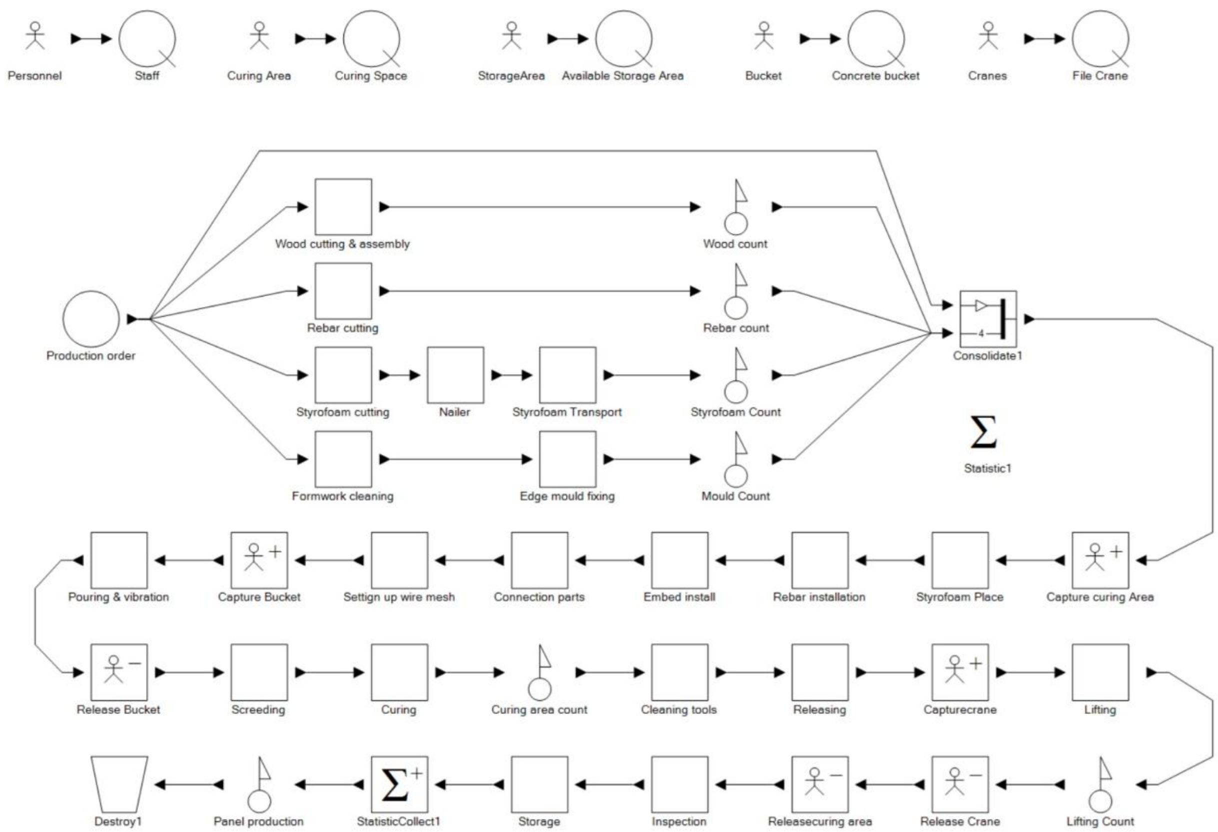

Figure 2. Developed simphony model.

3.3 Model Verification and Validation

The simulation model undergoes a comprehensive verification and validation (V&V) process to ensure accuracy, credibility, and alignment with real-world operations, as follows:

1. Logic Verification: The internal logic of the model is rigorously tested to confirm that each entity (i.e., panel) follows the intended process sequence. Task dependencies, delays, and queuing mechanisms are verified to reflect the actual workflow behavior observed at the facility.

2. Output Validation: Core simulation outputs—including daily production throughput, crane utilization rates, and panel waiting times—are compared against empirical data from the factory's operational logs, supplemented by detailed staff interviews. The simulation results demonstrate less than 10% deviation from actual values, supporting the model's reliability and validity.
3. Consistency Checks: Simulation outcomes are cross-referenced with findings from previous studies conducted on the factory production process, ensuring that model behavior aligns with known operational benchmarks.
4. Expert Review: A panel of experienced precast production specialists review the model's logic, task durations, and resource allocations. Their feedback confirms that the simulation accurately captures the nuances of real-world operations and resource usage.

Following model validation, the simulation is used to assess the factory's existing production capacity through the execution of two baseline scenarios. These scenarios provide insight into current system performance and serve as reference points for evaluating potential improvement strategies. Internal logic was desk-checked and then replayed in entity-trace mode, allowing the team to step through each event while subject-matter experts confirmed correct sequencing. Ten independent replications were run because pilot tests showed that this sample size shrank the 95 % confidence-interval half-width of average cycle time below 5 % of the mean, and larger samples yielded diminishing returns.

3.3.1 Scenario 1: Production of 100 Standard Panels

In the first simulation scenario, the objective is to evaluate the production capacity of the factory when tasked with manufacturing 100 standard precast panels, each measuring 12 feet by 45 feet. Each entity entering the simulation represents a single standard panel. The simulation is executed over 10 iterations to capture variability in total cycle times and ensure statistical robustness.

Table 1. Scenario 1 simulation output.

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Bucket (Inner Resource)	40,1 %	0,8 %	41,3 %	41,3 %	1,000
Cranes (Inner Resource)	5,3 %	0,1 %	5,5 %	5,4 %	2,000
Curing Area (Inner Resource)	86,1 %	1,5 %	88,8 %	88,0 %	12,000
Personnel (Inner Resource)	59,7 %	1,6 %	62,2 %	61,9 %	8,000
StorageArea (Inner Resource)	9,9 %	0,3 %	10,4 %	10,3 %	10,000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
Available Storage Area	0,014	0,003	0,021	0,012	1,402
Concrete bucket	1,597	0,071	1,707	1,458	160,858
Consolidate1 (InnerFile)	11,878	0,320	12,383	12,296	1.194,102
Curing Space	38,334	0,788	39,996	39,996	3.854,784
File Crane	0,001	0,001	0,002	0,001	0,102
Staff	26,788	0,692	27,929	27,573	149,621

The simulation yields, as shown in Table 1, an average total production duration of 18.4 working days, indicating that the facility, under current operating conditions, can produce approximately 48,000 square feet of wall panels within that timeframe. The average cycle time per panel is approximately 10 minutes, reflecting steady processing across most stages of the workflow.

Simulation outputs also provide detailed insights into resource utilization and waiting times, identifying the curing area as the primary bottleneck in the production process. Specifically:

- The curing area exhibits a utilization rate of 86.1%, significantly higher than any other resource.
- The average queue length (i.e., number of panels waiting) at the curing stage is 38.334 entities.
- Over the 18.4-day production period, the curing beds are fully occupied for approximately 15.84 days, limiting throughput and creating congestion in upstream tasks.

These results demonstrate that, while other resources—such as cranes, labor crews, and equipment—have excess capacity, the curing area constrains overall production output. Consequently, future optimization strategies should prioritize increasing curing capacity or reducing curing durations to alleviate this bottleneck.

3.3.2 Scenario 2: Time-Based Capacity Evaluation (5,100 Minutes)

The second simulation scenario focuses on assessing the production capacity over a fixed time window. More specifically, the model is run for 5,100 minutes—equivalent to approximately 85 hours, or two weeks of standard factory operations. Within this duration, the system processes a total of 51 entities, each representing a standard precast panel entering the production line.

The simulation results reveal that within this timeframe:

- 3i Precast is able to complete 48 panels, with 3 additional panels still in progress at the end of the simulation period.
- The operation spans 23 production shifts, assuming a standard 8.5-hour workday.
- The system bottleneck remains unchanged, with the curing area continuing to restrict overall throughput.

Further analysis of the curing area shows:

- A resource utilization rate of 85.5%, confirming near-continuous operation of the curing beds.
- An average queue length of 17.316 panels, indicating a consistent backlog and delayed access to curing space.

Table 2. Scenario 2 simulation output.

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Bucket (Inner Resource)	38,5 %	1,2 %	41,5 %	38,9 %	1,000
Cranes (Inner Resource)	5,1 %	0,1 %	5,4 %	5,1 %	2,000
Curing Area (Inner Resource)	85,5 %	0,8 %	87,0 %	85,0 %	12,000
Personnel (Inner Resource)	59,6 %	0,4 %	60,6 %	59,8 %	8,000
StorageArea (Inner Resource)	9,5 %	0,1 %	9,8 %	9,6 %	10,000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
Available Storage Area	0,016	0,005	0,023	0,009	1,712
Concrete bucket	1,594	0,120	1,745	1,533	159,391
Consolidate1 (InnerFile)	6,147	0,037	6,209	6,157	614,681
Curing Space	17,316	0,304	17,884	17,091	1.731,563
File Crane	0,001	0,001	0,003	0,000	0,124
Staff	14,189	0,088	14,350	14,179	79,635

As shown in Table 2, these findings reaffirm the conclusions drawn from the first scenario: the curing area is the dominant constraint in the production system. While other resources (such as cranes, crews, and preparation stations) operate below full capacity, the limited availability of curing space restricts the rate at which panels can be poured and processed downstream. Therefore, future production improvements should focus on expanding curing capacity, reducing curing times, or introducing parallel curing solutions to relieve system pressure and enhance throughput.

3.4 Optimization Experiments and Scenario Analysis (Scenario A and B)

Following the successful validation of the simulation model, optimization experiments are conducted based on the baseline scenario of producing 100 standard precast panels. The aim is to explore system enhancements that can reduce production time, minimize delays, and improve resource efficiency. The optimization scenarios are outlined below.

3.4.1 Scenario A: Doubling Curing Capacity via Additional Formwork Beds

This scenario focuses on alleviating the bottleneck caused by limited curing space, which in the baseline model significantly constrains the sequence and timing of concrete pours. By adding additional formwork beds, the curing area's capacity is effectively doubled, allowing more panels to be processed concurrently. The simulation results are shown in Table 3 and summarized as follows:

- Total production time to complete 100 panels is reduced to 7,487 minutes, or approximately 124.8 hours.
- Compared to the baseline (10,140 minutes), this represents a ~26% improvement in overall cycle time.

Table 3. Scenario A - doubling curing capacity.

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Bucket (Inner Resource)	55,3 %	0,7 %	56,5 %	55,4 %	1,000
Cranes (Inner Resource)	7,1 %	0,1 %	7,2 %	7,1 %	2,000
Curing Area (Inner Resource)	80,3 %	0,9 %	82,2 %	80,1 %	24,000
Personnel (Inner Resource)	80,2 %	0,9 %	81,6 %	80,2 %	8,000
StorageArea (Inner Resource)	13,3 %	0,2 %	13,7 %	13,2 %	10,000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
Available Storage Area	0,022	0,004	0,028	0,025	1,648
Concrete bucket	5,366	0,090	5,536	5,264	401,820
Consolidate1 (InnerFile)	15,930	0,169	16,192	15,869	1.192,643
Curing Space	31,263	0,336	31,994	31,265	2.340,651
File Crane	0,001	0,001	0,002	0,001	0,070
Staff	38,191	0,542	39,334	38,243	158,846

3.4.2 Scenario B: Reducing Curing Time by 50% Using Steam Curing

This scenario explores the impact of steam curing as a method to accelerate the curing process, with the goal of reducing overall production time and queue lengths in the curing area. By applying heat and moisture through steam, the standard curing duration is reduced by 50%, simulating faster concrete setting and turnover. The simulation results are shown in Table 4 and summarized, as follows:

- The total time required to produce 100 standard panels is reduced to 7,636 minutes, or approximately 127.3 hours.
- Compared to the baseline scenario (10,140 minutes), this reflects a ~24% reduction in production time.
- Curing area utilization decreases by 5%, indicating more availability of curing beds.

- The average queue length at the curing stage decreases by 8 panels, signifying reduced bottlenecks and improved process flow.

Table 4. Scenario B - reducing curing time.

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Bucket (Inner Resource)	55,1 %	1,2 %	57,2 %	54,3 %	1,000
Cranes (Inner Resource)	7,0 %	0,1 %	7,1 %	7,0 %	2,000
Curing Area (Inner Resource)	83,2 %	0,3 %	83,6 %	83,0 %	12,000
Personnel (Inner Resource)	78,6 %	0,4 %	79,3 %	78,7 %	8,000
StorageArea (Inner Resource)	13,1 %	0,1 %	13,2 %	13,1 %	10,000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
Available Storage Area	0,018	0,004	0,022	0,016	1,352
Concrete bucket	2,394	0,075	2,512	2,390	182,806
Consolidate1 (InnerFile)	15,615	0,077	15,736	15,511	1.192,397
Curing Space	36,885	0,298	37,363	36,753	2.816,648
File Crane	0,001	0,001	0,002	0,001	0,039
Staff	35,259	0,182	35,563	35,091	149,584

3.4.3 Simulation Methodology and Performance Monitoring

For both optimization scenarios, the simulation is conducted using 100 entities across 10 independent simulation runs per scenario to account for operational variability and randomness inherent in real-world production systems. The model tracks and evaluates the following key performance indicators (KPIs):

Table 5. Simulation KPIs.

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Bucket (Inner Resource)	55,1 %	1,2 %	57,2 %	54,3 %	1,000
Cranes (Inner Resource)	7,0 %	0,1 %	7,1 %	7,0 %	2,000
Curing Area (Inner Resource)	83,2 %	0,3 %	83,6 %	83,0 %	12,000
Personnel (Inner Resource)	78,6 %	0,4 %	79,3 %	78,7 %	8,000
StorageArea (Inner Resource)	13,1 %	0,1 %	13,2 %	13,1 %	10,000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
Available Storage Area	0,018	0,004	0,022	0,016	1,352
Concrete bucket	2,394	0,075	2,512	2,390	182,806
Consolidate1 (InnerFile)	15,615	0,077	15,736	15,511	1.192,397
Curing Space	36,885	0,298	37,363	36,753	2.816,648
File Crane	0,001	0,001	0,002	0,001	0,039
Staff	35,259	0,182	35,563	35,091	149,584

- Scenario Mean Values: Average time to complete production cycles.
- Resource Utilization Rates: Average percentage of time each resource (e.g., cranes, crews, curing beds) is in active use.

- Waiting Queues per Resource: Average number of entities waiting at each resource point, especially the curing area.

Together, these metrics, shown in Table 5, enable a comprehensive evaluation of how each scenario influences production performance and resource efficiency.

3.5 Interpretation and Implementation Recommendations

The simulation model effectively pinpoints specific operational bottlenecks, allowing for targeted analysis of which enhancements will deliver the greatest return on investment. The most significant constraints are observed in the concrete pouring and curing stages, where resource limitations and task durations have the highest impact on production throughput. By introducing an additional concrete bucket and implementing steam curing techniques to reduce curing time by 50%, the system achieves a more continuous and optimized workflow.

Furthermore, the reduction of task durations, including those related to tool handling and minor material operations, is found to require relatively minimal financial investment. Building on these findings, the research team develops a deployment framework that outlines the required resources, expected performance improvements, and risk mitigation strategies tailored for the factory.

Ultimately, the simulation equips the user with robust strategic decision-making capabilities, enabling the adoption of lean construction principles. These data-driven insights empower offsite construction operations to enhance productivity, minimize waste, and adapt proactively to fluctuating demand and production complexity.

4 RESULTS AND DISCUSSION

The simulation results lead to the development of several targeted production strategies that hold significant potential for enhancing operations at the factory. Each scenario addresses a specific bottleneck or inefficiency, offering data-driven recommendations for improvement, as follows:

- Expansion of Curing Capacity: Doubling the number of curing beds completely eliminates the curing bottleneck and results in a more than 15% increase in throughput. This intervention directly addresses the primary system constraint and facilitates a smoother production flow.
- Addition of Crane Resources: Introducing double cranes leads to a 42% reduction in crane-related waiting times, significantly accelerating panel handling and material movement. This measure effectively removes secondary delays and improves overall processing speed.
- Pre-Advanced Material Preparation: Enhancing the early-stage preparation of materials results in modest time savings, achieved without any increase in labor costs. While the gains are incremental, they contribute to improved scheduling flexibility and workflow readiness.
- Crew Rotation and Shorter Shifts: Implementing shorter shifts with increased crew rotation helps reduce worker fatigue and sustain consistent productivity levels. However, this approach requires careful workforce planning and scheduling to avoid understaffing or overlap inefficiencies.

Collectively, these findings demonstrate that small, strategic adjustments in resource allocation, task sequencing, and workforce management can generate significant efficiency gains. Moreover, a hybrid approach—combining elements from multiple scenarios—may offer the most effective solution for addressing specific bottlenecks while maintaining optimal resource utilization across the production system. Based on a capital estimate of CAD 180 000 for four extra curing beds, Scenario A generates an annual net benefit of roughly CAD 320 000, giving a simple ROI of about 78 % and a pay-back period of under seven months.

Study limitations and future work. The ROI estimate reported here covers only direct equipment and material outlays; indirect costs such as financing, overhead, and labour-rate changes were not included. In addition, the model assumes stable supply-chain deliveries, no labour absenteeism, and fixed plant layout outside the curing area. These factors can influence throughput and pay-back and will be examined in future studies through sensitivity tests and extended disruption scenarios.

5 CONCLUSION

This study successfully applied discrete-event simulation (DES) using the Simphony platform to evaluate and optimize production processes at 3i Precast. While the simulation model provided actionable insights and led to measurable performance improvements, several limitations must be acknowledged, along with opportunities for future research.

DES is, indeed, a crucial methodology for analyzing and optimizing precast concrete production processes. Through the use of the Simphony platform, the precast factory is able to identify production bottlenecks, evaluate multiple improvement strategies, and ultimately achieve quantifiable gains in both productivity and resource utilization.

The simulation results also clearly indicate that two key interventions—expanding curing bed capacity and streamlining crane operations—have the most significant impact in alleviating critical constraints and enhancing throughput. Additionally, low-cost process adjustments, such as pre-curing materials, offer modest efficiency improvements without incurring extra operational costs.

Overall, the adoption of simulation modeling provides powerful strategic planning capabilities for precast manufacturers. For companies, DES serves not only as a diagnostic tool but also as a decision-support system, enabling data-driven planning, lean implementation, and continuous performance optimization in offsite construction environments.

The current model was designed to simulate the production of standard precast concrete panels, excluding other panel types with varying sizes, shapes, or reinforcement complexities. As a result, its applicability across diverse product lines is limited. Additionally, the model assumed consistent labor performance and availability, without accounting for worker fatigue, skill differences, or unexpected absenteeism. Certain real-world operational factors—such as forklift traffic, raw material supply disruptions, and space constraints—were not explicitly included, which may affect the accuracy of real-time process flow representation. Moreover, while resource efficiency and throughput were assessed, the model did not incorporate financial metrics such as cost-benefit analysis or return on investment, which are essential for evaluating the feasibility of proposed improvements.

Future enhancements should aim to broaden the model's scope and increase its realism. This includes extending the simulation to account for multiple product types and production variants, which would improve its generalizability. Integrating real-time data via IoT or RFID technologies could allow for dynamic updates and predictive analytics, enabling real-time decision-making. Modeling human factors—such as shift rotation effects, fatigue, and skill variability—would create a more accurate representation of workforce behavior. Financial modeling should also be incorporated to support investment decisions through cost estimation and ROI calculations. Furthermore, future research could explore plant scalability and simulate production line expansion scenarios to guide long-term planning. Incorporating environmental performance indicators, such as energy consumption, material waste, and carbon emissions, would align simulation outcomes with sustainable construction goals.

By addressing these limitations and exploring these future directions, the simulation framework can evolve into a robust, holistic decision-support system for optimizing off-site construction operations.

REFERENCES

Abdel-Jaber, O., A. Itani, and M. Al-Hussein. 2022. "Hybrid Lean Decision-Making Framework Integrating Value Stream Mapping and Simulation: A Manufacturing Case Study." *Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC)*, 153–163.

AbouRizk, S., and D. Hajjar. 1998. "A Framework for Applying Simulation in the Construction Industry." *Canadian Journal of Civil Engineering* 25(3):604–617.

Altaf, M. S., A. Bouferguene, H. Liu, M. Al-Hussein, and H. Yu. 2018. "Integrated Production Planning and Control System for a Panelized Home Prefabrication Facility Using Simulation and RFID." *Automation in Construction* 85:369–383. https://doi.org/10.1016/j.autcon.2017.09.009.

Badreddine, A., O. Azakir, A. Itani, and M. Al-Hussein. 2022. "A Fuzzy-AHP and House of Quality Integrated Approach for Lean Construction Concepts Assessment in Off-Site Construction." *Modular and Offsite Construction (MOC) Summit Proceedings*, 130–137. https://doi.org/10.29173/mocs274.

Chen, J.-H., L.-R. Yang, and H.-W. Tai. 2016. "Process Reengineering and Improvement for Building Precast Production." *Automation in Construction* 68:249–258.

Halpin, D. W. 1977. "CYCLONE—Method for Modeling of Job-Site Processes." *Journal of the Construction Division* 103(3):489–499. https://doi.org/10.1061/JCCEAZ.0000712.

Itani, A., N. Malik, Q. Al-Khaldi, and M. Al-Hussein. 2022. "Simulation Analysis of Automated Factory Fabrication Operations for Steel Wall Frames." *Proceedings of the 17th International Inorganic-Bonded Fiber Composites Conference (IIBCC)*, October 18–20, Vancouver, Canada, 227–234.

Itani, A., R. Ahmad, and M. Al-Hussein. 2020. "A Decision-Making Tool to Integrate Lean 4.0 in Windows Manufacturing Using Simulation and Optimization Models." *Proceedings of the 32nd European Modeling & Simulation Symposium (EMSS 2020)*.

Liu, H., M. Al-Hussein, and M. Lu. 2015. "BIM-Based Integrated Approach for Detailed Construction Scheduling Under Resource Constraints." *Automation in Construction* 53:29–43. https://doi.org/10.1016/j.autcon.2015.03.008.

Lu, M. 2003. "Simplified Discrete-Event Simulation Approach for Construction Simulation." *Journal of Construction Engineering and Management* 129(5):537–546. https://doi.org/10.1061/(ASCE)0733-9364(2003)129:5(537).

Martinez, J. C. 1996. *STROBOSCOPE: State and Resource Based Simulation of Construction Processes*. Ph.D. Dissertation, University of Michigan, Ann Arbor, MI. https://deepblue.lib.umich.edu/handle/2027.42/199013.

Yusuf, M. H., N. Shafiai, M. A. S. M. S. Ariffin, and S. M. Sapuan. 2019. "A Stochastic Optimization Approach of Flow Shop Sequencing Problem for On-Time Delivery of Precast Components." *Proceedings of the 8th International Conference on Operations Research and Enterprise Systems (ICORES 2019)*, 245–252. https://doi.org/10.5220/0007309602450252.

AUTHOR BIOGRAPHIES

JULIE MUNOZ is an MSc student in the Department of Civil and Environmental Engineering at the University of Alberta. Her research interests include construction process simulation, production planning, and digital tools for improving efficiency in precast concrete manufacturing. Her email address is jamunoz@ualberta.ca.

MOHAMAD ITANI is an MSc student in the Department of Civil and Environmental Engineering at the University of Alberta. His research focuses on discrete-event simulation of construction operations, with emphasis on optimizing workflows for precast concrete systems and supporting lean implementation in off-site manufacturing. His email address is mitani1@ualberta.ca.

MOHAMMAD ELAHI is a Ph.D. student in the Department of Civil and Environmental Engineering at the University of Alberta. His research focuses on simulation-based modeling, construction productivity optimization, and data-driven decision-making in off-site construction systems. He has published several works on discrete-event simulation and lean construction integration. His email address is mhelahi@ualberta.ca.

ANAS ITANI is a Postdoctoral Fellow in the Department of Civil and Environmental Engineering at the University of Alberta, Canada. His research focuses on discrete-event simulation, construction automation, and optimization of off-site manufacturing systems, with a strong emphasis on digital transformation and lean construction practices. He is actively involved in the development of simulation-based tools to improve productivity and decision-making in precast concrete operations. Anas has contributed to multiple interdisciplinary projects and collaborates with academic and industry partners to advance innovation in construction engineering. His email address is aitani@ualberta.

YASSER MOHAMED is a Professor in the Department of Civil and Environmental Engineering and Director of the Hole School of Construction Engineering at the University of Alberta, Canada. His research focuses on construction automation, simulation and modeling, intelligent systems, and decision-support tools for complex infrastructure projects. He has led large multidisciplinary initiatives to improve productivity, safety, and sustainability and collaborates widely with academia, industry, and government. His email address is yaly@ualberta.ca and his website is https://apps.ualberta.ca/directory/person/yaly#Overview.