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Modelling and Performance Evaluation of Precast Concrete Segments Production Using Discrete-Event Simulation

Asser Letsatsi Tau
Department of Operations Management
Faculty of Management Sciences
Tshwane University of Technology
Pretoria, South Africa
taual@tut.ac.za

Emmanuel Innocents Edoun and Solly Pooe
Tshwane School for Business and Society
Pretoria, South Africa
edounei@tut.ac.za, PooeS@tut.ac.za

Abstract

This study presents a discrete-event simulation analysis of precast concrete segment production using Arena software, with the aim of enhancing system efficiency and throughput. The production system was modeled to include concrete batching, mould filling, low-heat and high-heat curing, segment unloading, cooling, and final transportation to curing basins. Key performance indicators measured included the number of segment batches fed into the system, number of completed batches, total number of concrete segments produced, work-in-progress, average waiting times, and resource utilization. Validation against real production data showed less than 10% deviation, confirming model reliability. Simulation results for a 10-hour production period revealed that the low-heat curing chamber was the primary bottleneck, operating at 96% utilization and causing significant delays. Reducing curing residence times increased the total number of segments produced from 42 to 56, improving system throughput by 33%. Based on these findings, recommendations include expanding low-heat curing capacity, reducing curing times through accelerated techniques, increasing mould availability, implementing parallel processing, and optimizing batch scheduling. These strategies are expected to enhance production efficiency, reduce waiting times, and increase the overall output of concrete segments.

Keywords
Precast Concrete Segments, Discrete-Event Simulation, Arena Software, Production Efficiency and Bottleneck Analysis

1. Introduction
The increasing demand for large-scale infrastructure development has led to widespread adoption of precast concrete components in modern construction projects. Precast concrete structures are widely used in tunnels, bridges, highways, and underground infrastructure because they improve construction speed, enhance structural quality, and allow production to occur in controlled factory environments. Compared with traditional on-site casting, precast concrete manufacturing enables standardized production processes, improved quality control, and reduced construction time, making it an important method in industrialized construction systems (Liang, et al., 2024). Furthermore, the growing need for efficient scheduling and resource utilization in precast production facilities has led researchers to explore advanced analytical and optimization techniques to improve productivity and operational performance (Shi, et al.,

2024). Despite these advantages, precast concrete manufacturing involves multiple sequential and interdependent production stages, including batching, mould filling, curing, cooling, and transportation. Each of these processes requires specialized equipment, skilled operators, and limited resources such as curing chambers, moulds, and material handling equipment. Inefficiencies in coordinating these processes can lead to production bottlenecks, long waiting times, and reduced throughput. Previous studies have shown that the performance of precast factories is significantly influenced by layout design, resource allocation, and process synchronization, where inefficient workflow arrangements can increase production cycle times and non-value-added activities (Assaf et al., 2024).

To analyze and optimize such complex production systems, simulation techniques have been widely adopted in construction and manufacturing research. Discrete-event simulation (DES) is particularly effective for modelling production environments where system states change at discrete points in time and where variability in processing times and resource availability influences overall performance. Simulation models enable researchers to replicate real-world production processes in a virtual environment, allowing alternative scenarios to be evaluated without disrupting actual operations. In the context of precast concrete supply chains and manufacturing systems, DES has been applied to improve production scheduling, evaluate resource utilization, and support decision-making for operational improvements (Phan & Athigakunagorn, 2022). Simulation-based performance tracking methods have also been used to analyze segmental precast production processes, helping identify inefficiencies and enabling managers to make data-driven operational decisions (Rai, et al., 2023).

1.1. Background to the problem

Precast concrete segments are widely used in infrastructure projects due to their durability, quality, and the efficiency offered by off-site production. However, manufacturing these segments involves multiple interdependent processes including concrete batching, mould filling, low-heat and high-heat curing, unloading, cooling, and final transportation that require careful coordination of resources and time. Inefficiencies in any stage, particularly in curing chambers, can lead to long waiting times, high work-in-progress (WIP) levels, and reduced overall throughput. Recent observations of production systems indicate that the low-heat curing stage frequently operates at maximum capacity, creating a significant bottleneck that restricts system performance.

Given these challenges, there is a need to analyze the production process quantitatively and identify opportunities for improvement. Discrete-event simulation provides a robust framework to model system operations, measure key performance indicators (KPIs), and evaluate alternative scenarios without disrupting actual production. The primary problem addressed in this study is how to enhance the efficiency and throughput of precast concrete segment production by identifying bottlenecks, optimizing resource utilization, and implementing operational improvements. Addressing these issues will enable manufacturers to increase segment output, minimize delays, and achieve more efficient operations in precast concrete production systems.

1.2. Objectives of the study

Thus, the primary objective of this study is to analyze and enhance the production efficiency of precast concrete segments by developing a discrete-event simulation model in Arena software that identifies system bottlenecks, evaluates resource utilization, and proposes strategies to increase throughput and reduce waiting times. To achieve the primary objective, the following secondary objective drives the main aim (i) to model the complete production process of precast concrete segments including batching, mould filling, low-heat and high-heat curing, unloading, cooling, and final transportation using Arena software, (ii) to measure key performance indicators (KPIs) such as total segments produced, work-in-progress (WIP), waiting times, and resource utilization under current system conditions, (iii) to identify bottlenecks and inefficiencies within the production system that limit throughput and cause delays (iv) To evaluate the impact of process optimizations such as reduced curing times on system performance and (v) to provide practical recommendations for improving overall production efficiency, reducing waiting times, and increasing the total output of concrete segments.

2. Literature Review

In recent years, discrete-event simulation has emerged as a valuable analytical tool for understanding and improving complex production processes in precast concrete and related construction environments. A notable example is the Simulation-Based Analysis of a Precast Factory Layout to Reduce Labor Travel Time and Production Time*,* which applied a DES model to evaluate the influence of factory layout on labor movement, cycle time, and overall production time. This study demonstrated that optimizing material preparation locations and handling systems can reduce

production time by approximately 10 % and cut labor travel hours by nearly 39 % relative to current layouts, while revealing unnecessary non-value-added transportation activities accounting for nearly 7 % of labor hours (Assaf et al., 2024).
Beyond factory layout, researchers are exploring broader simulation-driven frameworks. A discrete-event simulation-based value stream mapping approach has been developed to automate process improvement planning by integrating DES with lean-oriented performance evaluation, enabling practitioners to identify bottlenecks and inefficiencies in production flows (Sreram & Thomas, 2025).

Comprehensive reviews of simulation applications in construction also highlight the expanding role of DES in addressing the industry's inherent complexity and resource coordination challenges. A recent systematic analysis of simulation-based construction resource management identified key gaps, such as fragmented applications at specific hierarchical levels and insufficient integration of simulation across individual activities and broader process/site levels. It also highlighted emerging opportunities to integrate advanced technologies such as machine learning and real-time data fusion into traditional DES models to enhance decision-making for productivity improvement (Jung, et al., 2025). Table 1 summaries other literature review on the application of DES in precast concrete production.

Table 1. Summary of other literature review on the application of DES in precast concrete production

Authors/citation	**Study Focus / Method**	**Key Findings / Outcomes**	**Relevance to Current Study**
Rai, et al., (2023)	Discrete event simulation (ExtendSim) for segmental production performance at a precast yard.	Demonstrated how simulation models of segmental production can track cycle times, idle times, and productivity indicators to support performance monitoring and management decisions.	Provides recent evidence of DES use specifically for segmental precast production systems, validating the use of simulation in process performance analysis and decision support in your context.
Fadjar et al. (2025)	DES for repetitive construction resource utilization and scheduling.	DES provided dynamic analysis of resource allocation, improving resource management over traditional Critical Path Method .	Relevant for modelling repetitive, resource-intensive stages in concrete segment production.
Kim & Kim (2024)	Proactive production scheduling using simulation & genetic algorithm for off-site precast concrete production.	Used simulation to evaluate due date uncertainty with heuristic optimization, demonstrating robust scheduling strategies.	Supports integrating simulation with optimization for scheduling under variability, relevant to segment curing and batching.
Herrera-Vidal et al. (2026)	DES framework for waste minimization and productivity optimization in manufacturing.	Applied DES to identify waste reduction and efficiency improvements in manufacturing.	Shows how DES can aid production efficiency and waste reduction conceptually aligned with segment production enhancement.
Wooley et al. (2025)	Bridging DES and digital twin for dynamic manufacturing decision-making.	Proposed methodology to enhance DES with Digital Twin capabilities for real-time adaptability.	Highlights emerging directions for DES integration with digital twins, relevant for future efficiency improvements.

Although these studies demonstrate the effectiveness of DES for mapping production dynamics, evaluating layout scenarios, and testing optimization strategies, they also reveal a need for more comprehensive models that integrate stochastic variability, machine reliability, and multi-resource interactions specific to precast concrete segment production. Such models can provide deeper insights into throughput improvement, resource utilization, and operational resilience especially when implemented within robust simulation platforms like ARENA. Taken together, recent research confirms that DES remains a state-of-the-art methodology for analyzing complex manufacturing systems and supports its continued application in enhancing precast concrete production efficiency.

Despite extensive applications of discrete-event simulation in construction and manufacturing, existing studies largely focus on isolated aspects such as layout optimization or scheduling. There remains a gap in developing integrated simulation models that simultaneously capture multi-stage curing processes, and resource interdependencies specific to precast concrete segment production. This study addresses this gap by developing a comprehensive DES model that evaluates both system-wide performance and bottleneck dynamics within a unified system.

3. Research Methodology

This study adopts a quantitative research approach using Discrete-Event Simulation to model, analyse, and optimize the production process of precast concrete segments. The methodology is structured into several key stages, encompassing system definition, data collection, model development, validation, experimentation, and performance analysis.

3.1. System Definition

The first step involves a detailed description of the precast concrete segment production process, identifying all key stages and resources. These stages include concrete batching, loading into precast moulds, initial curing in a low-heat chamber, accelerated curing in a high-heat chamber, natural cooling, and transportation to curing basins. Resource constraints, such as the number of moulds, batch capacity, cranes, forklifts, and operators, are defined. Figure 1 illustrates the process flow of the precast concrete segment production system under study. The diagram presents all key stages, including concrete batching, mould filling, low-heat curing, high-heat curing, natural cooling, and transportation to the curing basins. It also highlights the sequence of operations, resource allocation points, and interdependencies between stages, providing a clear overview of the system's workflow. This visual representation supports the understanding of the discrete-event simulation model developed in this study.

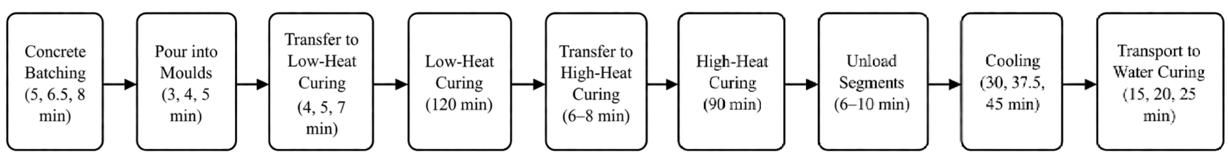

Figure 1. Process flow diagram of the precast concrete segment production system

3.2. Data Collection

Empirical data on process times, resource availability, and production schedules are collected from the target precast production facility. Time intervals for each process stage, such as batching (5-8 minutes), mould loading (3-5 minutes), low-heat curing (120-150 minutes), high-heat curing (60-90 minutes), cooling (30-45 minutes), and transportation (10 minutes), are captured and analyzed. Variability in processing times is modelled using triangular probability distributions to reflect realistic operational fluctuations. Resource utilization data, including crane and forklift availability, operator shift patterns, and chamber capacities, are also collected to parameterize the simulation accurately.

3.3. Model Development in ARENA

The DES model is developed using ARENA Simulation Software, which allows visual representation of production processes and detailed tracking of entities, resources, and queues. Each process stage is represented as a module in ARENA, with entities corresponding to precast segments and resources representing equipment and operators. The model incorporates stochastic processing times, resource constraints, and parallel operations (i.e. cooling and transportation can occur simultaneously).

3.3.1. Modelling statement for the base system

In a precast concrete segment production system, manufacturing begins with concrete batching using automated batching plant. Each batch, prepared to yield 14 precast segments takes approximately 5, 6.5 and 8 minutes batching time. The concrete is then poured into precast moulds at a triangularly distributed time interval of 3, 4 and 5 minutes. The filled moulds are transferred to a low-heat curing chamber where initial curing occurs for with a triangularly distributed transfer time of 4,5 and 7 minutes. The low heating process in chamber takes place for 120 minutes. After this stage, moulds are transferred to high heat curing process with transfer time taking between 6 and 8 minutes. The high heat curing chamber operates for 90 minutes for the accelerated curing process. Once curing is completed, the segments are unloaded with process taking between 6 and 10 minutes and allowed to cool naturally at a triangularly distributed time interval of 30, 37.5 and 45 minutes. Finally, cooled segments are transported to water curing basins for final curing. This process also triangularly distributed with time intervals at 15, 20 and 25 minutes. Thus, the concrete precast then leaves the system.

3.4. Model Verification and Validation

Verification ensures that the ARENA model correctly represents the intended production process without logical errors, while validation confirms that model outputs match real-world performance data. Validation involves comparing simulated throughput, cycle times, and resource utilization rates against actual measurements from the production facility. Thus, validation was performed by comparing simulation outputs with actual production data obtained from the facility over a 10-hour production period. Key performance indicators were used for validation, namely: total concrete segments produced, low-heat chamber utilization and resource utilization. The actual system has total concrete segments produced, low-heat chamber utilization and resource utilization of 40, 0.94 and 305 minutes respectively, meanwhile the simulation results indicates 42, 0.96 and 318 respectively. These indicated a percentage deviation of 5.0%, 2.1% and 4.3% for simulation results versus actual results at total concrete segments produced, low-heat chamber utilization and resource utilization. The deviation between simulated and actual results is within an acceptable range (less than 10%) as reported by Wai et al. (2026) and Halim et al. (2020) indicating that the model adequately represents the real system. Thus, the model is considered valid for scenario analysis and decision support.

3.5. Simulation Replications and Confidence Intervals

To ensure statistical reliability, the simulation model was executed for 10 independent number of replications, for both base system and improved system through the experimentation process. Confidence intervals at the 95% confidence level were generated by Arena Software for the selected key performance indicators.

3.6. Scenario Analysis and Experimentation

Once validated, the model is used to test alternative scenario aimed at improving production efficiency. Experimentation included reduced low-heat curing time from 120 minutes from current base to 90 minutes and high-heat curing residence time reduction from 90 minutes to 60 minutes. The reduction in curing time is achievable through the use of chemical concrete curing compound usage as concrete enhancer.

Performance metrics such as throughput, waiting time, and resource utilization are recorded for each scenario to identify optimal operational strategies.

3.7. Performance Evaluation and Recommendations

The results from the simulation experiments are analysed statistically to determine the impact of each intervention on production efficiency. Key bottlenecks are identified, and actionable recommendations are developed to optimize resource utilisation, reduce waiting times, and increase the overall throughput of precast segment production. Sensitivity analysis is performed to examine how changes in process times affect system performance.

4. Results and Discussion

4.1. Discussion of Simulation Results for Base System (10-Hour Productive Time)

The simulation results for the current precast concrete segment production system operating for 10 hours provide insights into system throughput, resource utilization, and bottlenecks. As shown in Figure 2 and Table 2, a total of 94 segment batches were fed into the system during the simulation period. However, only 3 batches were fully completed within the 10-hour timeframe. Given that each batch contains 14 concrete segments, the system produced a total of 42 concrete segments. This relatively low output compared to the number of batches entering the system indicates that a large portion of the production is still undergoing processing at the end of the simulation period.

The work-in-progress (WIP) level was recorded at 46 segments, confirming that many segments remained within the system, primarily in the curing stages. This accumulation suggests the presence of processing delays and capacity limitations within certain stages of the production process.

Waiting time results further highlight these limitations. The concrete batch plant recorded an average waiting time of 88.12 minutes, indicating moderate queuing before batches could proceed to the next stage. However, the most significant delay occurs at the low-heat curing chamber, where the average waiting time reached 214.74 minutes. This extremely high waiting time suggests that the low-heat curing stage is the primary bottleneck in the system.

In contrast, the high-heat curing chamber and curing basin recorded zero waiting time, indicating that these resources have sufficient capacity and are not constraining the production flow. This observation is further supported by the utilisation results. The low-heat curing chamber shows the highest utilisation at 0.96, meaning it is almost continuously occupied and therefore limits system throughput. The concrete batch plant utilisation is 0.70, indicating relatively high activity but not full capacity usage. Meanwhile, the high-heat curing chamber utilisation is 0.60 and the curing basin utilisation is only 0.10, suggesting significant underutilization of downstream resources.

The number of concrete segments per batch (14) remains constant as determined by the mould configuration in the production system. However, because only 3 batches were completed, the total output of 42 segments indicates that the system is unable to process all incoming batches within the 10-hour operating window. This further reinforces that the low-heat curing chamber residence time and capacity constraints significantly restrict overall production throughput (Table 2).

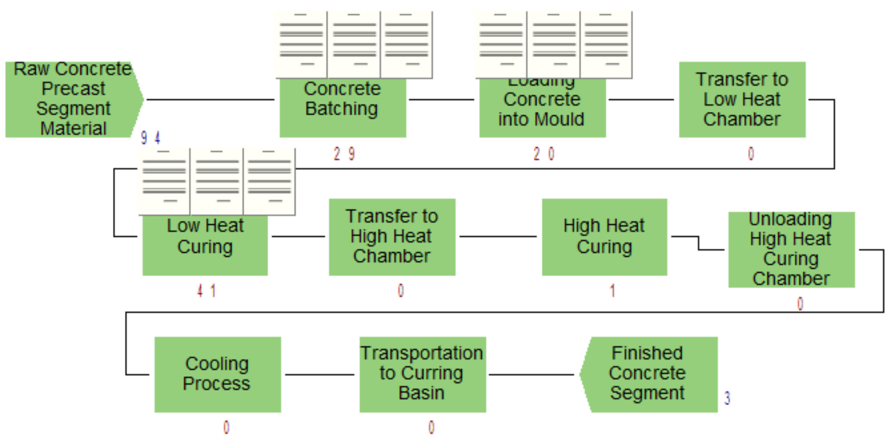

Figure 2. Simulated model for current system performance at 10 hours

Table 2. Results for current system performance at 10 hours

Performance Metric	Unit of Measure	Result
Number of Segments Batches Fed into System		94
Number of Segments Batches Produced		3
Number of Concrete Segments per Batch		14
Total Number of Concrete Segments Produced		42
Work in progress (WIP)		46
Concrete Batch Plant Average Waiting Time	Min	88.12
Low Heat Curing Chamber Average Waiting Time	Min	214.74
High Heat Curing Chamber Average Waiting Time	Min	0.00
Curing Basin Average Instantaneous Waiting Time	Min	0.00
Concrete Batch Plant Average Instantaneous Utilisation		0.70
Low Heat Curing Chamber Average Instantaneous Utilisation		0.96
High Heat Curing Chamber Average Instantaneous Utilisation		0.60
Curing Basin Average Instantaneous Utilisation		0.10

4.2. Discussion of Simulation Results for Optimized Scenario at 10 hours (Reduced Low-Heat and High-Heat Residence Time)

Figure 3 and Table 3 depict the developed model in Arena software and the results thereof for current base system operating at 10 hours respectively.

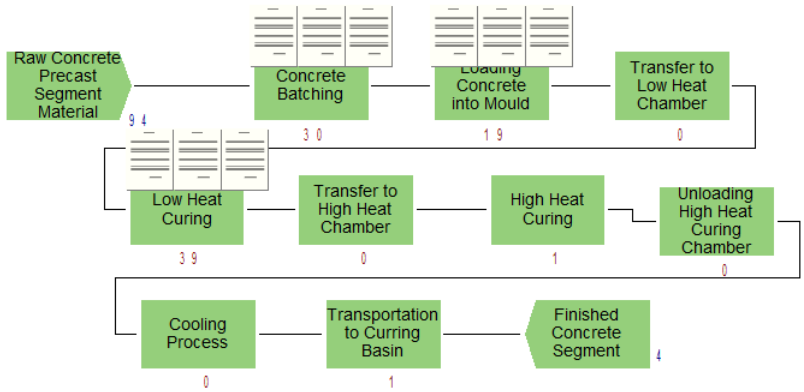

Figure 3. Simulated model for optimized scenario of reduced low heat and high heat residence time at 10 hours

Table 3. Results for optimized scenario of reduced low heat and high heat residence time at 10 hours

Performance Metric	Unit of Measure	Result
Number of Segments Batches Fed into System		93
Number of Segments Batches Produced		4
Number of Concrete Segments per Batch		14
Total Number of Concrete Segments Produced		56
Work in progress (WIP)		45
Concrete Batch Plant Average Waiting Time	Min	89
Low Heat Curing Chamber Average Waiting Time	Min	232.28
High Heat Curing Chamber Average Waiting Time	Min	0.00
Curing Basin Average Instantaneous Waiting Time	Min	0.00
Concrete Batch Plant Instantaneous Utilisation		0.70
Low Heat Curing Chamber Average Instantaneous Utilisation		0.96
High Heat Curing Chamber Average Instantaneous Utilisation		0.55
Curing Basin Average Instantaneous Utilisation		0.16

The optimized simulation scenario evaluates the impact of reducing the residence time in both the low-heat and high-heat curing chambers. As illustrated in Figure 3 and Table 3, the system performance shows noticeable improvements compared to the base case.

During the 10-hour simulation period, 93 batches were fed into the system, which is nearly identical to the base system input. However, the number of completed batches increased from 3 to 4 batches. With 14 concrete segments per batch, this results in a total production of 56 concrete segments, representing an increase of 14 additional segments compared to the base scenario. This corresponds to approximately a 33% improvement in production output.

The work-in-progress decreased slightly from 46 to 45, indicating a marginal improvement in the flow of segments through the system. Although the reduction is small, it suggests that faster curing times help move segments more efficiently through the production stages.

The average waiting time at the concrete batch plant remained nearly unchanged, increasing slightly from 88.12 minutes to 89 minutes, which indicates that the batching stage is not the primary limiting factor in the system. However, the low-heat curing chamber still shows a very high average waiting time of 232.28 minutes, even after reducing residence time. This indicates that while curing time reductions improved throughput, the low-heat curing chamber remains the dominant bottleneck due to its high demand and limited capacity.

Like the base scenario, the high-heat curing chamber and curing basin still recorded zero waiting time, demonstrating that these stages have sufficient capacity relative to the production flow. Resource utilisation results support this observation. The low-heat curing chamber utilisation remains extremely high at 0.96, confirming that it continues to operate near maximum capacity. The concrete batch plant utilisation remains at 0.70, while the high-heat curing chamber utilisation decreases slightly to 0.55, reflecting the faster processing time in this stage. The curing basin utilisation increases from 0.10 to 0.16, which indicates that more segments are reaching the final curing stage due to the improved flow earlier in the process.

The number of concrete segments per batch remains fixed at 14, consistent with the mould configuration used in the production system. However, the increase in the number of completed batches from 3 to 4 directly results in the increased total output of 56 segments. This demonstrates that improvements in curing time can significantly enhance system throughput even without increasing batch size or adding additional moulds.

Overall, the optimized scenario shows that reducing curing residence times improves production output and downstream resource utilisation. The observed increase in waiting time at the low-heat curing chamber (from 214.74 minutes to 232.28 minutes) despite improved throughput represents a system-level queueing effect rather than a modelling inconsistency. The reduction in curing residence times accelerates upstream processing rates, resulting in a higher arrival rate of concrete segments to the low-heat curing stage. However, because the capacity of the low-heat curing chamber remains unchanged and continues to operate at 96% utilization, the increased inflow intensifies queue formation. This phenomenon is consistent with queueing theory, where reducing service time without increasing capacity in a highly utilized system can lead to longer queues due to increased throughput pressure. Therefore, while throughput improves, localized waiting time increases, which confirms that capacity expansion is required, thus, not only time reduction for alleviation of the bottleneck.

4.3 Proposed Improvements

The simulation results indicate that the low-heat curing chamber is the primary bottleneck in the current precast concrete segment production system, operating at nearly full capacity and generating substantial waiting times. To increase production, expanding the low-heat curing chamber capacity or adding additional chambers would allow more segments to cure simultaneously, reducing queues and accelerating the overall workflow. Further improvements could be achieved by reducing curing times through techniques such as study on steam curing and humidity control parameters to allow segments to progress faster without compromising quality. Increasing batch size or mould availability, where feasible, would directly enhance throughput, provided downstream stages can handle the increased flow. Introducing parallel processing for curing stages would also help distribute the workload more evenly and minimize bottlenecks. Finally, optimizing batch scheduling and mould allocation ensures that resources are utilized efficiently, reducing idle times and improving system performance. Collectively, these strategies are expected to significantly increase the total number of completed concrete segments, enhancing the overall productivity of the precast production system.

5. Conclusion

This study applied discrete-event simulation using Arena software to model the production of precast concrete segments and evaluate system performance under both baseline and optimized scenarios. The simulation results identified the low-heat curing chamber as the primary bottleneck, with high utilization and long waiting times limiting overall throughput. By reducing curing times in both low-heat and high-heat chambers, production output increased from 42 to 56 segments over a 10-hour period, demonstrating the effectiveness of process optimization. Further improvements, including expanding curing chamber capacity, increasing mould availability, implementing parallel processing, and optimizing batch scheduling, are expected to enhance system efficiency and reduce work-in-progress. Overall, the study demonstrates that discrete-event simulation is a valuable tool for analyzing complex production systems, identifying bottlenecks, and supporting data-driven decisions to improve productivity in precast concrete segment manufacturing.

5.1. Limitation of the study

This study is subject to limitations, firstly, the processing times were modelled using triangular distributions based on observational data from the concrete manufacturing plant. Secondly, the model assumes constant resource availability and does not incorporate machine breakdowns or labor disruptions. Thirdly, the findings are based on a single concrete segments manufacturing plant, which may limit generalizability to other production environments with different configurations. Future studies should incorporate real-time data integration, use various concrete segments manufacturing plants and broaden datasets from various plants to improve model generalizability.

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Biographies

Asser Letsatsi Tau holds a Doctor of Philosophy (Ph.D) Degree in Operations Management and Master's Degree in Operations Management (with distinction) from the University of Johannesburg, a Master of Engineering (MEng) in Chemical Engineering from Tshwane University of Technology and a Postgraduate Diploma in Business Administration from the University of the Witwatersrand Business School. He is a researcher and engineer whose academic work focuses on operations management, industrial engineering, simulation modelling, manufacturing systems optimisation, and maintenance engineering. His research contributions are primarily centred on enhancing operational efficiency, improving equipment performance, and optimising processes across industrial and service systems.

Emmanuel Innocents Edoun is an academic, he holds a PhD from the University of Witwatersrand in Johannesburg South Africa. He has travelled widely between different countries in Africa while interacting with academic institutions, policy makers, policy implementers and community members. He is industrious and has good conceptual and organizational skills. He has consulted and spearheaded projects at the African Union, NEPAD , the Pan African Parliament ; AFRODAD. He has been involved as an academic at various University is South Africa and abroad. He has supervised more than 20 PhD Students, 30 full master's and 100 MBAs students. He has attended many conferences, locally and abroad, and has published many articles in the International accredited Journals.

Solly Pooe holds a Doctorate in Business Administration (DBA) and has extensive experience in higher education management and governance. His academic work focuses on public sector management, organizational effectiveness, and service delivery improvement. Solly has contributed to peer-reviewed research and is actively involved in postgraduate supervision and academic leadership, contributing to institutional development and strategic academic planning. He is currently a Deputy Registrar at the Tshwane University of Technology, Pretoria, South Africa.