

USING SIMULATION TO IMPROVE MARBLE WAREHOUSE OPERATIONS IN HOUSING PROJECTS

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Abstract

The Saudi 2030 Vision Housing Program aims to deliver high-quality, affordable housing on time. On-site warehouses are essential to the Jeddah Housing Project, which includes 8,649 residential units across 440 towers. High daily order volumes, a small workforce, and limited transportation resources have caused persistent delays in the marble warehouse.

This study uses Simio simulation software to model the marble warehouse as a complex socio-technical system, analyse workflow, identify bottlenecks, and evaluate operational alternatives. A base model representing current operations was created for 1,760 orders and verified with historical data.

Three alternative configurations were simulated: increasing preparation unit capacity, adding preparation and transportation resources, and deploying knuckle boom trucks to improve delivery efficiency. Performance metrics included total time in system, preparation unit utilization, and average waiting times. Alternative 3 significantly reduces delays and total time, optimizing warehouse operations for large housing projects and supporting strategic decision-making.

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Key Words: Warehouse Operations, Simulation, Marble Logistics, Jeddah Housing Project, Socio-Technical Systems

1. INTRODUCTION

Major Real Estate is spearheading the mega project known as the Jeddah Housing Project, which involves the construction of 440 towers including a total of 8,649 residential units. In an area of 2,700,000 square meters, the project boasts a total actual building area of 2,146,460 square meters. Additionally, the project includes six warehouses, each designated to provide specific items.

The original scientific contribution of this study lies in integrating socio-technical modelling with discrete-event simulation and statistically validated alternative configurations to optimize large-scale on-site warehouse operations in housing mega-projects.

Below is Fig. 1 that illustrates the current situation and how the supplied materials move from the warehouse to the destination by using specific routes where that available or not.



Figure 1: Base model layout of the marble warehouse.

1.1 System description

The warehouse system manages marble material orders for the Jeddah Housing Project, classified by material type, including stairs, walls, landings, and thresholds, and by building type, including A, B, C, and D. The number of buildings varies by type, with 221 for type A, 138 for type B, 39 for type C, and 42 for type D. Upon receiving an order, the warehouse team, consisting of four labourers, initiates preparation of the requested materials. Each order corresponds to one of sixteen predefined standard order types, with all necessary data stored in the warehouse database. Once prepared, orders are moved to the loading area to await truck availability. The number of shipments required for each order type is predetermined and recorded in the system.

The transportation process involves loading shipments onto trucks using forklifts, transporting both truck and forklift to the delivery site, and unloading the materials at the designated location. An order is considered fully delivered once all shipments are completed and the subcontractor signs the delivery documents. The subcontractor accompanies the truck and forklift to the site during unloading, after which the vehicles return to the warehouse to continue processing remaining items. The warehouse resources include the preparation unit of four workers, four forklifts for loading, unloading, and transport, and two standard trucks for delivering all orders to their designated locations.

1.2 The problem under investigation

The purpose of making a warehouse on the site of the project is to obtain the needed material in the shortest possible duration. However, in this project specifically, the warehouse operations maintain frequent delays of the requested materials to more than 5 days. These delays disrupt the project timeline which results in increasing the cost and delaying the completion of the project. The main issue here is the delay in marble delivery caused by several factors like limited resources, high volume of daily orders, inefficient material handling and loading processes, and potential bottlenecks in preparation and loading areas. The study considered the overall 1760 orders of the system. The warehouse operates for 8 hours a day over 6 days a week.

1.3 Study objectives

The study aims to achieve several quantifiable and measurable objectives to improve the efficiency and effectiveness of marble warehouse operations. The primary objectives of this simulation are as follows:

- Reduce the average waiting time for the orders on Preparation unit.
- Reduce the average waiting time for orders in the Loading area.
- Reduce the overall time in system for all order types.

This study aims to enhance the overall performance of the warehouse to deliver the project as the delivery plan.

1.4 Performance metrics

The performance metrics decided for this study are as follows:

- Preparation unit utilization,
- Average waiting time in the Preparation unit,
- Average waiting time in the Loading area,
- Average time in system (*TIS*) for each Entity.

2. LITERATURE REVIEW

Large-scale construction projects depend on efficient warehouse operations because material delivery affects project timelines and costs. Simulation-based methods have been used to model warehouse workflows, identify bottlenecks, and optimize resource allocation for a decade [1].

A study used simulation-based experimental designs for warehouse energy consumption and order tardiness. The study demonstrated that integrating resource allocation strategies with workflow simulation significantly improves operational efficiency [2]. Similarly, a study assessed the circular transformation of warehouse operations, highlighting how discrete-event simulation can guide strategic resource management and minimize delays [3].

Socio-technical perspectives have been emphasized in recent research, recognizing that human operators, material handling equipment, and process workflows interact dynamically. Vaičiūtė and Katinienė examined the critical role of information systems in warehouse management, showing that efficient communication between workers and logistics systems can reduce waiting times and improve throughput. A study highlighted the application of discrete-event simulation to improve workshop operations, demonstrating measurable gains in efficiency through resource reallocation and workflow redesign [4].

Numerous studies have used simulation to optimize material supply chains in logistics related to construction. Project budgets and schedules are greatly impacted by delays in the delivery of materials like marble and other finishing materials [5]. Project managers can test different configurations, assess trade-offs, and apply data-driven improvements thanks to advanced modelling of the loading, transportation, and preparation phases [6].

Because of their versatility in simulating intricate warehouse systems, simulation tools like Simio have gained widespread use. Multiple order types, stochastic processing times, and resource constraints can all be incorporated using Simio, which supports decision-making and offers realistic performance insights [7]. Furthermore, it has been demonstrated that utilizing cutting-edge delivery technologies, like knuckle boom trucks, can improve warehouse efficiency by cutting down on loading and unloading times [8].

Additionally, recent research has focused on striking a balance between transportation and preparation capabilities. Increasing preparation capacity alone may result in downstream bottlenecks [9], underscoring the significance of comprehensive system-level optimization. Managers are able to continuously validate improvements and modify operational strategies to meet changing demand patterns by integrating simulation and real-time monitoring [2, 10].

Simulation modelling has also been widely applied beyond construction and warehouse contexts, demonstrating its versatility across manufacturing and service industries. A study applied ARENA simulation to a mineral water production line to identify bottlenecks and enhance efficiency [11], while another combined simulation with an improved genetic algorithm to optimize garment production line balance [12, 13]. Moreover, a study has optimized healthcare maintenance workflows using multi-scenario simulation and simulation annealing [14], and another employed simulation for cost analysis in a leading optics business in Saudi Arabia [15]. Similarly a study highlighted its value in identifying cost reduction and performance improvement opportunities [16]. Advances in simulation methodology continue to support continuous improvement: Smith et al. provided practical guidance for modelling and analysis using Simio [17], while other has proposed a simulation-based algorithm to enhance enterprise performance iteratively [18]. These studies collectively demonstrate simulation's capacity to optimize processes and support data-driven decision-making in diverse operational settings.

In conclusion, there is substantial evidence in favour of using simulation-based methods to maximize warehouse operations during building projects. Among the main themes are:

Discrete-event simulation for resource allocation and workflow modelling; Socio-technical systems perspective for integrating technical and human resources; Balanced capacity planning to prevent bottlenecks during loading or preparation stages; Advanced material handling technologies to increase efficiency; and Constant monitoring and adaptation for sustained performance gains.

By simulating the Jeddah Housing Project's marble warehouse, incorporating operational and resource considerations, and assessing potential configurations for performance optimization, this study expands on these discoveries.

3. INPUT DATA AND COLLECTION METHODS

Table I shows the input data collected to simulate the marble warehouse system during daily operations. As the system is considered a terminating system and the focus is on evaluating overall system performance, the data was randomly collected over standard 8-hour working days.

Table I: Input data and collection methods.

Name	Description	Unit	Collection method
Order interarrival times	Time between consecutive orders	Minutes	Historical warehouse records
Preparation time	Time to prepare each order type	Minutes	Measured at Preparation station
Loading time	Time to load a shipment onto the truck	Minutes	Measured at Loading area
Unloading time	Time to unload a shipment at the site	Minutes	Measured at delivery site
Transportation time	Time to transport shipment to site	Minutes	Measured for trucks and forklifts
Number of trucks	Number of trucks available	Count	Warehouse logs
Number of forklifts	Forklifts available for loading/unloading	Count	Warehouse logs
Number of workers	Workers in Preparation unit	Count	Warehouse logs

3.1 Study and modelling assumptions

The study ran simulation as an approach to achieving its main goal while following are the assumptions:

1. Forklift movements to the destination site are considered negligible, as they occur simultaneously with the truck during the transportation process. Therefore, the transportation time in the model reflects Both the trucks and the forklift's travel duration. Additionally, the loading and unloading activities performed by the forklift are incorporated within the truck's operational time in the model.
2. The model is designed to encompass all potential orders associated with the project under study. As the total number of main orders across the four building types is 1,760, the simulation run time was set to 2,640 working hours to ensure the generation of all order types required by the project contractors. While the actual working hours in a single day are 8 hours.

The input data values were rounded up to the nearest whole number to ensure clarity and prevent potential misinterpretation.

3.2 Input data analysis

The collected data was analysed using EasyFit software to identify the best-fit probability distributions. Table II presents the fitted distributions for interarrival times and preparation times for each order type, as well as the loading, unloading, and transportation times, all determined at a 95 % confidence level.

Table II: Fitted probability distributions.

Activity	Distribution	Parameters (min)
Order Interarrival	Exponential	90
Preparation A1	Weibull	39, 165
Preparation A2	Weibull	10, 45
Preparation B1	Weibull	17, 127
Loading	Triangular	18, 21, 27
Unloading	Triangular	14, 18, 22
Transportation	Uniform	7, 27

4. MODELLING AND ANALYSIS

A base model simulating warehouse system was built, verified and validated. In addition, alternative models were built in order to improve the performance of the system and decrease the total average time in the system.

4.1 Base model description

A base model of the marble warehouse system was developed using Simio 5.0 simulation software. In this model, orders arrive at the warehouse as individual entities, with each of the 16 standard order types represented as a distinct entity type. The arrival process is governed by a predefined arrival mix that reflects the proportion of orders associated with each building type relative to the total project demand.

A single preparation unit with a capacity of one is responsible for preparing one order at a time. The preparation time varies depending on the order type. Once an order exits the preparation unit, it is assigned a unique order number that is used throughout the model to track and manage the corresponding shipments.

Following preparation, the system generates a new entity type called *ShipmentBatch*, which represents the number of shipments required to complete the delivery of the order. For example, if order A1 requires three shipments, the system creates three *ShipmentBatch* entities associated with order A1. Each *ShipmentBatch* is tagged with the same order number assigned to the original order entity. This number is later used to ensure that all corresponding shipments are correctly linked to their originating order.

After the preparation phase, the order is transferred to the loading area, where it waits for dispatch. The system includes two standard trucks responsible for transporting shipments to their designated delivery sites. Each truck performs the full delivery cycle, which includes loading the shipment, transporting it to the site, unloading it, and returning to the warehouse.

For orders requiring multiple shipments, the trucks deliver each shipment sequentially. Once all shipments related to an order are delivered and matched their original order number, the order is marked as fully delivered and is considered complete within the system. This matching process is carried out using a simulation model combiner. Fig. 2 provides a visual representation of the simulated system within Simio.

As illustrated in the figure above, each order type is represented by a distinct entity in the simulation model. The arrival of orders follows a predefined mix that reflects the proportion of each order type relative to the total number of orders in the project. Upon arrival, an order proceeds directly to the preparation units if available; otherwise, it joins the queue until a unit becomes available.

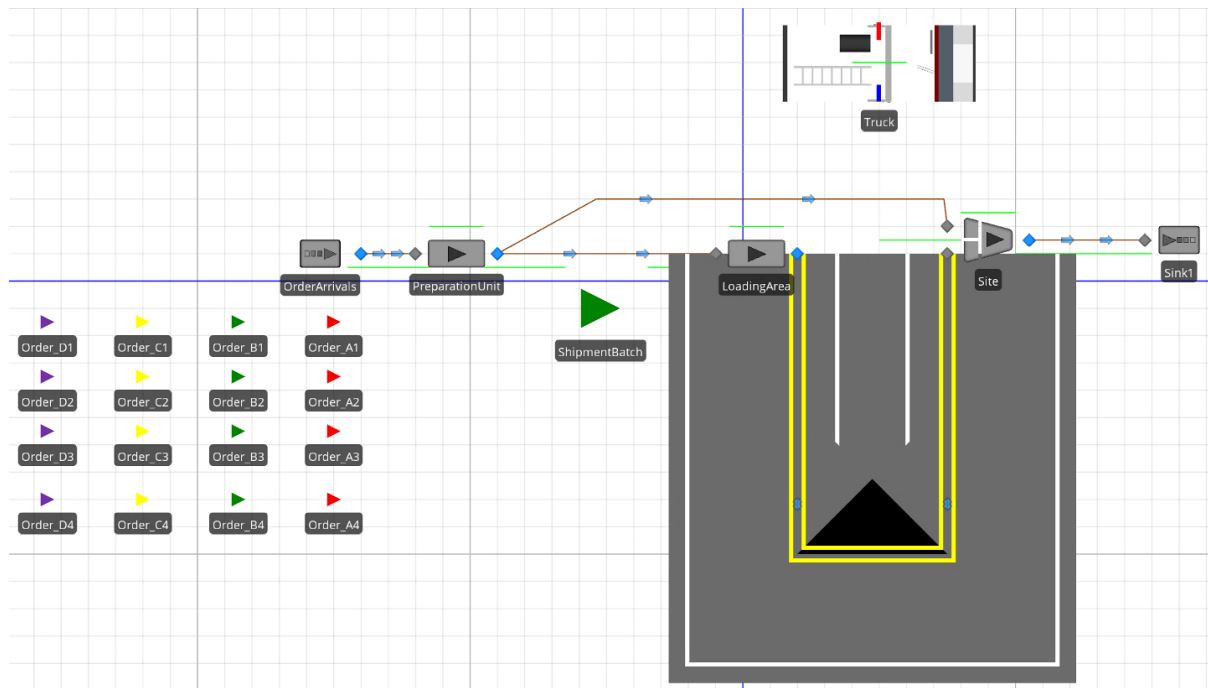


Figure 2: Simulation model of marble warehouse workflow in Simio.

Following the completion of the preparation process, the order is split into a predefined number of shipments, as specified in a data table within the model. Each shipment retains a reference to its corresponding order through an assigned order number. The individual shipments are then routed to the loading area to await transportation.

A combiner node is used to group the shipments with their corresponding order entity based on the shared order number. Once all shipments of an order have been successfully delivered to the destination site, the order is marked as fully delivered and exits the system.

This modelling approach enables precise tracking of partial deliveries and ensures that orders are only considered complete when all associated shipments reach their destination.

4.2 Simulation setup

The base and alternative models were each executed with 100 replications. The SMORE plots for all response measures were visually inspected to confirm that the number of replications was adequate to ensure stable and consistent results.

As previously illustrated, the total number of orders required to fulfil the project requirements is 1,760. Therefore, the run length for each replication was set to 2,640 hours to ensure that all orders enter the system within a single simulation run.

4.3 Verification and validation of base model

The base model was carefully checked at every stage of its development by running the simulation many times and closely watching how the system behaved. This step-by-step checking helped make sure that the model worked correctly and followed the intended process.

To validate the base model, a statistical comparison was performed across multiple performance measures to evaluate differences between the simulated and observed results. The following hypotheses were tested using a *t*-test in SPSS software (Table III): the null hypothesis (H_0) states that there is no significant difference between the simulation and observed results, while the alternative hypothesis (H_1) states that a significant difference exists.

Table III: Base model validation results.

Performance measure	<i>P</i> -value	Conclusion
<i>TIS</i> for A1 orders	0.102	Fail to reject H_0
<i>TIS</i> for B1 orders	0.877	Fail to reject H_0
<i>TIS</i> for C1 orders	0.301	Fail to reject H_0
<i>TIS</i> for D1 orders	0.263	Fail to reject H_0
Waiting time for shipment in the Loading area	0.145	Fail to reject H_0
Waiting time for orders in the Preparation unit	0.399	Fail to reject H_0

Based on statistical analysis, the null hypothesis was not rejected for any of the performance measures. This indicates that the differences between the simulation output and observed data are not statistically significant at the 95 % confidence level. Therefore, the simulation model is considered to be valid and representative of the real system under investigation.

4.4 Base model performance results

A summary of Base model results for performance measures of interest is given in Table IV. The level of significance used was 0.05.

Table IV: Base model performance measures.

Performance measure	Average	Half-width (95 % <i>CI</i>)
Preparation unit utilization (%)	82	0.46
Average waiting time in Preparation unit (min)	221.36	10.41
Average waiting time in Loading area (min)	143.79	4.97
Total time in system – Entity A1 (min)	579.25	13.97
Total time in system – Entity A2 (min)	505.04	14.04
Total time in system – Entity A3 (min)	503.99	13.85
Total time in system – Entity A4 (min)	470.9	13.94

4.5 Alternative models

Based on the simulation results of the base model, it appears that the model is sufficiently representative. However, the utilization of the preparation unit, along with the average waiting times in the preparation unit and loading area, as well as the overall time in system for all 16 entity types, are notably high. These metrics suggest opportunities for improvement. The following alternative models are proposed with the objective of reducing the average time in system (*TIS*), minimizing waiting times, and enhancing the overall performance of the system.

Alternative 1: Increase Preparation unit capacity with the same transportation resource.

The base model results reveal that the performance of the preparation unit is characterized by high scheduled utilization and extended queue waiting times. To address this, a potential improvement is tested by adding a second preparation unit, resulting in two units serving the orders for the project. It is assumed that the service time remains consistent for both units. Table V shows the results obtained from the alternative 1 model at 95 % confidence level.

Table V: Alternative 1 performance.

Performance measure	Average	Half-width (95 % CI)
Preparation unit utilization (%)	41.2	0.24
Average waiting time in Preparation unit (min)	10.58	0.3
Average waiting time in Loading area (min)	260.01	9.09

Alternative 2: Increase Preparation unit capacity and increase the transportation resource capacity.

Alternative model 2 includes the combination of increasing the capacity of preparation units to be 2 units and increasing the current transport capacity from 2 standard trucks to 3. Both preparation units considered have the same service time. In addition, all trucks considered to have the same transportation time. Table VI shows the results obtained from the alternative 2 model at 95 % confidence level.

Table VI: Alternative 2 performance.

Performance measure	Average	Half-width (95 % CI)
Preparation unit utilization (%)	41.12	0.22
Average waiting time in Preparation unit (min)	10.48	0.26
Average waiting time in Loading area (min)	75.39	0.75

Alternative 3: Increase Preparation unit capacity and replace the transportation resource with more effective truck with the same original capacity.

In alignment with industry best practices observed by a leading company in the marble sector, it is proposed that all in-city deliveries be conducted using knuckle boom trucks. These vehicles significantly reduce transportation time compared to standard trucks, as they eliminate the dependency on forklifts during the loading, unloading, and delivery processes. This proposed improvement aims to decrease waiting times in the loading area and minimize the overall time within the system. To evaluate this enhancement, the current standard trucks are replaced with knuckle boom trucks, with updated data related to transportation, loading, and unloading times, as presented in Table VII.

Table VII: Data collected for alternative models of knuckle boom truck.

Transportation time (minutes)	Loading time (minutes)	Unloading time (minutes)
Random.Uniform (5, 20)	Random.Triangular (12, 15, 19)	Random.Triangular (8, 12, 16)

Table VIII shows the results obtained from the alternative 3 models at 95 % confidence level.

Table VIII: Alternative 3 performance.

Performance measure	Average	Half-width (95 % CI)
Preparation unit utilization (%)	41.28	0.26
Average waiting time in Preparation unit (min)	10.74	0.28
Average waiting time in Loading area (min)	70.39	0.93

4.6 Statistical analysis

To evaluate the performance of the proposed alternative models against the base model, a Paired sample *t*-test was conducted using SPSS across four key performance indicators:

average time in system, average waiting time in the Preparation unit, average waiting time in the Loading area, and Preparation unit utilization. For each indicator, the hypotheses were defined as follows: the null hypothesis (H_0) states that there is no statistically significant difference in performance between the base model and the alternative model, while the alternative hypothesis (H_1) states that there is a statistically significant difference. The test was conducted at a significance level of 0.05. The results strongly reject H_0 , indicating significant differences between the base model and all three alternative models for the evaluated performance measures.

4.7 Results discussion

The results of the simulation study clearly highlight significant performance differences between the base model and the proposed alternatives. The base model, which reflects the current operational configuration, shows considerable inefficiencies, particularly in the Preparation unit utilization and the average waiting times for both the Preparation and Loading stages. The Preparation unit recorded a high utilization rate of 82 %, accompanied by prolonged average waiting times of over 220 minutes in the Preparation queue and nearly 144 minutes in the Loading area.

Alternative 1, which introduced a second Preparation unit without increasing transport capacity, resulted in a dramatic reduction in waiting times within the Preparation area (approximately 10.5 minutes). However, it also led to an unintended increase in waiting time in the Loading area (260 minutes), likely to be due to bottlenecks caused by the unchanged truck capacity. While time in system improved across all order types, the Loading stage emerged as a new constraint.

Alternative 2, which increased both the Preparation capacity and the number of trucks, addressed the Loading area bottleneck effectively. The average Loading area waiting time dropped significantly to about 75 minutes, and all order types experienced marked reductions in total time in system, with some orders dropping below 220 minutes.

Alternative 3, which introduced knuckle boom trucks with improved loading and unloading efficiency, produced the best results among all models. This configuration not only maintained low Preparation waiting times (≈ 10.7 minutes) but also reduced the Loading area queue to 70.3 minutes. More impressively, the average time in system for all entity types was significantly reduced, most falling between 170 and 270 minutes. This improvement is attributed to the knuckle boom truck's ability to eliminate forklift dependency during delivery, optimizing the entire delivery cycle.

Statistical analysis using Paired t -tests confirmed that all three alternative models showed statistically significant improvements across the performance metrics when compared to the base model, validating their effectiveness in enhancing the system.

5. CONCLUSIONS AND RECOMMENDATIONS

This simulation study aimed to evaluate and enhance the performance of the marble warehouse operations at the Jeddah Housing Project, with a particular focus on reducing delays in order delivery. Through the development and analysis of a base model using Simio simulation software, key performance issues were identified, including excessive waiting times in both the Preparation and Loading stages, and high utilization of the Preparation unit.

Three alternative system configurations were proposed and tested against the base model to assess their impact on the performance metrics. The first alternative addressed Preparation capacity alone, while the second combined increased Preparation and transportation capacities. The third alternative integrated the use of more efficient knuckle boom trucks, offering a more technologically advanced transportation solution.

The analysis confirmed that operational delays can be significantly minimized through targeted improvements in system design. Simulation modelling proved to be an effective decision-support tool, enabling the team to assess the trade-offs of various configurations before implementation. These findings reinforce the value of simulation in managing complex warehouse systems and guiding strategic planning in large-scale infrastructure projects.

Based on the simulation results and statistical analysis, the following recommendations are proposed:

1. Adopt Alternative 3 as the preferred configuration. Replacing standard trucks with knuckle boom trucks is strongly recommended. This change demonstrated the most substantial performance improvements across all metrics, especially in reducing the overall order delivery time. The model indicates that this alternative can significantly improve throughput and minimize delays without requiring additional trucks.
2. Increase Preparation unit capacity. Regardless of the transportation method, increasing the number of Preparation units from one to two is essential. This modification alone reduces the Preparation queue waiting time from over 220 minutes to around 10 minutes and brings down the Preparation unit utilization from 82 % to approximately 41 %, enhancing system flexibility.
3. Avoid increasing Preparation capacity alone (Alternative 1). While it may appear beneficial, increasing Preparation capacity without enhancing transportation capacity leads to a new bottleneck at the Loading area. Therefore, any investment in capacity expansion must be balanced across the full delivery chain.
4. Invest in integrated delivery resources. Knuckle boom trucks should be considered a long-term investment for urban project logistics. Their ability to load and unload without forklift support improves system autonomy and reduces resource dependency.
5. Continue monitoring system performance. Implementing the recommended changes should be followed by continued simulation and real-time performance tracking to validate assumptions and fine-tune operations as demand patterns evolve.

By implementing these strategies, the Jeddah Housing marble warehouse operations can achieve substantial improvements in delivery timeliness, customer satisfaction, and project schedule adherence.

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