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Impacts Identification of Supplier Reliability on Project Duration in Heavy Industrial Construction Supply Chain Using Discrete Event Simulation

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ABSTRACT: Driven by provisional project requirements, the heavy industrial construction supply chain (HICSC) is complex, dynamic, and uncertain. Supplier behaviors further complicate the HICSC, posing additional challenges for general contractors in managing material inventories and project schedules. A limited understanding of supplier reliability and its consequences on HICSC can adversely impact project duration and cost. Existing research on construction supply chain has focused on logistic optimization, material storage and inventory, supplier selection, knowledge management and coordination. None, however, has centered on assessing the impact of supplier reliability on project duration and identifying the critical materials within the HICSC. To address this gap, this study aims to quantify the impact of supplier reliability on project duration in HICSC and identify critical materials for heavy industrial construction projects. A discrete event model was developed using *Simphony.NET* to simulate a typical material procurement process within HICSC from a general contractor's perspective. The simulation evaluated how variations in supplier reliability affect project duration and identified critical metrical materials by analyzing scenarios derived from both artificial and historical project datasets. The findings demonstrate that unreliable suppliers significantly delay project durations, with materials characterized by short lead time and long delay being the most critical in heavy industrial construction projects. This paper advanced the body of knowledge by (1) abstracting and simulating a typical HICSC into a discrete event model from a general contractor's perspective, (2) quantifying the impact of supplier reliability on project duration, and (3) identifying critical materials for heavy industrial construction projects.

1. INTRODUCTION

Heavy industrial construction supply chain (HICSC) refers to the network of organizations, resources, activities, and technologies involved in the planning, procurement, production, transportation, and delivery of materials, equipment, and services required for large-scale construction projects in industries (Benton and McHenry, 2010, Irizarry et al., 2013). A typical HICSC involves multiple stakeholders, including general contractors, suppliers, manufacturers, subcontractors, specialty trades, government authorities, and end clients involved in delivering the necessary inputs for heavy industrial construction projects (Koc and Gurgun, 2021, Wu et al., 2022). Efficient management of the HICSC is crucial for ensuring timely project delivery, cost control, and quality assurance (Chen and Xu, 2011). Furthermore, heavy industrial construction projects are commonly fast-tracked and involve materials that are custom-designed and engineered to order, rendering the HICSC more susceptible to supply reliability than other construction supply chains (Wu et al., 2021). Therefore, a comprehensive understanding of the impact of supplier reliability on project duration and the identification of critical materials is imperative for general contractors to avoid delays and manage costs when managing HICSC.

Existing studies have applied numerous simulation techniques in the field of construction supply chain (CSC) management such as discrete event simulation (DES), Monte Carlo simulation, agent-based simulation, system dynamic, and Petri network simulation (Chen and Hammad, 2023). Among these, the DES is the most popular, due to its versatility. DES is a technique that discretizes a system into multiple consecutive events (Fahrland, 1970). It is particularly suitable for CSC management due to its ability to model the intricate interactions and dynamic nature of the construction process (Mostafa et al., 2016). In addition, it enables the simulation of various scenarios and what-if analyses, allowing users to make informed decisions to enhance efficiency, reduce costs, and improve project outcomes within the CSC (Demiralp et al., 2012).

Studies have adopted DES to examine CSC management focused on logistic optimization (Vidalakis et al., 2013, Chen and Liao, 2022), supplier selection (Chen et al., 2019), material storage and inventory (Pan et al., 2010), knowledge management (Chen and Hammad, 2023, Wang et al., 2019), and entire project performances (Wang et al., 2018, Hussein et al., 2022). Although the current literature showed that DES is a popular and suitable tool applied in the field of CSC management, the authors found that only one study identified and modeled (via DES) the potential disturbances caused by supplier uncertainties within the CSC for a precast construction project (Wang et al., 2018). Specifically, they quantified supplier uncertainties from the quality perspective, while ignoring the delivery delays. Delivery delays (i.e., delay of material lead time) caused by suppliers can have a major impact on the subsequent project tasks, leading to disruption of workflow, schedule delays, cost overrun, increased rework, and potential reputational damage to general contractors (Love and Edwards, 2004, Mello et al., 2015, Kayhan et al., 2019). Nevertheless, according to the authors' knowledge, no prior study has focused on quantifying the impact of supplier reliability on the project duration and identifying critical materials for heavy industrial construction projects.

To address the research gap, this study aims to quantify the impacts of supplier reliability on project duration and identify critical materials for heavy industrial construction projects. The structure of this paper is as follows. This study contributes to the academia by quantifying the impacts of supplier reliability on project duration in HICSC. Practically, it identifies the materials types that are most sensitive to supplier reliability, providing insights for procurement prioritization and risk mitigation. The structure of this paper is as follows. The structure of this paper is as follows. The next section presents a literature review on indicators measuring supplier reliability and the effect of supplier reliability on supply chain performance. Then, the conceptual model, data collection and DES model, are presented. The subsequent section introduces the methods applied for model verification and validation. Next, the simulation results are compared and discussed, followed by conclusions and limitations of the study.

2. LITERATURE REVIEW

2.1 Indicators Measuring Supplier Reliability

Supplier reliability refers to a supplier's ability to fufill commitments by delivering goods or services on time, in the correct quantity, and in the required quality standards (Huang and Keskar, 2007). This study identifies three primary indicators of supplier reliability: the probability of delayed delivery, accuracy of delivery quality, and accuracy of delivery quantity, discussed in the following subsections.

2.1.1 Probability of delayed delivery

This indicator refers to the probability of a supplier failing to deliver materials within the promised lead time. Delayed deliveries can disrupt project schedules, increase costs, and lead to resource idling in construction projects (Kikwasi, 2012). Thamhain (2013) states that the probability of delayed delivery is a key measure of supplier reliability, as it directly affects project timelines and can trigger cascading impacts. Due to the complexity of HICSC, even minor delays can propagate through the entire supply chain, significantly prolonging project duration and inflating costs. To mitigate the risks with high delay probability, general contractors often resort to contingency measures, such as material buffers or expedited transportation, which further strain budgets (Chopra and Meindl, 2007). Thus, this study primarily focus on the probability of delayed delivery as the core indicator of supplier reliability.

2.1.2 Accuracy of delivery quality

This indicator measures the percentage of materials delivered that meet predefined quality standards. Low-quality materials can cause rework, delays, and structural failures in construction projects (Balouchi et al., 2019). In HICSC, the interconnected nature of construction activities and the high-performance requirements of materials amplify the impact of quality defects. Such issues can escalate into safety risks and compromise the long-term integrity of construction projects (Stevenson and Spring, 2007).

2.1.3 Accuracy of delivery quantity

This indicator assesses whether the quantity of delivered materials matches the order specifications. In construction projects, under-delivery often forces general contractors to halt work or seek alternative suppliers, incurring premium costs and delays. Conversely, over-delivery leads to storage constraints and potential wastage, indirectly affecting project efficiency and increasing indirect costs (Manners-Bell and Lyon, 2022).

2.2 Effect of Supplier Reliability on Construction Supply Chain Performance

Supplier reliability is a crucial factor in supply chain performance as it directly affects project timelines, cost control, and stakeholder coordination (Chen et al., 2020). Delivery reliability (Pan et al., 2010), material quality (Wang et al., 2018), plan reliability (Kim et al., 2023), and information-sharing capabilities (Bäckstrand and Fredriksson, 2022) have been used to measure supplier reliability in CSC. However, these studies often rely on case-based evaluation, focusing on whether specific materials are delivered intact and on time, without quantifying the impact of supplier reliability on CSC performance or examining its effect on project duration.

While Wang et al. (2018) and Kim et al. (2023) quantify the impact of supplier reliability on CSC performance from the perspectives of material quality and plan reliability, respectively, they do not. address how supplier reliability influences the project duration. Disruptions caused by unreliable suppliers can cascade throughout the supply chain, leading to significant delays (Kamalahmadi and Mellat-Parast, 2016, Noori-Daryan et al., 2019). Furthermore, these studies fail to identify the critical materials in CSC — those that are sensitive to supplier reliability. This further highlights the gap that this study aims to address by quantifying the performance impact of supplier reliability on HICSC through project duration and identifying critical materials for heavy industrial construction projects.

3. MODEL DEVELOPMENT

3.1 Conceptual Model

Leveraging the insights from our industry partner, we have developed a conceptual model detailing a typical material procurement process for a general contractor in a heavy industrial construction project, as shown in Figure 1. A typical HICSC involves multiple stakeholders such as clients, general contractors, suppliers, and manufacturers. Notably, different departments of the general contractor are also engaged in this process as highlighted in green, while all external stakeholders are depicted in white. Since our research studied the HICSC from the general contractor's perspective, the conceptual model was established to emphasize the interactions and activities between the general contractor and external stakeholders, while simplifying the interactions among external stakeholders. The material procurement process starts with receiving the bill of material (BOM) from the client. Then, the project coordinator will prepare work packages and issue requisitions of required materials to the procurement team. Upon receiving requisitions, the procurement team initiates a request for quotes (RFQ) from potential suppliers. A minimum of three suppliers are contacted, and one is chosen. Following selection, the procurement team proceeds to issue purchase orders and negotiate contracts with the designated supplier outlining material specifics and delivery terms. Concurrently, the supplier commits to a lead time upon contract signing. When the materials are ready, they are shipped from upstream stakeholders – either the warehouse of the supplier or upstream ordering through the manufacturer. The material control team, then, receives the materials and compares the actual receipt time with the promised delivery time to verify timeliness. Additionally, quality assurance and quality control (QA/QC) are performed to ensure material quality aligns with specifications. Once all materials within a work package pass QA/QC, they are stored in an internal warehouse of the general contractor and ready for field installation. Any materials deemed unsatisfactory undergo a return to the upstream ordering process, awaiting further manufacturing and shipping cycles.

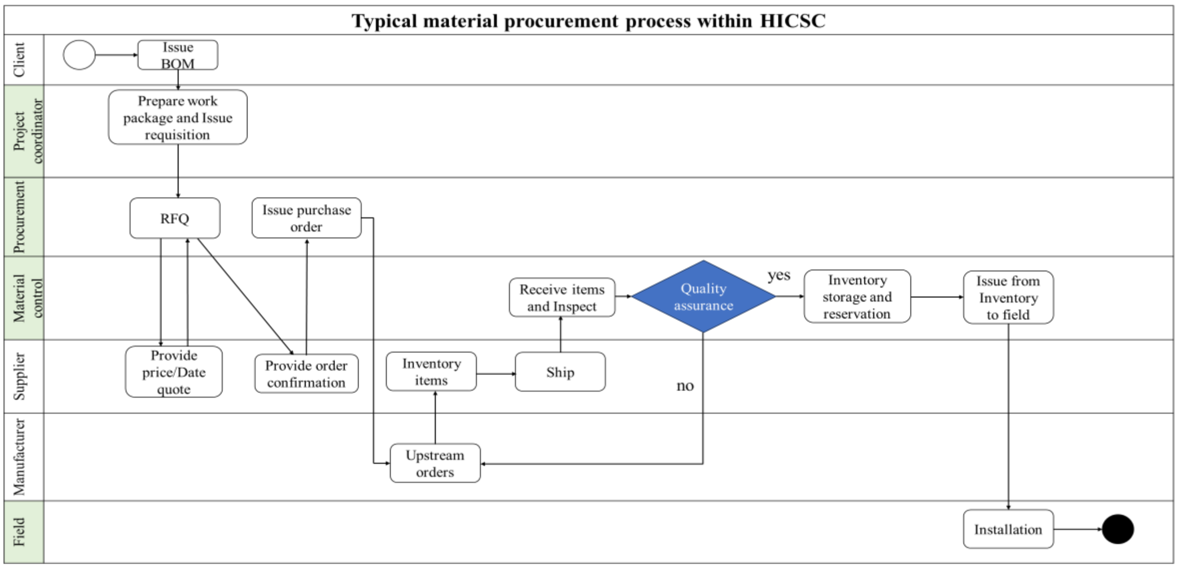

Figure 1: Conceptual model of a typical material procurement process within HICSC

3.2 Data Collection

The project data used for developing the simulation model were provided by local industrial partner technology team, including the supplier names, the types of materials, the quantities of materials, expected material lead time, the date of purchase order created, and the date of material received. The data contains 5000 records, from 2020 to 2024. Data was preprocessed to remove outliers, which mainly addressed the impact of Covid-19 when the lead time exceeded 100 days. First, according to the historical data, we simplified and abstracted three major material types, namely Material A (Pipe & Valve), Material B (Fitting), and Material C (Support). Each material type represents one material group with unique characteristics. Specifically, Material A represents a material type with a short lead time and a short delay; Material B represents a material type with a short lead time and a long delay; Material C represents a material type with a long lead time and a short delay. This classification captures the key variations in supplier reliability characteristics and was validated through discussions with procurement professionals to ensure practical relevance. Second, for each material type, we summarized the expected lead time, delay time, and probability of delayed delivery as listed in Tables 1 and 2. Table 1 and Figure 2 show the distributions of expected lead time and delay time for three major material types fitting using historical data. Table 2 presents the reliability of five suppliers, two hypothetical cases (HCs), and three actual cases (ACs) based on historical data. Due to the relatively low reliability of suppliers, as represented by the high probability of delayed delivery fitted from the real-world historical data, we added two hypothetical cases to represent highly reliable suppliers with delayed delivery probabilities of 0% and 30%, respectively.

Table 1: The material information used in the Simphony model

	Material A (Pipe & Valve)	Material B (Fitting)	Material C (Support)
Expected lead time	Weibull (0.68, 10.74)	Beta (0.72, 14, 0, 193)	Beta (0.68, 1.28, 0, 70)

Delay time	LogLogistic (3.73, 1.29)	LogLogistic (3.57, 1.37)	Weibull (0.92, 6.99)

Table 2: Reliability of suppliers

	Probability of delayed delivery				
	Hypothetical Case		Actual Case		
Material type	HC1	HC2	AC1	AC2	AC3
Material A	0%	30%	65%	85%	100%
Material B	0%	30%	80%	92%	100%
Material C	0%	30%	50%	90%	100%

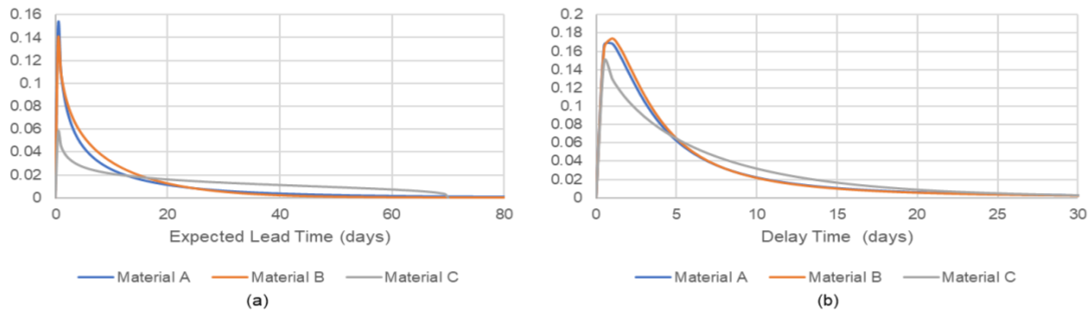

Figure 2: Distributions of expected lead time and delay time for three types of material

3.3 DES Model Development

Simphony.NET was chosen for this study due to its modular and hierarchical modeling environment, which facilitates a user-friendly experience in developing DES models (AbouRizk et al., 2016). It provides flexibility for users to adjust parameters and test various scenarios, making it an ideal tool for the proposed research. In this study, the model adopted the “General Purpose Template” of Simphony.NET, to represent material flow, resource utilization, and activity sequencing within the HICSC (AbouRizk et al., 2016).

The model was developed to simulate a heavy industry construction project’s material procurement process as illustrated in section 3.1. It takes the probability of delayed delivery of each material and the expected lead time and delay time of each type of material as the inputs, and outputs the duration of the material procurement process. This study specifically focuses on the material procurement process; therefore, the term “project duration” in this paper exclusively refers to the duration of the material procurement process, excluding the actual field installation.

The full list of the model parameters, including activity name, type of input, value, unit of measure, and definition are given in Table 3. The durations of activities were represented by distributions as suggested and validated by experts from our industrial partner.

Table 3: Model parameters

Conceptual model activity	Simphony model Activity	Type of input	Value	Unit of measure	Definition
Prepare and issue requisition	Prep and issue requisition and RFQ duration	Task/Distribution	Triangular (0, 1, 0.5)	Days	Time required from preparation of work package and issue requisition to RFQ
RFQ					

Provide price/Date quote	Supplier response time	Task/Distribution	Triangular (0, 1, 0.5)	Days	Time for one supplier to provide quote
Provide order confirmation Issue purchase order	Contract confirmation time	Task/Distribution	Triangular (0, 1, 0.5)	Days	Time required for contract drafting and purchase issuing
Upstream order, Inventory items & Ship	Expected lead time	Task/Constant	See Table 1	Days	Promised lead time to receive each material from supplier
	Probability of lead time delay	Probabilistic Branch/Possibility	See Table 2	Percentage	The probability of different supplier's delivery time later than promised
	Duration of lead time delay	Task/Distribution	See Table 1	Days	Duration of lead time delay based on different materials
Receive items and inspect	Duration of inspection	Task/Distribution	Triangular (0, 1, 0.5)	Days	Time required for inspection of each material
Quality assurance	Probability of failed material	Probabilistic Branch/Possibility	0	Percentage	Probability of material failure to pass QA/QC and need to rework
Issue from inventory to field	Shipping to filed	Task/Distribution	Triangular (0, 1, 0.5)	Days	Time for each type of material to be shipped from the inspection location to the field

The following assumptions of the model were made to facilitate the simulation of a realistic HICSC while highlighting the activities preceding inventory and shipping.

1) The installation process, general contractor's inventory costs, and site logistics were not considered.
2) All activities were continuous, not following business hours.
3) The initial number of work packages was 100, issued one by one with the interval of Uniform (0, 0.1). Those issued earlier will be completed first.
4) There were four types of work packages, each containing different types of materials as listed in Table 4.
5) The issuance probability of each type of work package is determined based on the historical data of the respective materials.
6) Each material type had 5% of the total project-required quantity in inventory at the start of the simulation.

Table 4 Work package types with their corresponding material types

	Material A	Material B	Material C
Work Package Type 1	✓		
Work Package Type 2		✓	
Work Package Type 3			✓
Work Package Type 4	✓	✓	✓

4. VERIFICATION AND VALIDATION

The developed conceptual model and *Simphony.NET* model were validated through face validation by PCL experts to ensure they are consistent with realistic situations. Additionally, following the suggestion by Sargent (2009), specification verification and implementation verification were completed to ensure the model design and implementation of the conceptual model on the specified computer system were correct. Furthermore, the DES model was validated by extreme condition tests and degenerate tests to ensure sufficient accuracy of model outputs within the intended model applicability and to achieve its model purpose. Figure 3 shows the extreme condition test of the model. In this test, the duration of all activities was set to zero, and the project duration undoubtedly ended up being zero. In addition, Figures 4(a) and 4(b) depict the different results generated by conducting a degenerate test. For example, the expected lead time of Material A was increased from 1 to 10. It can be seen from Figure 4(a) to 4(b), that the project duration increased with the lead time from 51.888 to 55.461. Due to the page limit, degenerate tests of other parameters were also conducted yet not included.

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Scenario1 (Termination Time)	0.000	0.000	10.000	0.000	0.000
Work Package Interval (Duration)	0.000	0.000	10.000	0.000	0.000

Figure 3: Extreme condition test of the DES model

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Scenario1 (Termination Time)	51.888	1.997	1,000.000	45.826	58.058
Work Package Interval (Duration)	0.500	0.020	1,000.000	0.437	0.562

Counters

Element Name	Final Count	Production Rate	Average Interarrival	First Arrival	Last Arrival
Material A Manufaction	22.061	0.369	2.166	5.703	49.791
Material B Manufaction	61.209	0.887	0.787	4.245	51.322
Material C Manufaction	13.189	0.327	3.627	7.357	48.466
Work Package Completion	100.000	1.689	0.505	1.922	51.888
Work Package ready	100.000	1.985	0.500	0.000	49.479
WP1 Completion	13.767	0.421	3.607	4.858	47.945
WP2 Completion	63.268	0.994	0.798	1.755	51.139
WP3 Completion	22.965	0.417	2.172	3.208	49.378
WP4 Completion	0.000	0.000	NaN	NaN	NaN

(a)

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Scenario1 (Termination Time)	55.461	3.344	1,000.000	45.448	64.405
Work Package Interval (Duration)	0.500	0.021	1,000.000	0.430	0.573

Counters

Element Name	Final Count	Production Rate	Average Interarrival	First Arrival	Last Arrival
Material A Manufaction	20.480	0.310	2.143	14.668	54.658
Material B Manufaction	62.486	0.956	0.794	4.252	52.764
Material C Manufaction	13.574	0.227	3.635	7.101	49.834
Work Package Completion	100.000	1.644	0.541	1.913	55.461
Work Package ready	100.000	2.050	0.500	0.000	49.509
WP1 Completion	13.737	0.283	3.625	4.616	47.821
WP2 Completion	63.070	1.065	0.802	1.764	51.211
WP3 Completion	23.193	0.432	2.394	3.174	54.544
WP4 Completion	0.000	0.000	NaN	NaN	NaN

(b)

Figure 4: Degenerate test of the DES model

5. RESULT AND DISCUSSION

A total of 14 scenarios were designed based on the inputs as summarized in Tables 1 and 2, aiming to examine the impact of supplier reliability on project duration and identify critical materials. The model was run 1000 times for each scenario to eliminate randomness. The design and results of 14 scenarios are presented in Table 5. As indicated in Table 5, with the increase in supplier reliability (i.e., the lower the probability of delayed delivery), the project duration decreased. The results show that choosing highly reliable suppliers can effectively reduce project duration and prevent project delays.

To better illustrate the results, we arranged these 14 scenarios into 4 comparison groups as demonstrated in Table 6. Scenario 1 served as the control group for all comparison groups, with all materials of all types being delayed. Group 1 compared the project duration changes affected by Material A suppliers with different possibilities of delayed deliveries. Similarly, groups 2 and 3 evaluated the impacts on project duration caused by the various possibilities of delayed delivery for Material B and C respectively. Group 4 evaluated the impact on project duration caused by the decreasing possibilities of delayed delivery (from 100% to 0%) for all materials.

Table 5: Scenario analysis of different supplier reliability and materials

Scenario	Material A	Material B	Material C	Project Duration (Mean)	Project Duration (Standard Deviation)
1	AC3	AC3	AC3	77.304	8.323
2	AC2	AC3	AC3	77.115	8.162
3	AC1	AC3	AC3	76.264	7.491
4	HC2	AC3	AC3	76.316	7.253
5	HC1	AC3	AC3	75.598	7.138

6	AC3	AC2	AC3	75.309	7.700
7	AC3	AC1	AC3	72.128	7.895
8	AC3	HC2	AC3	71.579	7.435
9	AC3	HC1	AC3	70.198	8.128
10	AC3	AC3	AC2	76.850	7.874
11	AC3	AC3	AC1	76.474	7.876
12	AC3	AC3	HC2	76.001	7.652
13	AC3	AC3	HC1	75.896	7.609
14	HC1	HC1	HC1	63.908	5.751

Table 6: Scenarios for evaluating the impact of material delivery delay on project duration

Group	Scenario Included	Purpose of Comparison
1	1, 2, 3, 4, 5	To evaluate the impact on project duration due to the various possibilities of delayed delivery of Material A
2	1, 6, 7, 8, 9	To evaluate the impact on project duration due to the various possibilities of delayed delivery of Material B
3	1, 10, 11, 12, 13	To evaluate the impact on project duration due to the various possibilities of delayed delivery of Material C
4	1, 14	To evaluate the impact on project duration due to the decreasing possibilities of delayed delivery of all materials

The results of the comparison groups were summarized as boxplots as shown in Figure 5. As illustrated in Figures 5(a), 5(b) and 5(c), when the probability of delayed delivery of Material A, B and C decreased from 100% to 0%, the median project duration dropped from 76.28 days to 75.07, 68.97, and 74.87 days. The findings suggested that Material B (material type with a short lead time and a long delay) is the most critical material, as improving the reliability of this material supplier leads to the most significant reduction in project duration, by 9.58%. While Material A (material type with a short lead time and a short delay) and C (material type with a long lead time and a short delay) are less sensitive to suppliers' reliability, rendering them less critical in a typical HICSC.

Another interesting finding is that improving the supplier reliability for a single material resulted in marginal improvements in overall project duration, with reductions of less than 10%. This may be because increasing the reliability of one material shifts the criticality to the other two materials, causing delays in those materials to dominate the critical path of the project. Consequently, the overall project duration is only slightly reduced since the constraints on the critical path are merely transferred rather than resolved. Based on this, we hypothesized that improving the supplier reliability for all materials simultaneously would more effectively reduce project duration. To test this, we ran another scenario where all materials had reliable suppliers, as shown in Figure 5(d). The result confirmed our hypothesis, showing a more significant reduction in project duration by 17.6%, highlighting the necessity of improving supplier reliability across all materials in HICSC.

In summary, the findings from this scenario analysis offer several practical insights for decision-makers in HICSC projects. First, the identification of Material B as the most critical material suggests that contractors should prioritize supplier management efforts—such as strict reliability-based performance assessments or contract incentives—for this material type. Second, the limited benefit of improving reliability for only one material type indicates that project-wide supplier reliability improvement is more effective than isolated efforts. This supports the implementation of portfolio-based supplier selection frameworks and diversification strategies, such as dual sourcing or supplier tiering, to mitigate supply-side risks across all material types.

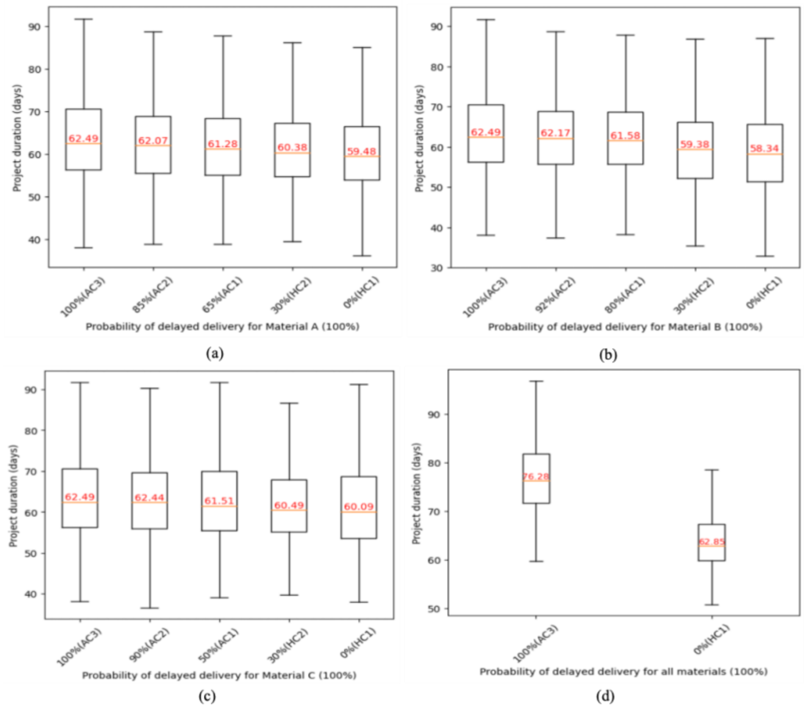

Figure 5: Impact on project duration from delayed delivery of (a) Material A; (b) Material B; (c) Material C; and (d) All materials

6. CONCLUSION

This study filled the research gap identified in the domain of HICSC by quantifying the impacts of supplier reliability on project duration and identifying critical material types that are most sensitive to supplier reliability using both historical data and hypothetical data. We first developed a conceptual model for a typical material procurement process within HICSC based on literature and inputs from our industrial partner. Based on the conceptual model, we then designed a DES model in Simphony.NET from a general contractor's perspective to (1) demonstrate the impact of supplier reliability on project duration (2) examine critical materials that are sensitive to supplier reliability based on scenario analysis, and (3) analyze the changes in project duration based on selected suppliers and material types. The scenario-based analysis indicates that increasing supplier reliability for all three types of materials reduces project duration, with Material B (material type with a short lead time and a long delay) being the most critical material of all. In addition, improving the supplier reliability for all types of materials results in a more significant reduction in project duration.

Despite the advancements, this study suffers from the following limitations. First, the specific negotiations such as the price quote of each supplier were not considered. Second, the details of shipping and inventory issues were not studied. Third, due to the data limitation, we simplified all materials involved in the process into three major material types and used four work package types to represent the material mix. Fourth, two hypothetical cases assumed the same lead time and delay duration patterns as observed suppliers, which may not fully capture the complexity of real-world supplier behaviors. Fifth, while the model includes a parameter for material quality, it assumes a zero probability of material failure based on case study data, which reported no instances of rework or material rejection. Future research can explore more complex and realistic material and work package assumptions. Despite these limitations, the findings of this paper are valuable as they will assist in HICSC management and provide information to industrial stakeholders to better understand the impact of supplier reliability on project duration, thereby contributing to supplier selection and material order decisions.

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