JNEST EISSN: 2961-8738 ● PISSN: 2961-8916 ● DOI: 10.56741/jnest.v5i03.2573

Article Received 15 August 2026, Revised 8 October 2026

Critical Supply Chain Risks in Modular Construction: Assessment of Cost, Time, and Quality Impacts

Dana Ayu Maharani*, Kartika Puspa Negara, Wisnumurti

***Abstract*—Modular Integrated Construction (MiC) offers opportunities to improve construction cost and time efficiency, but its implementation depends on supply chain readiness. In Indonesia, dependence on imported materials and an underdeveloped modular ecosystem complicate adoption amid substantial housing shortages. Previous studies have rarely distinguished supply chain risks affecting cost, time, and quality or examined state-owned enterprise (SOE) contractors as early MiC adopters. This study assessed these risks using practitioner perspectives from five SOE contractors in Jakarta. Thirty practitioners completed a questionnaire covering 37 risks across seven categories. Of these, 36 met validity and reliability requirements, with Cronbach's alpha values ranging from 0.955 to 0.982. Risk severity was evaluated using the Severity Index (SI) and classified through a Probability-Impact Matrix (PIM). Most risks were categorized as moderate. Four risks were classified as high: long distances between project sites and modular factories (LG3) for cost; inadequate assembly planning and scheduling (DP3) and delayed owner payments (PG3) for time; and delayed module installation (IM5) for quality. The findings highlight the importance of coordinated planning, contract management, and supply chain collaboration. Contractors should strengthen scheduling and stakeholder coordination, while module providers should improve production capacity, technical support, quality control, and workforce competencies. The study is limited by its Jakarta-based SOE sample and reliance on perceived risks. Future research should involve broader regional samples, quantify actual cost and schedule impacts, and examine risk relationships using observed project performance data to support more reliable modular construction implementation.**

***Index Terms*— Modular Construction, Severity Index, State-Owned Enterprise Contractor, Supply Chain Risk Management.**

I. Introduction

MODULAR Integrated Construction (MiC), one of the leading approaches within Off-Site Construction (OSC), enables approximately 80-90% of building works to be completed in a factory environment before the transportation and on-site assembly of the modules [1]. This approach can accelerate project delivery by around 20-50% [2] and reduce costs by up to 24% compared to conventional construction [3], while also improving project quality through a more controlled fabrication process. However, the design, production, transportation, and assembly stages can be integrated; these benefits entail a greater reliance on a complex supply chain. For modular construction approaches to be implemented successfully, supply chain risk management is essential since any interruption at any point might affect the project as a whole [4].

Based on data on Housing Backlog and Housing Provision Achievements in Indonesia 2025–Semester I 2026, the home ownership backlog still reached 9.29 million households (12.39%) and the habitability backlog was 18.01 million households (24.03%), almost double the ownership backlog. This indicates that improving the quality of existing homes is a crucial component in meeting housing needs. In 2026, among all Indonesian provinces, the highest habitability backlog rate was recorded in the Highland Papua Province at 91.76 percent, whereas the lowest was in the Special Region of Yogyakarta at 7.92 percent [5]. Due to these conditions, faster and more effective construction techniques are required. However, the implementation of Modular Integrated Construction (MiC) in Indonesia faces various challenges, such as limited modular manufacturing facilities, the complexity of module transportation, inadequate logistics infrastructure, and issues regarding the accessibility of imported materials, particularly aluminum and steel [6]–[7]. These conditions make the supply chain more susceptible to price fluctuations, supply delays, and supply uncertainty. Cost overruns, schedule delays or time overruns, and a decline in construction quality can directly result from these conditions [8]–[9].

Supply chain risks are among the most significant threats in modular construction projects [6], [10]. Advanced forms of the modular construction industry, design standardization, inter-connection coordination, and integrated logistics systems have reduced such risks [11]–[12]. However, research specifically focused on supply chain risks with separate evaluations of their impacts on cost, time, and quality remains limited. A review of 309 studies on off-site construction supply chain modeling found that logistics-related aspects received only around 7% of research attention, while studies on Supply Chain Risk Management (SCRM) within the context of developing countries remain very limited [4], [13].

Assessing risk in relation to cost, time, and quality is essential, as these aspects constitute the key parameters of construction project success. Consequently, supply chain disruptions that are not evaluated specifically against each of these parameters may lead to inaccurately targeted risk-control strategies [14]. The severity of a given risk can vary across different project performance parameters; a risk with no significant effect on schedule may not necessarily have the same effect on project cost or quality. A general

Dana Ayu Maharani (Corresponding Author), **Kartika Puspa Negara**, and **Wisnumurti** are with the Department of Civil Engineering, Brawijaya University, Malang, Indonesia.
Corresponding Author Email: danaayumaharani@student.ub.ac.id

© 2026 IISTR

risk assessment therefore tends to offer an incomplete picture of how risk influences project performance. Each risk can impact the relevant party's performance at varying levels; an assessment that simultaneously addresses cost, time, and quality yields more comprehensive results [15]. Consequently, to accurately reflect the impact on time, cost, and quality, the resulting risk visibility requires that each severity level be assessed individually.

Research on modular construction risks continues to grow, yet three critical gaps remain. First, in modular construction research, the Severity Index (SI) is commonly used to assess the overall severity of risks; however, it has not been used to examine how these risks affect cost, time, and quality in modular construction projects. in modular construction projects [16]. Second, empirical studies on supply chain risks in modular construction have largely been conducted in developed nations possessing mature modular manufacturing ecosystems and regulatory frameworks [4]. Recent studies in Indonesia have focused solely on stakeholder priorities regarding the adoption of modular construction [17], rather than on supply chain risks themselves. Third, the implementation of modular construction in Indonesia remains dominated by State-Owned Enterprise (SOE) contractors, who act as pioneers in adopting the modular approach [6]. The experiences regarding supply chain risks encountered by these pioneering companies in Indonesia have not yet been systematically examined, even though such experiences could serve as a vital reference for fostering wider adoption of modular construction.

Building on these identified gaps, this study aims to analyze supply chain risk in modular construction based on the experience of five state-owned enterprise (SOE) contractors in Jakarta, and to determine the severity level of risk at each supply chain stage in relation to cost, time, and quality, given their potential impact on project implementation.

Thus, the primary contribution of this research is to assess the severity levels of individual supply chain risks in modular construction based on their impacts on cost, time, and quality, and to present a comprehensive severity mapping that can be practically applied during the early stages of project risk management (addressing gap 1). In addition, by drawing on SOE contractors' experiences, this study addresses gaps 2 and 3 and offers a reference for strengthening the resilience of the modular construction supply chain in Indonesia.

II. Research Methods

A. Research Design and Framework

This study employs a robust research methodology. It utilizes digital calculations for risk assessment based on Severity Index (SI) distributions derived from survey responses provided by professionals working on modular construction projects. The objective is to leverage SI metrics to identify supply chain risks within the modular construction sector by shedding light on the perceptions of practitioners from the five state-owned enterprise (SOE) contractors in Jakarta. Subsequently, these results are used to classify risks into low, medium, and high categories.

The study underlying this survey serves as a preliminary step to identify risk performance levels. The data were cleaned to ensure their integrity prior to statistical analysis. Subsequently, the Severity Index (SI) was used to determine the severity level for each impact on cost, time, and quality. Risk factors classified as high-risk formed the basis for determining appropriate risk controls.

B. Research Instrument

This study employs a structured questionnaire as the primary data collection instrument, divided into three sections: respondent characteristics, level of understanding regarding modular construction, and risk assessment. Based on the literature review as presented in Table I, the risk assessment section comprises 37 items. While previous studies generally categorize MiC risks into four main stages [18], this study expands the classification to seven factors, namely design and planning, procurement, module production, logistics, transportation/delivery, on-site installation, and external risks, to obtain a more detailed overview of supply chain disruptions [1], [9]. Prior to the main survey, the questionnaire containing 37 risk items derived from the literature was pilot-tested and reviewed by experts. This stage involved four individuals: one academic and three industry practitioners who understand the modular construction supply chains. The evaluation was conducted online (via Google Forms) to assess content validity, evaluate sentence clarity and readability, and estimate the time required to complete the questionnaire. Based on feedback from the pilot test, the questionnaire was refined to eliminate ambiguity and ensure that all 37 risk items were suitable for use in the main survey.

All risk factors in Table I were assessed by respondents using a five-point Likert scale to measure the probability of occurrence and its impact on project cost, time, and quality.

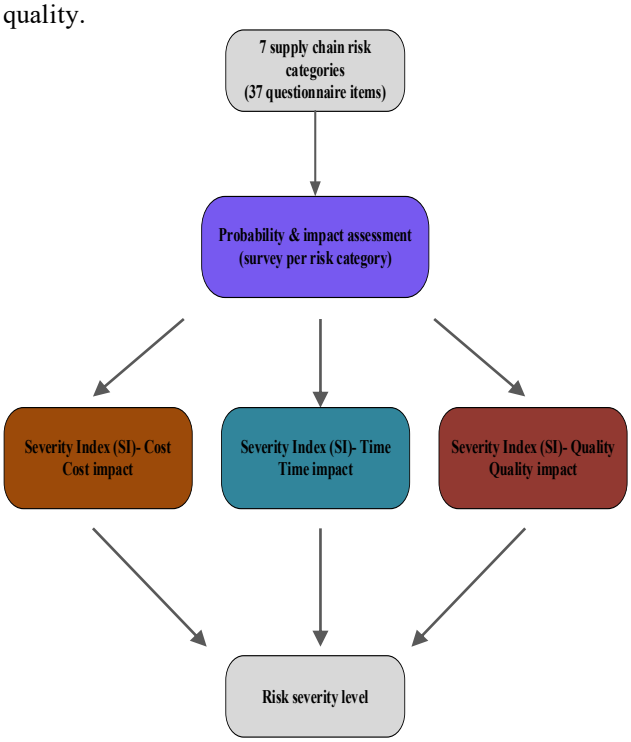


Fig. 1. Severity Index Analysis Flow

TABLE I.
SUPPLY CHAIN RISK FACTORS IN MODULAR CONSTRUCTION

Risk Factor		Code	Definition	References
Design and Planning Risk	DP	DP1	Changes in project design or scope	[1], [19]–[22]
		DP2	Failure to establish design standards and specifications in the early project stage	[18], [22]–[23]
		DP3	Suboptimal planning and scheduling of modular assembly	[19], [21]–[22]
		DP4	Lack of detailed information in modular construction designs	[18], [24]
		DP5	Obstacles to design approval	[6]
Procurement Risk	PG	PG1	Delays in product delivery	[19]
		PG2	Failure to select appropriate suppliers and supplier limitations	[22], [25]–[26]
		PG3	Late payments from the project owner	[22]
		PG4	Lack of workers with specific qualifications	[10], [22]
		PG5	Contract disputes with suppliers	[25]
		PG6	Inaccurate estimates of modular demand volumes	[22]
		PG7	Errors in route planning and safety measures during delivery	[24]
Module Production Risk	PM	PM1	Limited factory production capacity meeting project demand	[22], [26]–[27]
		PM2	Errors in module placement at the factory storage location (warehouse)	[1]
		PM3	Failure to meet quality standards and module fabrication defects	[1], [18], [22], [26]
		PM4	Design information gaps between planners and modular fabrication teams	[27]
Logistics Risk	LG	LG1	Increased module shipping costs	[28]–[29]
		LG2	Limited availability and damage to transport vehicles	[1], [26], [28]
		LG3	Long distance between the project site and the module production factory	[1], [18]
		LG4	Restrictions on transport type and capacity affecting module size	[18], [22]–[26]
		LG5	Lack of data accuracy in shipment coordination	[22]
		LG6	Long component lead time	[22]
Transportation/Delivery Risk	TP	TP1	Module damage during delivery	[18]–[19]
		TP2	Accidents during module delivery	[28]
		TP3	Delayed module delivery to the project site	[18], [23]–[24], [28]
		TP4	Early arrival or incorrect delivery of modules at the site	[18]
		TP5	Limited delivery routes to the project site	[6]
On-Site and Module Installation Risk	IM	IM1	Technical installation failure and geometric misalignment between modules	[1], [18]–[19], [21], [23]
		IM2	Inappropriate crane selection and operational constraints	[1], [19]–[20], [22]–[24]
		IM3	Module damage due to poor storage management and weak on-site quality control (QC)	[6], [18], [25]
		IM4	Work-related accidents	[22]
		IM5	Delays in module assembly/installation execution	[26]
		IM6	Poor cooperation and communication among project stakeholders	[10], [22]
External Risk	EKS	EKS1	Regulatory barriers, bureaucracy, and changes in government policy	[19]–[20], [22], [24]
		EKS2	Market fluctuations affecting module production availability	[28]
		EKS3	Price increases (inflation) in labor, materials, and equipment	[22], [24]
		EKS4	Risk of natural disasters and extreme weather conditions	[18], [22]–[23], [25]–[26]

The description of each rating level is presented in Table II for the probability assessment scale [30] and Table III for the assessment scale of impact on cost, time, and quality [31].

TABLE II.
LIKERT SCALE FOR PROBABILITY ASSESSMENT

Value	Category	Assessment Criteria
1	Very rare (VR)	<10%
2	Rare (R)	11-40%
3	Moderate (M)	41-60%
4	Frequent (F)	61-90%
5	Very frequent (VF)	>90%

Project impacts were evaluated separately based on cost, time, and quality dimensions using the five-point Likert scale shown in Table III.

TABLE III.
LIKERT SCALE FOR IMPACT ASSESSMENT

Aspect \ Scale	1	2	3	4	5
	Very Small (VS)	**Small (S)**	**Medium (M)**	**Large (L)**	**Very Large (VL)**
Cost	Cost increase, but not very significant	Cost increase of <5%	Cost increase of 5–10%	Cost increase of 10–20%	Cost increase of >20%
Time	Schedule delays are not very significant	Schedule delays <5%	Overall project schedule delays of 5–10%	Overall project schedule delays of 10–20%	Overall project schedule delays >20%
Quality	The decline in quality is not particularly significant	The decline in quality is limited to non-critical work, but still meets the specifications	The decline in quality affects some technical specifications, so the project owner's approval is required	The decline in quality is unacceptable to the project owner	The final project outcome fails to meet the building's functional requirements

C. Population and Sample

The accessible population for this study consisted of practitioners with direct experience in modular construction projects across five state-owned enterprise (SOE) construction companies in Jakarta: PT Wijaya Karya Gedung

Tbk, PT Adhi Persada Gedung, PT Pembangunan Perumahan (Persero) Tbk, PT Waskita Beton Precast Tbk, and PT Brantas Abipraya (Persero). Purposive sampling was employed to select the study sample. Respondents were selected using purposive sampling through direct contact with the divisions responsible for modular construction projects in each company. Respondent eligibility was based on direct involvement in the execution of modular construction projects specifically within engineering, procurement, logistics, and risk management teams, as well as managerial roles encompassing specialized modular business units (e.g., MOBOX and Modular divisions), precast and post-tensioning production units, and construction/installation execution teams.

Eligibility criteria did not mandate a minimum duration of experience. This approach aligns with the relatively nascent state of modular construction practices in Indonesia, where the pool of practitioners with specialized experience in this field remains limited (Table VI). A total of 38 respondents were initially identified; eight were excluded during the data screening phase due to a lack of direct experience in modular construction projects, resulting in a final analysis sample of 30 eligible respondents. A response rate could not be calculated relative to the accessible population because recruitment relied on direct, purposive contact with personnel in relevant divisions across the five companies, rather than the distribution of questionnaires to a fixed, quantifiable list. Within each company, the number of personnel with direct experience in modular construction projects is relatively limited. Furthermore, not all personnel within divisions that have handled modular projects were directly involved in the execution of those projects. Consequently, the exact number of individuals meeting the criteria for potential respondents could not be accurately determined. Due to the unavailability of a complete sampling frame for the population, the study employed purposive sampling, selecting respondents with direct and relevant experience in modular construction projects.

The adequacy of the sample in this study was supported by the involvement of respondents from all five state-owned construction companies headquartered in Jakarta, including divisions related to modular project implementation in each company. The limited number of respondents is one of the challenges in modular construction risk research in developing countries, because the adoption of MiC is still in its early stages, resulting in a relatively limited number of practitioners with direct experience in modular projects. A similar condition was also found by [9], who distributed 45 questionnaires but only obtained 15 valid responses due to the limited number of available modular experts, who had a context of early implementation of modular construction in a developing country comparable to Indonesia.

Furthermore, construction risk research in Indonesia using the Severity Index was also conducted with a relatively limited number of respondents, namely 24 respondents [32]. This indicates that a limited number of respondents can still be found in construction risk analysis research [9], [32]. Referring to previous research by [9] indicates that the limited number of respondents is a condition that can occur in research with the MiC context which is still in the development stage. Therefore, this study uses a purposive sampling method to ensure that the respondents involved have relevant experience and involvement with modular projects, so that the data obtained remains aligned with the objectives of the risk analysis.

D. Data Collection and Analysis

Data were collected through questionnaires and semi-structured interviews. The questionnaires were distributed both offline and online via Google Forms and PDF files from 16 January to 2 March 2026. To validate the quantitative findings related to critical risks, semi-structured interviews were conducted online via Zoom from June 5–8, 2026, with a duration of approximately one hour for each expert. The interviews involved three experts from three different state-owned construction companies, each with direct experience in managing the modular construction supply chain, namely PT Waskita Beton Precast Tbk, PT Adhi Persada Gedung, and PT Pembangunan Perumahan (Persero) Tbk. These experts were selected using purposive sampling based on their experience in modular construction and direct involvement in project execution; the group comprised a QHSE Manager, a Project Engineering Manager, and a Site Manager.

The interview protocol focused on risks with the highest severity based on the Severity Index (SI) on the dimensions of cost, time, and quality impact. The main questions include: (1) “Based on the analysis, risk (X) has a high severity level; do you agree with this finding and why?” and (2) “What is the underlying root cause of the issue in the field?” A semi-structured approach was selected to keep the interviews focused on research objectives while remaining flexible enough to explore the experts' experiences in depth. This method creates an open discussion space, so that researchers can explore new information without limiting expert responses to standard questions.

With the consent of the respondents, the interviews were audio-recorded and transcribed for analysis. Transcripts were analyzed thematically to identify patterns and risk factors, which were then categorized based on their impact on cost, time, and quality. The interview results were subsequently integrated with quantitative findings to provide a contextual explanation of the factors underlying high risk severity levels, based on the SI observed in the field.

All respondents and interviewees provided informed consent to participate after receiving an explanation of the research objectives, the procedures for completing the questionnaire or interview, and their right to refuse or withdraw participation at any time without consequence. To maintain confidentiality, questionnaire respondents and interviews were anonymized throughout the entire research reporting process. The data were afterward analyzed through the following stages, as shown in Fig. 2.

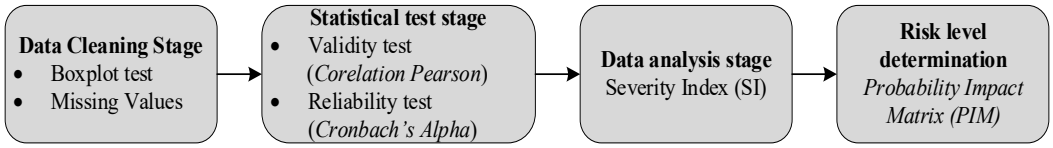


Fig. 2. Research Workflow

1) Data Cleaning Stage

The data cleaning stage is an important step in statistical analysis, as it aims to ensure data integrity before analysis. In research, collected data are often imperfect due to input errors, missing data, or extreme values (*outliers*) [33].

2) Statistical Test Stage

Statistical testing in this study consisted of validity and reliability tests. Validity indicates the extent to which an instrument measures what it is intended to measure, whereas reliability indicates the consistency of the instrument in measuring the same construct [34].

3) Severity Index (SI)

Based on the information gathered from the questionnaire, each risk's severity level is determined using the Severity Index (SI) approach. The Severity Index (SI) values are classified into five levels: very rare/very small, rare/small, moderate, frequent/large, and very frequent/very large. Based on [35], this classification employs a 20% threshold interval for each level, aligned with the 1–5 rating scale used in the questionnaire. Thus, the SI value range of 0–100% is divided evenly into five categories with equal interval widths. This approach is adopted to ensure consistency between the response scale provided by respondents and the interpretation of the resulting SI values.

TABLE IV.
SEVERITY INDEX PERCENTAGE PARAMETER VALUES

No.	SI percentage value	Category	
		Probability	Impact
1	0 % < SI ≤ 20 %	Very rare (VR)	Very small VS)
2	20 % < SI ≤ 40 %	Rare (R)	Small (S)
3	40 % < SI ≤ 60 %	Moderate (M)	Medium (M)
4	60 % < SI ≤ 80 %	Frequent (F)	Large (L)
5	80 % < SI ≤ 100 %	Very frequent (VF)	Very large (VL)

The survey results were calculated using the Severity Index formula for each variable, as follows:

$$SI = \frac{\sum_{i=1}^{5} ai.xi}{5\sum_{i=1}^{5} xi} x\ 100\% \quad (1)$$

In which:
ai = Assessment constant
xi = Respondent frequency
i = 1,2,3,4,5,…,n

4) Risk Level

Once the frequency (probability) and impact values are obtained, the Severity Index (SI) results for the four variables (probability, as well as cost, time, and quality impacts) must first be converted to a 1–5 scale to represent the levels of risk probability and impact [35], as shown in Table V.

TABLE V.
SCALE CONVERSION OF SEVERITY INDEX CATEGORIES FOR RISK ASSESSMENT DETERMINATION

No.	Category		Risk level conversion value
	Probability	Impact	
1	Very rare (VR)	Very small (VS)	1
2	Rare (R)	Small (S)	2
3	Moderate (M)	Medium (M)	3
4	Frequent (F)	Large (L)	4
5	Very frequent (VF)	Very large (VL)	5

This converted value is then used as an input in Equation (2) to generate the R-value (risk score) for the three impact dimensions: cost, time, and quality.

$$R = P\ x\ I \quad (2)$$

In which:
R = Risk Level
P = Probability of the risk occurring
I = Impact level of the risk

The R-value is subsequently plotted on the Probability-Impact Matrix (PIM) to determine the risk level based on the zone occupied within the matrix: low risk (green zone, R = 1–4), medium risk (yellow zone, R = 5–9), and high risk (red zone, R = 10–25) [36], as shown in Fig. 3. This classification is applied consistently across the three impact dimensions being assessed.

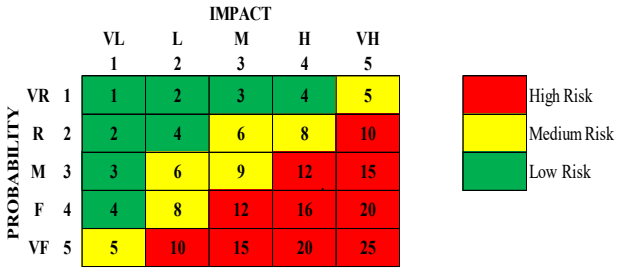


Fig. 3. Probability Impact Matrix (PIM)

III. RESULTS

A. Respondent Characteristics

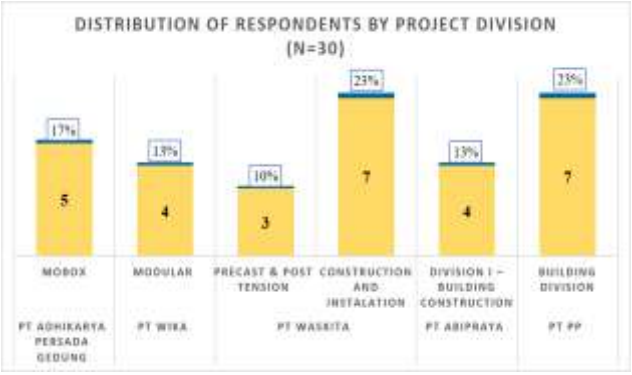


Fig. 4. Distribution of Respondents

A total of 30 practitioners from five state-owned enterprise (SOE) construction companies in Jakarta, all experienced in handling modular construction projects, participated in this study (Fig. 4). The majority of respondents

came from PT Waskita Beton Precast Tbk (33%). Table VI provides an overview of the respondents' demographics.

TABLE VI.
RESPONDENT CHARACTERISTICS (N=30)

Characteristics	Category	n	%
Years of Experience in Construction	<5 years	8	27%
	5–10 years	11	37%
	11–15 years	8	27%
	>15 years	3	10%
Number of Modular Projects Involved In	1–2 projects	17	57%
	3–4 projects	1	3%
	>5 projects	12	40%
Years of Experience Handling Modular Projects	<5 years	22	73%
	5–10 years	7	23%
	>15 years	1	3%

Table VI shows that the majority of respondents had 5–10 years of experience in construction (37%), had been involved in one to two modular projects (57%), and had less than five years of experience handling modular projects (73%). These results indicate that the implementation of modular construction in Indonesia is still relatively new, so practitioners' experience in this field remains dominated by less than five years of exposure.

B. Boxplot Test

Data cleaning is an important step in statistical analysis to ensure data integrity. In research, collected data are often imperfect due to input errors, missing data, or unusual extreme values (outliers) [33]. A boxplot outlier test was carried out at the initial stage of statistical testing to identify outliers in the raw data [33], using SPSS 27 statistical software. The research data were derived from the responses of 30 respondents from five state-owned enterprise (SOE) construction companies.

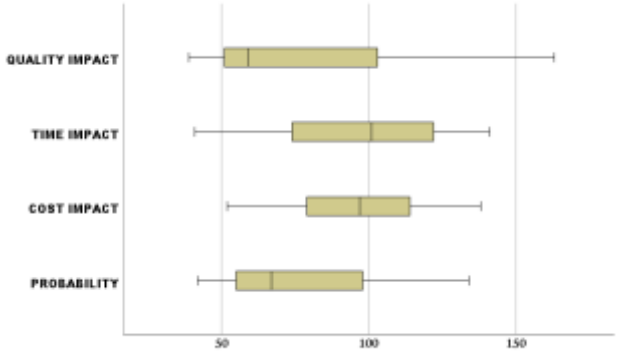


Fig. 5. Boxplot Diagram

The boxplot test results show no extreme outliers, as no symbols ★ indicating extreme outliers were found beyond the whisker range for any of the variables, so the data were considered consistent and suitable for further analysis. Although the distribution for the quality-impact variable is wider, this variation remains within a reasonable range and reflects differences in respondent perception.

C. Missing Value

Missing value handling is carried out in stages to ensure data completeness prior to further analysis, with the inspection and handling steps summarized in the following flowchart in Figure 6.

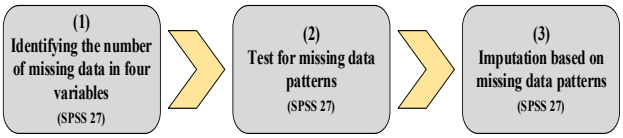


Fig. 6. Flowchart of Missing Data

1) Identifying the number of missing data in four variables

An assessment of missing data was conducted across the four variables (probability, cost impact, time, and quality) to determine the quantity and percentage of incomplete data within the dataset prior to further analysis. Missing data reduces the amount of data that can be analyzed and has the potential to impact analysis results if not addressed [33]. This allows the number of data points for each variable to be determined, as presented in Table VII.

TABLE VII.
IDENTIFICATION NUMBER OF MISSING DATA

Variable	Number of Missing Data	Missing Item
Probability	1	DP1
Cost Impact	3	DP1, IM1, IM3
Time Impact	3	DP1, DP2, DP4
Quality Impact	1	DP1

2) The Missing Data Test

Subsequently, the pattern of missing data is analyzed as part of the further data cleaning process. This stage aims to understand the characteristics of missing data that occur in the dataset, so that the most appropriate handling strategy can be determined.

TABLE VIII.
MISSING VALUE TEST RESULTS

Variable	A Little's MCAR test ($\rho > 0.05$)	Status
Probability	0.994	MCAR
Cost Impact	1.000	MCAR
Time Impact	1.000	MCAR
Quality Impact	0.917	MCAR

Based on Table VIII, the test results show a relatively small proportion of missing values. Based on the results of Little's MCAR Test ($\rho = 0.917–1.000$; $\rho > 0.05$), the missing data are categorized as Missing Completely at Random (MCAR) [37].

3) Median Imputation

There were eight missing data points across the four variables: probability, cost impact, time impact, and quality impact. Little's MCAR test indicated that the missing data were Missing Completely at Random (MCAR) ($p = 0.917–1.000$; $p > 0.05$). Given the ordinal Likert scale of the data, missing values were replaced with the median of valid responses for the corresponding item and variable using SPSS 27. This method was chosen because it is a comparatively more stable alternative that is robust to outliers (extreme values) [38] and was considered suitable for further analysis. Consequently, all respondents (N = 30) were included in the Severity Index (SI) calculation, ensuring that the imputed values were factored in as responses within the categorical distribution when computing the SI.

D. Validity and Reliability Test

The research instrument consists of 37 risk items grouped into seven risk categories, which serve as a clas-

sification framework. Each item was assessed on four variables: probability of occurrence, cost impact, time impact, and quality impact. Because the items represent various types of risk, validity and reliability tests were conducted separately for each variable, each including all risk items, to assess the consistency of respondents' answers rather than to assume that all items form a single, homogeneous construct.

Validity testing utilized Pearson item-total correlation with 30 respondents at a 5% significance level (r-table = 0.361). The test results showed that DP1 (changes in project design or scope) had an r-count of 0.120 and a significance value of 0.526 (>0.05), so it was excluded from the analysis. Contextually, the low correlation of DP1 suggests that this risk is subject to varied interpretations depending on the specific conditions of the project and the company.

The removal of DP1 (design or project scope changes) does not eliminate the overall representation of the design and planning category. The four remaining items continue to represent this category: (1) Failure to establish design standards and specifications in the early project stage (DP2); (2) Suboptimal planning and scheduling of modular assembly (DP3); (3) Lack of detailed information in modular construction designs (DP4); and (4) Obstacles to design approval (DP5). The design change aspect remains conceptually covered in DP2 and DP4, as both items address the issue of uncertainty in standards or specifications and limitations in design information detail, which are also related to the design change aspect [39]–[40].

Thus, 36 items were retained for subsequent analysis. Following the removal of DP1, validity and reliability tests were conducted separately for the four dimensions. Based on Table IX, Cronbach's Alpha values for the four dimensions ranged from 0.955 to 0.982, indicating consistent responses across each dimension.

TABLE IX.
RELIABILITY TEST RESULTS

Aspect	Reliability Statistics		
	Cronbach's Alpha	N of Items	Status
Probability	0.975	36	Reliable
Cost Impact	0.955	36	Reliable
Time Impact	0.965	36	Reliable
Quality Impact	0.982	36	Reliable

To assess potential redundancy, an inter-item correlation analysis was conducted, using an r-value > 0.90 as the threshold to flag potentially redundant item pairs. No pairs exceeding this threshold were found for cost impact or time impact; however, one pair was identified for probability (PM3–TP1, r = 0.906), and six pairs for quality impact (EKS1–EKS2, TP4–EKS1, TP4–EKS2, LG1–EKS1, LG1–LG3, and TP4–IM4; r = 0.901–0.943). These items were retained because they represent distinct, albeit interrelated, risks. High correlations may reflect risk interdependencies within the supply chain, leading respondents to rate them similarly. Each risk was analyzed individually using the Severity Index rather than a composite score. Nevertheless, the potential for redundancy could not be eliminated and is acknowledged as a study limitation.

E. Severity Index Analysis

A Severity Index (SI) analysis was carried out to ascertain the severity of each risk based on the gathered questionnaire responses after the data's validity and reliability had been verified. This allowed the risk-factor category values for each variable to be determined. Equation 1 was used to generate this SI analysis for the four variables: Probability (P), Cost Impact (CI), Time Impact (TI), and Quality Impact (QI), as shown in Table X.

TABLE X.
SEVERITY INDEX RESULTS

Risk Code	Severity Index (SI) $SI = \frac{\sum_{i=1}^{5} ai.xi}{5\sum_{i=1}^{5} xi} x\ 100\%$				Scale Conversion				Risk Level $R = P\ x\ I$					
	P	CI	TI	QI	P	CI	TI	QI	Cost Impact	Risk Level	Time Impact	Risk Level	Quality Impact	Risk Level
DP2	38%	55%	54%	47%	2	3	3	3	6	Medium	6	Medium	6	Medium
DP3	42%	55%	61%	45%	3	3	4	3	9	Medium	12	High	9	Medium
DP4	43%	53%	50%	45%	3	3	3	3	9	Medium	9	Medium	9	Medium
DP5	41%	43%	53%	40%	3	3	3	2	9	Medium	9	Medium	6	Medium
PG1	46%	53%	59%	39%	3	3	3	2	9	Medium	9	Medium	6	Medium
PG2	43%	55%	54%	37%	3	3	3	2	9	Medium	9	Medium	6	Medium
PG3	58%	55%	61%	41%	3	3	4	3	9	Medium	12	High	9	Medium
PG4	43%	49%	53%	47%	3	3	3	3	9	Medium	9	Medium	9	Medium
PG5	36%	47%	55%	39%	2	3	3	2	6	Medium	6	Medium	4	Low
PG6	41%	55%	49%	39%	3	3	3	2	9	Medium	9	Medium	6	Medium
PG7	35%	46%	50%	37%	2	3	3	2	6	Medium	6	Medium	4	Low
PM1	46%	56%	57%	39%	3	3	3	2	9	Medium	9	Medium	6	Medium
PM2	35%	42%	49%	43%	2	3	3	3	6	Medium	6	Medium	6	Medium
PM3	39%	54%	53%	59%	2	3	3	3	6	Medium	6	Medium	6	Medium
PM4	37%	48%	51%	48%	2	3	3	3	6	Medium	6	Medium	6	Medium
LG1	47%	58%	54%	37%	3	3	3	2	9	Medium	9	Medium	6	Medium
LG2	39%	47%	57%	42%	2	3	3	3	6	Medium	6	Medium	6	Medium
LG3	57%	61%	59%	40%	3	4	3	2	12	High	9	Medium	6	Medium
LG4	43%	57%	51%	35%	3	3	3	2	9	Medium	9	Medium	6	Medium
LG5	41%	47%	49%	51%	3	3	3	3	9	Medium	9	Medium	9	Medium
LG6	48%	51%	56%	36%	3	3	3	2	9	Medium	9	Medium	6	Medium
TP1	44%	54%	53%	57%	3	3	3	3	9	Medium	9	Medium	9	Medium
TP2	34%	54%	53%	52%	2	3	3	3	6	Medium	6	Medium	6	Medium

Risk Code	Severity Index (SI) $SI = \frac{\sum_{i=1}^{5} ai.xi}{5\sum_{i=1}^{5} xi} x\ 100\%$				Scale Conversion				Risk Level $R = P\ x\ I$					
	P	CI	TI	QI	P	CI	TI	QI	Cost Impact	Risk Level	Time Impact	Risk Level	Quality Impact	Risk Level
TP3	44%	51%	58%	39%	3	3	3	2	9	Medium	9	Medium	6	Medium
TP4	34%	38%	37%	35%	2	2	2	2	4	Low	4	Low	4	Low
TP5	41%	54%	47%	31%	3	3	3	2	9	Medium	9	Medium	6	Medium
IM1	44%	55%	56%	54%	3	3	3	3	9	Medium	9	Medium	9	Medium
IM2	38%	47%	50%	41%	2	3	3	3	6	Medium	6	Medium	6	Medium
IM3	40%	57%	55%	55%	2	3	3	3	6	Medium	6	Medium	6	Medium
IM4	31%	47%	44%	31%	2	3	3	2	6	Medium	6	Medium	4	Low
IM5	41%	50%	57%	71%	3	3	3	4	9	Medium	9	Medium	12	High
IM6	40%	42%	43%	39%	2	3	3	2	6	Medium	6	Medium	4	Low
EKS1	36%	46%	46%	35%	2	3	3	2	6	Medium	6	Medium	4	Low
EKS2	41%	55%	50%	36%	3	3	3	2	9	Medium	9	Medium	6	Medium
EKS3	51%	56%	47%	39%	3	3	3	2	9	Medium	9	Medium	6	Medium
EKS4	39%	52%	57%	44%	2	3	3	3	6	Medium	6	Medium	6	Medium

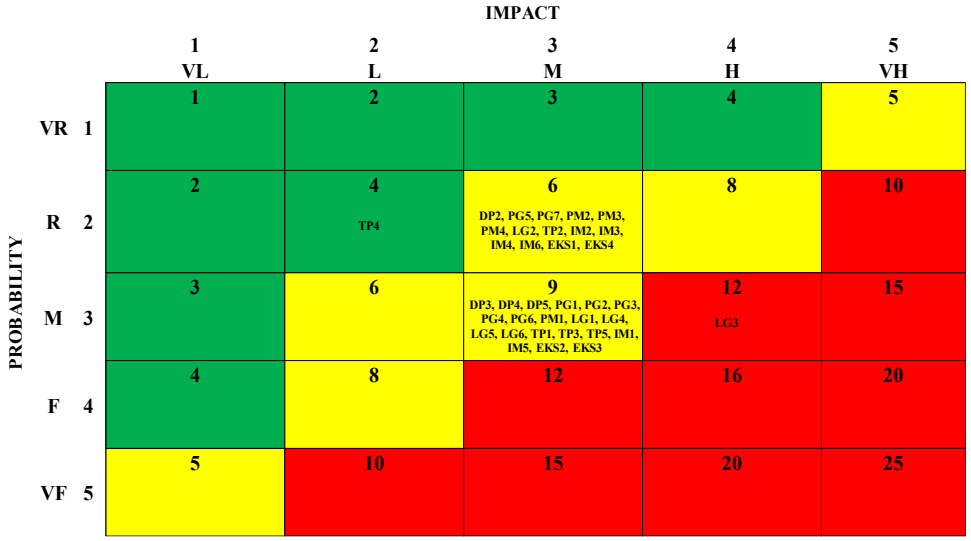


Fig. 7. Probability Impact Matrix (PIM) Cost Impact

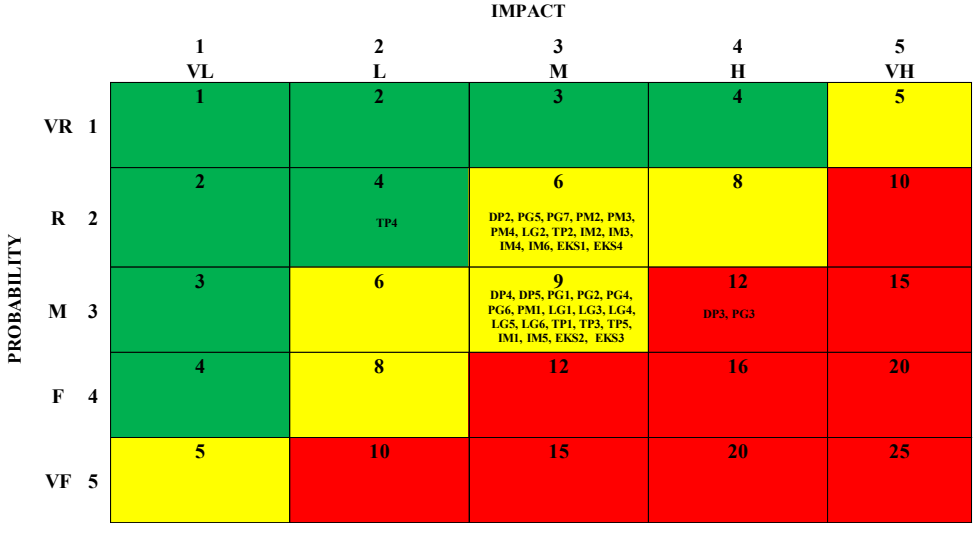


Fig. 8. Probability Impact Matrix (PIM) Time Impact

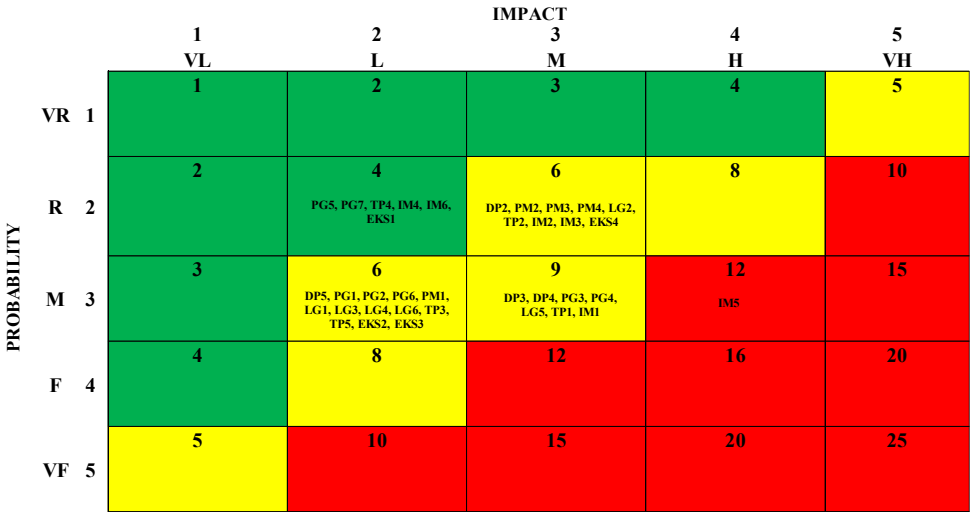


Fig. 9. Probability Impact Matrix (PIM) Quality Impact

The SI calculation results for the 36 supply chain risks show that the majority of risks fall into the medium risk level across all three impact aspects (cost, time, and quality), with scores R = P x I ranging from 6 to 9. This distribution is supported by the Probability Impact Matrix (PIM) diagrams, in which most risks consistently fall within the yellow zone across all three aspects. This suggests that the majority of supply chain risks associated with the modular construction projects handled by the five state-owned enterprise (SOE) contractors in Jakarta, in this study, are at a moderate level and can therefore be mitigated through commonly applied control mechanisms, without requiring special handling.

Only four risks were identified as High (R=12), while six other risks fall into the Low category (R=4). The four High-level risks show differing impact characteristics. LG3, with the highest cost-impact SI of 61%, is the only risk located in the red zone of the cost-impact PIM matrix (probability 3, impact 4). This condition indicates a risk that has the potential to cause significant cost overruns at the logistics stage.

Risks DP3 and PG3 are the two highest risks affecting implementation time and are located at different supply chain stages, both falling within the red zone of the time-impact PIM matrix, pointing to project schedule delay risk. Meanwhile, IM5 is the only risk indicated to affect project quality, with an SI of 71%, far exceeding the average quality-impact SI of other risks, which generally ranges between 31-59%. This is reinforced by the fact that IM5 is the only risk in the red zone of the quality-impact PIM matrix.

These findings indicate that a delay in module installation (IM5) is perceived by respondents as the highest-priority risk regarding quality impact. Meanwhile, the four risks classified as "High" overall demonstrate that critical risks within the modular integrated construction (MiC) supply chain are distributed across various impact areas throughout the supply chain stages. Furthermore, all three matrices consistently show that the majority of risks fall within the yellow zone. This indicates that MiC supply chain risks are generally assessed as moderate but still require attention, as risks in this zone have the potential to escalate into more serious issues if not properly managed.

On the other hand, TP4 is recorded as having the lowest risk level across all three aspects (R-value = 4 for cost, time, and quality). These results indicate that the TP4 risk has a relatively lower chance of occurring and impact compared to other TP risks.

IV. Discussions

The findings of this study directly address the three gaps identified in the introduction. First, the risk-level assessment across the three aspects (cost, time, quality) shows that critical risks are in fact distributed across different aspects (LG3 for cost, DP3 and PG3 for time, IM5 for quality). Previous studies had not specifically differentiated supply chain risk based on its impact on cost, time, and quality [1], [19], [26], [41]. Because of this, the differences in the impact of these risks have not yet been specifically identified (addressing gap 1). Second, the critical risk pattern identified based on the experience of the five state-owned enterprise (SOE) contractors handling modular construction projects in Indonesia differs from the pattern commonly reported in studies from developed countries (addressing gaps 2 and 3). A comprehensive study [18] on modular construction risk at the global level found that design and planning risk is the most critical category, whereas in this study, critical risks are spread across factors related to design and planning (DP3), procurement (PG3), logistics (LG3), and on-site installation (IM5). This difference is consistent with [7] and [9], which state that modular construction challenges in developing countries are more strongly influenced by limitations in the manufacturing ecosystem and supporting infrastructure. Conversely, in developed countries with a more established modular ecosystem, challenges tend to relate to the maturity of the design process.

A. Modular Construction Supply Chain Risk Related to Cost Impact

Most risks affecting the cost impact of the modular construction supply chain fall into the medium category, with one risk in the high category, LG3 (the long distance between the project site and the module production factory), and one risk in the low category is TP4 (modules arriving too early or delivery errors at the site). LG3 has the highest

cost-impact SI value among all 36 risk items, at 61%, with a probability score of 3 and an impact score of 4 (R=12), making it the only risk located in the red zone of the cost-impact Probability Impact Matrix (PIM). Although LG3 is in the High category, while LG1 (module shipping cost overrun, SI = 58%, R = 9) is in the Medium category, the difference in SI values between the two is relatively small, namely only 3 percentage points (61% and 58%). This indicates that the severity levels of the two risks are relatively close, despite their placement in different PIM categories. This variance in severity implies that, rather than the delivery process itself, the distance between the manufacturer and the project site is the most significant differentiator for the amount of the cost impact.

The high-risk priority of LG3 indicates that the module delivery distance can increase transportation and logistics costs, as well as the potential for distribution delays. Interview results with experts indicate that the limited number of modular factories in Indonesia forces projects to depend on specific production locations, so that inter-island shipping or the use of more than one mode of transportation increases distribution costs and creates the potential for additional costs due to delays or rescheduling of work. This is supported by [28], which identifies limited factory locations and the selection of optimal transportation routes as one of the main barriers to modular construction implementation in developing countries, given that the uneven distribution of modular manufacturing facilities forces projects to bear unavoidable long-distance distribution costs. This finding is consistent with [9], which states that transportation and logistics are among the primary risks in the modular construction supply chain, since long delivery distances increase transportation costs, delay risk, and the risk of component damage during distribution.

In contrast, TP4 is the risk with the lowest severity for cost impact (SI=38%, probability 2, impact 2, R=4), and is the only risk that falls into the Low category across all three aspects (cost, time, and quality). This is similar to [18], which states that the risk of modules arriving too early generally has no significant impact as long as adequate buffer/hedging space is available at the project site to temporarily store modules before the installation schedule arrives. Based on the interview results, experts noted that the availability of enclosed or open buffer space on-site generally depends on project duration. For short-duration projects, open buffer space is typically used to facilitate module mobilization. Conversely, for longer-duration projects, construction companies provide sufficiently adequate buffer space for module storage, allowing protection from external factors.

This situation differs from that of LG3, which cannot be resolved merely through adjustments at the project site but requires changes to the factory location strategy or the choice of transportation mode [28]. A comparison between LG3 and TP4 reveals that cost risks in the modular integrated construction (MiC) supply chain in Indonesia are not solely linked to technical constraints on-site; they are also influenced by regulatory limitations and the still-developing distribution of the modular manufacturing industry [7]. These findings indicate that some cost risks are structural in nature and require supply-chain-level interventions, whereas others can still be managed through technical controls on-site. Similar patterns were observed regarding time and quality aspects, as discussed in the following section.

B. Modular Construction Supply Chain Risk Related to Time Impact

On the other hand, there are two risks in the high category for time impact: DP3 (suboptimal planning and scheduling of modular assembly; SI=61%, R=12) and PG3 (delayed payment from the project owner; SI=61%, R=12). Therefore, it can be seen that DP3 and PG3 have the potential to have a greater impact on project time than most other risks, as indicated by their high level of severity. However, PG1 (SI=59%) has a value close to that of PG3 (SI=61%), with a relatively small difference in severity, even though they fall into different PIM categories. This occurs because risk categorization is based on the established SI interval thresholds presented in Table IV.

The DP3 risk indicates that inadequate planning can disrupt the coordination between production, delivery, and assembly components; consequently, a single delay has the potential to constrain the entire project schedule. This situation reflects the highly interconnected nature of the prefabricated construction supply chain, aligning with findings [21], that a disruption at one stage can impact subsequent stages and extend the overall delay. Discussions with experts reveal that the creation of a Work Method Statement (WMS) relies heavily on the integration of modular construction production processes, the master work plan, the project's critical path, and all project phases.

Meanwhile, PG3 risks can disrupt project cash flow. This could disrupt material procurement, the production process, and module delivery, and delay implementation. This is supported by [42], which emphasizes the importance of planning and coordination in modular construction, and by [43], which states that smooth cash flow is a key factor in maintaining project continuity. It can be concluded that DP3 and PG3 exhibit different risk characteristics one related to technical and planning aspects, the other to financial aspects yet both carry a high level of time risk. These findings indicate that delays in MiC projects can originate from different stages of the supply chain, so control priorities need to consider the characteristics of each risk.

C. Modular Construction Supply Chain Risk Related to Quality Impact

Risk IM5 (delay in module assembly/installation; SI=71%, R=12) is the only risk in the high category related to quality impact, compared to other module installation risks, namely IM1 (SI=54%, R=9), IM2 (SI=41%, R=6), and IM3 (SI=55%, R=6) which are in the medium category. Meanwhile, IM4 (SI=31%, R=4) and IM6 (SI=39%, R=4) fall into the low category.

This finding indicates that the installation stage is the most critical process in modular construction, as it strongly determines the quality of the final outcome. This is also supported by [16], regarding risk during the on-site assem-

bly stage in MiC projects, which found that module installation mismatches and errors carry a high risk level among the installation risks studied, consistent with the findings of this study.

Experts suggest that limited assembly time can increase pressure on field teams to accelerate the installation process. This can lead to geometric mismatches between modules and lapses in quality control (QC), ultimately resulting in rework and compromised final quality. This statement is supported by [18], which notes that a mismatch between the production schedule and field conditions is one of the risk factors with a serious impact at the installation stage, as it forces field teams to make alternative procedural decisions in order to meet time targets.

Interview results with experts indicate that installation errors can lead to rework and reduced quality, while limited workforce competence increases the potential for errors during the assembly process. This finding is consistent with [44], which states that the assembly stage is the phase most prone to defects, requiring quality control and improved workforce competence.

V. Conclusions

This study identifies and prioritizes risks in the modular construction supply chain based on the perceptions of 30 practitioners from five state-owned enterprise (SOE) contractors in Jakarta. A Severity Index analysis of 36 valid risk items reveals four risks falling into the high-severity category, distributed across different stages of the supply chain. Regarding cost, the risk associated with the long distance between the modular factory and the project site (LG3, logistics stage; SI = 61%) is the only high-severity risk. In terms of time, suboptimal assembly planning and scheduling (DP3, design and planning stage; SI = 61%) and delayed payments by the project owner (PG3, procurement and payment stage; SI = 61%) fall into the high-severity category. Meanwhile, regarding quality, delays in module installation (IM5, installation stage; SI = 71%) constitute the only high-severity risk. On the other hand, the risk of early arrival or incorrect delivery of modules at the site (TP4, transportation and delivery stage) is the only risk that is categorized as low in all three aspects (cost, time and quality impact). These findings indicate that critical risks in the MiC supply chain are multidimensional and distributed across various stages—ranging from logistics, design and planning, and procurement and payment to installation—rather than being concentrated in any single stage of the supply chain.

The results of exploratory interviews with three experts representing three of the five companies provide field context that helps explain the findings. Regarding the risk associated with the distance between the modular factory and the project site (LG3) the experts pointed to the limited number of modular factories in Indonesia, which makes projects dependent on specific production locations and may require inter-island or multi-mode transport; this may increase distribution costs and add expenses from delays or rescheduling. Regarding the risk of less-than-optimal assembly planning and scheduling (DP3), the experts emphasized the importance of integrating work method statements with the production process, master schedule, critical path, and project stages. Regarding PG3, the experts noted that delayed owner payments may hinder material procurement, production, and delivery, thereby stalling work execution. Regarding for the risk of assembly delays impacting quality (IM5), the experts explained that time constraints may force accelerated installation, increasing the likelihood of inter-module mismatches, QC oversights, and rework. Limited workforce competence can also heighten the risk of assembly errors. Conversely, regarding risk TP4, interviewees explained that long-duration projects generally offer adequate buffer space for module storage, which is consistent with its low severity.

These results' strategic ramifications highlight how crucial stakeholder cooperation is to Indonesia's adoption of modular construction. In addition, contractors need to strengthen project planning, contract management, and supply chain coordination, while modular providers need to improve production capacity, technical support, quality control, and workforce competence to support the implementation of modular construction in Indonesia.

This study has several limitations. First, respondents were drawn from only five state-owned enterprises (SOEs) in Jakarta; thus, the results may not necessarily be representative of private companies or projects outside Jakarta. Second, the magnitude of financial losses and schedule delays resulting from risks was not quantitatively measured. Third, the limited number of modular construction projects in Indonesia makes it difficult to find experienced respondents. Consequently, this study relies on the perceptions of practitioners experienced in modular construction projects as the primary data source. Given the limited number of such practitioners and the need for in-depth information, respondents were selected using purposive sampling. Although this approach is suitable for research involving practitioners with specialized experience, the limited number and specific characteristics of the respondents may affect the stability of risk priority rankings and constrain the generalizability of the research findings. Fourth, the SI and PIM only rank risk priorities based on practitioner perceptions; they do not establish causal relationships, statistically compare risk categories or supply chain stages, or measure actual field failures. The findings should therefore be used to prioritize risk management. Further research is recommended to use larger samples covering various regions, measure the magnitude of losses quantitatively, simplify the questionnaire by combining or removing highly correlated indicators and then retest the instrument, and apply analyses that test causal relationships with real project performance data.

Acknowledgment

The author would like to express his deepest gratitude to the respondents and informants from five state-owned enterprises (SOEs) in Jakarta who participated in the survey and shared their professional experiences regarding supply chain risk management in modular construction projects.

DATA AVAILABILITY

Data are included in the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

REFERENCES

[1] I. Y. Wuni and G. Q. P. Shen, "Risks identification and allocation in the supply chain of modular integrated construction (MiC)," *Modul. Offsite Constr. Summit Proc.*, pp. 189–197, 2019, doi: 10.29173/mocs93.

[2] N. Bertram, S. Fuchs, J. Mischke, R. Palter G. Strube, and J. Woetzel, *Modular Construction: From Projects to Products.* McKinsey & Company, 2019.

[3] M. Zohourian, A. Pamidimukkala, S. Kermanshachi, and D. Almaskati, "Modular construction: A comprehensive review," *Buildings*, vol. 15, no. 12, pp. 1–21, 2025, doi: 10.3390/buildings15122020.

[4] Y. Zhang, G. Q. Shen, and J. Xue, "A bibliometric analysis of supply chain management within modular integrated construction in complex project management," *Buildings*, vol. 14, no. 6, 2024, doi: 10.3390/buildings14061667.

[5] Badan Pusat Statistik, "Backlog Perumahan dan Capaian Penyediaan Perumahan di Indonesia , 2025 – Semester I 2026," 2026. [Online]. Available: https://www.bps.go.id/id/pressrelease/2026/08/31/2651/backlog-perumahan-mengalami-penurunan-dengan-backlog-1-tercatat-sebesar-12-39-persen-dan-backlog-2-sebesar-24-03-persen-pada-tahun-2026.html

[6] O. Turbaningsih, U. Mutaharah, and P. Saputra, "The study of potential application of modular construction in the development of Indonesia's new capital city," *J. Tek. Sipil*, vol. 29, no. 3, pp. 207-216, 2022, doi: 10.5614/jts.2022.29.3.1.

[7] O. Akinradewo, C. Aigbavboa, D. Aghimien, and A. Oke, "Modular method of construction in developing countries: the underlying challenges," *Int. J. Constr. Manag.*, vol. 23, no. 8, pp. 1344–1354, 2021, doi: 10.1080/15623599.2021.1970300.

[8] M. J. Ding and F. Jie, "Mitigating the supply chain uncertainties and risks in the construction projects: Case studies of Australian construction projects," *Clean. Logist. Supply Chain*, vol. 16, e100237, 2025, doi: 10.1016/j.clscn.2025.100237.

[9] H. Pervez, Y. Ali, D. Pamucar, M. Garai-Fodor, and Á. Csiszárik-Kocsir, "Evaluation of critical risk factors in the implementation of modular construction," *PLoS One*, vol. 17, no. 8, e0272448, 2022, doi: 10.1371/journal.pone.0272448.

[10] I. Y. Wuni, G. Q. Shen, and R. Osei-kyei, "Modelling the critical risk factors for modular integrated construction projects," *Int. J. Constr. Manag.*, vol. 22, no. 11, pp. 2013–2026, 2022, doi: 10.1080/15623599.2020.1763049.

[11] H. Arshad and T. Zayed, "Critical influencing factors of supply chain management for modular integrated construction," *Autom. Constr.*, vol. 144, e104612, 2022, doi: 10.1016/j.autcon.2022.104612.

[12] I. Y. Wuni and G. Q. Shen, "Exploring the critical production risk factors for modular integrated construction projects," *J. Facil. Manag.*, vol. 21, no. 1, pp. 50–68, 2023, doi: 10.1108/JFM-03-2021-0029.

[13] M. Hussein, A. E. E. Eltoukhy, A. Karam, and I. A. Shaban, "Modelling in off-site construction supply chain management: A review and future directions for sustainable modular integrated construction," *J. Clean. Prod.*, vol. 310, e127503, 2021, doi: 10.1016/j.jclepro.2021.127503.

[14] D. A. Alqahtani, M. Ahmed, J. Mallick, and M. D. S. Al Shahrani, "Integrated risk priority assessment of engineering and non-engineering factors influencing Saudi Arabian construction projects," *Buildings*, vol. 16, e1518, 2026, doi: 10.3390/buildings16081518.

[15] S. Husin, F. Fachrurrazi, M. Rizalihadi, and M. Mubarak, "Implementing Fuzzy TOPSIS on project risk variable ranking," *Adv. Civ. Eng.*, vol. 2019, e9283409, 2019, doi: 10.1155/2019/9283409.

[16] I. Y. Wuni, G. Q. Shen, and A. B. Saka, "Computing the severities of critical onsite assembly risk factors for modular integrated construction projects," *Eng. Constr. Archit. Manag.*, vol. 30, no. 5, pp. 1864–1882, 2023, doi: 10.1108/ECAM-07-2021-0630.

[17] N. Nizarli, A. Abdullah, Y. Away, and I. Mahdar, "Multi-stakeholder priorities for modular construction adoption under uncertainty: An analytic hierarchy process and Monte Carlo analysis in Aceh , Indonesia," *Sustainability*, vol. 17, no. 23, e10487, 2025, doi: 10.3390/su172310487.

[18] A. A. Khan, R. Yu, T. Liu, N. Gu, and J. Walsh, "Volumetric modular construction risks: A comprehensive review and digital-technology-coupled circular mitigation strategies," *Sustain.*, vol. 15, no. 8, e7019, 2023, doi: 10.3390/su15087019.

[19] Q. Cai, Y. Du, and R. Wang, "Analysis on supply chain risk factors of prefabricated buildings using AHP-DEMATEL-ISM model," *Teh. Vjesn.*, vol. 30, no. 5, pp. 1379–1386, 2023, doi: 10.17559/TV-20230508000614.

[20] H. X. Li, M. Al-Hussein, Z. Lei, and Z. Ajweh, "Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation," *Can. J. Civ. Eng.*, vol. 40, no. 12, pp. 1184–1195, 2013, doi: 10.1139/cjce-2013-0013.

[21] L. Wang, Y. Cheng, and Y. Zhang, "Exploring the risk propagation mechanisms of supply chain for prefabricated building projects," *J. Build. Eng.*, vol. 74, e106771, 2023, doi: 10.1016/j.jobe.2023.106771.

[22] H. T. Pham, T. Pham, H. Truong Quang, and C. N. Dang, "Supply chain risk management research in construction: A systematic review," *Int. J. Constr. Manag.*, vol. 23, no. 11, pp. 1945–1955, 2023, doi: 10.1080/15623599.2022.2029677.

[23] I. Y. Wuni, G. Q. P. Shen, and A. T. Mahmud, "Critical risk factors in the application of modular integrated construction: a systematic review," *Int. J. Constr. Manag.*, vol. 22, no. 2, pp. 133–147, 2022, doi: 10.1080/15623599.2019.1613212.

[24] M. Xia, L. Zhao, and L. Zhao, "A comprehensive risk-assessment method for prefabricated buildings using EPC: A case study from China," *Sustain.*, vol. 14, no. 3, e1910, 2022, doi: 10.3390/su14031910.

[25] S. Chai, M. Liu, Z. Zhang, and S. Li, "Study on risk identification and key risks of prefabricated building supply chain based on grounded theory," *E3S Web Conf.*, vol. 275, e3076, 2021, doi: 10.1051/e3sconf/202127503076.

[26] L. Luo, Y. Li, X. Wang, X. Jin, and Z. Qin, "Supply chain vulnerability in prefabricated building projects and digital mitigation technologies," *IEEE Trans. Eng. Manag.*, vol. 71, pp. 10686–10698, 2024, doi: 10.1109/TEM.2023.3272585.

[27] I. Y. Wuni, G. Q. Shen, and B. G. Hwang, "Risks of modular integrated construction: A review and future research directions," *Front. Eng. Manag.*, vol. 7, no. 1, pp. 63–80, 2020, doi: 10.1007/s42524-019-0059-7.

[28] A. O. Bello, A. A. Khan, A. Idris, and H. M. Awwal, "Barriers to modular construction systems implementation in developing countries' architecture, engineering and construction industry," *Eng. Constr. Archit. Manag.*, vol. 31, no. 8, pp. 3148–3164, 2024, doi: 10.1108/ECAM-10-2022-1001.

[29] Y. Mei, "Research on supply chain risk of prefabricated building based on AHP Model," in *ICMSEM*, 2024, pp. 1038–1046. doi: 10.2991/978-94-6463-256-9_102.

[30] A. Sharafat, K. Latif, and J. Seo, "Risk analysis of TBM tunneling projects based on generic bow-tie risk analysis approach in difficult ground conditions," *Tunn. Undergr. Sp. Technol. Inc. Trenchless Technol. Res.*, vol. 111, e103860, 2021, doi: 10.1016/j.tust.2021.103860.

[31] Y. O. L. Tobing, D. P. Sari, and P. A. Wicaksono, "Analisis risiko proyek konstruksi dengan importance index dan bowtie analysis," *Ind. Eng. Online J.*, vol. 7, no. 4, 2012. [Online]. Available: https://ejournal3.undip.ac.id/index.php/ieoj/article/view/23004/21044%0A

[32] A. R. Zaidan, K. Soeryodarundio, and S. Setiono, "Analisis manajemen risiko proyek dengan metode Severity Index (SI) pada proyek pembangunan gedung X Kota Surakarta," *Globe Publ. Ilmu Tek. Teknol. Kebumian, Ilmu Perkapalan*, vol. 2, no. 3, pp. 211–221, 2024, doi: 10.61132/globe.v2i3.501.

[33] Elfrianto, *Panduan Lengkap Analisis Statistik dalam Penelitian*, First Edit. Medan: UMSU Press, 2025. [Online]. Available: http://umsupress.umsu.ac.id/

[34] S. Widodo, L. Festy, and A. La Ode, *Buku Ajar Metodologi Penelitian*, 1st ed. Pangkalpinang: CV Science Techno Direct, 2023.

[35] L. Reginancy, M. Purba, G. Budianto, and N. Raya, "Analysis of material supply chain risk weight using severity index method," *J. Inov. Teknol. dan Rekayasa*, vol. 9, no. 2, pp. 551–557, 2024, doi: 10.31572/inotera.Vol9.Iss2.2024.ID423.

[36] H. A.Rani, *Manajemen Risiko Proyek*, 1 st edit. Yogyakarta,

Indonesia: Deepublish, 2025.
[37] C. Li, "Little's test of missing completely at random," *Stata J.*, vol. 13, no. 4, pp. 795–809, 2013, doi: 10.1177/1536867X1301300407.
[38] F. M. Kikhia, "A study on evaluation of mean and median imputation methods and their impact on statistical analysis of missing data," *Sirte Univ. Sci. J.*, vol. 14, no. 2, pp. 57–64, 2024, doi: 10.37375/susj.v14i2.3090.
[39] I. Y. Wuni, G. Q. Shen, and M. F. Antwi-afari, "Exploring the design risk factors for modular integrated construction projects," *Constr. Innov.*, vol. 23, no. 1, pp. 213–228, 2023, doi: 10.1108/CI-02-2021-0025.
[40] E. M. A. C. Sandeepani, T.A.S., Ekanayake and I. Ashayeri, "Modelling design stage risks in modular integrated construction in Sri Lanka," 2023, no. 21-22 July, pp. 821–832. doi: 10.31705/WCS.2023.66.
[41] L. Keda and Z. Weiwei, "Study on risk assessment of prefabricated construction supply chain based on AHP," in *E3S Web of Conferences*, 2021, vol. 275, e3083. doi: 10.1051/e3sconf/202127503083.
[42] A. O. Bello, K. S. Ihedigbo, T. Bello, and H. M. Awwal, "Implementation strategies for modular construction systems in developing countries: Perspectives of Nigerian AEC professionals," *J. Sustain. Environ.*, vol. 2, no. 2, pp. 106–114, 2023, doi: 10.3126/josem.v2i2.55203.
[43] M. Assaf, M. Hussein, B. T. Alsulami, and T. Zayed, "A mixed review of cash flow modeling: Potential of blockchain for modular construction," *Buildings*, vol. 12, no. 12, p. 2054, 2022, doi: 10.3390/buildings12122054.
[44] A. Gurmu, F. F. Tafti, A. Mills, and J. Kite, "Defects in modular building construction: A systematic lifecycle review and implications for sustainable delivery," *Sustainability*, vol. 18, no. 8, e4000, 2026, doi: 10.3390/su18084000.



Dana Ayu Maharani, S.Tr.T received a Bachelor of Applied Engineering degree in Civil Engineering from State Polytechnic of Malang, Indonesia, in 2023. She is currently pursuing a master's degree in Civil Engineering, with a concentration in Construction Management, at Brawijaya University, Malang, Indonesia. Her research interests include supply chain risk management and modular integrated construction (MiC) in the context of Indonesian construction projects. (email: danaayumaharani@student.ub.ac.id).



Ir. Kartika Puspa Negara, S.T., M.T., Ph.D., CDS is a lecturer and researcher in the Department of Civil Engineering, Faculty of Engineering, Brawijaya University, Indonesia. She completed her bachelor's degree in Civil Engineering at Brawijaya University (2007), her master's degree in Civil Engineering at Institut Teknologi Sepuluh Nopember (2010), and her Ph.D. in Built Environment at Queensland University of Technology, Australia (2020). Her research interests include sustainable construction management, circular economy, knowledge management, human resource management, and reliability analysis, with a primary specialization in construction management. Her publications address topics such as knowledge management and BIM in construction, public project manager competency, schedule acceleration, and quality management systems, published in Rekayasa Sipil, ARCEE, and IOP Conference Series. (email: kartika_puspa@ub.ac.id).



Dr. Ir. Wisnumurti, M. T. is a lecturer and researcher in the Department of Civil Engineering, Faculty of Engineering, Brawijaya University, Indonesia. He completed his bachelor's degree in Civil Engineering at Brawijaya University (1989), his master's degree in Civil Engineering at Universitas Gadjah Mada (1996), and his doctorate in Civil Engineering at Brawijaya University (2014). His research interests include structural engineering, local materials, and construction management, with a primary specialization in structural engineering. His publications address topics such as the behavior of concrete containing onyx stone waste, shear capacity of reinforced-concrete beam-column joints, Buton-based asphalt materials, and construction work safety, published in journals and proceedings such as Rekayasa Sipil, AIP Conference Proceedings, and Eastern-European Journal of Enterprise Technologies. (email: wsmurti@ub.ac.id).