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Original Article

An Integrated FMEA Action Priority and Dynamic RPN Model for Cost Overrun Risk Prioritization in Modular Construction: Evidence from Jakarta

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Abstract *- Modular construction promises productivity gains, shorter delivery times and improved sustainability, yet evidence on its cost performance is mixed: some studies report savings, whereas others report cost increases associated with design, manufacturing and logistics difficulties. Research on cost-overrun risk prioritization for modular construction in Indonesia remains limited, and the combined use of Action Priority (AP) and the Dynamic Risk Priority Number (Dynamic RPN) remains unexamined. This study proposes an integrated AP-based FMEA and Dynamic RPN framework in which AP determines the urgency of action and Dynamic RPN ranks risks within each AP level through an explicit integration rule. Data are obtained from 29 experienced practitioners in Jakarta through a questionnaire covering 34 risk factors in five lifecycle phases; 32 items are retained after validity screening. AP assigns all 32 risk factors to the Low level, whereas Dynamic RPN separates them into four classes (one Very High, seven High, sixteen Medium and eight Low) based on RPN share and percentile rank. Design or scope changes during module production rank first (6.39% of the total RPN), and the leading risk factor of every phase is classified as High or Very High, which indicates that cost-overrun risk spans the whole lifecycle. Because expert agreement is weak (Kendall's W = 0.083-0.144), the ranking is interpreted as a relative, perception-based ordering and not as a measure of realized cost overruns. The framework offers a transparent basis for differentiating cost-overrun risks when AP alone yields a uniform classification.*

Keywords *- Action Priority, Cost overrun, Dynamic risk priority number, Failure Mode and Effect Analysis with Action Priority, Modular construction.*

1. Introduction

The construction sector plays an essential part in national economic growth and infrastructure delivery [1]. However, the sector continues to be plagued with challenges in cost efficiency, schedule performance and sustainability [2]. Modular construction has been increasingly adopted in response to these pressures for its ability to increase productivity, reduce waste and shorten completion times [3]. Evidence on the cost performance of modular construction is nevertheless mixed. Studies in Indonesia have reported modular projects to be up to 1.62 times more expensive than conventional projects, primarily because of high initial capital investment, a shortage of skilled labor, and additional costs for module production and transportation [4, 5]. Other studies show a different picture with cost reductions of 20–24 % and shorter project times [6, 7]. The disagreement between these findings points to something important: cost outcomes in modular construction seem to hinge less on the method itself and more on which risk factors happen to dominate at a given stage of the project.

These cost-overrun risks emerge at multiple stages such as design and planning, construction documentation, factory production, transportation and logistics, and on-site construction [8]. So, it is essential to identify and prioritise them at every phase for cost control [9, 10]. One of the few studies to tackle this directly, who applied FMEA to cost-increasing factors in Korean modular construction and found that workforce shortages in the early design phase carried the highest risk, ranking factors using classical Risk Priority Number (RPN) [10].

Beyond this, however, most existing work on modular construction cost, including the study closest in spirit to this one, either sticks with RPN-based prioritization or centers on comparing overall project costs and feasibility, leaving relatively little room for a more discriminating, lifecycle-wide approach to risk prioritization. The gap is even wider in Indonesia, where modular construction is still a relatively new practice and no lifecycle-based cost-risk prioritization framework has yet been put forward [9, 11].

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For ranking risks of this kind, FMEA remains a long-established choice [12]. The AIAG-VDA framework replaces the conventional RPN with Action Priority (AP), which still draws on all three ratings but lets Severity weigh most heavily [13-15]. Anackovski et al. [13] explain this logic in principle, noting that AP avoids a common problem with RPNs, namely that risks of very different severity levels may receive the same score. This claim was later tested by [14], who simulated 10,000 randomized combinations of severity, occurrence, and detection, and found that AP-based prioritization required fewer corrective actions than an RPN threshold of 100 or above, without missing any high-severity risks in the process. That said, the simulation relied on generic, randomly generated data rather than a real industrial case, and it left one issue unaddressed, AP compresses 1,000 possible S-O-D combinations into just three bands (High, Medium, and Low), so risks with quite different RPN values or contribution levels can still land in the same bucket, which limits how well AP can tell apart truly dominant risks from the rest [14].

A separate line of work has tried to close that gap. [16] introduced the Dynamic Risk Priority Number (Dynamic RPN), which sorts risks by their share of total system risk and their percentile position within the overall RPN distribution, then combines the two through a decision matrix. Tested on ergonomic risks in a hospital's neonatal intensive care unit, the model reclassified several risks that classical RPN had placed in a single category and reached a weighted agreement of 93.7% with practitioner. The model was, however, compared only with classical RPN, not with AP, and the setting was healthcare ergonomics, not construction [16].

Taken together, these studies reveal two research gaps. The first is methodological: AP and Dynamic RPN have each been shown to offer advantages over classical RPN, but they have not been combined, and no existing framework specifies how the action-urgency logic of AP and the distribution-based ranking of Dynamic RPN should jointly determine a final priority. The second is contextual: cost-overrun risk in modular construction, and in Indonesian modular construction in particular, has not been prioritized with either tool. The combination is especially relevant to modular construction because its risks are spread across several interdependent phases. Relying on AP alone may treat many risks as equally urgent, whereas relying on Dynamic RPN alone discards the severity-first logic that makes AP useful for deciding whether action is required.

To close both gaps, the present work proposes a framework that integrates FMEA Action Priority with Dynamic RPN for prioritizing cost-overrun risk in modular construction. Three contributions follow. First, an explicit integration rule is defined: AP sets the urgency of action, and the Dynamic RPN class orders the risks inside each AP level. Second, the combination is applied to an empirical modular construction dataset of 32 validated risk factors across five lifecycle phases in Jakarta, Indonesia; no earlier application of this kind was found in the literature reviewed. Third, the resulting priorities are compared with classical RPN, with AP alone and with previously reported findings, and the classification is tested for sensitivity to the rounding convention. For contractors and project owners, the ranking shows which cost-overrun risks deserve attention first at each phase of a modular building project.

2. Literature Review

2.1. Modular Construction

In modular construction, much of the building is produced off site: components are fabricated and pre-assembled under factory conditions, delivered to the site, and erected there [2]. As opposed to traditional construction, project activities are distributed over multiple sequential stages of design, manufacture, transportation and installation processes [17, 18].

Modular construction can be divided into five stages: design and planning, construction documentation, factory production, transportation and logistics, and on-site construction [10, 19]. Due to the different activities, stakeholders and resources, sources of cost-overrun risks may differ across the project lifecycle [1]. Therefore, the present study adopts the five-phase life-cycle framework as the basis for classifying and analyzing cost-overrun risks. Table 1 lists the main activities of each phase.

Table 1. Phases of modular construction

Phase	Main Activities
Design and Planning	Project feasibility analysis, modular concept development, modular system selection, structural and connection design, BIM and DfMA coordination, preliminary cost estimation and scheduling
Construction Documentation	Shop drawings, technical specifications, Bill of Quantity (BoQ), engineer estimate, tender and procurement process
Factory Production	Material procurement, modular fabrication, MEP installation, quality control, delivery preparation
Transportation and Logistics	Route planning, permit processing, loading and unloading, transportation, temporary storage and monitoring
On-Site Construction	Site preparation, crane mobilization, module positioning, module connection, utility installation, commissioning and handover

2.2. Cost Overrun in Modular Construction

The cost overruns are the major challenge that adversely affects the performance and productivity of modular construction projects [20]. Although modular construction has advantages in productivity improvement and project delivery speed, its cost structure differs considerably from that of conventional construction [8]. In traditional construction, costs are concentrated in on-site activities, whereas in modular construction a larger proportion of project cost is incurred in design development, factory production and transportation logistics [1].

Because design, manufacture, transport and installation are tightly linked in modular construction, uncertainly can enter project cost at several points [21]. Earlier studies trace cost increases to complex designs, limited technical know-how, inaccurate estimates, manufacturing obstacles, uncertain material procurement, logistic constraints, transport damage and installation problems [1, 2, 20]. The consequences include design modifications, manufacturing delays, rework, extra resource needs and operational inefficiency across the project life cycle.

The phases of modular construction are complex and strongly interdependent, so a cost-overrun risk that arises in one phase can carry over into the activities that follow [2]. Prioritizing risks and making cost-control decisions therefore requires that risk factors be identified across the whole life cycle, not phase by phase in isolation [21]. Table 2 lists the risk factors drawn from the literature, grouped under the five lifecycle phases adopted here: design and planning, construction documentation, factory production, transportation and logistics, and on-site construction.

Table 2. Risk identifications

Code	Risk Factors
Design and Planning Phase	
A-1	Errors in conducting site feasibility studies for transportation and lifting equipment [10]
A-2	Inaccuracies in selecting the type and modular system for the project [10, 22]
A-3	Lack of experts and professionals in modular design [1, 2, 9, 10]
A-4	Inadequacy of modular design codes and standards [5, 19, 23]
A-5	Errors or inaccuracies in module design, including determination of dimensions, positioning, or connection systems [8, 23]
A-6	Difficulties in applying standard cost and productivity data to specific jobs [10]
Construction Documentation Phase	
B-1	Inaccurate cost estimate [10, 23]
B-2	Inadequate regulations and permits [23, 24]
B-3	Inappropriate contract and payment schemes [23, 24]
B-4	Lack of cost information for specific components or specific parts [10]
Factory Production Phase	
C-1	Unstable or insufficient factory production capacity to meet project requirements [10, 23]
C-2	Shortage of skilled personnel for modular fabrication [2, 10, 22, 23]
C-3	Weaknesses in the quality monitoring and control system [8]
C-4	Rework caused by discrepancies or errors in working drawings [10]
C-5	Uncertainty in material procurement (e.g., minimum order quantities, price volatility, supply delays) [5, 10, 23]
C-6	Design or scope changes occurring during the production process [8]
C-7	Mechanical failure of production machinery [8]
C-8	Limited availability of modular component suppliers [23, 24]
Transportation and Logistics Phase	
D-1	Delivery delays due to lack of synchronization between transport schedules and production/construction [5, 10, 23]
D-2	Damage to modules from handling, loading/unloading, or improper storage [5, 25]
D-3	Dimensional and weight restrictions during transportation [8, 25]
D-4	Constraints imposed by regulations or vehicle type [19, 25]
D-5	Inadequate module marking/labeling at shipment [26, 27]

D-6	External impediments such as traffic congestion, poor road conditions, or vehicle breakdowns [8]
D-7	Limited availability of specialized vehicles for oversized modules [23, 24]
On-site Construction Phase	
E-1	Inappropriate selection of lifting equipment for installation activities [10, 19, 22]
E-2	Execution errors due to insufficient coordination between factory and field teams [10, 23]
E-3	Lack of field personnel experience in module installation [23, 24]
E-4	Errors in module connections during on-site assembly [10, 19, 23]
E-5	Disturbances from surrounding environment affecting crane operations and module installation [23, 24, 28]
E-6	Rework due to discrepancies between on-site implementation and working drawings [8]
E-7	Inadequate planning and scheduling [8]
E-8	Damage to equipment [8, 19]
E-9	Delays in procuring installation support materials [10, 23]

Note. Items B-2 and B-3 were excluded from the FMEA/AP and Dynamic RPN analyses (Table 16) after failing the Pearson's Product-Moment validity test (r = 0.361 and r = 0.124, respectively, against a critical value of r = 0.3673); see Section 3 for details. All 34 risk factors are retained here to reflect the complete set identified through the literature review.

2.3. FMEA with Action Priority

Developed in the mid-1960s [10, 12], Failure Modes and Effects Analysis (FMEA) is now among the risk analysis techniques that international standards recommend [29]. Its results are regarded as comprehensive because three aspects are rated together: how serious a failure's consequences are, how often it arises, and how readily current controls reveal it [30].

In conventional FMEA, risk factors are ranked by their Risk Priority Number (RPN) [31], which needs three ratings for every failure mode:

- Severity (S): how serious the consequence of the failure mode is.
- Occurrence (O): how likely the cause of the failure mode is to arise.
- Detection (D): how likely that cause is to be caught before it takes effect.

Each rating runs from 1 to 10, and the RPN is their product (Equation 1).

$$RPN = S \times O \times D \quad (1)$$

Table 3. Classical RPN thresholds and risk levels

FMEA Risk Level	RPN Value
Low	1 – 100
Medium	101 – 200
High	201 – 500
Very High	501 – 1000

Source: [12, 16]

Tables 4-6 give the rating scales used for S, O and D in this study.

Severity expresses how much construction cost rises once a cost-increasing factor materializes [10, 12, 30]. The severity scale is presented in Table 4.

Table 4. Severity scale

Evaluation Criteria		Score
Very low increase in construction costs	Cost increase < 1%	1
The increase in construction costs is low	Cost increase between 1% and 5%	2
		3
Moderate increase in construction costs	Cost increase between 5% and 10%	4
		5
		6
High increase in construction costs	Cost increase between 10% and 50%	7
		8
The increase in construction costs is very high	Cost increase >50%	9
		10

Source: [12, 13, 32]

Occurrence is a measure of how often factors contributing to increased construction costs appear [10, 12, 30]. The occurrence levels are presented in Table 5.

Table 5. Occurrence scale

Assessment Criteria		Score
The likelihood of cost-increasing factors occurring is very low	Occurrence < 1%	1
The likelihood of cost-increasing factors is low	Occurrence frequency between 1% and 10%	2
		3
The likelihood of cost-increasing factors is moderate	Occurrence frequency between 10% and 20%	4
		5
The likelihood of cost-increasing factors is high	Occurrence frequency between 20% and 50%	6
		7
The likelihood of cost-increasing factors is very high	Occurrence frequency > 50%	8
		9
		10

Source: [12, 13, 33]

Table 6. Detection level scale

Assessment Criteria		Score
The likelihood of cost-increasing factors is very easy to detect and very easy to control	Very easy to detect	1
Cost-increasing factors are readily detected and controlled	Easy to detect	2
		3
		4
Potential cost-increasing factors can be detected and controlled with extra effort	Can be detected	5
		6
The likelihood of cost-increasing factors is difficult to detect and hard to control	Difficult to detect	7
		8
Cost-increasing factors are almost impossible to detect or control	Truly difficult	9
		10

Source: [12, 13]

Detection expresses how readily a problem can be identified before it affects the system; Table 6 gives the corresponding levels.

The 2019 AIAG/VDA FMEA Handbook replaces RPN-based ranking with Action Priority (AP) [13]. The motivation is that multiplying the three ratings can give near-identical RPN scores to risks with very different S, O and D profiles, which obscures which of them should be mitigated first [13].

AP instead assigns each of the 1,000 possible S-O-D triplets to a priority level through a lookup matrix (Table 7) that weights Severity most, then Occurrence, then Detection, so that the more severe risks are mitigated first [11, 13]. Each risk thereby receives a High, Medium or Low action priority [12], Table 8 explains the three levels.

Table 7. Action Priority (AP) matrix

Occurrence (O) Rating	Severity (S) Rating														
	1	**2–3**		**4–6**				**7–8**				**9–10**			
	1–10	**1–4**	**5–10**	**1**	**2–4**	**5–6**	**7–10**	**1**	**2–4**	**5–6**	**7–10**	**1**	**2–4**	**5–6**	**7–10**
8–10	Low	Low	Medium	Medium	Medium	High	High	High	High	High	High	High	High	High	High
6–7	Low	Low	Low	Low	Medium	Medium	Medium	High	High	High	High	High	High	High	High
4–5	Low	Low	Low	Low	Low	Low	Medium	Medium	Medium	Medium	High	Medium	High	High	High
2–3	Low	Low	Low	Low	Low	Low	Low	Low	Low	Medium	Medium	Low	Low	Medium	High
1	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
	1–10	**1–4**	**5–10**	**1**	**2–4**	**5–6**	**7–10**	**1**	**2–4**	**5–6**	**7–10**	**1**	**2–4**	**5–6**	**7–10**
	Detection (D) Rating														

(Based on the AIAG & VDA FMEA Handbook, 1st Edition, 2019)

The Action Priority (AP) method evaluates the combination of Severity (S), Occurrence (O), and Detection (D) to determine the priority of risk-reduction actions. Unlike the conventional RPN approach, AP does not rely on multiplication of the three ratings. Instead, the AP level is determined using the prescribed combination of S, O, and D ratings, resulting in High (H), Medium (M), or Low (L) action priority.

Table 8. Action Priority (AP) level categories

Action Priority (AP) Level	Description
High (H)	Must be addressed immediately or justified
Medium (M)	Recommended to be addressed, but may be prioritized according to policy
Low (L)	Optional action, monitoring is sufficient

Source: [12, 15]

2.4. Dynamic Risk Priority Number (Dynamic RPN)

Dynamic RPN extends FMEA by asking two things of every risk: how much of the summed RPN it accounts for, and where it sits, in percentile terms, among the other risks [16].

Because both indicators are computed from the data at hand, the classification adapts to the observed risk profile and is more sensitive to differences between risks than fixed thresholds are [16].

The first indicator is the contribution percentage, which shows the weight a single risk carries within the system as a whole [16]. It is computed with Equation 2 and assigned to a class using Table 9.

$$C_i = \frac{RPN_i}{RPN_{total}} \times 100\% \quad (2)$$

Where C_i denotes the percentage contribution of risk factor i, RPNi its RPN, and RPNtotal the RPN summed over all n risk factors.

Table 9. Contribution class

Contribution Class	Contribution to total system RPN (%)
Low	<2
Medium	2 to < 5
High	5 to < 15
Very High	≥15

Source: [16]

The second indicator is the percentile rank, which locates a risk in the upper, middle or lower part of the RPN distribution and so places its priority in context [16]. To obtain it, the RPN values are sorted in ascending order, and each is given a zero-based rank ri, with ri = 0 for the smallest RPN and $r_i = n - 1$ for the largest. Dividing this rank by the highest possible rank (Equation 3) yields a percentile rank between 0% and 100%, which is assigned to a class using Table 10. The RPN values are computed from the unrounded mean ratings; risk factors whose RPN values coincide after rounding to two decimals are therefore still ordered by their unrounded values.

$$PR_i = \frac{r_i}{n-1} \times 100\% \quad (3)$$

Where PR_i is the percentile rank of risk factor i (%), r_i is its zero-based rank after the RPN values are sorted in ascending order ($r_i = 0$ for the smallest RPN), and n is the number of risk factors (n = 32 in this study).

Table 10. Percentile class based on percentile rank

Percentile rank	Percentile class
≥75%	Very High
50% to < 75%	High
25% to < 50%	Medium
<25%	Low

Source: [16]

The decision matrix in Table 11 then combines the contribution class with the percentile class to give the final dynamic risk class.

Table 11. Dynamic risk classification

Percentile Class	Contribution			
	Low	**Medium**	**High**	**Very High**
Low	Low	Low	Medium	Medium
Medium	Low	Medium	Medium	High
High	Medium	Medium	High	Very High
Very High	Medium	High	Very High	Very High

Source: [16]

2.5. Comparison with Prior Studies on FMEA, AP, and Dynamic RPN

The limitations of the classical RPN have motivated numerous alternative prioritization schemes. Liu et al. [34] reviewed risk evaluation approaches in FMEA and grouped the alternatives into multi-criteria decision-making, mathematical programming, artificial intelligence and hybrid approaches, among which fuzzy rule-based systems were the most frequently applied.

In construction, Abdelmageed and Zayed [18] combined fuzzy FMEA with fuzzy AHP to derive a risk criticality number from linguistic assessments of impact, occurrence and detection, and Ciani et al. [30] compared alternative RPN formulations that were put forward to remedy the weaknesses of the conventional index. These approaches improve discrimination but require membership functions, pairwise comparisons or parameter weights that are demanding to elicit from practitioners judgment. AP and Dynamic RPN, in contrast, work directly with the S, O and D ratings already collected and ask nothing further of respondents, which motivates their use in this study.

Several studies bear directly on the approach adopted here, although each addresses only part of the problem. Lee and Kim [10] analyzed cost-increasing risks in Korean modular construction using a lifecycle structure similar to the one adopted in this study, but relied on classical RPN—substituting Detection with an Effect parameter without incorporating AP or Dynamic RPN. Anackovski et al. [13] explained the rationale behind AP's severity-first weighting in the AIAG/VDA handbook, but offered no empirical validation.

Panyukov et al. [15] examined the AP matrix structurally, showing that its 1,000 S-O-D combinations resolve unevenly across priority levels (62 Low versus 22 High) due to asymmetries in how qualitative bands are assigned to each parameter. Barsalou [14] later demonstrated a related limitation empirically: in a simulation of 10,000 randomized combinations, AP required fewer corrective actions than an RPN ≥ 100 threshold, but the tendency of AP to group risks of differing magnitude within a single level was not addressed, and simulated data were used instead of project data.

Narli [16] took a different approach and proposed Dynamic RPN as an alternative to fixed-threshold classification by combining the contribution of each risk to the total system risk with its percentile position in the RPN distribution. Applied to ergonomic risks in a hospital NICU, the method reclassified several risks that classical RPN had grouped together and achieved a weighted agreement of 93.7% with practitioner judgment. However, the comparison was made only against classical RPN, not AP, and the domain was healthcare, not construction. Table 12 summarizes these studies alongside the present one.

Table 12. Comparison of prior FMEA-based risk prioritization studies

Study	Method	Object	Key Finding	Gap Relative to This Study
[10]	Classical FMEA-RPN	Cost drivers across five lifecycle stages of modular projects in Korea	Design-phase workforce shortage identified as the dominant cost-overrun risk	RPN only; no AP or Dynamic RPN; no distribution-based adjustment
[13]	AP (AIAG/VDA 1st Edition), conceptual	Manufacturing/automotive PFMEA	Explains why severity-first weighting resolves the RPN threshold problem	Descriptive only; no case study or empirical dataset
[15]	Structural analysis of the AP matrix (1,000 S-O-D combinations)	AIAG/VDA AP matrix, automotive design/process risk	Reveals structural imbalance in the AP matrix; Low dominates (62/100), Severity's influence is asymmetric by design	Diagnoses AP's structural limits but proposes no alternative method; untested on empirical or construction data
[14]	AP vs. RPN, simulation (10,000 randomized combinations)	Generic automotive FMEA (simulated)	AP requires fewer actions than RPN ≥ 100 without omitting severe risks	Simulated data; does not address AP grouping dissimilar risks together; no link to Dynamic RPN
[16]	Dynamic RPN (contribution % + percentile rank)	Ergonomic risk, hospital NICU	Reclassifies risks classical RPN grouped together; 93.7% weighted agreement with practitioners	Healthcare, not construction; benchmarked only against RPN, not AP
This study	AP + Dynamic RPN, integrated	Cost-overrun risk, Indonesian modular construction	AP determines action urgency; Dynamic RPN orders risks within each AP level through an explicit integration rule	-

3. Material and Method

The multi-stage risk prioritization model was built quantitatively from questionnaire responses. The respondents were practitioners at state-owned construction companies in Jakarta who had worked on modular construction projects. Purposive sampling was adopted because modular construction projects remain relatively limited in Indonesia, and only practitioners with direct experience in modular projects, including design, manufacturing, transportation or on-site assembly activities, were considered capable of providing reliable expert judgments.

This criterion ensured that the collected judgments reflected practical risk conditions throughout the modular construction lifecycle. Table 13 lists the respondents by position.

Table 13. Positions and the number of respondents

Job Title	Number of Respondents	Percentage
Project Engineering Manager	2	7%
Marketing Manager & Project Engineering Manager	1	3%
Manager of Engineering & Innovation	1	3%
QSHE Engineering & Innovation Manager	1	3%
Marketing & Estimating	1	3%
Site Manager	1	3%
General Manager	1	3%
Engineering	4	14%
Site Engineering Manager	2	7%
Quality Control	1	3%
Assembly Coordinator	1	3%
Coordinator	1	3%
Head of Engineering and Quality Section	1	3%
Section Chief	1	3%
Project Manager	1	3%
Estimator & QS	1	3%
Quantity Surveying Manager	2	7%
Mid-Level Staff	1	3%
Cost Control	1	3%
Junior Specialist	3	10%
Not stated	1	3%

Source: Author's analysis (2026)

The risk factors were first compiled from the literature. Respondents then rated each factor for Severity, Occurrence and Detection in a questionnaire built on that list. Before moving to analysis, the instrument was checked for validity and reliability using Pearson's Product-Moment test and Cronbach's Alpha, respectively. Of the 34 risk factors initially identified, two items from the Construction Documentation phase, B-2 (inadequate regulations and permits, r = 0.361) and B-3 (inappropriate contract and payment schemes, r = 0.124), fell below the critical value (r = 0.3673 for n = 29, α = 0.05) and were excluded from subsequent analysis, leaving 32 validated risk factors.

The risk analysis first applied Action Priority-based FMEA (FMEA/AP), in which the Severity, Occurrence and Detection ratings of each risk factor define its AP level. The three ratings are means of the responses of the 29 respondents and are therefore decimal values, whereas the AIAG/VDA AP matrix is defined for integer ratings. Each mean was accordingly rounded to the nearest integer before being matched to its AP band. Several means lie within 0.1 of a band boundary (for example, S = 3.45 for D-5, O = 3.52 for A-4 and D = 4.48 for D-7). To check whether the rounding convention affects the AP classification, the classification was repeated with all means rounded down and again with all means rounded up. Each mean is reported together with its Standard Deviation (SD) across the 29 respondents, because a mean alone does not show whether respondents converged on a similar rating.

RPN values were then calculated from the unrounded mean ratings (Equation 1) and analyzed with Dynamic RPN. For each risk, the contribution percentage (Equation 2, Table 9) and the percentile rank (Equation 3, Table 10) were combined through the decision matrix in Table 11 to obtain the dynamic risk class.

The two results are integrated into a final priority through a two-step rule. In Step 1, the AP level determines the urgency of action as prescribed by the AIAG/VDA handbook (Table 8): a risk with AP = High precedes any risk with AP = Medium, which in turn precedes any risk with AP = Low, irrespective of its RPN. In Step 2, risks within the same AP level are ordered by their dynamic risk class (Very High, High, Medium, Low) and, within the same dynamic class, by their percentile rank.

The final priority is reported as the pair of AP level and dynamic risk class (for example, L-VH for AP = Low and dynamic class = Very High), together with an overall rank. Under this rule, severity-driven urgency is never overridden by a high relative RPN, and Dynamic RPN supplies the differentiation that AP lacks when many risks receive the same AP level. The dynamic class only indicates where a risk stands among the other assessed risks; it does not by itself imply that action is mandatory.

Because the ratings are perception-based, three checks were made on how stable the resulting ranking is: the level of agreement among respondents (Kendall's W), how widely the ratings are dispersed, and how far apart adjacent RPN values lie. Figure 1 outlines the workflow.

4. Result and Discussion

This section reports the validity and reliability of the instrument (Section 4.1), the AP classification (Section 4.2), the Dynamic RPN classification (Section 4.3) and the integrated final priority together with its sensitivity (Section 4.4). The leading risk of each phase is then identified (Section 4.5), and the findings are discussed in Section 4.6. In brief, AP places all 32 risk factors at the same level, and it is Dynamic RPN that separates them.

4.1. Instrument Validity and Reliability

Before the prioritization analysis, all 34 initial risk factors were screened for validity using Pearson's Product-Moment correlation. Two items did not reach the required threshold: B-2 (inadequate regulations and permits, r = 0.361) and B-3 (inappropriate contract and payment schemes, r = 0.124), both below the critical value of r = 0.3673. These two items were excluded, and all further analysis uses the remaining 32 validated risk factors.

Cronbach's Alpha was then computed for the 32-item instrument, separately for each FMEA parameter. Internal consistency was good on all three scales: α = 0.958 for Severity, α = 0.971 for Occurrence and α = 0.965 for Detection (Table 14), much above the 0.60 criterion traditionally used to establish whether an instrument is suitable for use. These results indicate that respondents' ratings on any given item corresponded closely with their ratings on the remaining items within each scale, with no evidence that a particular item undermined the instrument's overall consistency.

Table 14. Cronbach's alpha reliability results for severity, occurrence, and detection ratings

FMEA Parameter	Cronbach's Alpha	No of Items	Remarks
Severity	0.958	32	Reliable
Occurrence	0.971	32	Reliable
Detection	0.965	32	Reliable

Source: Author's analysis (2026)

A high Cronbach's Alpha, however, does not by itself indicate that respondents agreed with one another on the relative importance of each risk factor; this is a distinct question addressed by Kendall's coefficient of concordance (W). Computed across the same 32 items for all 29 expert respondents, W was considerably lower than Alpha: 0.144 for Severity, 0.083 for Occurrence, and 0.086 for Detection (Table 15), with all three coefficients statistically significant ($p < 0.001$). This pattern is not contradictory, since Alpha and W measure different properties of the data: Alpha evaluates

whether items within the instrument behave consistently, whereas W evaluates whether individual respondents converge on similar rankings across items. A significant yet weak W therefore suggests that respondents' judgments were not random, since they agreed more than chance alone would produce, even though individual assessments of risk priority varied considerably.

This level of variation is plausible given the composition of the 29-member panel, consisting of professionals in diverse roles including project engineers, cost estimators, QSHE personnel, and site managers (Table 13). Respondents in different positions would likely rate each factor from the standpoint of their own area of responsibility.

Table 15. Kendall's Coefficient of Concordance (W) for severity, occurrence, and detection ratings

Parameter	Raters (n)	Items (n)	W	χ^2	df	p
Severity	29	32	0.144	129.68	31	< 0.001
Occurrence	29	32	0.083	74.80	31	< 0.001
Detection	29	32	0.086	76.92	31	< 0.001

Source: Author's analysis (2026)

Table 16 provides standard deviations that confirm this pattern. For the 32 validated risk factors, SD values for ratings of Severity, Occurrence and Detection ranged from approximately 1.5 to 2.8. Thus, although the instrument demonstrated good internal consistency, individual judgments were widely scattered. Together, the weak Kendall's W and the comparatively large SD values reinforce the same conclusion, namely, that respondents' assessments of relative risk priority varied meaningfully, even though their ratings within the instrument remained internally coherent.

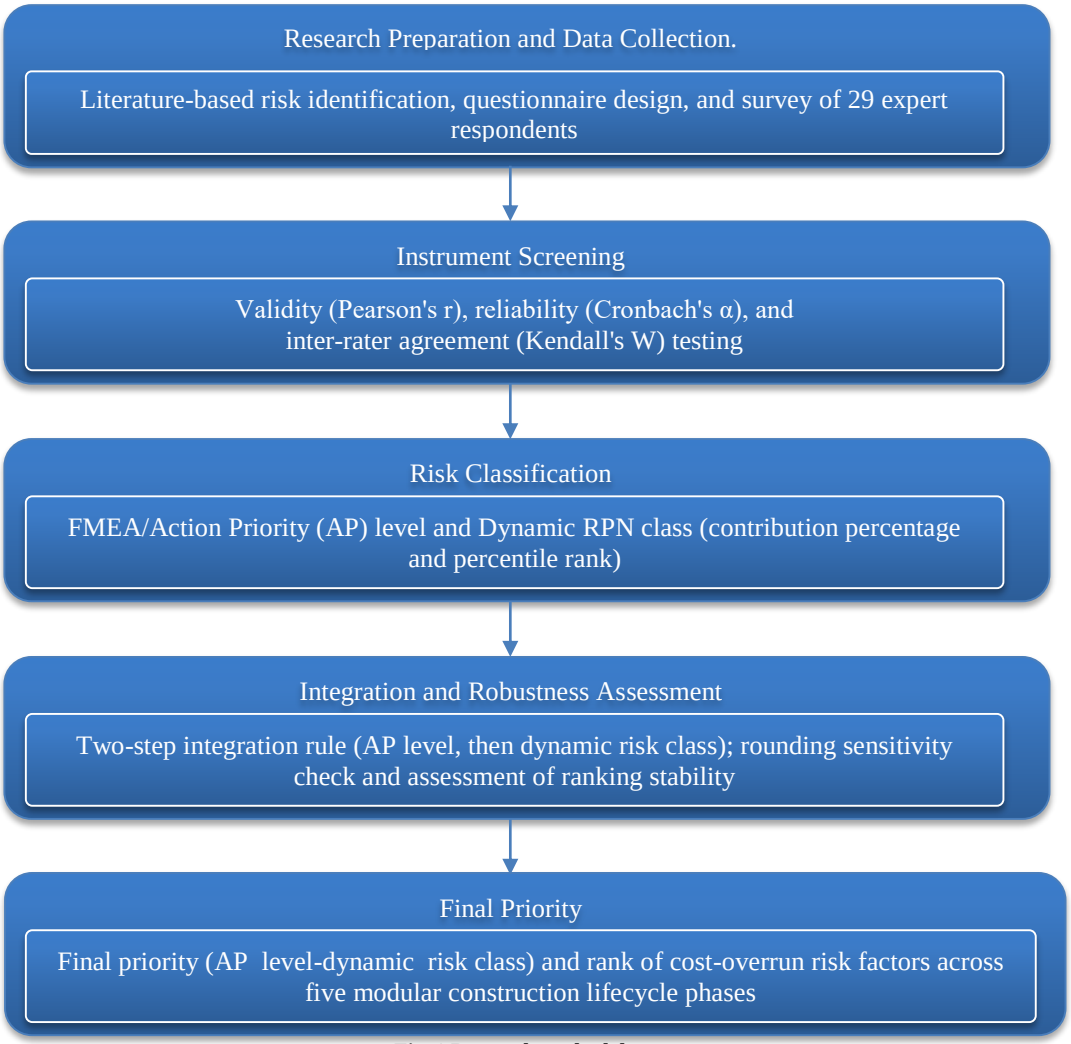


Fig. 1 Research methodology

Source: Author's analysis (2026)

4.2. FMEA Result with Action Priority (FMEA/AP)

Table 16 reports the AP levels, which were read from the AP matrix (Tables 7 and 8) using the rounded Severity, Occurrence and Detection ratings of every risk factor. All 32 risk factors fall into the Low level. The rounded Severity ratings lie between 3 and 6 and the rounded Occurrence ratings between 3 and 5, a region of the AP matrix in which a Medium level requires a Detection rating of 7 or more, whereas the highest mean Detection rating is 5.90 (C-6). The uniform result is therefore a direct consequence of the moderate mean ratings. It also shows the limited discriminatory capability of AP for this dataset: risk factors whose RPN values range from 33.20 to 191.18 receive the same action priority.

According to Table 8, a Low level means that action is optional and monitoring is sufficient. In practical terms, AP indicates that none of the assessed risks demands mandatory action, but it gives no guidance on which of the 32 risks should be monitored first. An additional approach that uses the distribution of the RPN values is therefore needed to differentiate the risk factors.

4.3. Dynamic RPN

Dynamic RPN was then applied so that the classification would follow the observed RPN distribution. It takes into account how much each risk adds to the summed RPN and where the risk falls within the RPN distribution.

The total RPN of the 32 risk factors is 2,992.09, so an equal share would be 3.13% per factor. The contribution percentages range from 1.11% (D-5) to 6.39% (C-6). With the thresholds of Table 9, 30 of the 32 factors fall into the Medium contribution class, one into the Low class (D-5) and one into the High class (C-6). The contribution class alone therefore differentiates the risks only at the two extremes. By construction, the percentile class places eight factors in each of its four classes, and the combination of both indicators through Table 11 yields one Very High, seven High, sixteen Medium and eight Low risk factors (Table 16).

Risks that share the same AP level are thus spread over four dynamic classes. This greater differentiation should not be read as greater accuracy: no external benchmark, such as recorded cost overruns or an independent expert ranking, is available against which either classification could be validated. What Dynamic RPN adds is an ordering of the risks relative to one another.

The contribution percentage measures a factor's portion of the summed perception-based RPN scores, not the portion of actual project cost overrun attributable to that factor. A contribution of 6.39% means that respondents rated C-6 highest on the combined S, O and D scale, and whether this factor also generates the largest realized cost overrun would have to be established with project cost data.

4.4. Integrated Final Priority and Sensitivity of the Classification

Under the integration rule of Section 3, every risk factor receives a final priority made up of its AP level and its dynamic class (last column of Table 16). Because every risk factor has AP = Low, Step 1 of the rule does not separate the risks in this dataset, and the final order is determined by Step 2, that is, by the dynamic class and the percentile rank. The final priority groups are L-VH (C-6), L-H (C-4, A-5, B-4, B-1, C-5, D-2 and E-6), L-M (16 factors) and L-L (8 factors). The interpretation is that no risk requires mandatory action under the AIAG/VDA logic, and that monitoring and voluntary mitigation resources should be directed first to C-6 and then to the seven L-H factors. In a dataset in which AP levels differ, the same rule would place any High-AP risk ahead of all Medium-AP and Low-AP risks regardless of its dynamic class.

The AP classification was checked against the rounding convention. Eight mean ratings of seven risk factors lie within 0.1 of an AP band boundary (S = 3.45 for D-5; O = 3.52 for A-4; O = 3.59 and D = 4.45 for E-8; D = 4.48 for D-7; D = 4.59 for E-5, E-4 and D-2), yet none of these factors change level under any rounding convention, because their other ratings keep them in the Low region. When all means are rounded down, all 32 factors remain Low. When all means are rounded up, A-5 and C-4 become Medium and C-6 becomes High, while the remaining 29 factors stay Low. The three factors that react to upward rounding are the three highest-ranked factors under Dynamic RPN, so AP and Dynamic RPN agree on which risks stand out.

The stability of the ranking must be judged against the weak agreement among respondents (Kendall's W between 0.083 and 0.144, Table 15) and the SD values of 1.5 to 2.8. Three observations follow from Table 16. First, the top position is well separated: the RPN of C-6 (191.18) exceeds that of the second-ranked C-4 (140.49) by 36%, and C-6 is the only factor that is raised by both the contribution and the percentile indicator. Second, a visible gap separates the High class from the Medium class (107.11 for E-6 against 101.56 for C-7, a difference of 5.5%), whereas no such gap separates the Medium class from the Low class (77.19 for A-6 against 76.97 for C-2, a difference of 0.3%). Third, within the Medium class most adjacent RPN values differ by less than 2%, so, given how dispersed the ratings are, individual mid-ranking positions cannot be told apart. The dynamic classes are accordingly more reliable at the top of the ranking than further down, and the classification serves best for picking out the leading group of risks, not for ordering every individual factor.

4.5. Dominant Risk in Each Phase of Modular Construction

To obtain a more complete picture of cost risk across the lifecycle, the top-priority risk factor of each phase was identified. The phases are not equally represented among the

leading risks: of the eight factors classified as L-VH or L-H, three belong to factory production (C-6, C-4 and C-5), two to construction documentation (B-4 and B-1) and one each to the remaining phases.

4.5.1. Design and Planning Phase

In the design and planning phase, A-5 (errors or inaccuracies in module design, including the determination of dimensions, positions or connection systems) has the highest priority (RPN = 134.39; L-H). Respondents thus see design decisions as shaping the later stages, since design errors can trigger design changes, rework and additional cost in subsequent phases.

4.5.2. Construction Documentation Phase

The main risk in the construction documentation phase is B-4, lack of cost information of specific components/parts (RPN=133.22; L-H). The availability of component-level cost information is thus perceived as a major difficulty in preparing cost estimates for modular projects, which increases uncertainty in budget planning and may lead to cost deviations during module procurement or project execution.

4.5.3. Factory Production Phase

In the factory production phase, the leading risk is C-6, design or scope changes during the production process (RPN = 191.18; L-VH). A change made at this point acts directly on fabrication that is already underway, and can therefore mean rework, wasted material, disruption to the production schedule and higher labor cost.

4.5.4. Transportation and Logistics Phase

In the transport and logistics phase, the most important risk is item D-2 (RPN = 110.12; L-H), i.e. damage to the module during handling, loading/unloading or improper storage.

Sound factory output is therefore not enough for modular construction to succeed; the modules must also arrive in good condition. Damage incurred at this stage can lead to repair or replacement of components and to installation delays, both of which add to project cost.

4.5.5. On-Site Construction Phase

During the on-site construction phase, the primary risk is item E-6: rework resulting from discrepancies between on-site implementation and the drawings (RPN = 107.11; L-H). This finding indicates that although most modules are completed during the manufacturing stage, the on-site installation phase remains a critical phase. Errors at this stage can lead to rework, delays, and additional implementation costs.

Table 16. Results of the risk classification analysis

Code	S (Mean, SD)	O (Mean, SD)	D (Mean, SD)	AP Level	Classical RPN Level		Contribution		Percentile		Dynamic Risk Level	Priority
					RPN	Level	% of RPN	Class	Rank (%)	Class		
D-5	3.45 (2.03)	3.03 (1.55)	3.17 (1.71)	Low	33.20	Low	1.11	Low	0.00%	Low	Low	L-L (32)
E-8	3.86 (2.07)	3.59 (1.94)	4.45 (2.35)	Low	61.61	Low	2.06	Medium	3.23%	Low	Low	L-L (31)
A-4	4.62 (2.44)	3.52 (1.86)	4.14 (2.45)	Low	67.25	Low	2.25	Medium	6.45%	Low	Low	L-L (30)
A-1	4.66 (2.21)	4.21 (1.74)	3.48 (2.10)	Low	68.21	Low	2.28	Medium	9.68%	Low	Low	L-L (29)
E-5	4.07 (2.03)	3.66 (2.38)	4.59 (2.31)	Low	68.21	Low	2.28	Medium	12.90%	Low	Low	L-L (28)
E-2	4.41 (2.40)	4.14 (2.22)	4.14 (2.23)	Low	75.58	Low	2.53	Medium	16.13%	Low	Low	L-L (27)
E-7	4.66 (2.47)	3.86 (1.90)	4.24 (2.03)	Low	76.25	Low	2.55	Medium	19.35%	Low	Low	L-L (26)
C-2	5.21 (2.37)	3.83 (1.95)	3.86 (2.07)	Low	76.97	Low	2.57	Medium	22.58%	Low	Low	L-L (25)
A-6	4.69 (2.25)	3.76 (1.88)	4.38 (2.34)	Low	77.19	Low	2.58	Medium	25.81%	Medium	Medium	L-M (24)
D-4	4.79 (2.38)	4.03 (2.20)	4.03 (2.43)	Low	78.02	Low	2.61	Medium	29.03%	Medium	Medium	L-M (23)
D-6	3.97 (2.08)	3.69 (1.83)	5.45 (2.73)	Low	79.72	Low	2.66	Medium	32.26%	Medium	Medium	L-M (22)

E-9	4.76 (2.10)	4.21 (2.13)	4.07 (2.28)	Low	81.46	Low	2.72	Medium	35.48%	Medium	Medium	L-M (21)
C-3	5.28 (2.40)	4.14 (1.94)	3.86 (1.88)	Low	84.31	Low	2.82	Medium	38.71%	Medium	Medium	L-M (20)
E-3	4.86 (2.10)	4.31 (2.17)	4.17 (2.38)	Low	87.44	Low	2.92	Medium	41.94%	Medium	Medium	L-M (19)
D-1	5.03 (1.99)	4.28 (2.09)	4.07 (2.00)	Low	87.59	Low	2.93	Medium	45.16%	Medium	Medium	L-M (18)
E-1	5.10 (2.29)	4.17 (2.11)	4.14 (2.25)	Low	88.11	Low	2.94	Medium	48.39%	Medium	Medium	L-M (17)
C-8	5.24 (1.96)	4.07 (2.07)	4.19 (1.87)	Low	89.35	Low	2.99	Medium	51.61%	High	Medium	L-M (16)
C-1	5.48 (2.05)	4.28 (1.85)	3.83 (1.89)	Low	89.73	Low	3.00	Medium	54.84%	High	Medium	L-M (15)
D-3	5.17 (1.95)	4.28 (2.12)	4.10 (2.19)	Low	90.75	Low	3.03	Medium	58.06%	High	Medium	L-M (14)
A-3	4.97 (2.54)	4.28 (2.39)	4.34 (2.35)	Low	92.25	Low	3.08	Medium	61.29%	High	Medium	L-M (13)
E-4	4.72 (2.34)	4.31 (2.36)	4.59 (2.41)	Low	93.39	Low	3.12	Medium	64.52%	High	Medium	L-M (12)
D-7	4.59 (2.11)	4.55 (2.16)	4.48 (2.28)	Low	93.58	Low	3.13	Medium	67.74%	High	Medium	L-M (11)
A-2	5.62 (2.47)	4.28 (2.25)	4.10 (2.16)	Low	98.62	Low	3.30	Medium	70.97%	High	Medium	L-M (10)
C-7	5.03 (2.43)	4.03 (2.11)	5.00 (1.93)	Low	101.56	Medium	3.39	Medium	74.19%	High	Medium	L-M (9)
E-6	5.17 (2.22)	4.45 (2.25)	4.66 (2.32)	Low	107.11	Medium	3.58	Medium	77.42%	Very High	High	L-H (8)
D-2	5.48 (1.81)	4.38 (1.52)	4.59 (1.70)	Low	110.12	Medium	3.68	Medium	80.65%	Very High	High	L-H (7)
C-5	5.28 (1.81)	4.90 (2.13)	4.28 (2.12)	Low	110.46	Medium	3.69	Medium	83.87%	Very High	High	L-H (6)
B-1	5.55 (2.35)	4.66 (2.00)	4.83 (2.11)	Low	124.77	Medium	4.17	Medium	87.10%	Very High	High	L-H (5)
B-4	5.29 (2.14)	4.72 (2.23)	5.33 (2.62)	Low	133.22	Medium	4.45	Medium	90.32%	Very High	High	L-H (4)
A-5	6.21 (2.80)	4.52 (2.43)	4.79 (2.64)	Low	134.39	Medium	4.49	Medium	93.55%	Very High	High	L-H (3)
C-4	6.21 (2.24)	4.86 (2.13)	4.66 (2.33)	Low	140.49	Medium	4.70	Medium	96.77%	Very High	High	L-H (2)
C-6	6.31 (2.30)	5.14 (2.53)	5.90 (2.30)	Low	191.18	Medium	6.39	High	100.00%	Very High	Very High	L-VH (1)

Source: Author's analysis (2026)

Note: Final priority = AP level - dynamic risk class (L = Low, M = Medium, H = High, VH = Very High); rank 1 = highest priority. Total RPN = 2,992.09.

4.6. Discussion

4.6.1. Evaluation of FMEA/AP and Dynamic RPN Integration

All 32 risk factors receive the same Action Priority level. AP is therefore unable to distinguish the relative dominance of risks when the Severity, Occurrence and Detection ratings fall within similar, moderate ranges. Although AP provides more systematic guidance on action urgency than the conventional RPN, its result for this dataset conveys a single message, namely that no risk requires mandatory action, and does not differentiate between the risks. Dynamic RPN, which considers the contribution percentage and the percentile rank, yields a more differentiated distribution and separates risks that share the same AP level. Narli [16], made the same observation: distribution-based classification separates risks which fixed-threshold classification groups together. In the present data, however, the differentiation stems mainly from the percentile rank: the contribution thresholds of [16] place 30 of the 32 factors in one class, because with n = 32 an equal share of the total RPN is 3.13%, which already lies inside the

Medium band. Combining AP and Dynamic RPN through the rule in Section 3 keeps the action-oriented logic of the AIAG-VDA FMEA and adds a transparent ordering within each AP level.

Applied to the same data, the methods differ in how finely they separate the risks (Table 16): classical RPN with fixed thresholds [13, 16] yields two levels (23 Low and 9 Medium), AP yields one level (32 Low), and the integrated framework yields four priority groups (1, 7, 16 and 8 factors). The finer differentiation is obtained because the classification is anchored to the observed RPN distribution instead of fixed cut-offs defined for the full scale of 1 to 1,000, on which the mean-based RPN values of this study (33.20 to 191.18) occupy only a narrow interval. This explains why the framework differentiates more, but it does not demonstrate that it prioritizes more correctly; the claim made here is limited to improved discrimination and transparency.

In substantive terms, the result differs from that of Lee and Kim [10], who identified the shortage of experts in the design phase as the dominant cost-increasing risk in Korea using classical RPN with an Effect parameter. In the present study, the corresponding factor (A-3) ranks 13th, whereas design or scope changes during production (C-6) rank first. A plausible explanation lies in the difference in context and in the Detection parameter: C-6 has the highest mean Detection rating (5.90), which means that respondents consider late design changes the hardest to detect and control, an aspect that the parameter set used in [10] does not capture.

4.6.2. Dominant Risks Triggering Cost Increases in the Modular Construction Cycle

The perceived risk of cost increase in modular construction is not confined to one phase but is spread across the entire project cycle, from design up to the on-site implementation. Keorapetse et al. [9], describe the same pattern, reporting that the cost in modular projects is built up over several phases and is shaped by design, manufacturing, logistics and installation alike. Cost control therefore has to be integrated across the phases and cannot be handled phase by phase.

In the design and planning phase, the main risk identified is the complexity of modular design due to inaccuracies in determining the size, position or connection systems between modules at early stages (A-5). Wuni et al. [23] likewise single out design as the leading source of uncertainty, since choices made there carry through to manufacturing, transport and installation, as design decisions impact on manufacturing, transportation and installation.

Previous studies [9, 26] add that the design phase offers the greatest leverage over cost, even though design itself accounts for a small part of total project cost. Design complexity and uncertainty are known to raise the risk of cost escalation because they can lead to design changes, rework and coordination problems in the later phases. The main risk during the construction documentation phase is the unavailability of cost information on specialized modular components (B-4). Therefore, the availability of cost information remains a major constraint in the implementation of modular construction in Indonesia. This is consistent with [10, 17, 21] who pointed out the limitations of traditional cost management systems in dealing with the cost features of modular construction.

Unlike traditional construction with a relatively extensive price database, modular construction requires more specific cost data regarding prefabrication, transport and specific modular elements, which may lead to inaccurate cost estimates and higher uncertainty when preparing project budgets.

The main risk during the module production factory phase is the change of design or scope of work additions during the ongoing production (C-6) represent the most dominant risk. Similar findings have been reported by [2, 11, 35, 37], who identify design changes as the most critical risk in the implementation of modular construction. [9] also explains that design changes during production are expensive to accommodate as they may interfere with production systems designed based on the principles of standardization and repetition. Therefore, design changes can cause rework, the use of more materials, disruptions to the production fLow, and additional labor costs. This evidence suggests that design stability is a critical prerequisite in realizing the cost efficiencies offered by modular construction.

The main risk in the transportation and logistics phase is damage to modules during handling, loading/unloading or storage (D-2). These results are consistent with [11] who found transportation to be the most vulnerable stage in the modular construction supply chain. [37, 38] report that dynamic responses from vibrations, road conditions, acceleration/braking, maneuvers and wind can damage structural components, interior finishes and module joints, resulting in rework, installation delays and increased costs. [11, 25, 31] also note that transportation costs and risk of damage to modules are major challenges in cost control as the large size and weight of modules lead to high distribution costs and risk of damage during shipping. In Indonesia, this risk may be worsened by the large geographical area, the different quality of transportation infrastructure, and the distance between factories and project locations.

The dominant risk in the on-site construction stage is rework caused by differences between on-site implementation and the working drawings (E-6). The results show that although most of the work has been done at the factory, the risk of cost overrun can still occur during installation if the on-site conditions do not match the design documents. This

finding is in line with [8, 10], who mentioned that rework can decrease the efficiency of modular construction due to interfering with the installation process that has been prepared since the design and manufacturing phases. The literature on cost overruns also consistently mentions rework as the main driver of cost overruns in construction projects because it not only increases direct costs but also indirect costs such as reduced productivity, disruption of workfLow, and project delays [35, 36]. The dominance of these risks shows that coordination between design, manufacturing and installation stages is still a major obstacle in the implementation of modular construction in Indonesia.

To summarize, the research findings show that the main identified risks are similar to several international studies related to modular construction and literature on cost overruns. However, the high prevalence of risks related to design complexity, lack of cost information, design changes during production, module damage during transportation, and rework during installation indicates that the application of modular construction in Indonesia still has difficulties in integrating processes and controlling costs across phases. This finding indicates the importance of an integrated risk management approach from planning to on-site construction in managing potential cost overruns in modular projects.

5. Conclusion

This study develops a risk prioritization model of cost overruns in modular construction by combining Action Priority-based Failure Mode and Effects Analysis (FMEA/AP) with the Dynamic Risk Priority Number (Dynamic RPN). A literature review extracted 34 risk factors, of which 32 were retained after validity screening, and categorized them in five phases of the modular construction cycle: design and planning, construction documentation, off-site module production, transportation and logistics, and on-site construction.

The Action Priority (AP) method provides ordered guidance on action urgency by considering combinations of Severity, Occurrence and Detection. In this dataset, however, all 32 risk factors receive the Low level, so AP alone cannot distinguish their relative dominance. AP was therefore integrated with Dynamic RPN through an explicit rule in which the AP level determines urgency and the dynamic class, derived from the contribution percentage and the percentile rank, orders the risks within each AP level. The integrated result separates the risks into four priority groups (one L-VH, seven L-H, sixteen L-M and eight L-L). This constitutes finer differentiation, not demonstrated higher accuracy, since no external cost benchmark was available for validation.

Prioritization identifies the dominant risks in each phase as folLows: in the design and planning phase: modular design complexity due to inaccuracies in dimensions, positions and inter-module connection systems (A-5); in the construction documentation phase: lack of cost information for specialized modular components (B-4); in the production phase: design or scope changes during module production at the factory (C-6); in the transportation and logistics phase: module damage due to handling, loading/unloading or storage (D-2); and in the on-site construction phase: rework due to discrepancies between on-site execution and drawings (E-6).

The results indicate that the perceived sources of increased cost in modular construction are not only related to the manufacturing phase, which is mostly the focus, but are spread throughout the entire project cycle. Cost risks arise as early as the design stage, continuing through document preparation, the manufacturing process, module distribution, and on-site installation. This situation indicates that effective cost control depends on the level of integration across project phases; therefore, cost control strategies must be implemented in an integrated manner from planning through to on-site module installation. The contribution percentages reported here express shares of the total RPN and should not be read as shares of realized cost overrun.

Theoretically, the work extends FMEA/AP by bringing Dynamic RPN into the same prioritization framework, which makes the assessment more sensitive to how construction risks differ in relative weight. For practitioners, the framework gives contractors, project managers, estimators and project owners a structured way to pick out critical risks and to direct mitigation resources toward the risks that dominate, rather than depending only on conventional priority categories.

The study is limited to practitioners from construction companies involved in modular projects in Jakarta and focuses only on cost-overrun risks. The results may therefore not be representative of other geographical areas or of other dimensions of project performance. The ratings are perception-based, and agreement among respondents is weak (Kendall's W = 0.083-0.144), so individual rank positions, particularly in the middle of the ranking, should be interpreted with caution, and the classification was not validated against recorded project cost data.

Future studies are encouraged to validate the proposed framework against actual cost-overrun records and with respondent-level resampling, to use larger datasets from other regions and countries, to include additional project objectives such as schedule, quality and safety performance, and to extend the integrated prioritization model with root-cause analysis techniques such as Fault Tree Analysis (FTA) to support more effective risk-control strategies.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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