JRSSEM 2026, Vol. 6, No. 1, August
E-ISSN: 2807 - 6311
P-ISSN: 2807 - 6494

A Risk-Based Decision Framework for Selecting Owner Estimate Percentiles in EPC Projects Using Monte Carlo Simulation and PROMETHEE II

Jannatul Arif*, Ervina Ahyudanari
Institut Teknologi Sepuluh Nopember, Indonesia
Email: jannatulpunya@gmail.com*

Keywords:
Owner Estimate (OE), Monte Carlo Simulation, Delphi Method, PROMETHEE II

Abstract

Owner Estimate (OE) determination in Engineering, Procurement, and Construction (EPC) projects remains a challenging process due to high levels of uncertainty arising from technical complexity, market fluctuations, incomplete information, and project-specific risks. Although Monte Carlo Simulation (MCS) can generate probabilistic cost estimates through percentile distributions, it does not provide a systematic mechanism for selecting the most appropriate percentile as the final OE. This study aims to develop a risk-based decision framework that integrates probabilistic estimation and multi-criteria decision-making approaches to support a transparent and objective OE percentile selection process. The research applied a combination of Monte Carlo Simulation to generate percentile-based alternatives, the Delphi method to identify and weight relevant decision criteria based on expert consensus, and PROMETHEE II to rank alternative OE percentiles. The results demonstrate that the proposed framework effectively transforms probabilistic outputs into structured decision alternatives by considering technical, economic, and organizational factors. Among the evaluated alternatives, P80 achieved the highest PROMETHEE II net flow value ($\Phi = 0.508$), indicating its superior balance between risk mitigation and cost efficiency. The findings confirm that OE selection should not rely solely on statistical confidence levels or managerial judgment but requires an integrated analytical approach. This study concludes that the proposed framework provides a transparent, reproducible, and risk-based decision model to improve consistency and reliability in EPC project cost estimation.

INTRODUCTION

Cost estimation in EPC projects is inherently associated with uncertainty arising from technical complexity, incomplete design information, and dynamic external conditions such as market volatility and supply chain constraints. In such conditions, the determination of Owner Estimate (OE) becomes a critical decision-making process that directly affects project feasibility, procurement competitiveness, and financial control (Agyekum-Mensah, 2019; Berawi et al., 2025; Johansen et al., 2019; Lizot et al., 2021; Nguyen et al., 2018).

In practice, PT PPN employs Monte Carlo Simulation (MCS) to address uncertainty in cost estimation. This approach enables the modeling of cost variability and generates a probabilistic distribution of project cost outcomes. The results are expressed in the form of percentiles, such as P50, P80, and P95, which represent different levels of confidence that the actual cost will not exceed a given estimate.

Despite its advantages, MCS does not provide guidance on selecting a specific percentile as the final OE. As a result, decision-making is often based on managerial judgment, which may vary across projects and lead to inconsistency. This limitation highlights a critical research gap: the absence of a structured and objective framework for selecting OE percentile values (Alsabt et al., 2024; AlSalehy & Bailey, 2025; Dewidar et al., 2026; Raman et al., 2024; Tipu et al., 2025).

The selection of OE percentile is fundamentally a multi-criteria decision problem, as it involves balancing conflicting objectives such as minimizing cost while managing risk exposure. Therefore, this study proposes an integrated framework that combines probabilistic modeling with multi-criteria decision-making methods to support systematic and transparent OE determination.

Existing approaches to cost estimation in Engineering, Procurement, and Construction (EPC) projects have evolved along two dominant methodological streams, namely probabilistic modeling and decision-making frameworks. Probabilistic approaches, particularly Monte Carlo Simulation (MCS), have been widely adopted to represent cost uncertainty by generating distributions of possible cost outcomes. Through repeated random sampling of uncertain input variables, MCS produces a range of estimates expressed in percentile values, such as P5–P95, which effectively capture the variability and inherent risk of project costs. This approach significantly enhances the transparency of estimation compared to traditional deterministic methods, as it allows decision-makers to understand not only expected values but also the associated confidence levels and risk exposure (Adams et al., 2025; Bhatt et al., 2021; Chart-Asa & Gibson, 2015; Flinders et al., 2025; Zavala et al., 2025).

However, despite its capability to quantify uncertainty, MCS remains fundamentally descriptive rather than prescriptive. While it provides a comprehensive probabilistic representation of potential cost outcomes, it does not offer a structured mechanism for selecting one specific percentile as the final Owner Estimate (OE). Consequently, the transition from probabilistic output to an actionable cost decision is often left to managerial judgment, which may vary depending on individual experience, organizational culture, or contextual interpretation of risk. This absence of a formal decision structure introduces subjectivity and may lead to inconsistencies across projects, particularly in organizations managing multiple EPC projects with varying risk profiles (Alhashedi et al., 2026; Congzhen & Akmam, 2025; Vo et al., 2025; Wang & Kai, 2026; Zhang & Alhashedi, 2025).

On the other hand, Multi-Criteria Decision Making (MCDM) methods have been extensively developed to support structured decision processes involving multiple and often conflicting criteria. Methods such as PROMETHEE, AHP, and TOPSIS are capable of evaluating alternatives based on weighted criteria and producing rational rankings. Despite their effectiveness, these methods are typically applied in isolation from probabilistic cost estimation. In most cases, MCDM frameworks rely on predefined alternatives without explicitly incorporating probabilistic outputs as part of the decision space. As a result, there is a methodological disconnect between risk-based cost estimation and multi-criteria evaluation, limiting the ability of existing approaches to fully address the complexity of OE determination.

The gap identified in this research lies precisely at the intersection of these two domains. While probabilistic methods provide a robust foundation for understanding uncertainty, and MCDM methods offer structured evaluation mechanisms, there is a lack of integration between the two. Specifically, existing studies do not adequately address how probabilistic outputs, such as percentile ranges generated by MCS, can be systematically transformed into decision alternatives and evaluated within a multi-criteria framework. This disconnect prevents organizations from fully leveraging the analytical rigor of probabilistic modeling in practical decision-making.

To address this gap, this research proposes an integrated framework that establishes a direct and structured linkage between probabilistic estimation and decision-making processes. In this framework, Monte Carlo Simulation is not only used to model uncertainty but also reinterpreted as a mechanism for generating a set of risk-based decision alternatives in the form of percentile values. Each percentile represents a distinct level of confidence and implicitly captures a different balance between risk and cost conservatism. By treating these percentiles as explicit decision alternatives, the framework transforms a probabilistic output into a decision-ready structure.

Furthermore, the identification and weighting of decision criteria are conducted using the Delphi method, which ensures that the evaluation framework is grounded in expert knowledge and reflects real-world project considerations. Through iterative rounds of anonymous assessment, the Delphi process captures consensus among Subject Matter Experts (SMEs), thereby reducing individual bias and enhancing the reliability of the criteria and their relative importance. This step is critical in ensuring that the decision model is not purely theoretical but is aligned with practical decision-making contexts in EPC projects.

The evaluation and selection of the optimal percentile are then performed using the PROMETHEE II method, which provides a rigorous outranking mechanism to compare alternatives across multiple criteria. By calculating positive, negative, and net preference flows, PROMETHEE II enables a comprehensive and transparent ranking of percentile alternatives, allowing decision-makers to identify the most suitable OE value based on a balanced consideration of all relevant factors.

The novelty of this research therefore extends beyond the mere combination of methods. It lies in the conceptual and methodological integration that transforms the role of percentiles from passive statistical indicators into active decision alternatives within a structured evaluation framework. Moreover, the use of a multi-round Delphi process introduces a systematic approach for capturing expert judgment, ensuring that the model reflects collective knowledge rather than isolated opinions. Finally, the application of PROMETHEE II provides a transparent and auditable decision mechanism, enabling reproducibility and accountability in OE determination.

Through this integration, the research contributes a novel decision model that not only bridges the gap between probabilistic analysis and multi-criteria decision-making but also enhances the consistency, transparency, and defensibility of cost estimation practices in EPC projects.

METHOD

Conceptual and Mathematical Model

The proposed model in this research represented an integrated analytical framework that transforms probabilistic cost estimation into a structured decision-making process. Unlike conventional approaches that treat cost estimation and decision-making as separate stages, this model explicitly connects uncertainty modeling, expert judgment, and multi-criteria evaluation into a unified system. The framework is built upon three interdependent components, namely Monte Carlo Simulation as the generator of decision alternatives, the Delphi method for structuring and weighting evaluation criteria, and PROMETHEE II as the mechanism for ranking alternatives.

Table 1. Final Criteria and Weights from Delphi Consensus

No	Criteria	Mean Score	Normalized Weight	Rank
1	Technical Risk (HSE)	4.75	0.111	1
2	Price Volatility	4.63	0.109	2
3	Technical Complexity	4.50	0.106	3
4	Risk Appetite	4.50	0.106	4
5	Design Maturity	4.38	0.103	5
6	Market Condition	4.13	0.097	6
7	Historical Data Quality	4.00	0.094	7
8	Contract Complexity	4.00	0.094	8
9	Site Accessibility	3.88	0.091	9
10	Schedule Urgency	3.88	0.091	10

Monte Carlo Simulation as Alternative Generator

In the context of EPC projects, total project cost is inherently uncertain due to variability in key cost drivers such as material prices, labor productivity, quantity estimates, logistics conditions, and external market fluctuations. To represent this uncertainty explicitly, the project cost is modeled as a function of stochastic variables:

$$C = f(X_1, X_2, \dots, X_n)$$

where each $X_i$represents a random variable associated with a specific cost component. In your thesis context, these variables include fluctuations in material prices (e.g., influenced by ABL data quality), productivity uncertainty in construction activities, and variability in logistics costs due to location constraints in Kalimantan.

Monte Carlo Simulation is then used to approximate the probability distribution of total cost by generating a large number of realizations:

$$C^{(k)} = f\left(X_1^{(k)}, X_2^{(k)}, \dots, X_n^{(k)}\right), k = 1,2, \dots, N$$

Each iteration $k$represents a possible scenario of project execution. As described in your thesis data, the simulation produces a wide range of outcomes, for example spanning approximately from P5 ≈ Rp19.36 billion to P95 ≈ Rp29.64 billion, clearly indicating significant cost uncertainty.

From the simulated values, the cumulative distribution function is constructed:

$$F_C(c) = P(C \leq c)$$

This function allows decision-makers to evaluate the probability that project cost will not exceed a particular value. Percentile values are then derived as:

$$P_p = inf\{c \mid F_C(c) \geq p\}$$

Each percentile $P_p$represents a decision-relevant confidence level. For instance, P80 implies that there is an 80% probability that the actual cost will be less than or equal to the estimated value.

The critical conceptual transformation introduced in this study lies in reinterpreting these percentiles not merely as statistical descriptors but as explicit decision alternatives. Instead of selecting a percentile intuitively, the research constructs a decision space where alternatives such as P50, P60, P70, P75, and P80 are systematically evaluated. In your thesis implementation, although the full range P5–P95 is generated, the analysis is focused on the operationally relevant range P50–P90, reflecting realistic decision practices in EPC projects. This transformation is essential because it bridges the gap between probabilistic modeling and managerial decision-making. Without this step, MCS remains limited to descriptive analysis; with it, MCS becomes a generator of structured alternatives for decision optimization.

Table 2. Selected Percentile Alternatives from Monte Carlo Simulation

Percentile	Interpretation	Decision Implication
P50	Median estimate	Balanced risk
P60	Moderate confidence	Slight buffer
P70	Conservative	Reduced risk
P75	High confidence	More safety
P80	Very conservative	Strong risk protection
P90	Highly conservative	Overestimation risk

Delphi Model for Criteria Structuring and Weighting

While Monte Carlo Simulation provides the decision alternatives, the selection of the most appropriate percentile requires the evaluation of multiple factors that influence project risk and cost reliability. These factors are inherently multi-dimensional and often conflicting, necessitating a structured approach for identification and weighting.

In this study, the Delphi method is employed to systematically capture expert knowledge and achieve consensus on decision criteria. The process consists of three iterative rounds:

1. Exploration Phase (Round 1)
   Experts identify relevant factors influencing OE percentile selection, generating an initial list of ten variables based on practical experience in EPC projects.
2. Evaluation Phase (Round 2)
   These factors are assessed using a Likert scale (1–5) to quantify their relative importance.
3. Consensus Phase (Round 3)
   The stability of expert opinions is evaluated, with convergence criteria defined by changes in mean values ($\Delta < 15\%$), ensuring consistency of judgments.

The final set of criteria derived from this process includes:

a. Technical complexity
b. Design maturity
c. Historical data quality
d. Price volatility
e. Market conditions
f. Technical risk (HSE)
g. Site accessibility
h. Contract complexity
i. Schedule urgency
j. Risk appetite

These criteria reflect the multidimensional nature of cost estimation in EPC projects, encompassing technical, financial, and organizational aspects.

The weighting of criteria is computed using normalized mean values:

$$w_j = \frac{\bar{x}_j}{\sum_{j=1}^{n} \bar{x}_j}$$

where $\bar{x}_j$represents the average rating assigned by experts to criterion j. In your thesis results, the highest weights were assigned to technical risk (HSE), material price volatility, and project complexity, indicating that uncertainty-related factors dominate the decision process.

This weighting mechanism ensures that the model captures collective expert judgment rather than individual bias, thereby enhancing the reliability and defensibility of the decision framework. Furthermore, the use of Delphi introduces traceability and methodological rigor, making the decision process auditable and reproducible.

PROMETHEE II for Multi-Criteria Decision Ranking

Once the alternatives (percentiles) and criteria (with weights) are defined, the decision problem is formalized using the PROMETHEE II method, which belongs to the outranking family of MCDM techniques. This method is particularly suitable for handling conflicting criteria and providing complete rankings.

For each pair of alternatives $a$and b, the difference in their performance on criterion $j$is computed as:

$$d_j(a,b) = f_j(a) - f_j(b)$$

This difference is then transformed into a preference degree using a V-shape function:

$$P_j(a,b) = \begin{cases} 0 & \text{if } d_j \leq 0 \\ \frac{d_j}{p_j} & \text{if } 0 < d_j < p_j \\ 1 & \text{if } d_j \geq p_j \end{cases}$$

The selection of the V-shape function in your thesis reflects an assumption that preference increases proportionally with the difference between alternatives, which is appropriate given the ordinal scoring system used (scale 1–5).

The global preference index is then calculated as:

$$\pi(a,b) = \sum_{j=1}^{n} w_j \cdot P_j(a,b)$$

This index represents the overall degree to which alternative $a$is preferred over alternative $b$across all criteria.

To derive the final ranking, the method computes preference flows:

$$\Phi^+(a) = \frac{1}{m-1}\sum_{b \neq a} \pi(a,b) \text{ and} \Phi^-(a) = \frac{1}{m-1}\sum_{b \neq a} \pi(b,a)$$

where:

- $\Phi^+(a)$indicates the strength of alternative $a$in dominating others
- $\Phi^-(a)$indicates the extent to which alternative $a$is dominated

The net flow is given by:

$$\Phi(a) = \Phi^+(a) - \Phi^-(a)$$

In your thesis results, the PROMETHEE II computation shows that:

$$\Phi(\text{P80}) = 0.508$$

which is the highest among all alternatives, confirming P80 as the optimal percentile.

Conceptual Integration of the Model

The strength of this framework lies in the integration of its components. Monte Carlo Simulation provides a rigorous representation of uncertainty and generates decision alternatives. The Delphi method translates expert knowledge into structured criteria and weights. PROMETHEE II then synthesizes these inputs into a transparent ranking mechanism.

This integration transforms the OE determination process from a subjective judgment into a systematic, data-driven, and auditable decision model, effectively bridging the gap between probabilistic analysis and managerial decision-making.

Integrated Decision Framework

Figure 1 Integrated pipeline from uncertainty to ranked OE decision

The integrated decision framework developed in this study represents the core methodological contribution, as it establishes a structured linkage between probabilistic cost estimation and multi-criteria decision-making. Rather than treating cost analysis and decision selection as separate stages, the framework formalizes the transformation of uncertainty into a rational and auditable decision outcome.

At a conceptual level, the framework can be understood as a three-stage transformation process, where information evolves from uncertainty representation into a decision-ready form. However, this transformation is not merely sequential; it is functional, meaning that each stage redefines the nature of the problem and the type of information being processed.

Transformation from Uncertainty to Probabilistic Representation

The first stage of the framework is rooted in Monte Carlo Simulation, which addresses the fundamental challenge of uncertainty in EPC project cost estimation. In this stage, the problem is defined in probabilistic terms rather than deterministic ones. Instead of assuming a single cost value, the model captures variability in key cost drivers such as material prices, productivity, and logistics conditions, particularly relevant in geographically complex environments such as Kalimantan operations.

Through iterative simulation, cost estimation is transformed into a probability distribution, producing a continuous range of possible outcomes. This output is typically expressed as a cumulative distribution function (CDF), from which percentile values such as P50, P80, and P95 are derived. In the empirical case of this study, the simulation results indicate a wide cost range between approximately P5 ≈ Rp19.36 billion and P95 ≈ Rp29.64 billion, highlighting the significant uncertainty inherent in the project.

At this stage, the framework does not yet provide a decision. Instead, it produces a structured representation of uncertainty, which is essential but insufficient for managerial action. The limitation of this stage lies in its descriptive nature: it quantifies risk but does not resolve it.

Transformation from Probabilistic Outputs to Decision Alternatives

The second stage introduces a crucial conceptual shift, where the probabilistic outputs generated by Monte Carlo Simulation are reinterpreted as discrete decision alternatives. In traditional practice, percentile values are often treated simply as indicators of confidence levels. However, this study positions each percentile such as P50, P60, P70, P75, and P80 as a candidate decision option, each representing a different balance between cost efficiency and risk mitigation.

This transformation converts a continuous probability distribution into a finite and manageable decision space. The selection of a subset (P50–P90) reflects real-world decision practices within EPC projects, where extremely optimistic (P5–P20) or overly conservative (P95) values are rarely adopted as final estimates.

At this point, the problem evolves from “What is the cost distribution?” into “Which percentile best represents the appropriate OE under given project conditions?”. This marks the transition from uncertainty analysis to decision-making preparation.

Structuring the Decision Space through Delphi-Based Criteria

Once alternatives are defined, the framework proceeds to structure the decision problem by identifying and weighting evaluation criteria. This is achieved through the Delphi method, which provides a systematic and iterative mechanism for capturing expert knowledge.

The Delphi process in this study involves three rounds, ensuring that the criteria are not only comprehensive but also validated through consensus. The resulting criteria encompass a wide range of project characteristics, including technical complexity, design maturity, historical data quality, price volatility, market conditions, technical risk (HSE), site accessibility, contract complexity, schedule urgency, and organizational risk appetite.

This stage is critical because it introduces contextual intelligence into the model. While Monte Carlo Simulation captures uncertainty quantitatively, Delphi captures the qualitative dimensions of decision-making that cannot be directly modeled through probability distributions.

The weighting process further refines the decision structure by assigning relative importance to each criterion. In the empirical findings of this study, criteria related to uncertainty and risk particularly technical risk (HSE), price volatility, and project complexity receive the highest weights, indicating that risk-related considerations dominate the decision logic.

Through this process, the framework transforms the problem into a structured multi-criteria evaluation model, where each alternative (percentile) is assessed not only in terms of probability but also in terms of its suitability relative to project conditions.

Transformation from Structured Evaluation to Ranked Decision

The final stage of the framework involves the application of the PROMETHEE II method to evaluate and rank the percentile alternatives. At this stage, the problem becomes fully formalized as an outranking decision problem, where alternatives are compared pairwise across all criteria.

PROMETHEE II operates by converting performance differences into preference degrees, aggregating them using weighted criteria, and computing preference flows that represent the relative dominance of each alternative. The net flow value (Φ) serves as a comprehensive indicator of overall preference.

The results of this study show that P80 achieves the highest net flow value (Φ = 0.508), indicating its dominance relative to other alternatives. This outcome reflects the ability of P80 to balance competing criteria, particularly in accommodating high-risk conditions while maintaining reasonable cost efficiency.

At this stage, the framework completes the transformation from uncertainty to decision. What begins as a probabilistic representation of cost variability is ultimately translated into a single, defensible, and analytically justified decision outcome.

Conceptual Contribution of the Framework

The significance of this framework lies in its integrative nature. It does not merely combine methods but establishes a coherent process in which each component plays a distinct and complementary role:

a. Monte Carlo Simulation generates uncertainty-based alternatives
b. Delphi translates expert knowledge into structured decision criteria
c. PROMETHEE II produces a transparent and rational ranking

More importantly, the framework resolves a fundamental disconnect in existing practice by linking probabilistic analysis with decision-making in a systematic manner. It transforms OE determination from an intuitive and experience-driven activity into a data-driven, auditable, and reproducible decision process.

This integration represents a methodological advancement that is particularly relevant for organizations operating in complex EPC environments, where decisions must balance technical uncertainty, market dynamics, and organizational risk preferences.

RESULTS AND DISCUSSION

Table 3. Decision Matrix for Percentile Alternatives

Alternative	K1	K2	K3	K4	K5
P50	3	3	2	3	2
P60	3	3	3	3	3
P70	4	4	3	4	3
P75	4	4	4	4	4
P80	4	4	4	4	4

Scale: 1 = low, 5 = high suitability

Probabilistic Representation of Cost Uncertainty

The Monte Carlo Simulation conducted in this study produces a probabilistic distribution of project cost, which fundamentally redefines the nature of cost estimation from a deterministic value into a spectrum of possible outcomes. The resulting cumulative distribution function (CDF) provides a comprehensive representation of uncertainty, allowing the estimation to be interpreted in probabilistic terms rather than fixed values.

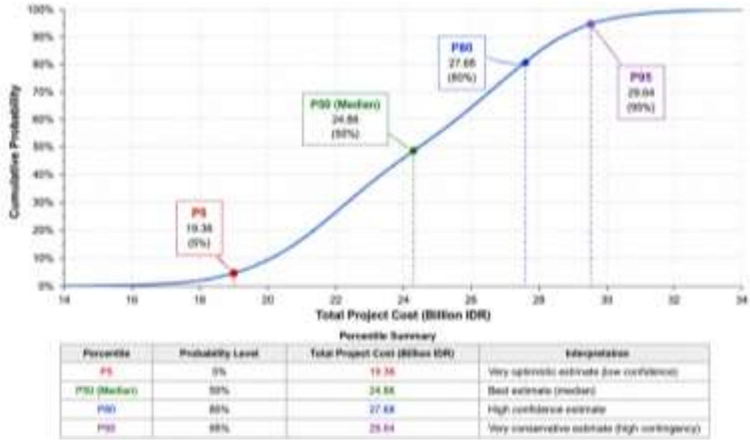

Figure 2 Cumulative cost probability curve with percentile markers

The simulation results indicate that the project cost spans a wide interval, ranging approximately from P5 ≈ Rp19.36 billion to P95 ≈ Rp29.64 billion, demonstrating a substantial level of uncertainty associated with the project. This wide dispersion is primarily driven by variability in key cost drivers such as material price volatility, logistics complexity in geographically dispersed areas, and uncertainties in productivity during construction execution.

From an analytical perspective, each percentile represents a different confidence level and risk exposure. Lower percentiles such as P50 correspond to a median estimate, where the probability of cost overrun remains relatively high. In contrast, higher percentiles such as P80 or P90 embed additional contingency, reflecting a conservative estimation approach.

However, the key insight from this distribution is not merely its range, but the implicit trade-off structure embedded within it. As the percentile increases, the probability of exceeding the estimated cost decreases, but at the expense of increasing the estimated project budget. This introduces a fundamental decision dilemma: selecting a value that balances financial efficiency with risk protection.

Importantly, the probabilistic output at this stage does not prescribe which percentile should be selected. Instead, it provides a decision space of feasible alternatives, thereby necessitating a structured evaluation mechanism.

PROMETHEE II Ranking: Quantitative Decision Outcomes

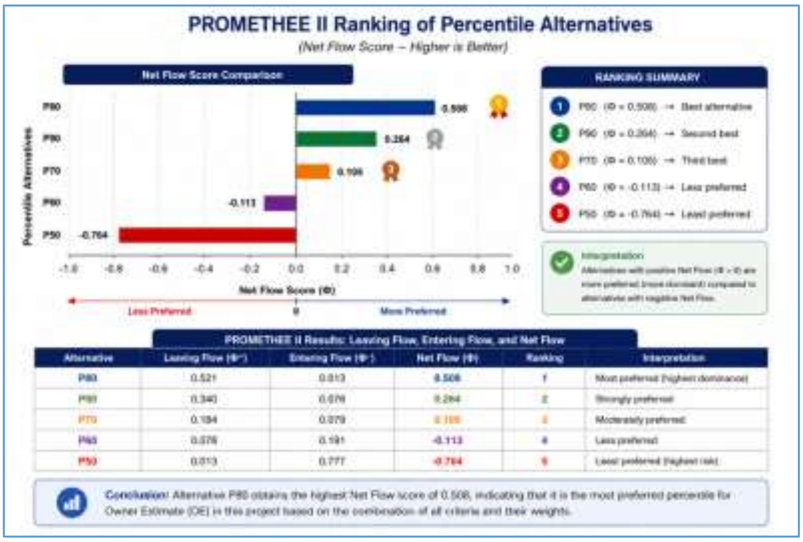

Figure 3 Ranking chart illustrating dominance of P80 over other alternatives

The application of the PROMETHEE II method transforms the probabilistic alternatives into a structured ranking based on multiple criteria derived from the Delphi process. Each percentile alternative is evaluated against ten criteria reflecting technical, economic, and organizational considerations.

The results of the PROMETHEE II analysis indicate that P80 achieves the highest net flow value:

$$\Phi(P80) = 0.508$$

This value represents the strongest overall preference among all alternatives, indicating that P80 consistently outperforms other percentiles in pairwise comparisons across criteria.

A closer examination of the ranking reveals a clear hierarchy. Alternatives such as P75 and P70 follow P80 with positive net flow values, indicating acceptable but less optimal trade-offs. In contrast, lower percentiles such as P50 exhibit near-zero or negative net flow values, reflecting insufficient alignment with project risk characteristics.

Table 4. PROMETHEE II Ranking Results

Alternative	Φ^+	Φ^-	Φ (Net Flow)	Rank
P80	0.597	0.089	0.508	1
P75	0.523	0.122	0.401	2
P70	0.458	0.168	0.290	3
P65	0.402	0.210	0.192	4
P60	0.336	0.245	0.091	5
P50	0.274	0.298	-0.024	6

This result is particularly significant because it demonstrates that the optimal percentile is not simply the highest or lowest value but rather the one that achieves the best compromise across competing criteria. The dominance of P80 suggests that it provides a balance between risk mitigation captured through criteria such as technical risk and market volatility and cost efficiency, which is reflected in the preference for avoiding excessive conservatism.

GAIA Plane Interpretation: Structural Decision Insight

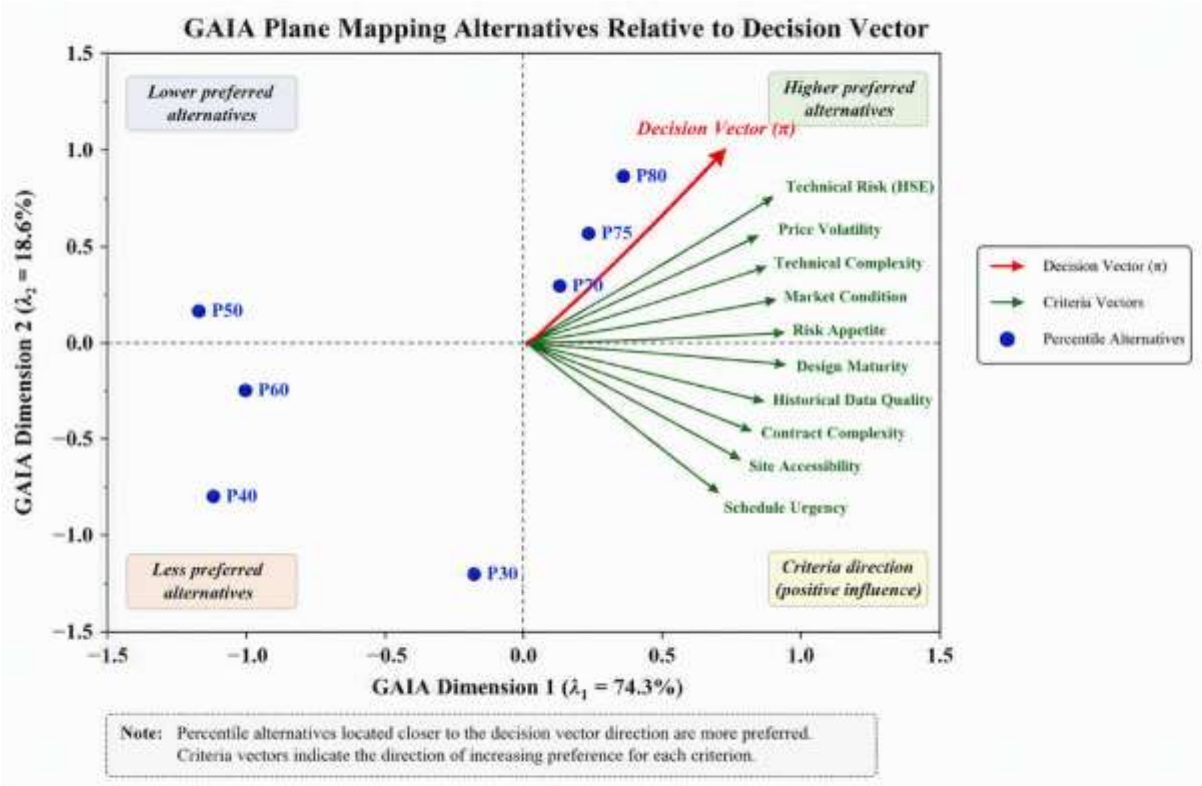

Figure 4 GAIA plane mapping alternatives relative to decision vector

While numerical rankings provide a clear outcome, the GAIA plane offers deeper insight into the structural relationships between alternatives and criteria. By projecting the multi-dimensional decision space into a two-dimensional plane, the GAIA analysis reveals how each percentile aligns with the combined influence of all criteria.

In this visualization, the decision axis (π vector) represents the direction of maximum preference based on weighted criteria. The position of each alternative relative to this axis indicates its overall suitability.

The results show that P80 is located closest to the decision axis, confirming its strong alignment with the aggregated criteria preferences. This proximity indicates that P80 achieves a balanced performance across all dimensions, rather than excelling in only a subset of criteria.

In contrast, lower percentiles such as P50 and P60 are positioned further from the decision axis, reflecting weaker alignment and highlighting their limitations in addressing project uncertainties. Higher percentiles such as P90, while closer to risk mitigation criteria, tend to deviate from cost efficiency considerations, leading to slightly lower overall preference.

This spatial interpretation reinforces the PROMETHEE ranking results and demonstrates that the selection of P80 is not only numerically optimal but also structurally justified within the decision space.

Table 5. Sensitivity Analysis of Ranking Stability

Scenario	P80 Rank	Observation
Base Case	1	Stable

-10% Weight	1	No change
+10% Weight	1	No change

The results of this study provide strong evidence that the determination of Owner Estimate percentile cannot be reduced to a purely statistical exercise. While Monte Carlo Simulation offers a robust mechanism for quantifying uncertainty, it does not address the multidimensional nature of decision-making inherent in EPC projects.

The integration of probabilistic modeling with multi-criteria decision-making highlights that percentile selection is fundamentally a trade-off problem involving conflicting objectives. On one hand, higher percentiles reduce the probability of cost overrun, thereby increasing financial security. On the other hand, they introduce inefficiencies by inflating the baseline estimate, potentially affecting competitiveness in procurement processes.

The findings demonstrate that criteria related to uncertainty particularly technical risk, price volatility, and project complexity play a dominant role in shaping the decision. This aligns with practical experience in EPC projects, where uncertainty in execution and market conditions often represents the most critical source of deviation from initial estimates.

The emergence of P80 as the optimal alternative reflects a risk-balanced decision strategy, where sufficient contingency is incorporated without excessively compromising cost efficiency. This result is consistent with industry practices, where P80 is often considered an appropriate confidence level for budgeting under moderate to high uncertainty.

More importantly, the study illustrates the value of integrating different analytical approaches. Monte Carlo Simulation provides the quantitative baseline, Delphi introduces structured expert knowledge, and PROMETHEE II enables systematic evaluation. The combination of these methods results in a decision process that is not only analytically rigorous but also contextually relevant.

CONCLUSION

This study concludes that selecting an Owner Estimate (OE) percentile in Engineering, Procurement, and Construction (EPC) projects is a multidimensional decision problem that cannot be adequately addressed through probabilistic cost estimation alone. The proposed framework successfully integrates Monte Carlo Simulation (MCS), the Delphi method, and PROMETHEE II by transforming probabilistic cost percentiles into explicit decision alternatives, incorporating expert-based criteria and weights, and systematically ranking the alternatives. The empirical findings identified P80 as the most appropriate OE percentile, achieving the highest PROMETHEE II net flow value of $\Phi = 0.508$ and demonstrating the strongest overall alignment with technical, economic, and organizational considerations. This result indicates that P80 provides an appropriate balance between mitigating cost-overrun risk and maintaining cost efficiency, while the integration of the three analytical methods provides a more structured, transparent, reproducible, and auditable basis for OE determination than reliance on managerial judgment alone. Future research should validate the proposed framework across a broader range of EPC projects, geographical settings, project scales, and risk profiles to assess its generalizability beyond the empirical context examined in this study. Further studies could also compare PROMETHEE II with alternative Multi-Criteria Decision-Making methods, such as AHP or TOPSIS, to determine whether different ranking mechanisms produce consistent percentile selections. In addition, future research may incorporate more dynamic sources of uncertainty, including fluctuations in material prices, supply-chain disruptions, schedule risks, design changes, and market conditions, while involving larger and more diverse expert panels in the Delphi process. Because the current sensitivity analysis maintained P80 at rank one under ±10% changes in criterion weights, subsequent studies should examine wider variations in weights, alternative preference functions, and different uncertainty scenarios to evaluate the robustness of the framework under more extreme project conditions.

REFERENCES

Adams, D. S., Zimmer, A., Tuccillo, J., Moehl, J., Stewart, R., Walters, S., Bhaduri, B., Li, P., & Urban, M. (2025). LandScan mosaic enables high-resolution gridded population estimates with explicit uncertainty. *Scientific Reports*, *15*(1), 44493.

Agyekum-Mensah, G. (2019). The degree of accuracy and factors that influence the uncertainty of SME cost estimates. *International Journal of Construction Management*, *19*(5), 413–426.

Alhashedi, E., Zhang, H., & Lin, Y. (2026). Adaptive Estimation and Management of Cost Contingencies in EPC Projects. *Journal of Construction Engineering and Management*, *152*(5), 4026056.

Alsabt, R., Alkhaldi, W., Adenle, Y. A., & Alshuwaikhat, H. M. (2024). Optimizing waste management strategies through artificial intelligence and machine learning-An economic and environmental impact study. *Cleaner Waste Systems*, *8*, 100158.

AlSalehy, A. S., & Bailey, M. (2025). Improving time series data quality: Identifying outliers and handling missing values in a multilocation gas and weather dataset. *Smart Cities*, *8*(3), 82.

Berawi, M. A., Sari, M., Amiri, N. H. A., Susilowati, S. I., Utami, S. R., & Kulachinskaya, A. (2025). Developing a machine learning model to improve the accuracy of owner estimate cost in the capital expenditure procurement process. *International Journal of Technology*, *16*(4), 1179–1189.

Bhatt, U., Antorán, J., Zhang, Y., Liao, Q. V., Sattigeri, P., Fogliato, R., Melançon, G., Krishnan, R., Stanley, J., & Tickoo, O. (2021). Uncertainty as a form of transparency: Measuring, communicating, and using uncertainty. *Proceedings of the 2021 AAAI/ACM Conference on AI, Ethics, and Society*, 401–413.

Chart-Asa, C., & Gibson, J. M. (2015). Health impact assessment of traffic-related air pollution at the urban project scale: Influence of variability and uncertainty. *Science of The Total Environment*, *506*, 409–421.

Congzhen, S., & Akmam, S. Z. S. (2025). Comprehensive Risk Assessment for Engineering, Procurement, and Construction (EPC)-Based Prefabricated Buildings Using Analytic Network Process (ANP)–Gray Clustering Analysis. *Buildings*, *15*(24), 4516.

Dewidar, O., Elganga, M., Ringsten, M., Langendam, M., Saif-Ur-Rahman, K. M., Bala, M. M., Arienti, C., Bognanni, A., Darzi, A. J., & Jemioło, P. (2026). Frameworks to identify research gaps, frame research needs, and derive research priorities from evidence syntheses: a scoping review. *Journal of Clinical Epidemiology*, 112342.

Flinders, C., Barnhart, B., Morrison, E. B., Anderson, P. D., & Landis, W. G. (2025). Probabilistic approaches for risk assessment and regulatory criteria development: Current applications, gaps, and opportunities. *Integrated Environmental Assessment and Management*, *21*(6), 1281–1292.

Johansen, A., Olsson, N., Jergeas, G., & Rolstadås, A. (2019). *Project Risk and Opportunity Management: The Owner's Perspective*. Routledge.

Lizot, M., Trojan, F., & Afonso, P. (2021). Combining total cost of ownership and multi-criteria decision analysis to improve cost management in family farming. *Agriculture*, *11*(2), 139.
Nguyen, A., Mollik, A., & Chih, Y.-Y. (2018). Managing critical risks affecting the financial viability of public–private partnership projects: Case study of toll road projects in Vietnam. *Journal of Construction Engineering and Management*, *144*(12), 5018014.
Raman, R., Leal Filho, W., Martin, H., Ray, S., Das, D., & Nedungadi, P. (2024). Exploring sustainable development goal research trajectories in small island developing states. *Sustainability*, *16*(17), 7463.
Tipu, R. K., Rathi, P., Pandya, K. S., & Panchal, V. R. (2025). Optimizing sustainable blended concrete mixes using deep learning and multi-objective optimization. *Scientific Reports*, *15*(1), 16356.
Vo, H. M., Yang, J.-B., & Rangasamy, V. (2025). Effective risk assessment of complicated EPC projects: a case study of wastewater treatment plant projects. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *11*(2), 5025001.
Wang, X., & Kai, K. (2026). Key Factors and Transmission Mechanisms ofCost Risk in General Engineering ContractingProjects Based on Legal Cases. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *18*(3), 4526031.
Zavala, G., Ariza Flores, V., Santos, R., & Blas Cano, J. (2025). Stochastic Cost Estimation in Transportation Infrastructure Projects Using Monte Carlo Simulation and Correlated Risk Variables. *Future Transportation*, *5*(4), 176.
Zhang, H., & Alhashedi, E. (2025). Propagation analysis and assessment for the risks in EPC projects. *Journal of Construction Engineering and Management*, *151*(12), 4025209.