A Hybrid Monte Carlo-AHP Based Model for Integrated Risk Management of Material Delivery Delays in Construction Supply Chain

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Abstract

Material delivery delays in construction supply chains constitute critical disruptions that compromise project schedules and escalate operational costs. Conventional deterministic risk assessment models inadequately capture the stochastic uncertainties and multidimensional complexities inherent in supply chain disruptions, necessitating advanced probabilistic methodologies. This investigation develops an integrated Monte Carlo simulation (MCS) and Analytic Hierarchy Process (AHP) framework for comprehensive risk evaluation and prioritization. AHP methodology systematically derives priority weights for critical risk factors including supplier reliability, transportation constraints, meteorological conditions, and geopolitical variables through structured expert pairwise comparisons. These weights are subsequently integrated with MCS to execute 10,000 probabilistic scenario iterations, quantifying delay impact distributions. The analytical framework identifies supplier reliability and transportation issues as dominant risk contributors, generating mean delays of 1.96 and 1.45 days respectively within the total mean delay of 4.85 days, with 95th percentile delays reaching 8.13 days. This hybrid methodology effectively synthesizes quantitative stochastic modeling with qualitative expert judgment, providing robust decision-support capabilities for supply chain risk management and enhancing project resilience.

Keywords: Monte Carlo Simulation; Analytic Hierarchy Process (AHP); Material Delivery Delays; Construction Supply Chain; Risk Assessment

1. Introduction

The construction industry demonstrates critical dependence on sophisticated supply chain networks to facilitate timely procurement and delivery of essential materials including structural steel, concrete assemblies, and prefabricated components [1], [2], [3]. These supply chain systems exhibit increasing vulnerability to multifarious unpredictable disruptions encompassing supplier reliability failures, transportation network constraints, and exogenous factors including adverse meteorological conditions and geopolitical instabilities [4], [5], [6], [7]. Material delivery delays constitute substantial risks to project scheduling integrity, precipitating cost escalations and compromising stakeholder credibility [8], [9]. As construction projects demonstrate escalating complexity, particularly within urban development and infrastructure sectors, systematic risk assessment and mitigation methodologies have transitioned from optional considerations to critical success determinants [10], [11], [12].

Conventional supply chain risk management approaches predominantly utilize deterministic modeling frameworks, which demonstrate inadequate capacity for addressing inherent uncertainties and variabilities characteristic of real-world operational environments [13], [14], [15]. Probabilistic analytical techniques, particularly Monte Carlo simulation methodologies, have emerged as sophisticated tools for uncertainty modeling through comprehensive simulation of potential

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outcome ranges. These methodologies demonstrate particular efficacy in material delivery delay assessment, accommodating the stochastic nature of factors including supplier performance variability and transportation network reliability [16], [17], [18], [19].

Previous investigations have implemented Monte Carlo simulation within construction supply chain risk management contexts. Panova and Hilletofth [20] demonstrated Monte Carlo model effectiveness in supply chain disruption evaluation, emphasizing safety stock implementation for delay mitigation. Sadeghi et al. [21] developed Monte Carlo-based frameworks for uncertainty modeling in construction cost estimation procedures. These studies, however, predominantly focus on quantitative risk factors while inadequately incorporating subjective assessments essential for real-world decision-making processes.

The integration of Analytic Hierarchy Process (AHP) within risk assessment frameworks addresses the imperative for qualitative factor consideration in construction supply chain management [22], [23], [24]. AHP provides structured methodologies for risk assessment and prioritization based on expert judgment, enabling comprehensive evaluation of supply chain vulnerabilities [25], [26]. Multiple studies have demonstrated AHP utility in construction project risk management applications, including cost estimation and risk prioritization procedures [22], [27]. AHP has been systematically applied in material supplier evaluation and logistical risk assessment, where expert subjective assessments are integrated with quantitative data to inform decision-making processes [28], [29]. However, while AHP demonstrates effectiveness in subjective judgment integration, it faces criticism regarding limited probabilistic modeling capabilities and reliance on pairwise comparison procedures that may introduce systematic biases [30], [31].

To address these methodological limitations, this investigation develops a hybrid model integrating Monte Carlo simulation with AHP to incorporate both quantitative and qualitative uncertainties. The Monte Carlo simulation component enables comprehensive simulation of multiple potential outcomes, providing probabilistic perspectives on material delivery risks, while the AHP component captures expert opinions and prioritizes critical risks based on structured subjective assessments. This hybrid approach constitutes a comprehensive framework for material delivery delay assessment, enhancing risk evaluation processes by systematically addressing both objective data and expert insights.

This research extends published literature demonstrating dynamic modeling roles in supply chain disruption evaluation through systematic AHP integration with Monte Carlo simulation methodologies. The investigation offers enhanced modeling capabilities for construction supply chain risk evaluation, particularly regarding material delivery delay phenomena. The hybrid model provides valuable insights to project managers, facilitating informed decision-making processes and improving construction supply chain resilience capabilities.

2. Methodology

2.1 Data Collection

Data was collected through a structured survey targeting industry professionals. The survey included 100 respondents representing project managers, supply chain managers, and contractors from various geographical regions. The survey captured subjective assessments of four primary risk factors, see Table 1.

Table 1: Risk factors assessed in survey

Sr No	Risk Factors
1	Supplier Reliability
2	Transportation Issues
3	Weather Conditions
4	Geopolitical Factors

The responses were analyzed to derive pairwise comparisons for the AHP and statistical distributions for Monte Carlo simulation inputs.

2.2 Analytic Hierarchy Process (AHP)

The AHP was employed to prioritize the risk factors based on expert judgment. The steps for AHP implementation are detailed below.

2.2.1 Pairwise Comparison Matrix

A pairwise comparison matrix was constructed to evaluate the relative importance of the risk factors. The matrix is defined as

$$A = \begin{bmatrix} 1 & \frac{4}{3} & 2 & 4 \\ \frac{3}{4} & 1 & \frac{3}{2} & 3 \\ \frac{1}{2} & \frac{2}{3} & 1 & 2 \\ \frac{1}{4} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix}$$

2.2.2 Normalization and Weight Derivation

The matrix was normalized by dividing each element by the sum of its column. The normalized values were averaged across rows to compute the priority weights of the risk factors. The weights derived from the survey responses are presented in Table 2.

Table 2: Weights of Risk Factors

Risk Factor	Weight
Supplier Reliability	0.40
Transportation Issues	0.30
Weather Conditions	0.20
Geopolitical Factors	0.10

2.2.3 Consistency Ratio (CR)

To verify the logical consistency of the pairwise comparison matrix, the Consistency Ratio (CR) is computed as:

$$CR = \frac{CI}{RI}$$

where:

CI: Consistency Index, which is defined as

$$CI = \frac{\lambda max - n}{n - 1}$$

where:

λmax: The largest eigenvalue of the pairwise comparison matrix

n: The number of factors (e.g., 4 in this case)

RI: Random Index, For a 4x4 matrix, the Random Index is predefined as 0.90 (based on Saaty's AHP guidelines).

The CR value is considered acceptable if CR< 0.1

2.3 Monte Carlo Simulation (MCS)

The Monte Carlo simulation was applied to quantify the probabilistic impact of each risk factor on material delivery delays. This involves the following steps:

2.3.1 Input Data

Probability distributions for each risk factor were determined based on survey data as given in Table 3.

Table 3: Input Data

Risk Factor	Distribution	Mean (days)	Standard Deviation
Supplier Reliability	Normal	5	2
Transportation Issues	Log-normal	3	1.5
Weather Conditions	Exponential	2	-
Geopolitical Factors	Uniform	0.5 to 1.5	-

2.3.2 Simulation Process

Random values were sampled 10,000 times from the respective distributions for each risk factor. Delays were calculated by applying the AHP-derived weights to the sampled values:

$$D_{total} = \sum_{i=1}^{n} w_i D_i$$

where:

- wi: The AHP-derived weight for the i-th risk factor.
- Di: The randomly sampled delay for the i-th risk factor.
- n: The total number of risk factors (e.g., n=4 in this case).

Metrics such as mean delay, standard deviation, and 95th percentile delay were computed from the simulation results.

$$Mean\ Delay\ (\mu) = \frac{1}{N}\sum_{j=1}^{N} D_{total,j}$$

where

N=10,000 is the total number of simulations, and Dtotal,j is the total delay for the j-th simulation.

$$\boldsymbol{Standard\ Deviation}\ (\sigma) = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(D_{total,j} - \mu\right)^2}$$

The 95th percentile delay is computed by sorting the simulated D total values and identifying the delay value at the 95th percentile of the distribution.

2.4 Computational Implementation

The methodology was implemented using Python. Libraries such as NumPy and SciPy were used for statistical analysis, and Matplotlib was employed for visualizing simulation outputs. A histogram of the total delays from Monte Carlo simulation was generated to depict the probability distribution.

3. Results and Analysis

The Monte Carlo simulation, based on 10,000 iterations, quantified the probabilistic impact of risk factors on material delivery delays. Key metrics and insights derived from the simulation are presented in Table 4.

Table 4: Key Metrics From Simulation

Metric	Value (Days)
Mean Delay	4.85
Standard Deviation	1.76
95th Percentile of Delay	8.13

3.1 Analysis of Total Delays

The histogram of total delays demonstrates, as shown in Figure 1, that most delays cluster around the mean delay of 4.85 days. The 95th percentile indicates that delays exceeding 8.13 days are rare, accounting for only 5% of all simulations.

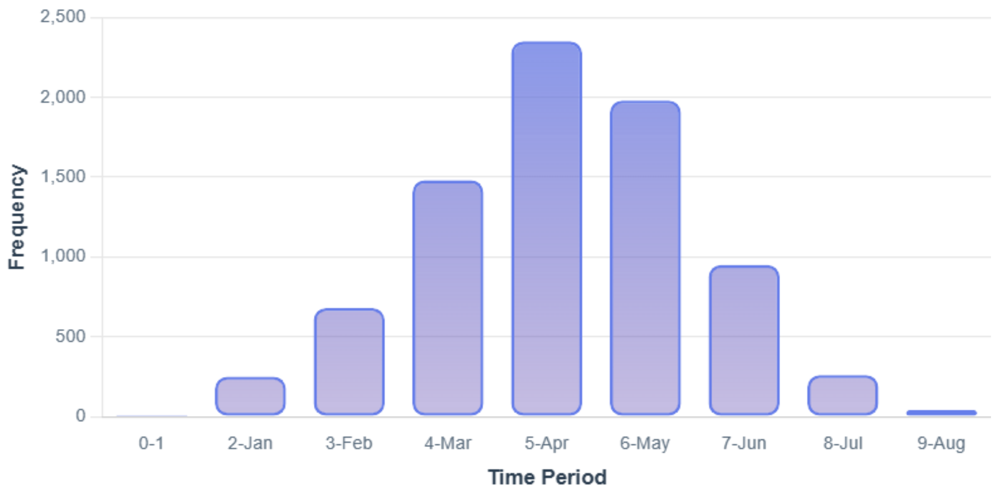

Figure 1: Histogram of total delays based on the Monte Carlo simulation

3.2 Contribution of Risk Factors

The contribution of each risk factor to the total delay was assessed based on AHP-derived weights and probabilistic inputs. The average contributions are shown in Figure 2.

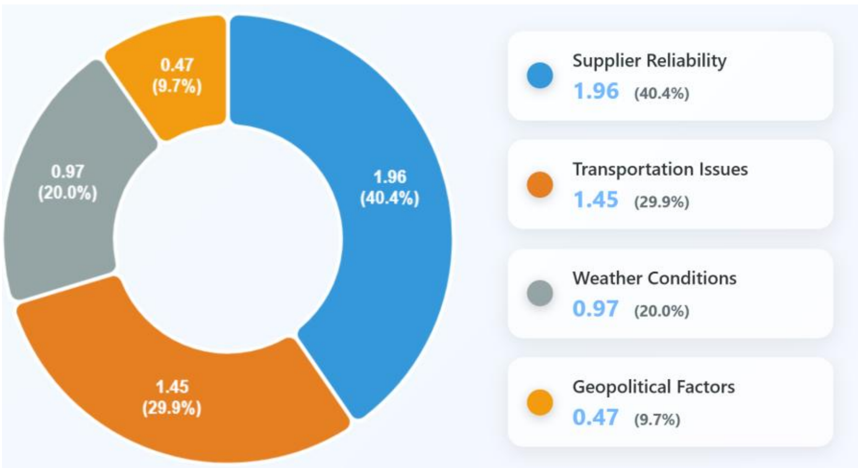

Figure 2: Contribution of Risk Factors

5. Conclusions

This study employed a hybrid Monte Carlo simulation (MCS) and Analytic Hierarchy Process (AHP) approach to evaluate and prioritize risks associated with material delivery delays in the construction supply chain. The findings underscore the criticality of supplier reliability and transportation issues as primary contributors to delays, while also highlighting the utility of probabilistic and qualitative methods in risk assessment. By combining quantitative simulations with expert judgments, the methodology provides a comprehensive framework for identifying and mitigating risks. The following conclusions are drawn from the analysis.

- Supplier reliability emerged as the most significant contributor to material delivery delays, with an average impact of 1.96 days. This highlights the importance of robust supplier evaluation, diversification, and contingency measures such as maintaining safety stocks.
- Transportation-related delays contributed an average of 1.45 days, emphasizing the need for predictive logistics tools, route optimization, and real-time tracking systems to enhance supply chain efficiency.

- Weather conditions and geopolitical factors accounted for 0.97 days and 0.47 days, respectively. While these risks are less critical, they require attention in regions prone to extreme weather or political instability to avoid potential disruptions.
- The integration of Monte Carlo simulation and AHP provides a balanced approach to risk assessment, accommodating both quantitative variability and qualitative expert insights. This model is particularly effective in guiding decision-making under uncertainty.
- The methodology's reliance on expert judgment and predefined probability distributions introduces potential biases and assumptions. Future research should focus on incorporating dynamic risk factors, leveraging machine learning for predictive modeling, and expanding the scope of risk factors for a more holistic assessment.

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