Mathematical Modelling of Risk Management in the Shipping Industry

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Abstract
Supply chain risk management (SCRM) is primarily a process of systematic identifying, assessing, and mitigating risks within supply chain systems. Despite its complexity and criticality, the offshore and marine industry, particularly the rig-building segment has received limited attention in SCRM literature. This study centers on managing risks in oil rig building projects. A structured risk mitigation framework is proposed to comprehensively identify potential risks, filter out minor ones, and prioritize the remaining based on their impact. A mathematical model is then developed to analyze one of the most significant risks: raw material price fluctuation. To quantify this risk, Monte Carlo simulation is applied using the Risk Solver platform. The study presents two case scenarios demonstrating the implementation of various risk management strategies and evaluates their effectiveness in enhancing the resilience of the rig-building supply chain.

Keywords: Risk management, simulation, risk mitigation, marine and offshore industry.

Introduction

In the era of globalization, managing supply chain risks has become a critical focus across various industries, including the marine and offshore sectors. These industries operate in complex, high-stakes environments where risk events, if not properly addressed can propagate throughout the supply chain, affecting multiple stakeholders. While many organizations strive to anticipate and mitigate risks before they materialize, the effectiveness of these preventive measures often involves trade-offs that require scenario-based evaluation and strategic decision-making. Importantly, risks not effectively managed within an organization can cascade to other entities in the supply chain, underscoring the need for a coordinated and data-driven approach to risk management.

Despite a growing awareness of supply chain risk management (SCRM), one of the persistent challenges is the difficulty in quantifying risks and conducting scenario analyses without robust data support. In response, numerous mathematical and simulation-based models have been developed to enhance decision-making in risk-prone environments. For instance, Pujawan and Geraldin introduced the "House of Risk" (HOR) model, which operates in two stages: HOR1 ranks risk agents based on their risk potential, while HOR2 prioritizes proactive actions to address the most critical risks. Similarly, Wang et al. proposed a controllable risk transmission model that clarifies how risks are transferred between supply chain entities, specifically from raw material suppliers to construction enterprises. Liu et al. contributed to the field by using multistage influence diagrams, enabling both controllable and uncontrollable risks to be evaluated graphically and systematically.

While research in SCRM is expanding, covering industries such as energy, pharmaceuticals, construction, and software, there remains a notable gap in the literature concerning the marine and offshore industries. Existing studies often lack comprehensive mitigation frameworks and simulation models tailored to the complex supply chains within this sector. Given the high capital intensity, project complexity, and logistical challenges of marine operations, especially in oil rig construction, there is a pressing need for specialized risk management approaches.

This paper aims to address that gap by developing a quantitative risk management framework specifically for the rig-building segment of the shipping industry. Using Monte Carlo simulation, the study seeks to model and quantify one of the most pressing risks, raw material price fluctuations and demonstrate how simulation tools can inform more resilient and data-driven supply chain decisions.

Methodology

To analyze and measure the risks, this paper proposes the following framework which is divided into four main steps and a quantitative method that takes place before the risk management step:

Figure 1. Framework of Risk Mitigation Process

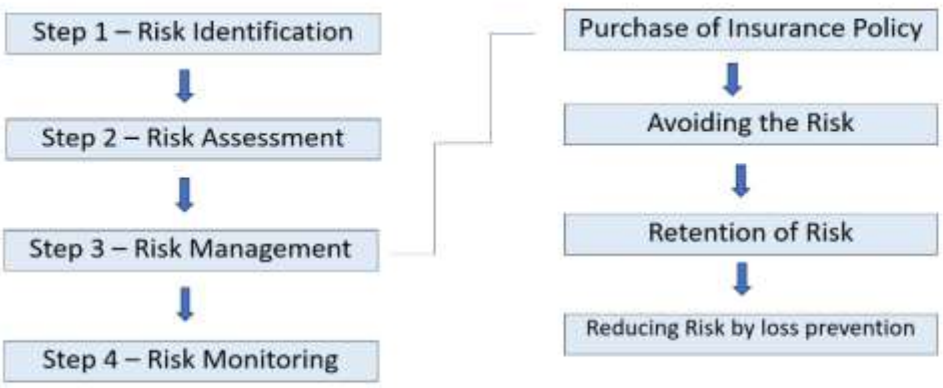

Figure 1 – Framework of Risk Mitigation Process

Step 1: Risk Identification

The foundational step in understanding and managing risk transfer within supply chains is the systematic identification of risks specific to the context under examination. Through thorough investigation and research, one can uncover the challenges and disruptions these risks may pose to the supply chain system. Once sufficient information is gathered, the next step involves selecting and applying an appropriate method for identifying the full spectrum of relevant risks. The choice of method often depends on the nature of the industry and the specific operational context.

Several widely recognized approaches to risk identification include:

1. **Scenario-Based Analysis** – This method involves envisioning alternative pathways to achieving a particular objective. Risks are identified by analyzing events that could trigger deviations or failures in these scenarios, particularly those leading to undesired outcomes.
2. **Taxonomy-Based Approach** – This technique involves a structured breakdown of potential risk sources. A comprehensive questionnaire is developed based on industry best practices and domain knowledge. The responses to this questionnaire help reveal specific risks relevant to the organization or project.
3. **Common Risk Checklists** – In many industries, standardized lists of known risks have been developed over time. These checklists serve as a valuable reference for validating which of the predefined risks are applicable in a given situation

Step 2: Risk Assessment

Primary Elimination of Identified Risks

The risk assessment process begins with an initial screening stage aimed at filtering out low-impact and low-probability risks identified during the risk identification phase. This step is essential to ensure that attention and resources are focused on the most critical risks that could disrupt the supply chain.

In the first stage of assessment, the we adopt a qualitative evaluation approach based on informed judgment and expert insight to categorize risks by their likelihood of occurrence and potential severity of impact. Risks deemed to have both a low probability and minimal organizational impact are eliminated from further consideration.

However, it is important to acknowledge that risk assessment must extend beyond evaluating isolated nodes of the supply chain. The potential for risk transfer must also be considered. A risk that appears negligible within one department or function may escalate in impact if transmitted to another part of the supply chain, where its consequences could be more severe. Therefore, the assessment framework must incorporate a holistic, system-wide perspective to capture the dynamic and interdependent nature of risk propagation across the supply chain.

This dual-stage approach enables the organization to focus on significant and transferable risks, laying the groundwork for more precise modeling and mitigation in subsequent phases

Formulation of the Mathematical Model

In the second stage of the risk assessment process, a mathematical model is developed to analyze and prioritize the most critical risks retained after the preliminary screening. This stage requires that the risks under consideration be quantifiable meaning they must be expressed in measurable terms to allow for accurate modeling and simulation.

The quality and reliability of the model depend heavily on the availability of prior data. Accurate, context-specific data ensures that the model reflects real-world behavior and enhances the credibility of the results. To validate the model and enhance its robustness, two key evaluation techniques can be employed:

1. **Empirical Fit Testing through Cross-Validation** – This method involves partitioning available data into two subsets: a training dataset, which is used to estimate the model parameters, and a validation dataset, which is used to test the model's predictive performance. This approach helps verify whether the model maintains accuracy when exposed to new, unseen data from the same system.
2. **Scope Assessment** – This evaluation focuses on determining the range of data and operating conditions to which the model remains applicable. Understanding the model’s scope ensures that it is not only accurate but also generalizable within the defined system boundaries.

Once the quantifiable risks and associated variables are defined, and the model is evaluated appropriately, the next step is to incorporate uncertainties and constraints into the framework. These arise from different types of risks such as fluctuations in raw material prices, demand variability, or logistical delays.

The finalized mathematical model is then subjected to Monte Carlo simulation using the Risk Solver platform. This simulation technique allows for the modeling of uncertainty by running thousands of iterations based on probabilistic inputs. The Risk Solver program enables analysts to observe the impact of each risk on key performance metrics such as net profit and to determine which risks exert the most significant influence. The results provide a basis for prioritizing risks according to their potential impact, thereby supporting informed decision-making in subsequent risk mitigation strategies

Step 3: Risk Management

Once the critical risks have been identified, assessed, and prioritized through quantitative modeling, the next step involves implementing appropriate risk management strategies. This phase focuses on applying effective and feasible control measures, starting with the highest-priority risks as determined in the preceding steps. Various mitigation strategies are proposed and evaluated to determine their suitability and effectiveness within the operational context of the offshore rig-building supply chain.

The following are key approaches commonly adopted in supply chain risk management:

a) Risk Transfer via Insurance: One of the most widely used strategies is to transfer the financial burden of risk to a third party by purchasing an insurance policy. This method allows the organization to maintain its operational structure and strategic objectives while shifting potential losses to an insurer. It is particularly useful for risks that are infrequent but have high financial impact.

b) Risk Avoidance: This approach involves eliminating activities that give rise to specific risks. While theoretically effective, risk avoidance is generally considered impractical in most business contexts, as it often entails forfeiting potential opportunities. Therefore, it is used sparingly and typically only in extreme cases where the risk outweighs the benefits of the activity.

c) Risk Retention: Risk retention—either consciously or passively—is one of the most common strategies. Organizations may opt to absorb certain risks, particularly when the cost of mitigation exceeds the potential loss. In some instances, minor risks may not be formally recognized or documented but are nonetheless tolerated because they pose limited threat to operational performance.

d) Risk Reduction through Loss Prevention and Control: This method emphasizes minimizing the likelihood or severity of risk through preventive measures. Common examples include implementing fire protection systems, installing security alarms, conducting regular equipment maintenance, and ensuring adequate healthcare and emergency services. These controls help to reduce both the probability of occurrence and the impact of adverse events.

Each risk management technique must be selected based on a thorough cost-benefit analysis and alignment with the organization's risk appetite and operational capabilities. Where appropriate, simulation tools like the Risk Solver platform can be used to model and compare the potential effectiveness of various control strategies under different scenarios.

Step 4: Risk Monitoring

The final phase of the risk management process is continuous risk monitoring. No risk mitigation strategy is flawless from the outset; the effectiveness of any risk management plan is best evaluated over time through implementation, real-world feedback, and analysis of actual outcomes. As the business environment evolves and new risks emerge, the original risk assumptions and control strategies may become outdated or insufficient.

Ongoing risk monitoring is therefore essential to ensure the adaptability and relevance of the risk management framework. This step involves periodic reviews and updates of the risk analysis findings and mitigation strategies to achieve the following objectives:

a) Effectiveness Validation

Regular monitoring helps determine whether the existing risk control measures remain effective in mitigating previously identified risks. Through performance metrics and incident analysis, organizations can assess whether their strategies are delivering the intended outcomes.

b) Responsiveness to Emerging Risks

Given the dynamic nature of supply chain operations and external market conditions, new risks can arise that were not previously identified. Continuous monitoring allows organizations to recognize these evolving threats promptly and adapt their risk management strategies accordingly, maintaining alignment with operational realities and strategic goals.

Risk monitoring should be embedded into the organization’s governance and operational processes. It may involve the use of key risk indicators (KRIs), feedback loops from operational teams, regular audits, and scenario-based reviews. Leveraging tools such as simulation software and data analytics can further enhance the organization’s ability to track risk exposure and make timely adjustments.

Case Study

To facilitate the development of an effective risk simulation model, an overview study was conducted on the supply chain dynamics of the marine and offshore industry, with a specific focus on the procurement and management of steel, a critical raw material in oil rig construction. This analysis is crucial in enabling firms to enhance forecast accuracy, optimize purchasing strategies, and minimize unnecessary expenditure in a volatile market environment.

The marine and offshore sector faces several prevalent risks, including but not limited to project delays, fluctuations in raw material prices, limited storage capacity, and dependency on single-source suppliers. For the purpose of this study, the risk of raw material price fluctuation, specifically in the steel supply chain was selected for detailed modelling and simulation.

Two procurement strategies were compared in this context: the **Make-to-Order (MTO)** policy and the **Purchase-in-Abundance (PIA)** policy. The following constraints and assumptions were applied in formulating the mathematical model:

i. **Steel Plate Quantity**: The average steel requirement for a single oil rig construction project is estimated at 6,000 metric tonnes.
ii. **Steel Plate Price**: Market prices for steel plates ranged between INR 53,281 and INR 69,041 per metric tonne, based on actual price data collected between January and February 2024.
iii. **Inventory Holding Cost Rate**: A monthly holding cost of 5% of the total steel value was applied, representing opportunity costs and storage expenses.
iv. **Stock Keeping Period**: Excess steel inventory is assumed to be stored for a maximum of two months before usage.

Comparison of Procurement Strategies

- **Make-to-Order (MTO)**: Under this traditional approach, the procurement department acquires steel only after the company secures a confirmed order for an oil rig. While this method avoids holding costs, it exposes the organization to raw material price volatility, particularly if prices spike post-contract.
- **Purchase-in-Abundance (PIA)**: This strategy involves proactively purchasing steel when market prices dip below a predefined threshold. The acquired inventory is intended to cover the needs of at least two upcoming rig projects. Although this approach mitigates price fluctuation risks, it incurs storage and holding costs, introducing a trade-off between price stability and inventory overhead.

The comparative analysis and simulation of these policies help determine which strategy offers greater resilience to price fluctuations in the context of a volatile supply chain environment. Using Monte Carlo simulations executed through the Risk Solver platform, the study assesses the impact of each strategy on cost efficiency and project risk exposure

Simulation Results and Analysis

To evaluate the impact of the Make-to-Order (MTO) and Purchase-in-Abundance (PIA) procurement strategies on the overall risk profile of the marine and offshore supply chain, a Monte Carlo simulation was conducted using the Risk Solver software. Monte Carlo simulations were conducted to quantify risk exposure, optimize procurement costs, and evaluate the financial impact of raw material price fluctuation with and without the aid of forecasting and market monitoring tools.

1. Simulation Objective and Setup

The primary objective was to compare the True Total Cost of steel procurement under two strategies:

- **MTO**: Steel plates are purchased only upon receipt of a rig-building contract.
- **PIA**: Steel plates are bought in advance in large quantities when market prices are favorable, covering two projects (12,000 metric tonnes total), but incurring inventory holding costs.

Key simulation parameters included:

- Steel price distributions using **triangular probability functions** derived from historical prices (January–February 2024).
- Inventory holding cost: 5% of the inventory value per month.
- Storage duration: Two months.

Software Used: Risk Solver with 1,000 Monte Carlo iterations per simulation run.

2. Make-to-Order Policy Simulation

Price Distribution (INR/tonne):

- Minimum: 53,281
- Most Likely: 62,203
- Maximum: 69,041
- Distribution: PsiTriangular(53281, 62203, 69041)

Formulas Used:

- Total Steel Cost (1 rig, 6000 tonnes): =Price * 6000
- Total Cost (2 rigs): =Total * 2
- True Total Cost: =PsiMean(Total Cost over 1000 trials)

Results Summary:

Statistic	Value (INR)
Mean	738,375,323
Minimum	642,731,952
Maximum	825,501,001
Standard Deviation	38,753,579
Mode	748,132,593
Range	182,769,048

This simulation shows high sensitivity to market fluctuations, with a broad range of possible cost outcomes and a higher mean procurement cost.

Purchase-in-Abundance Policy Simulation

Price Distribution (INR/tonne):

- Minimum: 53,281
- Average: 57,701
- Maximum: 62,203
- Distribution: PsiTriangular(53281, 57776, 62270)

Formulas Used:

- Steel Cost (2 rigs): = Price * 12000
- Inventory Holding Cost (2 months): = (Steel Cost * 0.05 * 0.5) * 2
- Total Cost: = Steel Cost + Holding Cost
- True Total Cost: = PsiMean(Total Cost over 1000 trials)

Results Summary:

Statistic	Value (INR)
Mean	727,981,922
Minimum	673,615,228
Maximum	782,718,589
Standard Deviation	23,127,289
Mode	727,870,522
Range	109,103,361

This simulation demonstrates lower average costs and significantly reduced cost variability due to proactive monitoring and advance purchasing.

Comparative Analysis

Metric	Make-to-Order (MTO)	Purchase-in-Abundance (PIA)
Mean Cost (INR)	738,375,323	727,981,922
Cost Variability (Std Dev)	38,753,579	23,127,289
Minimum Cost	642,731,952	673,615,228
Maximum Cost	825,501,001	782,718,589

- The **PIA policy** results in a **lower mean cost** and **reduced cost volatility**, even after accounting for the inventory holding charges.
- The **MTO policy**, while leaner in inventory, is highly vulnerable to price surges and lacks predictability in procurement budgeting.
- Forecasting and market monitoring prove critical to cost optimization in the **PIA scenario**, reducing average cost by **INR 10.4 million** compared to MTO.

The simulation validates that a Purchase-in-Abundance strategy supported by market forecasting and monitoring provides a more resilient and cost-effective procurement framework for the marine and offshore steel supply chain. Despite incurring holding costs, the strategy minimizes risk exposure and improves financial predictability, making it the preferred choice in a volatile commodity market.

Conclusion:

This research provides a structured exploration into the marine and offshore industry's complex supply chain, specifically within the rig-building segment where high-value, high-risk projects are the norm. Despite being a capital-intensive and technically demanding sector, existing procurement and supply chain mechanisms often overlook inherent vulnerabilities, particularly the financial impact of raw material price fluctuations. This study highlighted how such oversights could lead to significant cost overruns and eroded profit margins.

To address this, a risk mitigation framework was developed and applied to one of the industry's most critical challenges**:** steel price volatility. The framework adopted a systematic approach identifying, assessing, managing, and monitoring risk using a quantitative model focused on steel, the primary raw material in oil rig construction. The study introduced and compared two procurement strategies “Make-to-Order” and “Purchase-in-Abundant” through Monte Carlo simulations. The results clearly indicated that implementing forecasting and price monitoring mechanisms could yield tangible cost savings, thereby validating the practicality of a proactive, data-driven procurement strategy.

While the model serves as a valuable foundational tool, it is not without limitations. The scope was intentionally narrowed to steel plates for simplification, though rig construction also relies on other critical materials such as copper, aluminum, and oil-based components. Future iterations of this research should incorporate these commodities for a more comprehensive cost analysis. Moreover, the assumption of uniform project size and revenue omits market variability. By integrating historical revenue data from past projects, the model's accuracy and predictive power could be significantly enhanced.

In summary, this paper not only underscores the importance of risk-aware procurement in the shipbuilding and offshore engineering industry but also provides a replicable analytical model for improving supply chain resilience. With further refinement, such frameworks can serve as critical decision-support tools for firms aiming to thrive in a volatile global marketplace.

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