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Original Article

Empirical Analysis of Time-Cost Risk Coupling in Construction Projects using FMEA, Correlation, and Regression Models

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Abstract - *Construction project time and cost overruns continue to pose a significant performance challenge, hindering financial viability, delivery certainty, and stakeholder confidence. Although time and cost overruns are common, treating them as separate issues often diminishes the effectiveness of risk mitigation strategies. Current research is often limited to either a single aspect of delay or cost escalation, or it relies on qualitative rankings and complex predictive models that lack substantial empirical evidence regarding the general causes and systematic transformation of time-based risks into cost overruns. This research focuses on empirically studying the coupling of time and cost risks in construction projects by combining Failure Mode and Effects Analysis (FMEA) with statistical correlation and FMEA with statistical regression models, and conceptually relating the results to Earned Value Management (EVM) indicators. Major factors that cause internal and external delays are identified and quantified in terms of FMEA-derived Risk Priority Numbers for time and cost (Time-RPN and Cost-RPN). The magnitude of factors with regard to risk and time is tested with a Pearson correlation study, and regression analysis is conducted factor-wise to determine the contribution of each factor while predicting the cost risk and the contribution of time risk. The results reveal that the time–cost coupling is quite beneficial, and statistically significant results are obtained for all significant risk factors of Delay, thus validating the idea of schedule-related risks as cost escalation indicators. From the results of the regression analysis, it can be seen that there are risks related to time that significantly affect the variability of the project costs, in particular related to the availability of labor, time for design changes, and coordination problems. The robustness of the proposed framework was verified through the sensitivity analysis, with results being very close (ρ = 0.952 - 0.988) for different alternative weighting scenarios. The relationship between an EVM indicator and the schedule inefficiencies is now empirically proven and can be used to act sooner before any financial consequences may occur. The transparent framework developed in this study is based on an empirical process and can be used to establish a time-driven risk governance process that assists in schedule control, serving as a proactive measure to avoid cost overruns in construction projects.*

Keywords - *Construction risk management, Correlation analysis, Earned Value Management (EVM), Failure Mode and Effects Analysis (FMEA), Regression analysis, Time–cost coupling.*

1. Introduction

Construction projects are prone to cost overrun and schedule delays, which are, in most cases, interdependent and driven by multifaceted risk factors [1]. Over the last 10 years, methodologies have diverged from conventional risk assessment to newer and more sophisticated modelling for quantitative analysis [2-5] and fuzzy logic-based models [6] to perform results due to the increasing need for accurate prediction and management of project uncertainties [7, 8]. The practical significance of the conducted research is underscored by statistics showing that about 86% of construction projects face a cost overrun bringing the dire need for integrated risk analysis frameworks to improve project delivery outcomes [9, 10]. Existing studies frequently either address time and cost risk separately, or they are based on isolated methods such as the hybrid method [11] or fuzzy logic [12], which may omit the interdependencies and dynamic correlations between risk factors [15, 16]. Moreover, while FMEA has been widely adopted to overcome risk identification and prioritization [15], the ability to integrate correlations and regression analyses, which can be used to measure the impact of risk interactions on the project objectives [16]. Contradictive views exist about the appropriate methodology to capture these complexities [17], where some stress on AI and machine learning approaches for predictive accuracy, while others express the relevance of interpretability and practicality of the integrated statistical and fuzzy-based approaches [9, 18]. In response to the identified limitations, an increasing need has emerged for an empirical and interpretable framework that explicitly quantifies the coupling between time-related and cost-related risks in construction projects. While advanced approaches such as fuzzy logic, simulation, and machine learning have proven to be compelling predictors, one issue that often restricts their openness and practical use by project managers is their complexity. Moreover, the existing FMEA-based studies mainly focus on risk prioritization without statistical validation of how the time overruns lead to cost overruns. The novelty of this study is the explicit combination of FMEA-derived risk indices with correlation and regression models for the empirical validation of time cost risk coupling instead of treating the time and cost risks separately. Unlike previous research involving methods that use black boxes or simulations, this work defines a transparent and data-driven methodology that measures quantitatively the strength, direction, and predictability of interactions between time and costs through easily interpretable statistical measures. Furthermore, the study contributes to the existing literature by relating FMEA-based risk prioritization with empirical statistics validation to fill the gap between qualitatively identifying risks and quantitatively modeling performance. By anchoring analysis in observed data and focusing on interpretability, the proposed framework is a contribution that brings a practically implementable approach to proactive construction risk management and decision-making.

1.1. Research Objectives

The study explores the relationship between time-related and cost-related risks. Specific objectives are the following:

1. To use Failure Mode and Effects Analysis (FMEA) to identify and prioritize key time-related and cost-related risk factors influencing the performance of construction projects.
2. Perform the Pearson correlation analysis to analyze the strength of the association between the time risk and cost risk.
3. To develop regression models that quantify the predictive influence of risks related to time on risks related to cost.
4. To interpret the time–cost risk relationship from a project control perspective using Earned Value Management (EVM) principles.

2. Study of Literature

Table 1 shows literature on the integrated application of FMEA, correlation, and regression techniques in the analysis of time-cost-risk coupling in construction projects, with a focus on diverse methodologies that address the complex interdependencies between the time, cost, and risk factors.

Table 1. Comparative review of previous studies

Study	Integration Level	Risk Coupling Characterization	Predictive Accuracy	Methodological Diversity	Practical Applicability
[1]	High integration of FMEA, regression, and simulation	Quantitative via Monte Carlo and regression correlation	High accuracy with 4-6% deviation from actuals	Delphi, FMEA, Monte Carlo, regression	Validated on real road projects in Iran
[7]	Fuzzy logic models for time, cost, and risk in construction	Fuzzy inference and case-based reasoning for cost and schedule	Flexible scheduling and cost estimation under uncertainty	Fuzzy logic, CBR, Mamdani inference	Construction investment risk and cost modeling
[8]	Integrated FMEA with fuzzy logic and simulation	Fuzzy logic combined with Monte Carlo for risk interdependencies	Improved schedule reliability under uncertainty	Expert judgment, fuzzy logic, Monte Carlo	Applied to project scheduling with expert input
[9]	Bayesian network integrating risk correlations for prediction	BN classifier modeling interdependent cost overrun risks	High prediction accuracy (~79%) outperforming NB and DT	Bayesian networks, ML classifiers, feature selection	Cost overrun prediction in construction projects
[10]	Risk prioritization with regression and correlation	Regression and P-I matrix for risk impact on cost/time	Strong correlation coefficients indicate risk impact	Survey, regression, P-I matrix, interviews	Regional construction projects in Ethiopia
[19]	Integration of WBS with linear regression for task forecasting	Linear regression for task completion prediction	Strong predictive performance with low error	WBS, linear regression, data analytics	Construction project performance management
[13]	Monte Carlo simulation with subjective correlation in FMEA	Subjective correlation matrices for contingency estimation	Accurate cost contingency estimation with/without simulation	Monte Carlo, fuzzy logic, correlation analysis	Cost data from multiple construction databases
[16]	Hybrid FMEA with ANFIS and fuzzy	Fuzzy AHP combined with FMEA for cost-time impact	Enhanced assessment accuracy over traditional FMEA	ANFIS, fuzzy AHP, hybrid modeling	Applied to troubled Iraqi building projects

	AHP for risk prioritization				
[18]	AI and ML for predictive analytics in project management	Linear regression and correlation for effort and duration	Reasonable effort estimation with data-driven insights	AI, ML, regression, correlation analysis	Software project resource and risk management
[20]	Choquet integral FMEA for green retrofit project risks	Fuzzy FMEA with triangle fuzzy numbers for risk ranking	Quantitative risk assessment with preference relations	Fuzzy FMEA, Choquet integral	Public building green retrofit projects in China
[21]	Regression machine learning for duration and resource prediction	Support vector regression with cross-validation for accuracy	High accuracy (80-82%) in duration and labor estimates	SVR, ridge regression, Gaussian NB regressor	Data from 186 construction projects with uncertainties
[22]	Fuzzy grey comprehensive evaluation for construction risks	Grey correlation and fuzzy theory for phase risk assessment	Identified phase-specific risk impacts on cost and quality	Fuzzy theory, grey correlation	Tendering phase risk in a residential complex
[23]	Moderate integration; correlation with survey data	Qualitative and correlation analysis of delay drivers	Moderate, focused on change management impact	Mixed methods: survey, case study, correlation	Applied to hospital construction project data
[24]	Integrated risk and quality in scheduling with optimization	Correlation and sensitivity analysis of time-cost-quality-risk	Effective multiobjective optimization outcomes	Python-based optimization, correlation, and sensitivity	Applied to building project scheduling scenarios
[25]	Fuzzy chance-constrained programming with scheduling	Triangular fuzzy numbers and genetic algorithm for tradeoffs	Superior risk management in repetitive projects	Fuzzy logic, genetic algorithm, scheduling, and repair	Street renovation project case study
[26]	Fuzzy Delphi and FFMEA integrated with fuzzy inference system	Fuzzy inference for the productivity impact of risk factors	Quantified risk impacts on time, cost, and quality	Fuzzy Delphi, FFMEA, fuzzy inference system	PPP urban underground construction projects
[27]	Machine learning models for time-cost tradeoff prediction	ML algorithms, including MLP, Bayesian networks for prediction	High accuracy (~96%) in time-cost tradeoff forecasting	ML algorithms, Delphi survey, questionnaire	Managerial aspects of tradeoff in construction projects
[28]	FMECA with regression for formwork cost and failure analysis	Regression modeling of failure mode costs in formwork	High accuracy (89%) in cost prediction	FMECA, regression, semi-structured interviews	Building construction projects in the UAE
[29]	Comparative analysis of risk score calculation methods	Statistical methods, including PCA, logistic regression, and clustering	The multiple-attribute approach showed the highest efficiency	PCA, logistic regression, clustering	Cost overrun causes evaluation in urban projects
[30]	FMEA combined with fuzzy logic for risk evaluation	Fuzzification of RPN values for risk prioritization	More accurate risk ranking than traditional FMEA	Fuzzy logic, MATLAB simulation, surveys	Case study on mixed-use construction projects
[31]	Fuzzy FMEA integrated with adaptive buffer sizing	FFMEA combined with APRT for realistic schedule buffers	More realistic scheduling under uncertainty	Fuzzy logic, buffer management, APRT	Renewable energy construction project case study
[32]	Integrated FMEA-SWARA-WASPAS under a fuzzy environment	Multicriteria fuzzy decision-making for risk assessment	Effective risk prioritization in an Iranian construction project	Fuzzy MCDM, FMEA, SWARA, WASPAS	Case study in Iran construction project
[33]	Correlation and PCA integrated with FMEA for cost risk	Pearson correlation, PCA, and decision trees for cost overrun	Effective identification of cost overrun indicators	PCA, decision trees, correlation analysis	Analysis of 55 road construction contracts

[34]	FMEA with probabilistic preferences and multicriteria weighting	The CPP method to consider risk interrelationships	Improved prioritization in complex scenarios	CPP, multicriteria decision-making, FMEA	Oil and gas project risk prioritization
[35]	Integrated fuzzy expected value and FMEA for metro rail risk	Fuzzy expected value combined with FMEA for risk quantification	Improved risk analysis for mega infrastructure projects	Fuzzy logic, expected value, FMEA	Elevated metro rail project in India
[36]	Hybrid MADM and failure analysis for project configuration	Integrated FTA-DFMEA with AHP-TOPSIS for failure prioritization	Effective time and cost reduction through configuration	FTA, DFMEA, AHP-TOPSIS, WBS	Building construction project configuration
[37]	Statistical computing with regression and correlation for delays	Regression and variance analysis for delay cause identification	Effective identification of delay-prone activities	Statistical software, regression, correlation	Industrial construction project data analysis
[38]	Fuzzy MCDM integrated with FMEA and linear programming	Fuzzy SWARA, PROMETHEE, and multiobjective programming	Prioritized HSE risks with optimized response strategies	Fuzzy MCDM, linear programming, FMEA	Oil and gas construction project risk planning
[39]	DEA and machine learning integrated for risk management	DEA cross-efficiency combined with ML for risk prediction	Enhanced risk level evaluation and monitoring	DEA, machine learning, FMEA	Logistics business risk management under COVID-19
[40]	Multiobjective optimization for time-cost-quality tradeoff	NSGA-II genetic algorithm for tradeoff solutions	Practical tradeoff identification with quality improvement	Multiobjective optimization, genetic algorithms	Construction project planning with 20 activities
[41]	Fuzzy-AHP and simulation for cost-risk contingency framework	Fuzzy logic and Monte Carlo for cost-risk contingency estimation	Practical contingency model for metropolitan transit projects	Fuzzy AHP, Monte Carlo simulation	Metropolitan rapid transit project budgeting
[42]	Multiobjective optimization with risk correlation for safety	Fuzzy measure and particle swarm optimization for risk control	Improved safety risk reduction with cost minimization	Fuzzy measure, MOPSO, risk correlation	Prefabricated building construction safety
[43]	Fuzzy combinatorial optimization for cost-time-quality-risk	Innovative fuzzy algorithms for ambiguous risk tradeoffs	Robust fuzzy optimization for multi-dimensional tradeoffs	Fuzzy logic, novel algorithms	Fully fuzzy four-dimensional tradeoff problem
[44]	FMEA combined with big data and regression for quality risk	Regression and ANN for schedule-quality risk correlation	Improved prediction of quality risk linked to the schedule	Big data analytics, ANN, regression, FMEA	Shanghai apartment construction projects
[45]	Time-dependent hierarchical FMEA with probabilistic loss model	Probabilistic loss modeling replacing traditional RPN	Quantitative risk evaluation over time in a hierarchical structure	Probabilistic modeling, hierarchical FMEA	Application in failure causes economic loss estimation
[46]	Fuzzy logic model for risk effects on construction activities	Fuzzy logic with correlation tests for cost and time impact	Accurate quantification of cost overruns and delays	Fuzzy logic, Spearman/Kendall correlation	HVAC system activities in real projects

2.1. Integration Level

- 15 of the studies showed a high level of integration of FMEA with correlation and regression techniques, including the use of fuzzy logic and simulation applications for comprehensive risk analysis in most cases.
- Several studies used moderate integration in which the correlation or regression was used separately, in addition to qualitative methods.
- Some research focused on the use of hybrid models that coupled FMEA with machine learning or multicriteria decision-making to improve risk prioritization.

2.2. Risk Coupling Characterization

- 12 studies were quantitative using methods such as Monte Carlo simulation, fuzzy logic, and probabilistic models to account for the interdependencies between time and cost risk.
- Correlation analysis and regression were extensively applied to the identification and modelling of risk coupling effects within the time delays and cost overruns.
- A few studies proposed new methods, such as Bayesian networks and fuzzy grey correlation, to address complex risk interactions.

2.3. Predictive Accuracy

- 10 of the studies indicated high predictive accuracy, with predictive models being close to actual project outcomes or showing superior forecasting capabilities.
- Several studies pointed to the improvement of the risk prediction when fuzzy logic or machine learning is combined.
- Some models exhibited moderate accuracy, often due to data constraints or the provision of qualitative information.

2.4. Methodological Diversity

- A variety of analytical tools were applied, which are generally used for analysis.
- Specific parts of the risk were also tackled using innovative solutions like the Pythagorean fuzzy digraph, Choquet integral and big data analytics.
- Many studies still relied on traditional statistical techniques, such as regression, PCA and correlation analysis.

2.5. Practical Applicability

- 20 studies used construction project data from the real world across different geographic locations to validate the models, maximizing practical value.
- Most of the frameworks designed for usability and democratized the decision-making the decision-making tools at the disposal of the project manager and stakeholders.

A few models are still theoretical in nature or derived in specific scenarios and need to be improved to support wider use. Studies were categorized based on their predominant methodological approach to locate the proposed framework among the previous studies. The comparison reveals the weaknesses and strengths of the various research streams, as well as the present study's ability to combine the concepts of risk prioritization, statistical validation, and project control in a combination. Table 2 shows a comparative analysis.

Table 2. Comparative analysis of existing and proposed approaches

Research Category	Representative Studies	Key Strength	Limitation	Advancement in the Present Study
Fuzzy Logic-Based Risk Assessment	[7 , 16, 30, 35, 47]	Handles uncertainty and expert judgement effectively	Complex implementation and limited interpretability	Uses transparent statistical validation of time–cost relationships
Simulation and Probabilistic Models	[1, 8, 13, 41, 48]	Strong predictive capability under uncertainty	Computationally intensive and difficult for practitioners	Provides a simple empirical framework using FMEA and regression
AI and Machine Learning Approaches	[9, 18, 21, 27, 49, 50]	High prediction accuracy	Black-box nature and limited managerial interpretability	Offers explainable relationships between time and cost risks
Correlation and Regression-Based Studies	[10, 19, 23, 37, 51]	Quantifies risk relationships	Generally, lacks integration with structured risk prioritization methods	Integrates FMEA, correlation, regression, and EVM interpretation
Present Study	Current Research	Integrated time–cost risk coupling framework	—	Combines risk prioritization, statistical validation, and project control interpretation in a single framework

It has been seen in the studies reviewed here that substantial achievements have been made in construction risk assessment by using fuzzy logic, simulation techniques, machine learning models, and statistical approaches.

However, the majority of the studies in the literature have only a single goal—either risk prediction, risk prioritization, or risk forecasting—and a few studies have considered the empirical interaction between time-related and cost-related risks.

3. Research Gap

Although much research exists on construction risk management, most suffer from one or more of the following limitations:

- Fragmented treatment of time and cost risks- Time and cost overruns are often treated separately without assessing the empirical validity of their interrelations.
- FMEA used only as a ranking tool- Traditional FMEA studies prioritize risks but do not statistically examine how time-related risks propagate down to cost overruns.
- Lack of empirical coupling models- Many of the studies performed are based on fuzzy logic or simulation, or an AI model that provides predictive power but lacks interpretability with respect to time-cost interactions.
- Weak linkage between risk analysis and project control systems- Existing research rarely connects risk prioritization results with operational control tools such as Earned Value Management.

This means that there is a need to develop a unified and coherent framework that can combine risk prioritization with statistical validation for use in proactive project control and decision-making. Thus, it is still needed: an open, statistically validated, and implementable framework that can quantify the interaction between time-related and cost-related risks. This study aims to fill this gap by combining FMEA-based risk prioritization with correlation and regression techniques to investigate the time–cost risk coupling and to provide a proactive project control approach in an empirical study.

3.1. Novelty and Contributions

The contribution of the study is the integrated and interpretable framework developed to analyze the time–cost risk coupling in construction projects, which is a novelty. Past research is largely focused on risk prioritization, simulation-based forecasting, fuzzy logic approaches, or developing machine learning models; however, few efforts have been made to establish an empirical link between time-related risks and cost-related risks using statistically transparent methods.

This research has been seen to make the major contributions listed below:

1. A combination of the three methods (Failure Mode and Effects Analysis (FMEA), Pearson correlation analysis, and regression modelling) under a single roof in construction risk.
2. Empirical quantification of the values of Time-RPN and Cost-RPN, establishment of statistical validation for time–cost risk coupling.
3. Construction of factor-wise regression models for examining the predictive effects of time-related risks on the cost-related risks.
4. Applying the lessons learned from statistical results using Earned Value Management (EVM) principles to improve real-world project decisions and control.
5. Provision of a meaningful approach alternative to complex simulation-based and black box type of predictions that are reported in the literature.

The framework combines principles of risk prioritization, statistical validation, and project control interpretation to assist in a comprehensive understanding of the potential pathways through which scheduling risks may have indirect impacts on project cost performance.

4. Methodology

Based on the above, Figure 1 depicts an integrated methodology for time-cost risk coupling analysis in construction projects using FMEA. The Process begins by collecting data on the construction process and identifying major risks; then, the impact of these risks, their causes, and the measures in place to control them are evaluated.

The risks are investigated using the FMEA parameters occurrence, severity, and detection to determine Risk Priority Numbers (RPN) for time and cost impacts. Afterwards, the generated Time RPN and Cost RPN values are considered for a statistical analysis of the correlation and regression models to do an empirical study of the Time-Related and the Cost-Related Risk coupling.

Given a mix of FMEA and statistical results, a determination of the need for corrective actions, suggestions for mitigation, responsibilities, and process changes is made, ultimately leading to an FMEA report for decision support.

4.1. Data Collection and Risk Identification

A structured questionnaire survey was used to identify and evaluate the major risk factors that lead to the time and cost overruns in residential township construction projects in Tier 1 and Tier 2 cities of Maharashtra. First, possible risk factors were derived from the extensive volumes of literature published and from discussions with construction experts. From this Process, 10 factors were identified as critical risks: delays in statutory approvals, design changes, poor planning and control, financial instability, labor problems, material supply problems, problems with coordinating the parties, availability of equipment, weather problems, and regulatory changes.

A questionnaire was sent to construction practitioners with different professional backgrounds and levels of experience on residential township projects in Tier 1 and Tier 2 cities, which yielded a valid response from 227 practitioners. The respondents were asked to evaluate the likelihood of each risk factor occurrence, its effect on the project time, and its effect on the project cost on a 5-point Likert scale from 1 (Very Low) to 5 (Very High).

The responses gathered were used as the basis for the following Failure Mode and Effects Analysis (FMEA), correlation analysis, and regression modeling performed to determine the relationship between the construction risk categories that are time-related and cost-related.

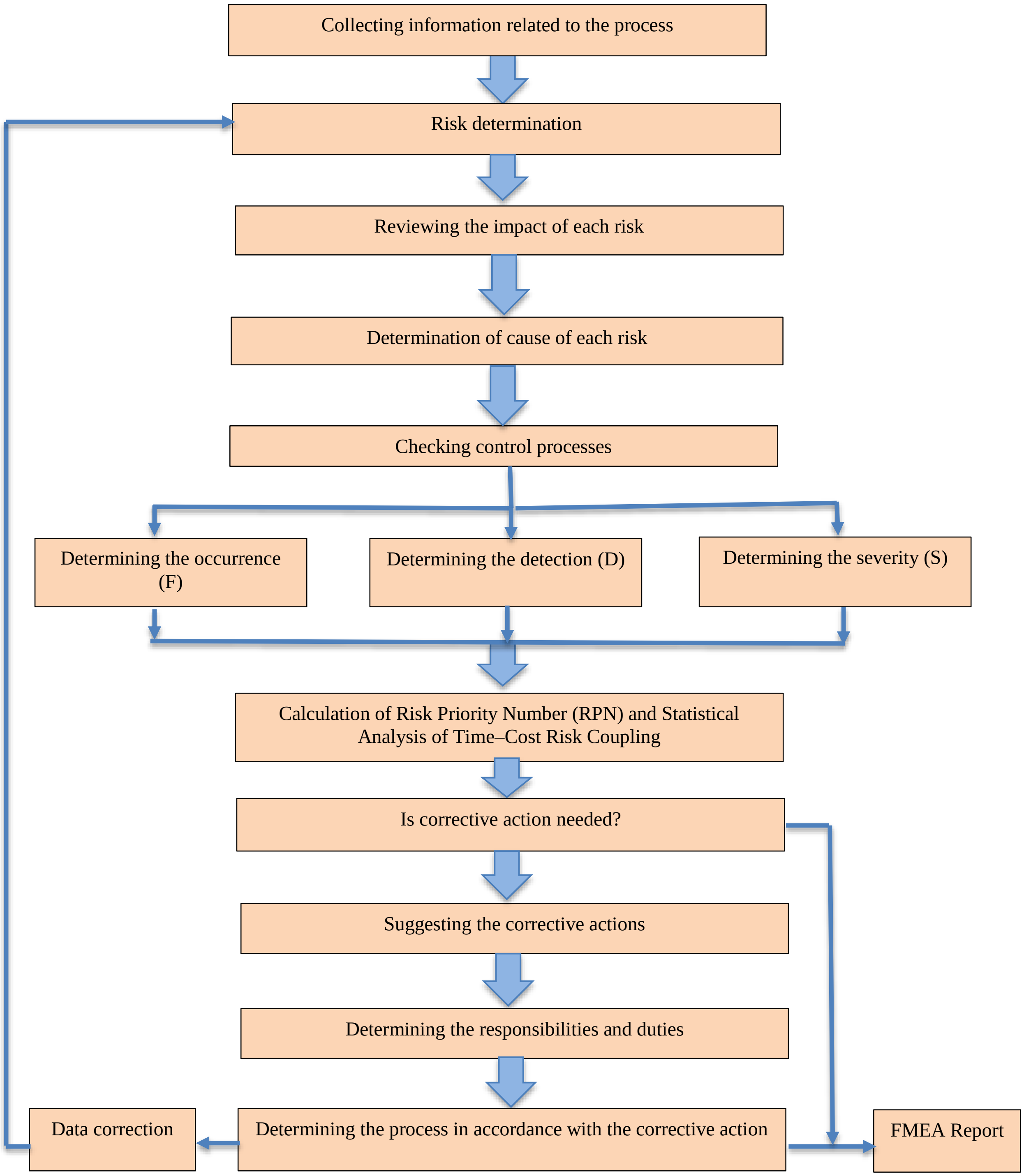

Fig. 1 Methodology flow chart

4.2. FMEA-Based Risk Prioritization

Failure Mode and Effects Analysis (FMEA) was used to prioritize the identified risk factors according to the possibility of their occurring and also the impact on the project time and project cost. A structured questionnaire with a five-point Likert scale was used to collect the ratings from 227 construction professionals. The mean scores for the probability (P), the time impact (T), and the cost impact (C) were determined for each risk factor. Using these values, Time-RPN indices and Cost-RPN indices were calculated to assign a numerical value to the relative importance of each risk for use in subsequent statistical analysis. The values of the resulting RPN were then used for risk ranking, correlation analysis, and regression modeling.

4.3. Regression Model and Statistical Justification

Simple linear regression was performed for all risk factors to estimate the relationship between the time-related and cost-related risks. Time-RPN was the independent variable, and Cost-RPN was the dependent variable in the regression models.

The aim was to evaluate the influence of the time-related risk exposure on the cost-related risk exposure and to determine the strength to which the schedule-based risks can predict cost performance. Linear regression was chosen, as it is an interpretable and statistically sound model of cause–effect relationships between two continuous variables.

The analysis is based on the assumptions of linearity between the two RPNs (Time-RPN, Cost-RPN), independence of observations, homoscedasticity of residuals, and normal distribution of the error terms. An Analysis Of Variance (ANOVA) was carried out to test the significance of the model equations and the coefficient of determination (R2) to understand the proportion of the variance in the Cost-RPN that is accounted for by the variance in the Time-RPN.

Furthermore, descriptive statistics were applied to describe the identified risk characteristics and Failure Mode and Effects Analysis (FMEA) was used to systematically prioritize the risk and correlation analysis was conducted to study the correlation between strength and direction of the identified risks with the Time-Cost team. The reason for choosing these statistical techniques was that they are transparent, easy to interpret and are commonly used in construction risk management studies.

5. Result and Discussion

The analysis was performed by first categorizing the construction delay factors into internal and external risks and then quantifying the time-related and cost-related impact of these factors using the Failure Mode and Effects Analysis (FMEA) framework. Risk Priority Numbers (RPN) for time and cost based on frequency, severity, and detection ratings were calculated, and the risks were further categorized and ranked based on their criticality. To empirically validate the interaction between time and cost risks, correlation and regression analyses were performed using the derived Time RPN and Cost RPN values. The results are discussed in a structured manner, beginning with risk classification and FMEA-based prioritization, followed by integrated time–cost risk assessment, statistical interpretation of correlation and regression outcomes, and finally their managerial, policy, and project control implications, including linkage with Earned Value Management (EVM).

5.1. Descriptive Statistics of Risk Variables

This data collected from the respondents' risk assessment was first subjected to descriptive statistical analysis to assess whether the risk will appear and what impact it will have on project time and cost. The mean and standard deviation values were computed for each risk factor, and the most significant ones that affect construction project performance were identified. The higher the mean values, the more severe was the perceived risk; the higher the standard deviation, the more agreement there was among respondents.The descriptive statistics in Table 3 provide a preliminary understanding of which of the identified risk factors are more important before doing FMEA-based prioritization and statistical modeling.

Table 3. Descriptive statistics of risk factors

Risk Factor	Probability (Mean ± SD)	Impact on Time (Mean ± SD)	Impact on Cost (Mean ± SD)
D1 – Delay in statutory approvals and clearances	4.11 ± 1.06	4.09 ± 1.08	4.13 ± 1.05
D2 – Design changes and scope variations	4.04 ± 1.08	4.09 ± 1.10	4.03 ± 1.07
D3 – Poor planning, monitoring and control	4.17 ± 1.07	4.20 ± 1.04	3.97 ± 1.10
D4 – Financial instability of contractor or developer	3.85 ± 1.05	3.83 ± 1.04	4.01 ± 1.11
D5 – Labour availability and productivity risks	3.86 ± 1.11	3.92 ± 1.08	3.78 ± 1.07
D6 – Material price fluctuation and supply disruption	4.16 ± 1.07	4.00 ± 1.06	4.28 ± 1.01
D7 – Coordination issues among stakeholders	3.91 ± 1.04	4.14 ± 1.07	3.83 ± 1.09
D8 – Equipment failure and logistics constraints	3.55 ± 1.10	3.69 ± 1.07	3.56 ± 1.08
D9 – Monsoon and climate-related risks	4.19 ± 1.07	4.26 ± 1.06	3.85 ± 1.06
D10 – Policy, regulatory and local authority changes	3.94 ± 1.08	3.99 ± 1.09	4.12 ± 1.04

Table 3 shows that there are significant differences in the perceived importance of the risk factors identified. Monsoon risk and climatic risk (D9) obtained the highest mean probability score (M = 4.19, SD = 1.07) and the highest score on impact on project time (M = 4.26, SD = 1.06), respectively, indicating a significant effect of climatic risk on project time in Maharashtra.

Poor planning, monitoring, and control (D3) were also found to be significant risk factors, with a high probability score (M = 4.17, SD = 1.07) and time impact score (M = 4.20, SD = 1.04), in which good project management practices are important to prevent delays in the project. Cost performance showed that Material price fluctuation and supply disruption (D6) had the highest mean cost impact score (M = 4.28, SD = 1.01), which illustrates that they played an important role in cost overruns in the projects. Moreover, Delay in statutory approvals and clearances (D1) was found to have consistently high ratings in the three dimensions of probability, time impact, and cost impact, indicating its overall impact on the project performance.

On the other hand, the mean scores of Equipment failure and logistics constraints (D8) were the lowest in all 3 dimensions, indicating comparatively low perceived impacts. The standard deviations varied from 1.01 to 1.11, which showed moderate variations in responses and a reasonable amount of agreement between the professionals surveyed on the importance of the risk factors identified.

5.2. FMEA-based Risk Management Plan

The integrated risk management plan, shown in Table 4, uses FMEA-based Risk Priority Numbers to consolidate time overruns and cost overruns for systematic decision-making for construction projects. By combining Time-RPN and Cost-RPN rankings, the table serves to identify important and high-risk factors that must receive urgent attention from management and be specifically addressed. The framework goes further to provide translation of empirical risk prioritization in terms of actionable strategies by incorporating the link between each risk and specific impacts, mitigation measures, and assigned responsibilities.

Table 4. Integrated FMEA-based risk management plan for time and cost overruns risks

Risk No.	Risk Factor (Code)	Risk Type	Time-RPN (Rank)	Cost-RPN (Rank)	Risk Category	Key Impacts (Time / Cost)	Key Mitigation Measures	Responsibility
1	Monsoon & Climate Risks (D9)	External	65.705 (1)	59.257 (4)	Critical / High	Work stoppage, idle resources, repair costs	Monsoon-adjusted scheduling, buffer time, insurance, protective	Planning Team, Site Engineers
2	Material Price Fluctuation & Supply Disruption	External	65.289 (2)	69.968 (1)	Critical	Procurement delays, cost escalation	Long-term contracts, escalation clauses, safety stock, multi-vendor	Procurement & Contracts Team
3	Policy & Regulatory Changes (D10)	External	59.831 (3)	61.814 (2)	High	Approval delays, redesign, penalties	Regulatory scanning, early liaison, compliance	Legal & Compliance Team
4	Financial Instability (D4)	Internal	58.182 (4)	60.857 (3)	High	Cash-flow disruption, payment delays	Escrow payments, milestone-based funding, contingency	Finance Dept., Project Sponsor
5	Equipment Failure & Logistics (D8)	Internal	49.884 (5)	48.096 (5)	High / Moderate	Critical path delays, repair costs	Preventive maintenance, redundancy, vendor SLAs	Plant & Equipment Manager
6	Poor Planning & Control (D3)	Internal	34.370 (6)	32.497 (6)	Moderate	Accumulated delays, cost creep	Project management software, EVM, variance tracking	Planning Engineer, PM
7	Design Changes & Scope	Internal	32.920 (7)	32.424 (7)	Moderate	Rework, sequencing issues, claims	Design freeze, change control	Design Manager, Client

	Variations (D2)						board, BIM coordination	
8	Stakeholder Coordination Issues (D7)	Internal	32.150 (8)	29.787 (9)	Moderate / Low	Decision delays, rework	Coordination meetings, RACI matrix, document control	Project Manager
9	Statutory Approval Delays (D1)	External	31.937 (9)	32.212 (8)	Moderate	Work stoppage, overhead escalation	Early submission, parallel approvals, liaison team	Liaison Officer
10	Labour Availability & Productivity (D5)	Internal	29.361 (10)	28.304 (10)	Low	Slow execution, overtime costs	Retention programs, incentives, training, and mechanization	HR & Site Management

The results indicate that external risks are in the upper rank, with material price fluctuation and supply disruption (D6) leading the way, stresses on material prices and supply, and monsoon and climate-related risks (D9) having the highest impact on the project timelines.

Regulatory changes (D10) and financial instability (D4) also show relatively high RPN values in both dimensions, indicating the susceptibility of construction projects to institutional and financial uncertainties.

In opposition to this, the managerial and coordination-related risks, such as poor planning (D3) and stakeholder coordination issues (D7), have moderate RPN values that indicate they may have lower individual impacts, but together can result in an aggregate impact on performance if not managed.

5.3. FMEA-Derived Risk Priorities and Earned Value Management

A further exploration of the correlation between time and cost risks was made by integrating the findings of the empirical correlation with logic defined in Earned Value Management (EVM) performance. The analysis establishes a Time-Cost correlation strength to the behavioral pattern of the Schedule Performance Index (SPI) and Cost Performance Index (CPI) and provides the statistical result in actionable project control insight.

Table 5. Integrated correlation-based interpretation of time–cost risk coupling and EVM control implications

Delay Factor	Time–Cost Correlation (r)	Correlation Strength	Expected EVM Behavior	Managerial Signal
D1 – Statutory approvals	0.788	Strong	SPI ↓ → CPI ↓ rapidly	Immediate intervention
D2 – Design changes	0.736	Strong	SPI ↓ → cascading CPI loss	Early change control
D5 – Labour availability	0.751	Strong	SPI ↓ → prolonged overheads	Resource stabilization
D7 – Coordination issues	0.713	Strong	Productivity loss → CPI erosion	Interface management
D3 – Poor planning	0.639	Moderate–Strong	SPI drift → delayed CPI impact	Early corrective action
D4 – Financial instability	0.653	Moderate–Strong	SPI ↓ precedes CPI stress	Financial monitoring
D6 – Material volatility	0.640	Moderate–Strong	Schedule slippage inflates cost	Supply-chain buffering
D8 – Equipment/logistics	0.631	Moderate	Operational delays	Preventive maintenance
D9 – Climate risks	0.556	Moderate	Seasonal SPI loss	Weather contingency
D10 – Regulatory changes	0.579	Moderate	Late-stage CPI impact	Policy preparedness

Table 5 illustrates a strong empirical coupling between the time-related and the cost-related risks for major construction delay factors, which confirms that schedule inefficiencies do indeed consistently translate into cost overruns.

Delay factors (D1-D2), (D5), and (D7) have high correlation coefficients (>0.7), which means that a simple delay in these aspects can lead to a bigger cost delay.

These risks thus warrant instant attention from the management and need to be proactively controlled on a schedule. Cost impacts mostly correlate moderately or strongly with time impacts, including those on poor planning (D3), financial instability (D4), and material volatility (D6), providing a long window of time for effective early action.

Conversely, the linkage between climate-related risks (D9) and regulatory changes (D10) is of a moderate degree and indicates that while time implications are inevitable, there is also some degree of contingency planning and policy preparedness that can help lower the costs. Overall, the combination of the correlation strength with EVM-based interpretation shows the importance of using schedule performance indicators as leading signals for cost control and the ability to take timely and risk-specific managerial actions.

5.4. Regression Analysis of Time–Cost Risk Coupling

The results of the regression analysis conducted to quantify the relationship between time-related risk and cost-related risk for individual construction delay factors. Separate regression models were developed using Time_RPN as the independent variable and Cost_RPN as the dependent variable.

Table 6. Regression analysis of time–cost risk coupling for major construction delay factors

Delay Factor	Regression Equation	B (Unstd.)	Std. Beta	R^2	Adjusted R^2	F-value
D1	Cost = 7.406 + 0.787(Time)	0.787	0.788	0.621	0.619	368.256
D2	Cost = 7.889 + 0.750(Time)	0.750	0.736	0.542	0.540	266.342
D3	Cost = 11.248 + 0.605(Time)	0.605	0.639	0.408	0.406	155.214
D4	Cost = 19.770 + 0.712(Time)	0.712	0.653	0.426	0.423	166.978
D5	Cost = 7.160 + 0.710(Time)	0.710	0.751	0.564	0.562	290.954
D6	Cost = 26.650 + 0.665(Time)	0.665	0.640	0.409	0.407	155.903
D7	Cost = 8.742 + 0.657(Time)	0.657	0.713	0.509	0.506	232.925
D8	Cost = 17.436 + 0.613(Time)	0.613	0.631	0.398	0.395	148.754
D9	Cost = 24.875 + 0.518(Time)	0.518	0.556	0.309	0.306	100.460
D10	Cost = 28.475 + 0.566(Time)	0.566	0.579	0.335	0.332	113.570

The results of the regression analysis presented in Table 6 are strong empirical evidence of the predictive relationship between time-related risks and cost-related risks in all of the identified construction delay factors. The positive unstandardized regression coefficients (B) observed for all the regression models show that an increase in time-related risk is consistently associated with an increase in cost-related risk, demonstrating the existence of systematic time-cost risk coupling. The D values for time delays due to delay factors like statutory approvals (D1), labour availability (D5) and design changes (D2) are relatively larger, and hence, the standardized beta values are relatively large, showing greater sensitivity of cost escalation to time delays of these factors. This is because any slight deviation of the schedule associated with these risks can lead to an escalating number of additional charges on the project, such as overtime costs, wasted hours, and work overrides.

The R-squared and adjusted R-squared values of the regression models provide an added measure of the explanatory power of the regression model and provide a source of robustness to the time-cost relationship. High values for R^2 of D1 (0.621), D5 (0.564), and D2 (0.542) reflect that over half of the variability in the cost-related risk can be captured by time-related risk for these delay factors alone, and this indicates their critical role in project performance. Moderate R^2 for factors like poor planning (D3), financial instability (D4), and material price volatility (D6) show that, in addition to time risk, other contextual factors are also important in the identification of cost escalation in the construction industry. In addition, the relatively high F-values of all the models indicate that the regression relations were all statistically significant and reliable, so the fitted models were adequate.

5.5. Sensitivity Analysis

Different weighting schemes, which account for different stakeholder perspectives, were tested to ensure the stability and reliability of the suggested risk prioritization framework through sensitivity analyses. The baseline risk score was contrasted with three other models: a time-oriented model, a cost-oriented model, and an equal composite model. Concordances of the rankings of risk with the three weightage assumptions were tested using Spearman's correlation analysis. Table 7 presents the results from ranking identified risk factors in the basic model and three alternative models with varying weights representing different priorities of the various stakeholders. By using this comparison, one can analyze the stability of the risk rankings based on different weights for project time and project cost, as well as weights that are equal across all risk dimensions. Consistently ranking across scenarios demonstrates the robustness of the proposed risk prioritization framework and the reliability of the rankings.

Table 7. Final consolidated ranking table

Risk Factor	Baseline = (P×(T+C) /2)	S1 (Time-Oriented) = (P×(0.7T+0.3C)	S2 (Cost-Oriented) = P×(0.3T+0.7C)	S3 (Equal Composite) = (P+T+C)/3)
D1	4	4	2	3
D2	5	5	5	5
D3	2	2	3	2
D4	8	8	8	8
D5	9	9	9	9
D6	1	3	1	1
D7	7	7	7	7
D8	10	10	10	10
D9	3	1	4	4
D10	6	6	6	6

Table 8. Spearman correlation table

Comparison	Spearman's ρ	p-value	Interpretation
Baseline vs S1	0.952	< 0.001	Very Robust
Baseline vs S2	0.964	< 0.001	Very Robust
Baseline vs S3	0.988	< 0.001	Very Robust

The analysis of Spearman's rank correlation was conducted between the baseline model and each alternative scenario to quantitatively assess how consistent the sets of risk rankings are for the different weighting scenarios. Spearman's correlation coefficient (ρ) is a measure of the agreement between two ranking schemes, where a value closer to 1 is more consistent. Table 8 shows the final results. Spearman's rank correlation coefficients were high, as shown above, ranging between 0.952 and 0.988, indicating excellent agreement between the baseline and alternative ranking models. Statistically, all correlations were significant (at the 0.001 level), so the risks' priorities obtained were similar regardless of the differences in the assumptions for their weights.

For all scenarios, material price fluctuation and supply disruption (D6), poor planning, monitoring, and control (D3), and monsoon and climate-related risk (D9) were always among the top three and equipment failure and logistics constraints (D8) among the last three risks considered. These findings show that the proposed framework in the study is very robust, and it is valid in providing risk ratings that can be used in construction project risk management and decision-making.

5.6. Framework Comparison

The proposed framework shown in Table 9 was contrasted with other frequently used frameworks, such as ISO 31000 and PMBOK, to put the framework into perspective with the construction risk management literature. All of these frameworks describe in detail, at various risk categories, how to identify, evaluate, and plan for risks, but they no longer explicitly describe the empirical correlation between the time-related and cost-related risk categories.

The proposed framework proposed nowadays is the mixture of Traditional Risk Management Technique and Risk Prioritization Technique, which is based on FMEA; moreover, it includes correlation, regression, and EVM-based risk interpretation techniques to assess the time–cost risk coupling. The comparison demonstrates that the proposed Risk Management framework complements other existing risk management standards. ISO 31000 and PMBOK present a process for risk governance; the proposed one is a series of empirical processes to determine the value of schedule risk to cost. Such an approach can facilitate more proactive decisions without the Delay and onus of attendant financial implications.

Table 9. Comparison of risk management frameworks

Aspect	ISO 31000	PMBOK Risk Management	Proposed Framework
Primary Focus	General risk management principles	Project risk management processes	Empirical time–cost risk coupling
Risk Identification	Qualitative and semi-quantitative	Qualitative and quantitative	FMEA-based risk prioritization
Risk Assessment	Probability and consequence evaluation	Probability–impact assessment	Time-RPN and Cost-RPN analysis
Quantitative Validation	Limited	Optional	Correlation and regression analysis
Early Warning Capability	Generic monitoring	Project performance monitoring	EVM-linked predictive interpretation
Practical Output	Risk treatment strategy	Risk response planning	Identification of time-driven cost escalation mechanisms

6. Conclusion

This research is empirically validated to assert that time overruns are a major channel through which cost overruns manifest in construction projects. The findings from the research indicate that the timing risks cannot only be clearly ranked using FMEA but also can be correlated and applied to regression analysis with a consistent and predictable cost escalation depending on the delay factors. The results are quite clear—that time risk is not only an operational issue but also a significant financial risk driver. The results indicate that various sources of risk, not just one, cause the construction delays. The main types of risk within the critical risk categories are external risks; they also include internal risks, which are related to managers and coordinators, but they have relatively low detectability. Further, utilizing regression analysis along with Earned Value Management (EVM) shows that a few high-impact risk factors can be helped by signs of deteriorating schedules as beneficial early warning indicators. The results overall emphasize the necessity to use risk-specific mitigation strategies and have proactive project management tools in place to ensure effective time and cost overrun handling. Moreover, sensitivity analysis showed the stability of the proposed risk prioritization framework for other weighting scenarios. There were variations in stakeholder risk priorities; however, the high and consistent Spearman's rank correlation coefficients indicated that the businesses faced the same risks, and some were just listed in a different order. This result reinforces the validity of the proposed framework and makes it practically usable to estimate risk and make decisions for residential township construction projects. Overall, the research promotes construction risk management from a descriptive ranking standpoint toward a mechanism-based understanding of time-cost interaction. By creating an empirically based framework that will connect risk identification, statistical validation, and performance control, the research is a solid foundation for time-based governance, selective EVM adoption, and enhanced predictability in construction project delivery.

6.1. Limitations and Future Work

The analysis is based on some risk factors associated with construction-related operations and an assessment by experts, which may not reflect all uncertainties in the projects. Furthermore, the regression models created in this research are based on linear correlation between the time and cost risks, and the relationships between each other may not fully be represented under complex project conditions. Future research could enhance the proposed framework by validating the models with additional data from various project types and geographical regions. Future research can focus on exploring nonlinear interactions between time-related risks and cost-related risks and contrast the effectiveness of the proposed regression-based approach with that of more advanced analytical approaches. Moreover, the combination of FMEA-based risk assessment with Earned Value Management (EVM) and Digital Project Monitoring Systems could yield better early-warning systems for controlling project delays and cost overruns.

Statements & Declarations

Author Contributions

Each Author was actively engaged in the Process of development and implementation of this study. The major responsibility of DSJ was in the material preparation, data collection, and data analysis. DSJ first wrote the manuscript, and then AMK proofread and reviewed. All authors approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Data Availability

The data supporting the findings of this study are available from the corresponding Author upon reasonable request.

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Not applicable.

Consent for Publication

Not applicable.

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