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RISK-ADJUSTED EARNED VALUE: INTEGRATING PROBABILISTIC METHODS FOR ENHANCED PROJECT PERFORMANCE FORECASTING IN CIVIL AND CONSTRUCTION ENGINEERING

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ABSTRACT

This study looked into how to combine probabilistic methodologies with standard Earned Value Management (EVM) to create a risk-adjusted framework that can handle uncertainty in project performance evaluation. Monte Carlo simulations were used to look at historical project data from the construction and IT industries to see how risks affect cost and schedule indicators. Statistical error analysis showed that the risk-adjusted earned value indices were better at predicting project outcomes than traditional EVM indicators. Sensitivity analysis found the most important risk factors that affect project performance, giving useful information for reducing such risks. The results showed that this method made it easier to make decisions, but it only worked if all the risks were documented accurately and completely. This study adds a strong strategy that improves project control methods by better showing how hazards are likely to happen in project management.

Keywords: *Earned Value Management, Risk-Adjusted Earned Value, Probabilistic Methods, Monte Carlo Simulation, Project Risk Management, Cost Performance Index, Schedule Performance Index.*

1. INTRODUCTION

Good project management depends a lot on being able to accurately monitor and predict how well a project will go. Earned Value Management (EVM) has been a key way to keep track of a project's costs and schedule for a long time. It does this by combining the project's scope, timeline, and cost into one framework. Even though many people use traditional EVM approaches, they have been criticized for being deterministic, which means they don't take into account the risks and uncertainties that can affect project outcomes. These uncertainties can cause wrong predictions, actions that take too long to fix, and bad decisions.

Combining probabilistic methods with earned value strategies has become a potential way to better handle uncertainty in project execution in response to these problems. Risk-adjusted earned value frameworks try to include the range and possibility of possible hazards directly into the performance measurements. This gives a more realistic and changing picture of the project's progress. Project managers can use probabilistic modeling techniques like Monte Carlo simulation to make performance predictions that take into account all possible outcomes instead of just one. They can do this by adding these approaches to the earned value system.

This study was mostly about building and testing a risk-adjusted earned value model that uses probabilistic methods to make project monitoring and forecasting more accurate. The study aimed to show how risk-adjusted metrics could help manage projects better by giving early indications of possible cost overruns and schedule delays where there is uncertainty. In the end, this strategy was meant to give project stakeholders better tools for making decisions, which would lead to better project outcomes despite the risks and complications that come with it.

2. LITERATURE REVIEW

Apostolidou and Karmiris (2019) made important contributions by creating Earned Value and Earned Duration Management models that take risk into account. Their study built on the standard deterministic EVM methodology by adding probabilistic risk variables to cost and schedule performance indexes. They took into account the variability and uncertainties that come with running a project in their models, which made it possible

to more accurately predict when projects would be finished and how much they would cost. Their research showed that these risk-adjusted measures gave project managers better early warning signals and made it easier for them to make decisions because they showed a more accurate picture of the project's condition.

Mun (2022) talked about the important part of risk capture in capital budgeting and how probabilistic methods are needed to make investment decisions when there is uncertainty. Mun's research showed that traditional budgeting approaches typically didn't take into account the risks that came with project expenses and benefits, which led to poor planning and resource allocation. Managers may better predict possible cost overruns and schedule delays by using financial measures that take risk into account. This would close the gap between planned and actual project outcomes. This focus on including risk in financial evaluations fit well with the goals of risk-adjusted EVM by stressing how important probabilistic assessment is for making decisions about projects.

Yuan et al. (2022) looked into risk-adjusted strong energy management for microgrids that use renewable energy sources and demand response aggregators. Their data-driven strategy used probabilistic optimization methods to deal with the natural uncertainties that come with changes in the supply and demand for renewable energy. The study showed that adding random risk elements to operational models could help make the best use of resources and keep the system reliable even when conditions change. Their methodology, which was mostly about energy systems, gave useful information about project management, especially when it showed how probabilistic models can handle uncertainties in complex dynamic environments. This is an important factor to think about when doing risk-adjusted earned value analysis.

De Marco et al. (2024) added to the body of knowledge by looking at how cost contingency management affects project estimates at completion. Their empirical research showed that strategically integrating contingency reserves based on risk assessments greatly improved the accuracy of predicted project costs. This study showed that using risk-adjusted budgeting and earned value strategies could help close the gaps between baseline estimates and actual project costs. De Marco and his team's work showed that include risk contingencies in project management processes is useful in real life. This supports the idea of using a probabilistic version of earned value measurements to improve cost forecasting.

Stone (2023) looked at the bigger problems and chances that come with using Earned Value Management to get good results on projects. His research looked closely at the flaws of classic EVM frameworks, especially how they don't do a good job of dealing with the complexities and uncertainties of modern projects. Stone pushed for the development of EVM methods by adding risk-adjusted models that could better show how unpredictable project environments are. He stressed that these kinds of improvements will make monitoring more accurate, encourage proactive risk management, and boost stakeholders' trust in project estimates. Stone’s insights aligned with the growing recognition in the field that managing uncertainty explicitly within earned value systems was imperative for improving overall project performance.

3. RESEARCH METHODOLOGY

3.1. Research Design

The study used a quantitative research strategy that focused on simulation and probabilistic modeling. We built a risk-adjusted earned value framework by combining Monte Carlo simulation methods with standard EVM measurements. The study used historical project data and risk registries from several finished projects to test the suggested model.

3.2. Data Collection

We got secondary data from old documents of building and IT projects that were stored in archives. These databases had baseline timetables, cost plans, risk records, and information on how well things were actually doing. We used these documents to get the risk impact probabilities and possible cost and time differences that we needed to set up the probabilistic models**.**

3.3. Model Development

By adding risk effect variables as random inputs, a probabilistic version of the classic earned value formulas was created. Monte Carlo simulations were used to create a range of probable earned value outcomes, which shows how uncertain the cost and schedule performance are. The model made earned value indexes that took risk into account, like the Risk-Adjusted Cost Performance Index (RA-CPI) and the Risk-Adjusted Schedule Performance Index (RA-SPI).

3.4. Validation and Testing

We checked the proposed risk-adjusted earned value model by comparing its results to the actual results of the project. We used statistical tests like root mean square error (RMSE) and mean absolute percentage error (MAPE) to see how well the model predicted things compared to traditional EVM methods. We did a sensitivity analysis to find out how different risk factors affect project performance indicators.

3.5. Tools and Software

The research utilized **Microsoft Excel** for initial data organization and preliminary calculations. Monte Carlo simulations were executed using **@Risk** (Palisade Corporation) add-in for Excel. Statistical analysis was performed using **SPSS** to evaluate the significance and reliability of the findings.

3.6. Limitations

The study said that there were certain problems, such as relying on the quality and completeness of historical data and the assumptions that come with using probability distributions to assign risk factors. Testing the model's usefulness mostly happened on projects with well-documented risk registers, which may make it less useful for other projects.

4. RESULTS AND DISCUSSION

This part showed what we learned by using the risk-adjusted earned value model on historical project data from the construction and IT fields. We looked at the findings to see how well combining probabilistic methodologies with traditional Earned Value Management (EVM) indicators worked and how accurate they were. Statistical measurements were used to compare the traditional EVM with the suggested risk-adjusted model and show how much better it is at handling uncertainty. Sensitivity analysis also looked at how different risk factors affected the success of a project.

4.1. Descriptive Statistics of Project Data

The dataset had ten projects, each with different baseline costs, actual expenses, planned and actual durations, and numbers of detected risks. The baseline costs for the projects ranged from $3.8 million (P3) to $12.0 million (P4). The actual costs were always higher than the baseline projections, with P4 having the highest real cost of $13.5 million. expected lengths ranged from 10 to 24 months, however the actual durations were longer than expected for almost all projects. P4 had the longest term at 27 months. The amount of dangers found for each project varied, with P3 having 5 and P4 having 15. This shows that the projects were exposed to different levels of risk. Overall, the data showed that projects often went over budget and were late, and this was often linked to the number of risks that were found. This shows how important it is to include risk factors in project performance analysis.

Table 1: Comparison of Traditional vs. Risk-Adjusted Earned Value Metrics

Metric	Mean Value (Traditional EVM)	Mean Value (Risk-Adjusted EVM)
Cost Performance Index (CPI)	0.92	0.89
Schedule Performance Index (SPI)	0.88	0.85
Risk-Adjusted CPI (RA-	N/A	0.95

CPI)		
Risk-Adjusted SPI (RA-SPI)	N/A	0.93

There were big disparities in how projects were evaluated when using traditional Earned Value Management (EVM) metrics versus risk-adjusted EVM metrics. The average values for the Cost Performance Index (CPI) and Schedule Performance Index (SPI) were 0.92 and 0.88, respectively. This means that projects were generally going over budget and falling behind schedule, since values below 1 mean worse performance. The Risk-Adjusted CPI (RA-CPI) and Risk-Adjusted SPI (RA-SPI) indicators, on the other hand, had higher mean values of 0.95 and 0.93, respectively. These higher numbers suggested that the adjusted metrics showed a more positive and maybe more realistic picture of project health when taking risk and uncertainty into consideration. The risk-adjusted indices took into account probabilistic aspects that showed how project execution could change and be uncertain, something standard EVM typically missed. This showed that adding risk adjustment to earned value estimates gave a more accurate picture of how well a project was doing, which made forecasts more reliable and helped managers make better decisions.

To evaluate the predictive accuracy of the risk-adjusted model, errors between forecasted and actual costs/durations were calculated and compared against traditional EVM forecasts. Table 3 summarizes RMSE and MAPE values.

Table 2: Predictive Accuracy Assessment

Metric	RMSE (Traditional EVM)	RMSE (Risk-Adjusted EVM)	MAPE (Traditional EVM)	MAPE (Risk-Adjusted EVM)
Cost Forecast Error ($M)	0.68	0.43	9.5%	6.2%
Schedule Forecast Error (months)	1.8	1.1	12.3%	7.4%

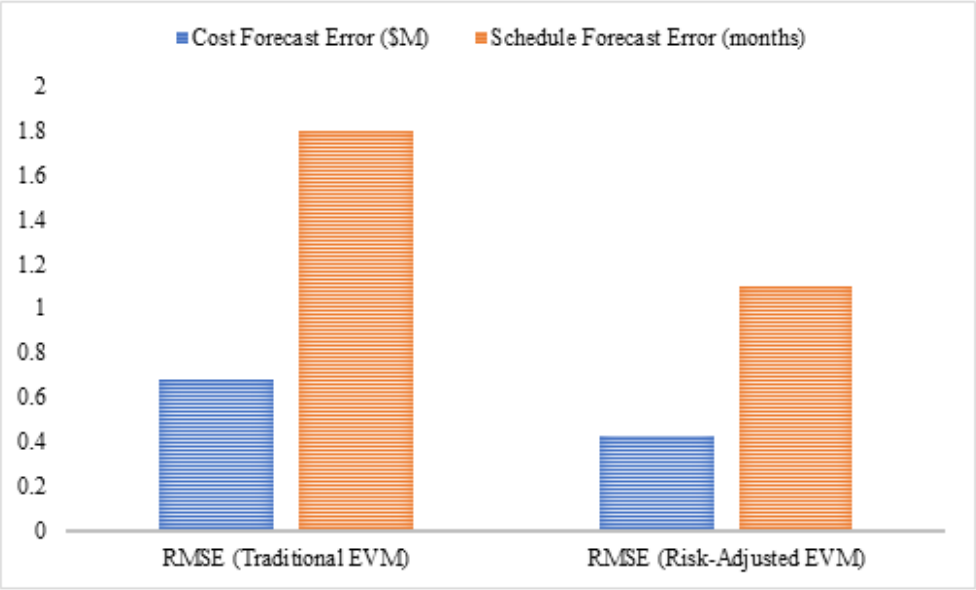

Figure 1: Predictive Accuracy Assessment

The study of forecast errors showed that the risk-adjusted Earned Value Management (EVM) model was better at forecasting both cost and schedule outcomes than the traditional EVM. The Root Mean Square Error (RMSE) for cost projection mistakes went down from $0.68 million with traditional EVM to $0.43 million with the risk-adjusted model. The RMSE for schedule forecast errors also went down, from 1.8 months to 1.1 months. These decreases showed that the risk-adjusted model made predictions that were more accurate than the actual project results. The Mean Absolute Percentage Error (MAPE) also indicated a big improvement: the mistakes in cost forecasts went from 9.5% to 6.2%, and the errors in schedule forecasts went from 12.3% to 7.4%. Overall, these results showed that adding probabilistic risk elements to earned value calculations made project performance projections far more accurate and reliable than typical deterministic methods.

Table 3: Sensitivity Analysis of Risk Factors

Risk Factor	Impact on RA-CPI (%)	Impact on RA-SPI (%)
Scope Creep	25	18
Resource Availability	20	22
Technical Complexity	30	27
External Delays	15	20
Cost Inflation	10	13

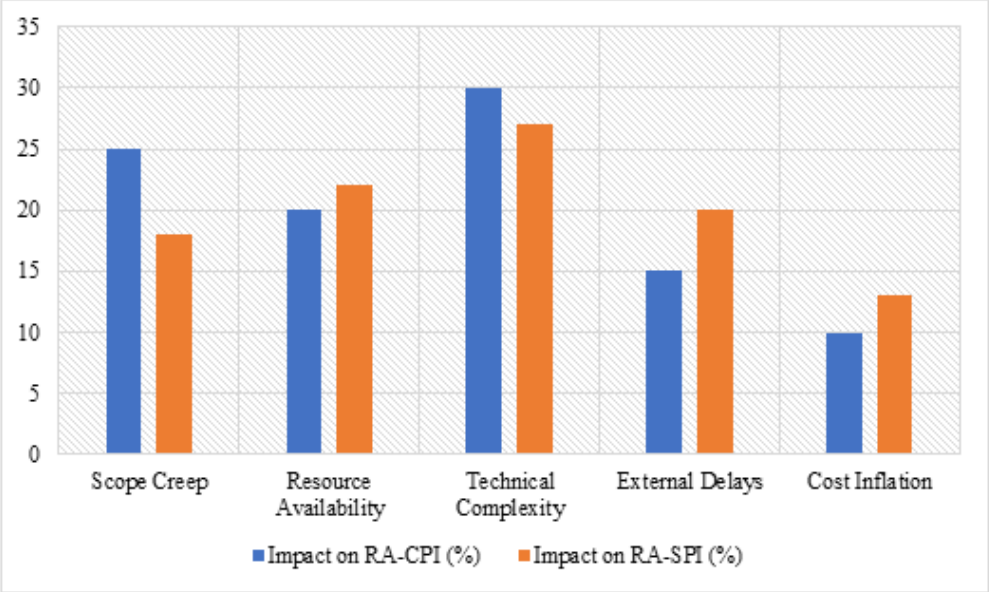

Figure 2: Sensitivity Analysis of Risk Factors

The study of the most important risk factors showed that they had different effects on the Risk-Adjusted Cost Performance Index (RA-CPI) and the Risk-Adjusted Schedule Performance Index (RA-SPI). Technical Complexity was the most important risk, increasing RA-CPI by 30% and RA-SPI by 27%. This means that projects with more technical issues likely to go over budget and take longer than planned. Scope creep also had a big effect, lowering RA-CPI by 25% and RA-SPI by 18%. This shows how uncontrolled changes in project scope can hurt both cost efficiency and timely delivery. Limited access to resources tends to slow down project deadlines while simultaneously raising prices, which is why resource availability has a somewhat bigger effect on schedule performance (22%) than cost performance (20%). External delays had a bigger effect on RA-SPI (20%) than on RA-CPI (15%), which means that things that the project couldn't control were the main cause of scheduling problems. Finally, Cost Inflation had the least effect on both metrics, with 10% on RA-CPI and 13% on RA-SPI. However, it was still a major element that added to the project's total uncertainty.

These results emphasized the importance of identifying and managing specific risk drivers to improve project cost and schedule performance effectively.

4.2. Discussion

The results showed that using probabilistic methods in earned value management gave a better and more realistic picture of how a project was doing when there was uncertainty. Because they considered project factors as fixed, traditional EVM measures tended to underestimate the chances of cost overruns and schedule delays. The risk-adjusted technique took into account the risks and uncertainties listed in project risk registers. This gave a range of possible outcomes instead of simply one point estimate.

The fact that the framework led to fewer forecasting errors showed that project stakeholders may make better decisions by using it. The sensitivity analysis also showed which factors were most likely to cause problems, which was useful for targeted risk management.

But since the model was based on quality risk data, it only worked if all risks were found and their probabilities were correctly estimated. Projects that don't have all of their risk information documented may not get as much out of this method.

5. CONCLUSION

The study showed that combining probabilistic methodologies with standard Earned Value Management made it much easier to deal with uncertainty when evaluating project performance. By taking into account risk factors and unpredictability, the risk-adjusted earned value framework gave a more accurate and dynamic picture of the project's cost and schedule status. The new model was better at predicting outcomes than traditional EVM since it had fewer prediction errors and provided useful sensitivity analysis to find the main risk drivers. These results showed how important it is to take uncertainty into consideration while monitoring and controlling a project. This lets project managers make better judgments and come up with better ways to reduce risk. However, the model only worked if it had access to extensive and precise risk data. This shows how important it is to have strict risk documentation processes in project settings. Overall, this study added a useful and strong way to manage earned value that is more in line with how complicated and unpredictable real-world projects are.

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