Risk analysis in road infrastructure construction projects using the FMEA method - Failure Modes and Effects Analysis

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Abstract. In the road infrastructure construction sector, where challenges are complex and varied, the success of a project essentially depends on efficient risk management. The FMEA method (Failure Modes and Effects Analysis) offers a strategic and systematic approach, allowing project managers to anticipate and develop action plans to minimize the impact of potential risks. This article explores the applicability of FMEA in road infrastructure construction, a field marked by high uncertainties. Through FMEA, risks are proactively identified and managed, contributing to the optimization of resources and the reduction of unexpected costs, thus improving the safety and durability of the infrastructure. Emphasis is placed on risk analysis and the planning of mitigation measures, demonstrating the method's effectiveness in reducing delays and budget overruns, as well as in ensuring a high level of quality in construction. The article illustrates the practical implementation of FMEA, highlighting its contribution to improving the sustainability and efficiency of projects. The article emphasizes the essential role of FMEA in risk management in road infrastructure projects, arguing that, in a field exposed to variations and uncertainties, the proactive and systematic approach provided by FMEA is of major importance in ensuring the success, sustainability and safety of projects.

Key words: cost reduction, financial efficiency, infrastructure project management, failure mode and effects analysis, risks in road infrastructure projects, planning, monitoring, construction investment projects.

1. Introduction

The development of road infrastructures is a complex process involving numerous stakeholders, various technologies and unpredictable environmental conditions. In this context, efficient risk management becomes a key aspect in achieving quality, budget and time objectives. FMEA (Failure Modes and Effects Analysis) provides a structured framework for risk analysis, being essential for the successful planning and execution of road infrastructure projects.

The road infrastructure construction sector is a vital field for economic and social development. However, it is accompanied by significant challenges, ranging from technical and logistical complexities to financial and environmental uncertainties. The success of projects depends on both technical and management skills and the ability to identify, assess and manage risks effectively. In this sense, the FMEA (Failure Modes and Effects Analysis) method is an essential tool in the arsenal of project managers.

Road and highway construction involves a number of complex stages that must be carefully managed to ensure the project is completed on time, within budget and with the expected level of quality. Each stage, from planning and design to execution and maintenance, presents its own risks and challenges. These risks can range from land stability issues and supply delays to material cost fluctuations and legislative and environmental challenges.

FMEA provides a structured approach to address these risks. By systematically identifying and analyzing potential failure modes and their effects, FMEA enables project managers to develop proactive risk management strategies. This process not only increases the safety and quality of the project, but also contributes to cost efficiency and delivery deadlines.

This article provides a comprehensive insight into the importance and effectiveness of FMEA in the road infrastructure construction sector, demonstrating how this methodology can transform challenges and uncertainties into a structured and effective risk management plan. In the field of highway construction, risks can range from technical and logistical issues to financial and environmental issues. In this context, the FMEA (Failure Modes and Effects Analysis) method appears as an essential tool, offering a structured and systematic approach to the identification, assessment and management of risks. This article proposes an exploration of the application of FMEA in the context of road infrastructure construction, emphasizing how this methodology can be adapted to meet the specific needs of this sector, while illustrating how a deep understanding and systematic risk assessment can lead to more informed decisions and to an overall efficiency of the construction process.

2. Overview

Risk management methodology is a systematic process used to identify, analyze and manage the risks associated with a project or business, including the following steps (Fig. 1):

- Risk identification: In this stage, all the risks associated with the project are identified.
- Risk analysis: In this stage the identified risks are analyzed to determine their likelihood and impact.
- Risk prioritization: In this stage, the analyzed risks are prioritized to determine which are the most important.
- Risk management: In this stage measures are taken to manage the prioritized risks.
- Risk monitoring and reporting: In this stage the risks and the measures taken to manage them are monitored and reported[1].

These steps are essential to ensure that risks are properly identified, analyzed and managed, which can help minimize their impact on the project.

Project risk management should not only be seen as a systematic methodology, but should be brought to a level where the participants, both the contractor and the client, are bound by the single goal of successfully executing the project. The main sources of risk that generate cost overruns in construction works must be very clearly defined in order to be able to identify those that have a significant impact, with the aim of reducing them as much as possible. These risks can arise from a variety of sources, such as financial sources, legal liabilities, technological problems, strategic management errors, accidents and natural disasters[2].

The implementation of road infrastructure construction projects involves certain forms of risk. These risks are manifested by failure to achieve established objectives, delays in

[1] MIGSO-PCUBED
[2] Baker *et al* 1999

execution, financial losses, corruption, inefficiency or the opportunity cost of different approaches to the project[3]. However, despite the significant complexity and importance of developed road infrastructure projects, risk management often remains highly variable, intuitive, subjective and unsophisticated [4].

Fig. 1. Steps of the risk management process.

Risk factors occur at every stage, from design and planning to execution and completion, and successful project performance is highly dependent on risk management based on successfully identifying, assessing and mitigating the impact of risk factors for a safe, scheduled and cost-effective execution and delivery of the construction project[5].

3. The main sources of risks

Risk is an important component of infrastructure projects and construction contracts. It is important to identify and manage risks properly as they can have a significant impact on the project and the contract. This may include implementing risk management plans, insurances and other risk mitigation measures[6].

Risks in road infrastructure construction projects can be classified into several categories, as follows:

- Technical risks: these are related to technical issues that may arise during the project, such as problems with equipment or materials used.

[3] National Audit Office 1999
[4] Akintoye *et al* 2001
[5] Vishwakarma *et al* 2016
[6] Perry și Hayes 1986

- Financial risks: these are related to unforeseen costs, increases in raw material prices, or project delays and can affect the project budget.
- Legal risks: these are related to legal issues that may arise during the project, such as litigation or disputes with suppliers or local authorities.
- Environmental risks: these are related to the impact of the project on the environment and may include issues with pollution or destruction of natural habitat.
- Social risks: these are related to the impact of the project on local communities and may include issues with the relocation of people or violation of the rights of communities.
- Quality risk: this risk can be caused by problems with materials or non-compliance with quality standards.
- Risk of accidents: this risk can be caused by non-compliance with safety rules or faulty equipment[7, 8].

4. FMEA methodology (Failure Modes and Effects Analysis)

The FMEA method (Failure Modes and Effects Analysis) is an analytical tool used to identify and assess risks in complex projects. This methodology is based on the systematic identification of potential failure modes and their effects on the project, aiming to provide solutions to reduce risks. The FMEA process in road infrastructure construction is carried out in several key stages:

4.1. Identifying critical elements

The initial stage involves identifying all the components and processes in the road infrastructure project. This includes materials, equipment, utilized technologies, work procedures, as well as environmental conditions and human factors.

A detailed analysis of each element is performed to determine possible failure modes, their causes, and potential effects. For example, for a bridge, failure modes might include calculation errors in design, material deterioration, or deficiencies in execution.

4.2. Risk evaluation

Each identified failure mode is evaluated based on the severity of its impact (such as the impact on safety or the durability of the structure), the frequency with which it can occur, and its detectability (i.e., the ease with which it can be discovered before causing problems).

A rating scale, typically from 1 to 10, is used to quantify these aspects, and a risk score is calculated by multiplying these values. Higher scores indicate a higher risk and require priority attention.

[7] Khan și Parra 2003
[8] Issa *et al* 2021

4.3. Planning mitigation actions

Based on the risk assessment, mitigation strategies are developed to reduce or eliminate risks. These may include design changes, improvements in work processes, additional professional training for employees or the implementation of new safety measures.

Specific action plans are established for each identified risk, including responsibilities, required resources and deadlines for implementation.

The importance of this stage lies in transforming the theoretical analysis into practical measures that increase the safety and efficiency of the project.

4.4. Periodic review and updating

The FMEA method is not a static process; it is essential to periodically reassess risks throughout the project to reflect changing conditions, work progress or new information.

This continuous updating ensures that the risk analysis remains relevant and effective throughout the life of the project.

The RPN score or Risk Priority Number is a key concept used in the FMEA (Failure Modes and Effects Analysis) methodology. RPN is a numerical score used to assess and rank the risks associated with different aspects of a project or process. Its purpose is to help identify and prioritize potential problems or risks in an organized and systematic manner. RPN is calculated by multiplying three specific factors:

- Severity (S): This measures the gravity of the consequences if the risk or problem materializes. It is rated on a scale, usually from 1 (least severe) to 10 (most severe).
- Frequency or probability (O): This indicates the probability or frequency with which the risk or problem is expected to occur. It is also rated on a scale of 1 (very unlikely) to 10 (very likely).
- Detectability (D): This reflects the probability of detecting the risk or problem before it occurs. It is rated on a scale from 1 (very easy to detect) to 10 (very difficult or impossible to detect)[9].

The formula for calculating the RPN (Risk Priority Number) is:

$$RPN = S * O * D$$

A higher RPN score indicates a higher risk, suggesting that the issue requires urgent attention and action. The FMEA methodology and RPN calculation are widely used in engineering, quality management and risk management to improve the safety and efficiency of processes and products. By applying the FMEA method, road infrastructure construction projects can benefit from a systematic and structured approach to risk management, leading to more informed decisions and better management of potential problems.

[9] Learn Lean Sigma

5. Applying the FMEA method in road infrastructure construction projects

Each step of the FMEA process is tailored to fit the project's unique specifications and challenges:

- Identifying elements and failure modes: This stage involves a thorough examination of every aspect of the project. Materials, technologies, work processes and human factors are analyzed. Potential failure modes for each component and process are identified.
- Risk assessment: Each failure mode is assessed to determine its potential impact. This is done by analyzing severity, frequency and detectability. A rating scale is used to quantify these aspects, allowing for effective prioritization of risks.
- Development of mitigation plans: Specific strategies are developed to reduce or eliminate the identified risks. It may include changes in construction processes, implementation of new technologies or additional professional training of employees.
- Continuous monitoring and review: FMEA is not a static process. Periodic risk reassessment is vital to reflect changes in the project or new information available. This ensures that risk analysis remains relevant and effective throughout the project.

6. Case study

A specific example is analyzed in detail, illustrating how FMEA was applied in the construction project of a new road infrastructure. The case study covers the identification of risks such as ground instability, delays in material delivery and challenges related to work safety. It discusses how the FMEA analysis led to the implementation of effective solutions for these problems.

6.1. Project context

The new construction project is a major road infrastructure project intended to connect two large cities, crossing a variety of terrains, including mountainous areas and river valleys. The project includes the construction of bridges, tunnels and sections at ground level, involving a wide range of construction activities and diverse materials, each with its own technical and logistical challenges.

6.2. Implementation of the FMEA method

The implementation of the FMEA method brings significant benefits to the project. Risks identified and addressed in a structured manner reduce the probability of delays and budget overruns. In addition, the focus on worker safety and environmental protection improves the project's reputation and ensures compliance with legal and environmental standards. Through these measures, the project meets its technical objectives, managing to improve sustainability and social responsibility. The analysis enables teams to respond quickly to challenges, minimizing delays and extra costs. It also ensures that the impact on the environment and local communities is significantly reduced, thereby contributing to the sustainability and social acceptability of the project.

A road infrastructure construction project can have multiple risks, but for the purpose of illustrating the FMEA method, only a few of them have been analyzed below. The RPN (Risk priority number) score chart was created to illustrate and prioritize the risks associated with the project. This chart is an essential tool in the FMEA methodology, used to evaluate and classify risks based on their severity, frequency and detectability.

6.3. The process of applying RPN scores

Risk identification: Initially, a number of potential risks were identified such as ground instability, urban traffic disruption, environmental impact, delays in material delivery and workplace safety issues, interest rate increase, currency exchange rate fluctuations.

Assessment of each risk: Each risk was assessed based on three criteria: severity (how severe the impact would be if the risk were to materialize), frequency (how often it could happen) and detectability (how easily it could be detected before it causes problems).

Calculating the RPN score: Scores for each criterion were assigned on a scale from 1 to 10, and the RPN score for each risk was calculated by multiplying these three values. A higher RPN score indicates a higher risk and a higher priority in managing it.

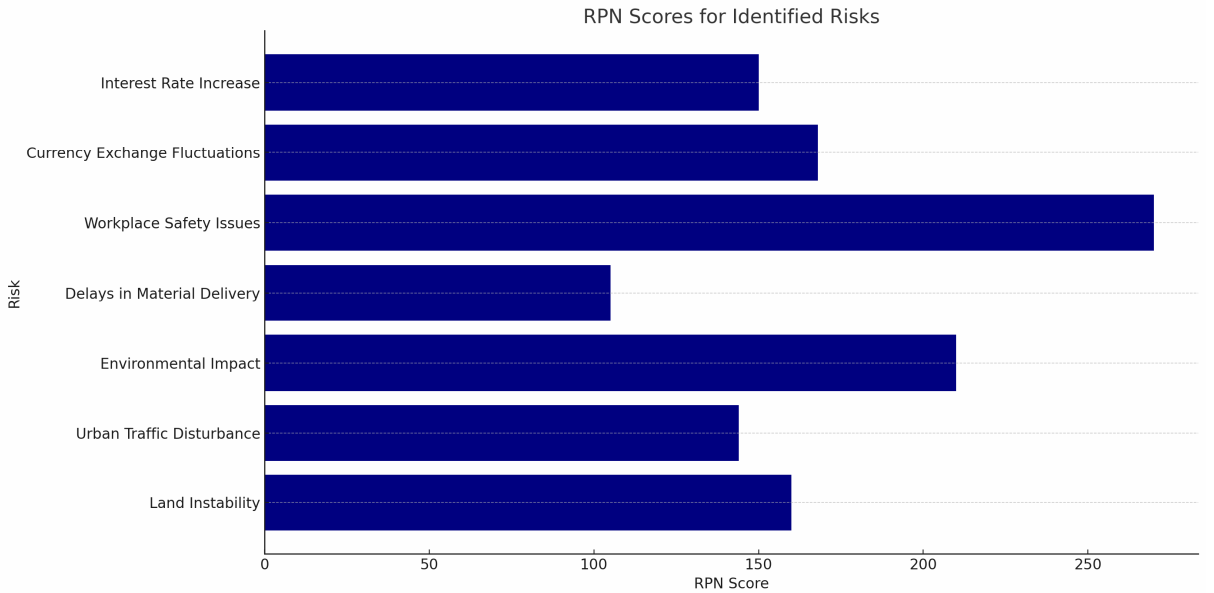

Fig. 2. RPN scores for identified risks.

Table 1. Identified risks.

Risk	Severity (1-10)	Frequency (1-10)	Detectability (1-10)	RPN score
Land instability	8	5	4	160
Urban traffic disturbance	6	4	6	144
Environmental impact	7	6	5	210
Delays in materials delivery	5	7	3	105
Workplace safety issues	9	5	6	270
Currency exchange fluctuations	7	6	4	168
Interest rate increase	6	5	5	150

Fig. 2 shows risks on the vertical axis and RPN scores on the horizontal axis. Each bar represents a specific risk, with the length corresponding to the calculated RPN score. This visual format facilitates a quick and clear interpretation of risk management priorities. To better illustrate the assigned values, Table 1 presents the risk assessment identified using the FMEA method.

The risk classification process was conducted following the steps below:

- Identification and categorization of risks: Initially, a comprehensive assessment of the risks associated with the construction of the project was performed. These risks were then classified into several main categories, such as technical, logistical, financial, and environmental risks.
- Counting the risks in each category: For each category, the total number of identified risks was calculated. This step is essential for understanding the distribution and density of risks across different aspects of the project.
- The total number of risks in each category is calculated simply by counting them, using the formula:

$$N_C = \sum_{i=1}^{k} 1$$

where: N_C is the total number of risks in category C,
k is the number of risks identified in category C.

- Calculation of the percentages for each category: After all the risks in each category have been counted, the percentage of each category can be calculated in relation to the total risks, using the formula:

$$P_C = \frac{N_C}{N_{Total}} x\,100$$

where: P_C is the percentage of category C,
N_C is the total number of risks in category C,
N_{Total} is the total number of risks identified in all categories.

The identified risks were divided into four main categories: technical risks, logistical risks, financial risks and environmental risks, as follows:

- Technical: Land instability, Urban traffic disturbance, Workplace safety issues
- Logistics: Delays in material delivery
- Financial: Increase in interest rates, Currency exchange fluctuations
- Environmental: Environmental impact

Calculation of percentages: Each risk was considered to have the equal weight in the overall analysis. Thus, to calculate the percentages, the number of risks allocated to each category was divided by the total number of risks. Therefore, the percentages are as follows: technical risks: 42.86%, logistical risks: 14.29%, financial risks: 28.57%, environmental risks: 14.29% (Fig. 3).

The risk distribution chart by category provides a clear perspective of the areas that require additional attention and resources within the risk management process. This analysis facilitates the appropriate allocation of resources and focus. For instance, a high concentration of logistics risks would suggest the need for enhanced planning and management of traffic and supply chains. Table 2 details the mitigation strategies for the identified risk categories, as well as the responsible parties and deadlines for implementing these strategies.

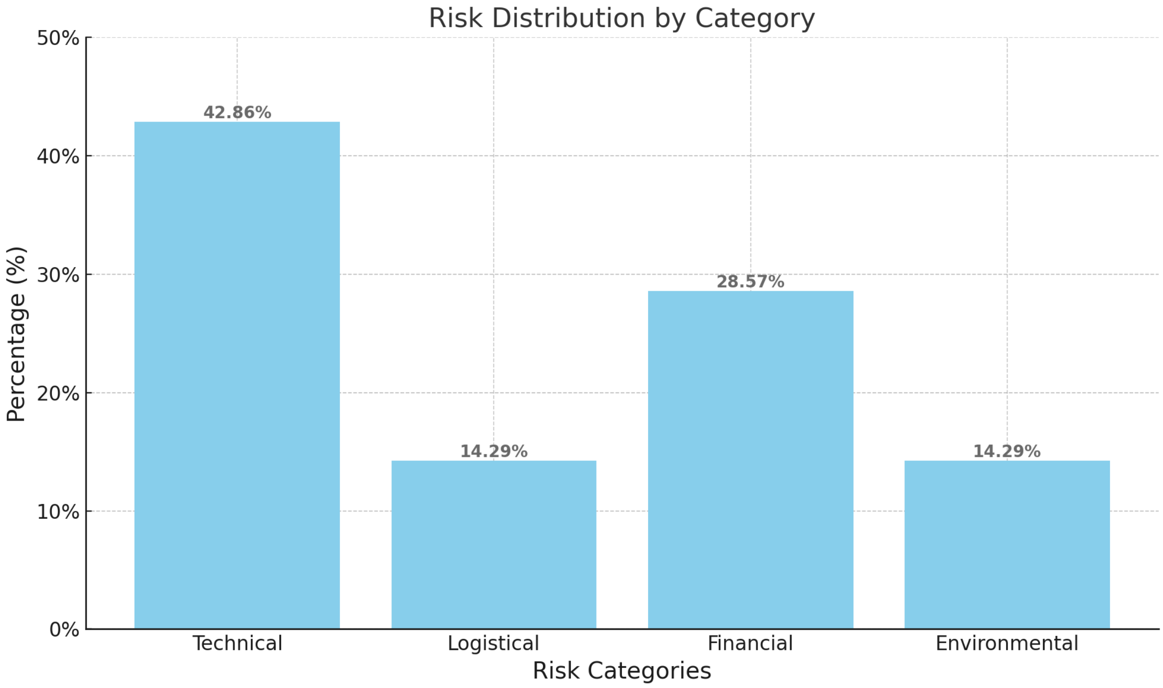

Fig. 3. Distribution of risks by category.

Table 2. Risk mitigation strategies.

Risk categories	Risk mitigation strategy	Responsible party	Deadline
Tehnical	Implementation of advanced technologies and technical training	Technical team	2024 Q3
Logistical	Optimization of transport routes and traffic planning	Logistics department	2024 Q4
Financial	Effective budget management, risk insurance, currency hedging strategies and periodic analysis of market conditions for interest rates	Financial department	2024 Q1
Environmental	Ecological impact monitoring and rehabilitation plans	Environmental department	2024 Q2

This table provides an illustrative framework for effective risk management within a road infrastructure construction project, ensuring that each risk category is appropriately addressed.

7. Financial aspects and cost reduction

Effective cost management: FMEA plays an essential role in identifying and mitigating risks that can lead to cost overruns. By anticipating problems and implementing proactive solutions, the project can avoid costly delays and design revisions at advanced stages, which would significantly increase the overall budget.

Significant savings: Systematic risk analysis and implementation of effective mitigation measures lead to significant savings.

Strategic investments: Investments in advanced technology and employee training can prove to be strategic, generating long-term savings by improving efficiency and reducing costly errors.

Impact on the overall budget: Implementing the FMEA can help keep the project's overall budget within planned limits. Even if it initially requires an additional investment in analysis and planning, in the long run the savings achieved will offset these initial costs.

Therefore, the application of FMEA not only improves risk management from a technical and operational point of view, but also has a substantial positive impact on the financial efficiency of construction projects. This methodology provides a way to balance initial costs with long-term savings, contributing to sustainable and economically viable infrastructure projects.

8. The efficiency of the FMEA method in risk management for road infrastructure construction projects

As demonstrated in the analysis presented in this article, the FMEA methodology is a vital tool in risk management for road infrastructure construction projects. This method offers a systematic and structured approach, enabling the project team to identify, assess and proactively manage risks, thereby contributing to the overall success of the project.

8.1. The value of proactive risk identification

Implementing FMEA leads to a deep understanding of potential risks and their impact on the project. This anticipation of problems allows the project team to develop effective mitigation strategies, thereby reducing the probability of delays and budget overruns.

8.2. Contribution to safety and sustainability

FMEA plays a major role in improving work safety and environmental protection. By identifying risks related to worker safety and environmental impact, preventive measures can be implemented to ensure a safer work environment and to comply with environmental standards.

FMEA contributes to achieving a balance between development needs and ecological and social responsibilities, demonstrating that infrastructure projects can be carried out in a sustainable way and with a positive impact on communities.

8.3. Resource optimization

Applying FMEA contributes to more efficient use of resources. By identifying and addressing problems before they become critical, the project can save time and financial resources, thereby reducing unexpected delays and costs in the advanced stages of construction.

8.4. Benefits of implementing the method

The implementation of FMEA has a positive impact on various aspects of the project, including improving work safety, minimizing the impact on the environment and local communities and increasing transparency and confidence in attracting investments.

Therefore, the case study illustrates the added value of applying FMEA in risk management. This methodology not only optimizes the construction process, but also contributes to creating safer, more sustainable and socially responsible projects.

9. Conclusions

FMEA represents an essential methodology for any road infrastructure construction project. Its ability to identify and manage risks in a structured manner not only enhances the project's chances of success, but also contributes to increased safety, sustainability, and efficiency in the road infrastructure construction sector. By integrating FMEA into standard project management practices, the road construction industry can make significant progress towards safer, more sustainable and more efficient projects.

In conclusion, this article highlights the importance of the FMEA method as an essential risk management tool for road construction projects, underscoring its benefits in terms of safety, efficiency and sustainability. FMEA proves to be a valuable tool in risk management of road infrastructure construction. By proactively identifying potential problems and developing mitigation strategies, project managers can ensure better control of projects, reduce unexpected costs, and improve safety and quality of work.

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