

ROOT FACTORS AND EFFECTIVE MITIGATION METHODS FOR CONSTRUCTION SAFETY: AN ANALYTICAL EMPIRICAL MODEL

Reem Zeibak-Shini¹, Hofit Maharabani², Kun-Chi Wang³, and Igal M. Shohet^{2,3}

1 Department of Civil Engineering, Braude College of Engineering, Karmiel, Israel, reemz@braude.ac.il

2 Department of Civil and Environmental Engineering, Ben-Gurion University of the Negev, Beer Sheva, Israel, igals@bgu.ac.il

3 Department of Civil and Construction Engineering, ChaoYang University of Technology, 168, Jifeng E. Rd., Wufeng District, Taichung 41349, Taiwan

Abstract

The construction industry plays a crucial role in contributing to the economy and developing sustainable infrastructure. In addition, it is known as one of the most dangerous industrial domains in the world. Over the years, special attention has been paid to developing models for managing and planning safety. Many research studies were conducted to develop models for preventing work accidents and mitigating their consequences. Usually after the occurrence of an accident, a learning process through investigation is required. To identify indirect systematical reasons for an accident, there is a need for an investigating model, which can identify, control, and resolve risk factors in the workplace. In most cases, the goal is to find the point on the timeline that starting from it, it is impossible to come back, whereas in construction sites this is much harder, mainly because of the influence of various risk factors. Assessing safety risks across various dimensions, from macro to micro levels, including project type (residential, roadways, bridges, etc.), construction stages (planning, site organization, excavation, construction, finishing, etc.), professional tasks (formwork, casting, crane operations, rebar installation, etc.), and even considering time of day, offers the opportunity to formulate a strategic safety plan. Such a plan could entail targeted safety training and specific controls, facilitating thorough risk identification and implementation of an effective control process. In this paper, we present a review of work-accident-related research, categorized into five root causes: Medium, Mission, Man, Management, and Machinery, using the 5M method. This paper suggests a comprehensive methodology that uses the 5M model for investigating work accidents and implements the Analytical Hierarchy Process (AHP) for organizing and analyzing safety resource allocation decisions, in the process of risk management in construction sites, based on structured analysis and probabilistic risk analysis. The proposed model was validated in a case study.

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Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2024.

Keywords: AHP, Construction Management, Safety, 5M model, Risk Management.

1. Introduction

The construction industry plays a pivotal role in the global economy and infrastructure development but is also recognized as one of the most hazardous sectors. Construction sites are characterized by constant dynamism, presenting daily changes that introduce varying accident risks. Hazardous activities such as excavations, working at height, exposure to dust and noise, and operation of heavy machinery pose significant risks to workers' safety. Research emphasizes the correlation between safety practices

and construction quality [1], underlining the critical need for stringent safety measures to mitigate risks effectively. Collaboration among diverse teams on construction sites adds complexity and underscores the importance of analyzing safety risks by occupation to ensure comprehensive accident prevention strategies.

Management personnel typically undergo more systematic safety training compared to frontline workers, leading to a heightened focus on accident prevention. However, visibility issues, particularly related to construction machinery, remain a significant contributing factor to accidents. Accidents in the construction industry are often attributed to a combination of factors, necessitating comprehensive risk assessment and management approaches. Models like the 5M model (Man, Machinery, Medium, Management, Mission), illustrated in Fig. 1, and the Analytical Hierarchy Process (AHP) are utilized to analyze and prevent accidents, acknowledging the complex interplay of various factors. These models help identify the root causes of accidents and enable the implementation of control measures to mitigate risks effectively.

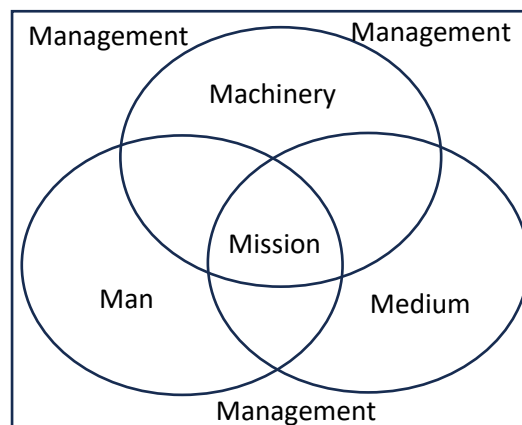


Fig. 1. The 5M model interactions in investigating work accidents.

Addressing safety concerns in the construction industry requires a proactive approach, meticulous planning, and a deep understanding of the complex dynamics inherent in construction site operations. By systematically identifying and addressing hazards, construction companies can create safer working environments for their employees. Additionally, promoting a safety culture, enhancing training programs, and implementing advanced technologies can further improve safety outcomes in the construction industry. These measures ultimately ensure the well-being of workers and the successful completion of projects.

1.1. Research Objective

The research objective is to investigate and analyze various aspects related to safety in the construction industry. This includes assessing the effectiveness of safety practices, identifying root causes of accidents, and developing comprehensive risk assessment and management strategies. The research aims to enhance safety outcomes in construction by examining the interplay of factors such as management practices, workers' behavior, machinery, working conditions, and project objectives. Additionally, the research seeks to explore the applicability of models such as the 5M model and the Analytical Hierarchy Process (AHP) in accident prevention and risk analysis within the construction context. Overall, the objective is to contribute to the development of proactive and effective safety measures to ensure the well-being of workers and the successful execution of construction projects.

1.2. Research Contribution

The research aims to address the intricate challenges associated with safety in the construction industry by thoroughly investigating various factors influencing work accidents. Employing the 5M method—focusing on Medium, Mission, Man, Management, and Machinery—the study seeks to dissect these

factors and their interplay within construction environments. Emphasizing the need for a comprehensive approach, the research categorizes safety risks across project types, construction stages, professions, and timeframes to formulate strategic safety plans and training protocols tailored to specific risk scenarios.

Examining the Medium component, the research delves into the relationship between unsafe working conditions and worker behavior, highlighting the critical role of hazard perception in accident prevention. By exploring factors influencing human behavior on construction sites, such as lack of training, information, or personal protective gear, the study aims to identify key areas for intervention and develop risk mitigation strategies. Additionally, the Mission aspect underscores the dynamic nature of construction work, necessitating innovative risk assessment models that account for the evolving work environment and project-specific challenges. Through attribute-based risk analysis and customized safety plans, the study seeks to improve safety outcomes on various construction projects.

By assessing risk perception among different stakeholders, including managers, workers, and safety personnel, the study aims to uncover insights into safety decision-making processes and inform targeted safety training programs. The research also examines resource allocation practices, advocating for optimal safety investments to mitigate the financial and reputational costs of workplace accidents. By identifying the most effective strategies for safety management and investment, the research seeks to promote a culture of safety and reduce the incidence of work accidents in the construction industry.

2. Literature review

Typically, a learning process through investigation follows the occurrence of an accident. In construction sites, this process is notably challenging due to the wide variety of risk factors influencing operations. This paper provides a comprehensive review of research related to work accidents, categorized into five groups by the 5M method for investigating work accidents: Medium, Mission, Man, Management, and Machinery.

- **Medium:** The relationship between unsafe working conditions and workers' behavior, and their impact on the severity of injuries, has been thoroughly investigated across various industries. Unsafe actions by workers, including incorrect assessments of situations or improper operations, combined with hazardous working environments like bad weather or unstable surfaces, are significant root causes of workplace accidents. Heinrich [2] noted that 88% of workplace accidents were due to unsafe worker actions within dangerous environments. For example, a study in Hong Kong explored why construction workers engaged in unsafe behavior and identified factors such as lack of skill or safety training, disregard for safety protocols, failure to use personal protective equipment, and difficulty in recognizing unsafe conditions [3]. Another study categorized human errors into two main types: cognitive-related failures, such as limited human capability, and deviations from established safe work practices [4].
- **Mission:** Assessing risks in construction work is challenging due to the dynamic nature of the construction environment, which differs significantly from other industries where the work environment is generally static. Construction sites undergo constant changes, including team rotations, high turnover rates, varying ground conditions, diverse technologies and execution methods, unique project-specific environments, and different teams with distinct missions operating in the same area. These characteristics increase the complexity of safety risk assessment [5]. Esmaeili et al. [6] developed an attribute-based model for risk assessment using accident reports from OSHA's Integrated Management Information System (IMIS) [7]. The model aims to identify measurable safety attributes and incorporate them into a risk analysis approach based on historical data. However, this model has limitations, notably the need to expand attribute-based safety risk analysis beyond specific risk types and accommodate variations in risk perception among different construction professions. Xiao et al. [8] developed a quantitative analysis method for generating a loss index for various accidents on construction sites. This method, based on the Bayesian Network and AHP solution, calculates the contribution rate of each risk factor to a particular accident.

- **Man:** Furthermore, psychological factors significantly influence safety behavior, as evidenced by studies on risk perception among construction workers in different roles, professions, and levels of experience [9], [10]. For example, management personnel tend to perceive certain situations as more dangerous than workers, possibly due to their higher level of education and safety training. Fan et al. [11] proposed using the AHP method to evaluate the impact of aging construction workers on safety risk factors. Profession also plays a role in risk assessment; for instance, experienced workers may assess certain scenarios differently from new workers or those in mid-career, reflecting differences in risk tolerance and perception [9], [10]. Additionally, studies have highlighted that designers often lack familiarity with construction risks and may be reluctant to prioritize safety in their design decisions [12]. Collaboration among stakeholders, ongoing training, and the integration of safety considerations into design and planning processes are essential for mitigating risks and promoting a safer work environment.
- **Management:** Management plays a crucial role in ensuring safety on construction sites, particularly through the supervision and control actions exercised by construction managers and supervisors. However, studies have highlighted challenges in effectively identifying and assessing risks by construction supervisors. Research conducted in 2006 [13] revealed that only 6.7% of construction supervisors were able to identify all relevant safety risks presented to them. Additionally, familiarity with a project's mission may lead to underestimation of associated risks [14]. The dynamic nature of construction work often requires on-the-spot solutions to various interferences, underscoring the critical role of foremen and construction supervisors in managing physical site conditions [15], [16]. However, studies have shown variations in risk assessment abilities among construction supervisors. For instance, a study conducted at the Technion [17] found that experienced supervisors and safety managers demonstrated better risk assessment abilities compared to students with minimal working experience and formal safety training. This study involved evaluating risks within a virtual construction site, revealing that experienced professionals typically rated risks as more severe and identified a greater number of risks compared to students. In terms of resource allocation, organizations often underestimate the importance of preventing work accidents, frequently due to a lack of credible data. Research conducted in 2018 [18] aimed to estimate the optimal budget for construction safety investment. Findings suggested that an optimal investment of 1% of the project scope could significantly reduce accident rates and overall safety costs.
- **Machinery:** Construction equipment is typically categorized into four main families: concrete creation and handling equipment, transport equipment, earthworks equipment, and formworks and scaffolding [19]. The choice of equipment for construction sites depends on various factors such as site organization, execution methods, technological constraints, costs, and safety considerations. Tower cranes, a major component of construction sites, pose significant safety risks due to their widespread use and complex operations. A significant challenge encountered by crane operators is the restricted field of vision, which can compromise safe operation. Limited visibility, whether due to inadequate lighting or physical obstructions, hampers the operator's ability to safely carry out tasks and inspect cargo. To mitigate these risks, measures such as employing signalmen and installing auxiliary vision systems, like cameras on cranes, have been adopted [20], [21]. These technologies enhance operator visibility and improve overall safety on construction sites.

The intersection of various factors such as Man, Machine, Medium, Mission, and Management highlights the critical importance of fostering an organizational culture that prioritizes safety. This includes enhancing workers' awareness of risk identification. Familiarity with the construction site, creating a safe work environment, and providing both general and specific guidance—combined with knowledge and technology—empower project managers, safety managers, constructors, and foremen to receive scenario-based information tailored to different construction stages. While advanced technology can enhance safety practices, the human factor remains crucial. Effective safety management begins with organizational leadership promoting safe behavior and allocating sufficient budgetary resources.

Understanding the interconnectedness of Medium, Man, Mission, and Machinery is essential for optimizing safety management.

In terms of construction design, promoting collaboration among all stakeholders to enhance worker safety through additional legislation and updates can significantly improve safety practices. Integrating proactive safety approaches into the education and training of all construction professions, including foremen, safety helpers, crane operators, engineers, and practical engineers, is beneficial.

Investing in safety management typically reduces the probability of accidents and minimizes financial losses post-accident. While direct costs, such as medical care and compensation, are the main financial losses, indirect costs, including legal expenses and damage to the firm's reputation, can be even more substantial. Finding the optimal investment level for each construction project ensures that safety investments are financially viable without compromising safety standards. Striking this balance helps mitigate accidents while controlling overall safety expenses.

3. Research Methodology

To address the need for reducing the extent and severity of accidents in construction, the implementation of the AHP model is suggested for risk management and the integration of key root causes for work accident mitigation on construction sites (see **Hiba! A hivatkozási forrás nem található.**). Emphasizing cooperation and hierarchy among risk factors and construction stages is crucial. The model aims to understand how fatal accidents manifest at different project stages, thereby optimizing risk management effectively.

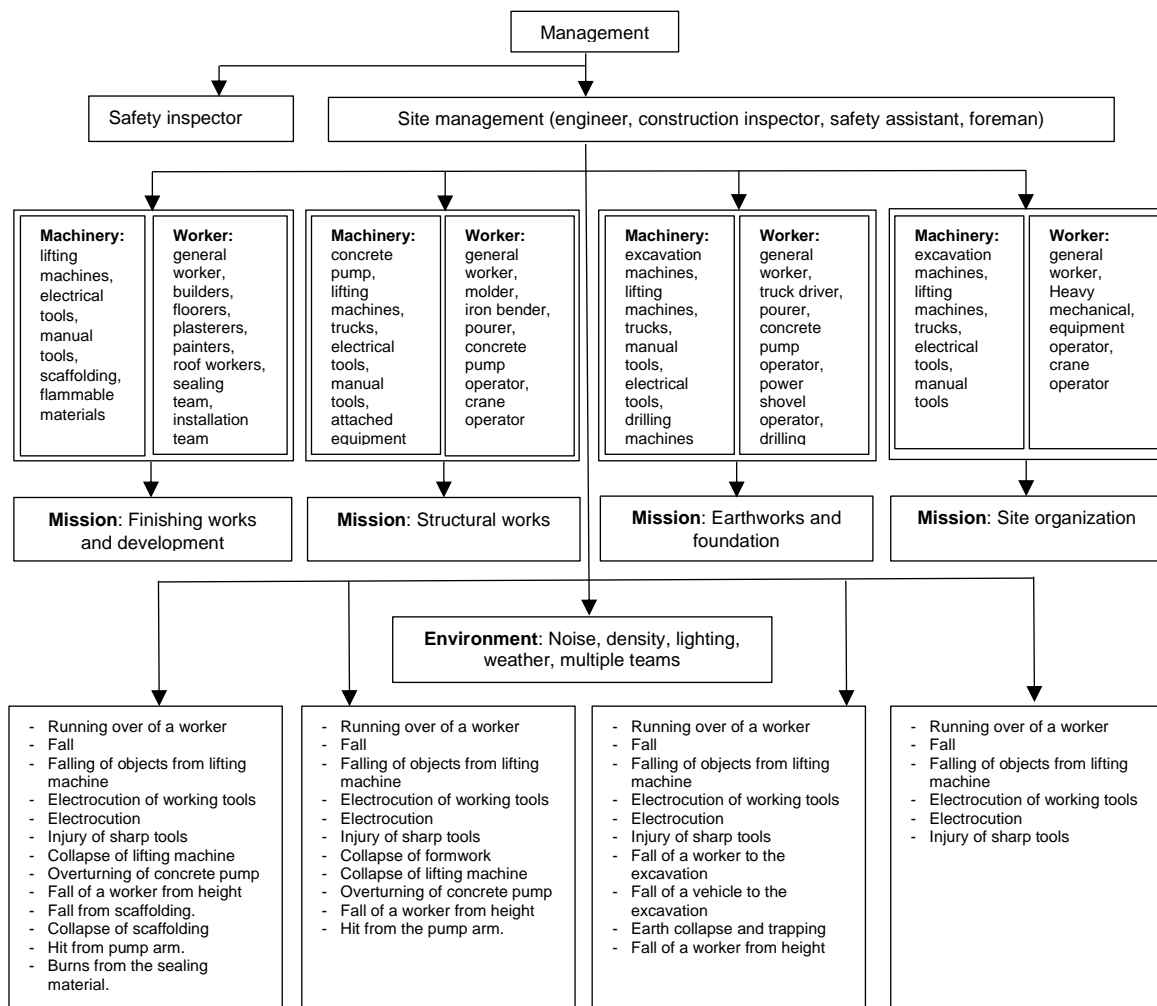


Fig. 2. Root cause analysis of fatal accidents in construction.

The AHP method, originally developed by Saaty L. Thomas in the 1970s, [22], has been widely used for decision-making across various industries such as automotive, chemistry, energy, machinery, and medicine. This method is suitable for determining priorities, allocating funds based on performance indicators, designing systems, ensuring system stability, and optimization purposes.

In this research, the AHP model was constructed to provide at least two alternatives for each identified root factor in the construction process. For each identified risk, two alternatives were proposed to mitigate accident severity and reduce the potential materialization of the risk. The AHP method facilitates ranking risk control options by considering the probability of occurrence and the severity of injuries if the risk materializes (See **Hiba! A hivatkozási forrás nem található.**). This enables the selection of the most suitable alternative, ensuring optimal results while satisfying project budget constraints and meeting the needs of entrepreneurs, management, and execution teams on-site.

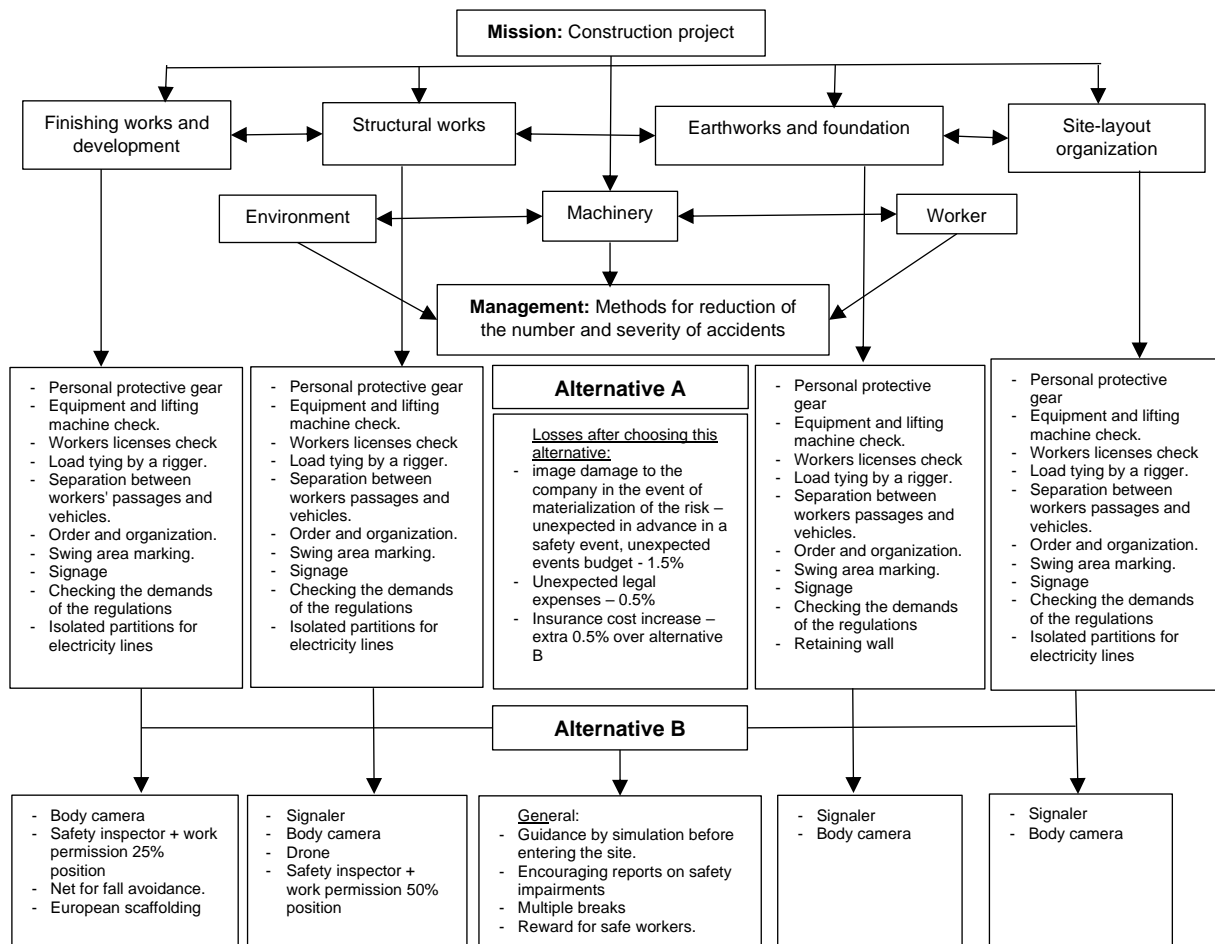


Fig. 3. Risk mitigation alternatives in different construction stages.

In **Hiba! A hivatkozási forrás nem található.**, possible solutions are proposed for risk control in identified dangerous construction stages, aiming to reduce both the probability and the severity of injuries if the risk materializes. Using the proposed model, it is possible in some cases to reduce the risk to the required acceptable level as defined in the regulations of the Israeli labor regulation organization (safety management program), 2013, [23]. These regulations are compatible with OSHA's regulations.

Table 1. 4x4 matrix for construction safety risk management

Probability	Probably will never happen (very low-1)	Might happen rarely (low-2)	Might happen occasionally (medium-3)	Might happen every day (high-4)
Severity of injury				
Death or permanent disability (Highly Severe-4)	4	8	12	16
Hard injury or sickness of over 3 days (Severe-3)	3	6	9	12
Medical treatment and up to 3 days of incapacity (Light-2)	2	4	6	8
Only first aid (Minor-1)	1	2	3	4

Legend: Risks in size of 1-3 describe an acceptable risk by its definition in the regulations of the labor regulation organization (safety management program), 2013; Risks in size of 4-11 describe an unacceptable risk – requires handling but a work manager that was qualified for that can authorize work for a limited time; Risks in size of 12-16 describe an unacceptable risk – high-level risk, it is necessary to operate immediately even if the thing requires stopping of the work process.

"Acceptable risk – a risk that was reduced to the level defined as acceptable by the holder of the workplace, considering his duties by law and the safety policy of the workplace" (Ministry of Labor, Social Affairs and Social Services, 2013).

To assess the model's feasibility, it was implemented on a construction project in central Israel. This project comprised 10 floors (9 residential and one basement), covering a built area of 5,968 m² with an estimated construction period of 24 months. The project's total budget, including fees, is estimated at \$9.019 million. Additionally, a safety budget of 0.5% of the total project cost was allocated for apartment delivery, contingency, liability period, and safety measures.

The safety budget for the project can be calculated using the formula:

$$TPB = \frac{TPBWSB}{1 - p_{safety}} = \frac{TPBWSB}{1 - 0.005} = 9,018,987\$ \quad (1)$$

$$SB = TPB - TPBWSB = TPB - TPB * (1 - p_{safety}) = TPB * (p_{safety}) \quad (2)$$

Where:

TPB = total project budget

$TPBWSB$ = total project budget without safety budget

p_{safety} = safety budget in Percentage of total project budget

SB = safety budget

4. Results analysis

For the exploitation of the safety budget in the test project, results are analyzed, and suggestions are discussed. The risk assessment, focused on the probability of materializing, was calculated based on fatal accidents in Israel. Therefore, there is no reference for light accidents, nor for accidents in other countries. The model focuses on structural and finishing work stages, and it would be worthwhile to check its feasibility in other work stages as well.

Project cost: $TPB = 9,018,987\$$ (3)

According to alternative A: A safety budget in a scope of 1% of the project cost was allocated:

$$P_{safety} = 0.01 \quad (4)$$

$$SB_{1\%} = TPB * (P_{safety}) = 9,018,987 * 0.01 = 90,190\$ \quad (5)$$

Cost to the owner including safety costs according to alternative A is:

$$TPB_{1\% \text{ safety improvement-included}} = 9,109,177\$ \quad (6)$$

According to alternative B: A safety budget in a scope of 0.5% of the project cost was allocated:

$$P_{safety} = 0.005 \quad (7)$$

$$SB_{0.5\%} = TPB * P_{safety} = 45,095\$ \quad (8)$$

Cost to the owner including safety costs according to alternative B is:

$$TPB_{0.5\% \text{ safety improvement-included}} = 9,064,082\$ \quad (9)$$

Extra available safety budget: $\Delta_{for \text{ safety budget}} = 45,095\$ \quad (10)$

To maximize the utilization of this budget, we propose leveraging the AHP model. Initially, we prioritized risk control measures falling within the ranking zone of 12-16 based on the risk control matrix (as shown in **Hiba! A hivatkozási forrás nem található.**). Subsequently, we recommend the following technical solutions:

- The estimated duration of the structural works is 6 months.
 - The cost of a safety inspector in a 50% position scope in addition to the existing professional team on site - 15,142\$
 - An extra worker for directing concrete trucks for an estimated duration of 20 minutes in casting - 3,114\$
 - 3 body cameras (one for the workers' team, one for the foreman, and one for the pump operator) - 870\$
 - A drone for 2 workdays for each (total cost for worker + drone) – 5,063\$

A total of 24,189\$ for a safety upgrade in structural works.

Now, the available safety budget is:

$$\Delta_{for \text{ safety budget}} = 45,095 - 24,189 = 20,906\$ \quad (11)$$

- The estimated duration of the finishing and developing works is 13 months.
 - The cost of a safety inspector in a 25% position scope in addition to the existing professional team on site – 13,880\$
 - 3 body cameras (one for the workers' team, one for the foreman, and one for the lifting machine) – 1,344\$
 - The cost of an upgrade to a European scaffold – after a cost reduction of the scaffold in a total front area of 4,662 m² – 12,392\$

A total of 27,616\$ or a safety upgrade in finishing works.

Now, the available safety budget is:

$$\Delta_{for \text{ safety budget}} = 20,906 - 27,616 = -6,710\$ \quad (12)$$

Allocating an additional \$6,710 from the safety budget is a prudent investment. When comparing this relatively modest expense to the potential costs associated with construction accidents, it becomes clear that prioritizing safety expenditures is essential. The financial consequences of a severe accident can be substantial, encompassing not only direct costs but also long-term effects on the individuals involved, their families, and the overall project. By proactively investing in safety measures, construction companies can mitigate risks, prevent accidents, and foster a culture of well-being. Ultimately, the

savings achieved by preventing accidents far outweigh the initial budget allocation. This strategic decision not only safeguards lives but also contributes to the overall success and sustainability of construction projects.

It is also worth noting that before implementing this model, no investigations of near accidents were conducted. However, with the allocated funds for hiring a safety inspector to supervise and conduct such investigations, it is expected that at least two investigations will be carried out each quarter, totaling about eight investigations per year. These efforts are anticipated to significantly enhance safety conduct.

5. Discussion and conclusions

Understanding the specific risks associated with different construction tasks and predicting these risks based on the nature of the work, duration, and worker profiles can significantly enhance safety on construction sites. This study highlights that fostering a corporate culture prioritizing safety and raising worker awareness of risk identification can reduce work-related accidents. Several strategies can be employed to achieve this goal. First, conduct a thorough risk assessment specific to the project. This involves analyzing project-specific risk factors to formulate and implement an effective construction risk management strategy. By identifying potential risks early, project teams can proactively address them. Second, clearly define risk ownership within the project team. Assign responsibility for managing and mitigating specific risks to relevant stakeholders, such as project managers, safety managers, and foremen. Third, develop comprehensive risk response plans. These plans should outline how to handle identified risks, including preventive measures, contingency plans, and emergency protocols. Finally, monitor risks throughout the project's duration. Regularly assess risk factors, adapt strategies as needed, and stay informed about any changes or emerging risks. In addition to these steps, leveraging technology and utilizing tools and software designed for construction risk management can significantly enhance safety execution. These strategies can help track risks, automate processes, and provide real-time insights to project stakeholders. By integrating these practices, construction companies can create safer work environments, reduce accidents, and improve overall safety performance. Project managers, safety managers, and workers on construction sites all play crucial roles in ensuring safety through informed decision-making and proactive risk management.

In the case study project described, the initial safety budget was 0.5%. Following a recommendation to increase it to 1%, the remaining safety budget was allocated based on the model's recommendations. Several technological solutions were adopted during implementation, including body cameras, drones, scaffolding adhering to European regulations, an additional safety inspector, and a traffic management worker at the construction site. The impact of these solutions was evident in the subsequent risk survey. After implementing the suggested solutions, the average risk associated with construction work decreased significantly, aligning with the expected outcomes from the model's recommendations. Although the deviation from the budget was relatively small for a \$9 million construction project, it underscores the importance of optimizing safety investments for each specific project. It is crucial to recognize that the potential costs resulting from severe accidents far outweigh the expenses incurred by safety investments. Therefore, leveraging models like the one developed in this study is essential to ensure optimal safety practices and effectively mitigate risks.

Future endeavors will focus on refining this model to cater to specific roles during the construction phase. The goal is to provide a practical and profitable alternative, beginning with selecting appropriate personal protective equipment. The model will also offer tailored recommendations based on the work stage and address specific timeframes within the workday. Additionally, it is essential to explore allocating a portion of the safety budget toward incentivizing workers to embrace a safety-conscious culture. This can be achieved by integrating them into technological guidance systems, such as augmented reality tools. Safety initiatives at the company level can also play a pivotal role in fostering a safety climate. To promote awareness of the investment's viability, an advocacy program should be implemented. This program would target entrepreneurs and managers, emphasizing the importance of safety and encouraging their active participation in driving positive safety changes.

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