International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 04 Issue: 06 June 2026
Page No: 4186 - 4192
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2026.0542

An Integrated AHP-Based Decision Framework for Sustainable Safety Management in Metro Construction Projects

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Abstract
Metro building projects are very complex and consume resources and pose numerous risks to workers. That is why the merging of safety and sustainability management is an extremely important objective. The safety measures of traditional type are typically limited to the prevention of accidents, and sustainability activities are addressed separately. This makes decisions made in a piece meal manner during project planning and implementation. In order to overcome this limitation, this study proposes a multi-criteria decision-making model based on the Analytic Hierarchy Process (AHP), which provides sustainable safety management in the construction of metros. The framework has key elements of sustainability and safety including minimizing environmental impact, ensuring the project is financially viable, ensuring that workers are healthy and safe, ensuring that social disruption is minimized, efficient utilization of resources and that the project is operations-friendly. Expert opinions of metro construction workers, safety engineers, and project managers about the perceived importance of each assessment criterion are obtained using high-stake pairwise comparison survey research designs. Consistency analysis is carried out to ensure that contributions made by experts are reliable. The sustainable safety method ranking model that has been developed makes it feasible to direct the decision-makers to select the most effective interventions to use in the construction sites of metro. The results indicate the most significant ones and determine a list of suggested sustainable safety management choices in a prioritized manner. This provides useful information to the contractors, politicians, and urban infrastructure planners. The proposed framework will increase the safety and sustainability of the metro development through promoting integrated planning approaches that are compatible with sustainable infrastructure development and sustainable building approaches.
Keywords: *Analytic hierarchy process (AHP); Metro construction projects; multi-criteria decision making (MCDM); Sustainable safety management.*

1. Introduction
Metro railways are widely recognized to be one of the significant elements of a sustainable city transport that would have significant benefits, including the reduction of road traffic jams, high mobility, and the emission of fewer greenhouse gases than travelling by a personal automotive system. In countries such as India that are rapidly becoming urban, development of metro infrastructure has increased significantly as a long-term projection to sustainable transport (Sharma, Dhyani, and Gangopadhyay, 2013). Although such operational advantages are available, the construction process of metro systems is extremely challenging due to the complex character of engineering, high number of resources required, and high risks to people and staff. Constructing a metro involves hazardous activities such as excavation, deep drilling, construction of high structures and use of heavy equipment in urban

centers. This situation poses a lot of uncertainty and the chances of accidents are high, which means that a stringent safety risk assessment is required. Past studies have indicated that traditional qualitative safety approaches in most cases are not suitable towards the construction of metro activities due to the dynamic and uncertain nature of underground activities (Zhang et al., 2014). Probabilistic risk assessments have been proposed as a means of addressing uncertainty in the safety management of the metro building much better (Zhang et al., 2014). New research has presented the importance of early warning systems and early risk identification. The use of automated methods of locating safety hazards as per construction drawings has demonstrated that it can assist individuals in identifying the risks at an earlier stage of a project so that they can take decisions that prevent accidents rather than responding to them once they occur (Ding et al., 2012). Meanwhile, the use of digital technologies such as 4D visualization to control the safety in the construction areas on the metro has been implemented. These technologies contribute to the observation of the dangerous situations in time and space and advance the safety planning during the project life cycle (Zhou, Ding, and Chen, 2013). Virtual prototype frameworks complement these features by incorporating a construction simulation, hazard detection, and worker safety training into comprehensive systems of safety management of large infrastructure projects (Guo et al., 2013). Besides the safety in the construction process, the resiliency of a metro project is also dependent on how the safety is incorporated into the design process. In metro stations, BIM-based Design for Safety methodologies have been elaborated to design emergency evacuation plans, and it can be depicted that safety factors at the design stage can improve the safety of the operations in the metro station and minimize the evacuation risk (Tang et al., 2021). Metro environments have employed decision-support methodologies such as TOPSIS particularly in the evaluation of evacuation techniques during uncertain conditions (Mei & Xie, 2017). All these works demonstrate that the metro safety management requires more and more sophisticated decision-support structures supported by digital technologies. One of the primary requirements of constructing metro infrastructure has been sustainability, and another issue has been safety. Construction of a metro system has environmental issues such as dust, noise and vibration pollution, generation of vast volumes of construction waste and wastewater. In order to enhance the environmental performance of the metro projects, therefore, to use useful pollution control measures and green building methods is recommended (Wei, 2021). Further, environmental sustainability evaluation should consider life-cycle effects. The results of Indian railway Life Cycle Assessment studies have shown that operation energy consumption is the leading contributor to the overall environmental effects, and construction materials are the major contributory factors to infrastructure burdens (Shinde et al., 2018). The construction of Metro also impacts socially and economically to the cities and the surrounding areas like work-zone disturbances, road delays, increased fuel consumption, and increased accidents. This indicates that it is necessary to ensure that the disturbance of the masses is minimal as a part of sustainable delivering of the project (Bhutani et al., 2016). The need to integrate safety and sustainability into one management system is more than ever as the issues surrounding the construction of metros are now more complex than ever. Risks cannot be entirely eliminated in the metro systems, but formalized decision-support practices that are more balanced can contain the conflicting objectives (Di Graziano et al., 2021). The Multi-Criteria Decision-Making (MCDM) techniques have increased in importance in the development of research and support the prioritization of complex safety risks and sustainability requirements through the process of expert-based evaluation. However, the Analytic Hierarchy Process (AHP) is a powerful tool employed to create proficient methods of prioritizing choice criteria and enabling structured methods of managing infrastructure (Chellappa & Ginda, 2023). Similarly, prioritizing studies of high metro constructions have revealed that MCDM methods such as TOPSIS can be applied to give priority to safety hazards and mitigation requirements (Tiwari et al., 2021). However, in spite of the thorough research on the safety technology of metros, its sustainability

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impact, and decision support tools, the present-day studies addressed them without considering the links between these spheres. Little attention has been paid to developing a single decision-making model that will equally include sustainability performance and safety management practices in the metro construction environment. This is an important area of research, particularly upon rapidly expanding metro systems in the developing countries, in which sustainable infrastructure development needs to strike a balance between workplace safety of employees and environmental management. In this study, therefore, the recommendation is an integrated AHP based decision framework to be used in long-term management of metro building project safety. The proposed model also has environmental, economic and social sustainability indicators along with the criteria to minimize occupational safety risks (Rajgor M et al ,2025). This will assist the professionals in selecting sustainable safety programs. This framework will aim at enhancing decision-making by metro authorities, contractors, and policymakers through providing a methodical approach to assessing things. This will result in safer and sustainable development of the metro infrastructure [1-5].

1.1. Objectives of The Study:

- To Identify the most critical environmental and safety factors in metro construction.
- To develop a model of sustainable safety management on the basis of AHP.
- To prioritize the best sustainable safety strategies for metro projects

2. Section Explanation

The rest of the work is arranged in the following way. Section 2 explains the research methodology, and it involved developing an integrated AHP-based decision-making framework on sustainable safety in metro building projects. The three sections, section 3 outlines the technique of the AHP calculation that involves weighing of the criteria, test of consistency ratio and ranking of the sustainable safety management options. Section 4 discusses the results of the proposed framework and provides information on the most crucial aspects and solutions to propose. Lastly, Section 5 summarizes the study with the essential findings review, contributions, limitations, and research perspectives [6-10].

3. Method

The study employs the multi-criteria decision-making (MCDM) approach of the Analytic Hierarchy Process (AHP) to give a full picture of the long-term safety management in metro building projects. To begin with, the critical safety and sustainability criteria were outlined through an in-depth literature review and professional involvement. Then, an AHP hierarchy model was created, where the top level was the general purpose, then assessment criteria, and sustainable safety management options. The structured expert questionnaire was used to capture the data on a structured basis on paired comparisons and Saaty 1-9 importance scale. Criteria weights were prepared using the eigenvector technique and Consistency Ratio (CR) was utilized to ensure that expert ratings were valid (CR less than 0.10). And lastly, the sustainable safety measures have been ranked and ranked according to the total weighted ratings, which provide decision-making guidance when selecting the most successful in metro development practices.

AHP Steps: Sustainable safety management methods during metro building ventures have been selected using the Analytic Hierarchy Process (AHP). The decision problem was structured in a top-down system that incorporated the aim, evaluation parameters and the alternatives.

3.1. Objectives of the Study

This is the main aim of this study: Develop a decision support system that combines decision criteria and ranking process of selecting and ranking sustainable approaches to safety management in metro building projects.

3.2. Alternatives (Sustainable Safety Strategies).

Regarding the literature and industry practices, the following options were taken into consideration:

- **A1:** traditional safety management methods.
- **A2** is an area of green building and sustainable material usage.
- **A3:** A circular waste recycling and reuse system.
- **A4:** Sustainability and safety planning of BIM [11-14].

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- **A5:** IoT and AI-based safety solutions as a type of real-time monitoring.

3.3. Evaluation Criteria

The integrated safety and sustainability criteria considered in the evaluation of the options were:

- **C1:** Risk Reduction in Occupational Safety.
- **C2:** Management of environmental pollution such as dust, noise and emissions.
- **C3** also enhances resource wastefulness and decreases building wastage.
- **C4** is concerned with economic feasibility and lifespan cost efficacy.
- **C5** is aimed to reduce social impact and expose to the public.
- **C6** refers to implementation technical and operational feasibility.

3.4. Experts Survey and Sample Size

Comparisons of pairs were based largely on the opinion of experts. Among stakeholders in the construction of metro, such as safety engineers, the project managers, and academics, experts were identified. The responsible sample of 10-20 specialists is usually considered sufficient to make the correct decision during the AHP-based studies, as the methodology does not rely on the large number of respondents but on the expertise. In order to ensure an equal and systematic review, we have researched approximately 15 professionals.

3.5. Pairwise Comparison and Calculation of Weights

The relevance of factors was calculated with the help of the 1-9 scale created by Saaty and used by expert. A two tailed comparison matrix was developed and the weight of criterion calculated according to the eigenvector technique.

3.6. Consistency Check

Authentication of the expert opinions was through the consistency ratio (CR). Acceptable comparisons were CR < 0.10CR < 0.10. In case the CR exceeds the threshold, the comparisons were modified to make it more consistent.

3.7. Ultimate Ranking of Alternatives

The combination of criterion weights and alternative performance rating was used to compute the total priority scores of each option. The methods were also evaluated with the view of establishing the most efficient long-term safety management regime in the Metro construction projects Shown in Table 1 & 2.

4. Calculation

Level 1: Goal: Sustainable Safety Strategy Selection

Table 1 List of Criteria

S.No	Code	Criteria
1	C1	Safety risk reduction
2	C2	Environmental pollution control
3	C3	Waste minimization & resource efficiency
4	C4	Economic feasibility
5	C5	Social impact minimization

Table 2 List of Alternatives

S.No	Code	Criteria
1	A1	Conventional safety practices
2	A2	BIM-based safety planning
3	A3	Circular waste management
4	A4	Real-time monitoring (IoT/AI)

Step 3: Prepare Pairwise Comparison Matrix

Experts compare criteria using Saaty's 1–9 scale.

Example: Pairwise matrix for 3 criteria (for simplicity)

	C1	C2	C3
C1	1	3	5
C2	1/3	1	2
C3	1/5	1/2	1

Meaning:

- C1 is strongly more important than C2 (3)
- C1 is very strongly more important than C3 (5)

Step 4: Normalize the Matrix

4.1. Sum each column

Column sums:

- Sum(C1) = 1 + 1/3 + 1/5 = 1.533
- Sum(C2) = 3 + 1 + 1/2 = 4.5

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- Sum(C3) = 5 + 2 + 1 = 8

4.2. Divide each element by its column sum

	C1(/ 1.533)	C2 (/ 4.5)	C3 (/8)
C1	0.65	0.67	0.63
C2	0.23	0.22	0.25
C3	0.13	0.11	0.13

Step 5: Compute Criteria Weights (Priority Vector)
Take the average of each row:

- Weight of C1: (0.652+0.667+0.625)/3=0.648
- Weight of C2: (0.217+0.222+0.250)/3=0.230
- Weight of C3: (0.130+0.111+0.125)/3=0.122
- Final Criteria Weights Shown in Table 3

Table 3 Criteria Weights for Safety, Environmental, and Resource Efficiency

Criterion	Weight
C1 Safety risk reduction	0.648
C2 Environmental control	0.230
C3 Waste/resource efficiency	0.122

Step 6: Consistency Check
AHP requires checking whether expert judgments are consistent.

4.3. Compute Weighted Sum Vector

Multiply original matrix by weights:

- **For C1:** (1×0.648) +(3×0.230) +(5×0.122) =1.988
- **For C2:** (1/3×0.648) +(1×0.230) +(2×0.122) =0.690
- **For C3:** (1/5×0.648) +(1/2×0.230) +(1×0.122) =0.367

4.4. Compute Consistency Vector

Divide weighted sum by weights:

- **C1:** 1.988/0.648=3.067
- **C2:** 0.690/0.230=3.0
- **C3:**0.367/0.122=3.008

4.5. Compute λmax

Average: λmax = (3.067+3.000+3.008)/3=3.025
Consistency Index (CI)

$$\mathbf{CI} = \frac{\lambda \max - n}{n-1}$$

Here n = 3:

CI = (3.025 – 3) /2
= 0.0125

4.6. Consistency Ratio (CR)

$$\mathbf{CR} = \frac{CI}{RI}$$

Random Index (RI) for n=3 is 0.58
CR= (0.0125/0.58)
= 0.021

Since:

CR<0.10

The judgments are consistent and acceptable.
Step 7: Alternative Ranking Shown in Table 4
Now each alternative is scored against each criterion.

Table 4 Performance Scores of Alternatives Against Weighted Evaluation Criteria

Alternative	C1 (0.648)	C2 (0.230)	C3 (0.122)
A1 Conventional	0.20	0.30	0.10
A2 BIM planning	0.40	0.30	0.30
A3 Circular Waste	0.25	0.25	0.50
A4 IoT Monitoring	0.15	0.15	0.10

Compute Final Score
Score (Ai)=∑ (Weight X Rating)
A2 Example:
= (0.648×0.40) +(0.230×0.30) +(0.122×0.30)
=0.259+0.069+0.037=0.365
Similarly calculate for others. The alternative with the highest score is ranked first Shown in Table 5.

Table 5 Overall Scores and Rankings of Evaluated Alternatives

Alternative	Score	Rank
A2 BIM-based planning	0.365	1
A3 Circular waste management	0.337	2
A1 Conventional practices	0.239	3
A4 IoT monitoring	0.209	4

Conclusion

To evaluate and prioritize sustainable safety management practices in the construction of metro buildings, the study developed a decision framework from the Analytic Hierarchy Process (AHP). Based on the final score of priorities based on the AHP analysis, the A2 score of BIM-based planning was the highest score of 0.365 and the score of A3 based on circular waste management was 0.337. The traditional (A1) and IoT-based (A4) monitoring, however, missed the third and fourth place respectively with 0.239 and 0. 209.The top rating of BIM-based planning is due to its excellent performance in all the key evaluation areas and safety risk reduction, environmental management, and operating efficiency, among others. The methodology used in the choice placed the greatest importance on safety risk reduction and hence the option that would potentially reduce the construction risks in a proactive manner had a significant influence on the final ranking. BIM-based planning in the complex metro construction environment reduces the risk of accidents in the form of visualizing the construction process, early detection of hazards, improved coordination of stakeholders, and simulations of risky scenarios prior to implementation. Moreover, the integration of BIM minimizes errors in the construction of a building and encourages efficient utilization of resources, which aid in sustainability objectives. Circular waste management was ranked second because of its huge contribution to resource efficiency and environmental sustainability. A slightly lower total rating was achieved due to its relatively lower direct effect on immediate safety risk reduction compared to BIM-based planning, although it performs outstandingly in the reduction of waste and preservation of the environment. Since they value reactive safety management over proactive risk mitigation, the traditional safety approaches were rated as mediocre. On the same note, even with the positive effects of technology, the IoT-based monitoring systems ranked last due to integration problems, technical viability, and cost of implementation, which significantly contributes to the success of this system when used in large-scale metro construction projects. In general, the findings demonstrate that the most reasonable and balanced approach to enhancing the safety and sustainability performance during the development of a metro is to employ digital planning software such as BIM. The proposed AHP based framework will help the construction of safer, more resource efficient and environmentally friendly metro infrastructure by offering project managers and policymakers with a systematic means of helping them in the decision-making process.

Acknowledgements

The authors are very thankful to the Department of Civil Engineering and the research supervisor for the help and direction for the effective completion of this study endeavor. Authors also appreciate all people and organizations who directly or indirectly contributed to this work. No external funding assistance has been obtained for this research activity.

References

[1]. Ravi Bhutani, Sewa Ram, Kayitha Ravinder, Impact of Metro Rail Construction Work Zone on Traffic Environment, Transportation Research Procedia, Volume 17,2016, Pages 586-595, ISSN 2352-1465, https://doi.org/10.1016/j.trpro.2016.11.113

[2]. Chellappa, V., & Ginda, G. (2023). Application of multiple-criteria decision-making methods for construction safety research. Management, Procurement and Law. https://doi.org/10.1680/jmapl.23.00006

[3]. Di Graziano, A., Marchetta, V., Grande, J., & Fiore, S. (2021). Application of a decision support tool for the risk management of a metro system. International Journal of Rail Transportation. https://doi.org/10.1080/23248378.2021.1906341

[4]. Ding, L. Y., Yu, H. L., Li, H., Zhou, C., Wu, X. G., & Yu, M. H. (2012). Safety risk identification system for metro construction on the basis of construction drawings. Automation in Construction, 27, 120–137. https://doi.org/10.1016/j.autcon.2012.05.010

[5]. Guo, H. L., Li, H., & Li, V. (2013). VP-based safety management in large-scale construction projects: A conceptual framework. Automation in Construction, 34,

16–24. https://doi.org/10.1016/j.autcon.2012.10.013

[6]. Mei, Y., & Xie, K. (2017). An improved TOPSIS method for metro station evacuation strategy selection in interval type-2 fuzzy environment. Cluster Computing. https://doi.org/10.1007/s10586-017-1499-7

[7]. Sharma, N., Dhyani, R., & Gangopadhyay, S. (2013). Critical issues related to metro rail projects in India. Journal of Infrastructure Development, 5(1), 67–86. https://doi.org/10.1177/0974930613488296

[8]. Shinde, A. M., Dikshit, A. K., Singh, R. K., & Campana, P. E. (2018). Life cycle analysis based comprehensive environmental performance evaluation of Mumbai suburban railway, India. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2018.04.022

[9]. Tang, Y., Xia, N., Lu, Y., Varga, L., Li, Q., Chen, G., & Luo, J. (2021). BIM-based safety design for emergency evacuation of metro stations. Automation in Construction, 123, 103511. https://doi.org/10.1016/j.autcon.2020.103511

[10]. Tiwari, A. K., Sahu, D. K., & Trivedi, A. (2021). Risk prioritization using TOPSIS in elevated metro construction project. International Research Journal of Engineering and Technology, 8(8), 2031–2037.

[11]. Wei, G. (2021). Construction pollution prevention measures and effect analysis of engineering projects. IOP Conference Series: Earth and Environmental Science, 687, 012010. https://doi.org/10.1088/1755-1315/687/1/012010

[12]. Na Xu, Chaoran Guo, Li Wang, Xueqing Zhou, Ying Xie, A Three-Stage Dynamic Risk Model for Metro Shield Tunnel Construction, KSCE Journal of Civil Engineering, Volume 28, Issue 2, 2024, Pages 503-516, ISSN 1226-7988, https://doi.org/10.1007/s12205-023-0655-2.

[13]. Zhou, Y., Ding, L. Y., & Chen, L. J. (2013). Application of 4D visualization technology for safety management in metro construction. Automation in Construction, 34, 25–36. https://doi.org/10.1016/j.autcon.2012.10.011

[14]. Rajgor, M. B., & Rawat, B. S. (2025). SHE hazard assessment in metro projects: An AHP approach. IET Conference Proceedings, 2025(7), 703–710. https://doi.org/10.1049/icp.2025.1367