Enhancing High-Speed Train Line Design: The Role of Multidimensional Assessment Tools

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Abstract. Decision-making in complex environments, such as the implementation of high-speed railway networks, requires a comprehensive approach considering diverse criteria and stakeholder perspectives. This paper presents a model for evaluating alternative scenarios in a multidimensional manner to support Decision-Makers (DMs) in making informed choices. Drawing on the Italian context, where high-speed rail networks have been successfully implemented, the study emphasizes the need for a systematic framework to assess socio-environmental impacts and technical-economic considerations. The proposed model integrates Multicriteria Decision Analysis (MCDA) to provide a structured approach for comparing alternatives based on various criteria, including social, environmental, and technical-economic factors. Through a detailed analysis of the decision problem, the model identifies fundamental objectives and instrumental criteria, reflecting the interests and priorities of stakeholders. A systematic evaluation process, including problem structuring, criteria measurement, weighting, and aggregation, enables DMs to assess each alternative's performance comprehensively. Adopting such a multidimensional approach makes understanding the trade-offs involved and making more informed and sustainable decisions regarding high-speed railway network implementation possible. This framework promotes transparency, stakeholder engagement, and equitable distribution of benefits, ultimately facilitating the achievement of broader societal goals.

Keywords: Multicriteria Decision Analysis (MCDA) · Complex decision problems · Stakeholders values

1 Introduction

High-speed trains represent a pivotal advancement in modern transportation, offering several benefits that extend far beyond the mere rapidity of travel [1, 2]. These infrastructures not only revolutionize the concept of traveling but also address some of today's most pressing challenges, ranging from environmental concerns to accessibility and territorial equity [1].

One of the primary benefits of high-speed trains is the promotion of accessibility. Thanks to their speed and efficiency, they allow people from diverse regions to connect quickly and easily, drastically reducing travel times compared to conventional modes

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of transportation. This is particularly significant for rural and peripheral communities, previously isolated or difficult to reach, which can now enjoy greater accessibility to urban centers, services, and opportunities. Another positive benefit concerns the reduction of car usage. By providing a convenient and efficient alternative to road transport, they encourage a decrease in vehicular traffic, reducing greenhouse gas emissions and atmospheric pollution. This positive impact on the environment contributes to the climate change issue by promoting public health, improving air quality, and reducing dependence on fossil fuels [3].

However, despite these evident benefits, some concerns arise regarding territorial equity. Specific communities, especially those outside the routes of high-speed trains, may feel excluded from these advanced connections. This disparity could exacerbate socio-economic and geographical inequalities, limiting access to job opportunities, essential services, and infrastructural development. Addressing these challenges requires strategic policies not to worsen regional gaps [2].

Focusing on the Italian context, high-speed trains have emerged as an example of the successful implementation of the transformative mode of transportation [4]. Italy boasts an extensive high-speed train network connecting major cities and regions nationwide. This network links vital urban centers such as Milan, Rome, Florence, Naples, Turin, and various regions. Introducing high-speed trains in Italy has yielded economic and environmental benefits [5]. These include i) reduced travel times between major cities, enhancing connectivity and facilitating business and leisure travel; ii) economic growth, fostering tourism, facilitating trade, and attracting investment to regions along the network; and iii) environmental sustainability, offering a more sustainable mode of transportation compared to air and road travel, resulting in reduced carbon emissions, and mitigating environmental impact [6].

Despite their benefits, high-speed trains in Italy face several challenges, including i) infrastructure investment; sustaining and expanding the high-speed rail network requires substantial investment in infrastructure development and maintenance, posing financial challenges for policymakers; ii) accessibility disparities; rural and peripheral regions may experience limited accessibility, exacerbating socio-economic disparities and iii) environmental concerns regarding their energy consumption and potential ecological impact, particularly during construction phases [7, 8]. It is relevant to underline all the significant achievements and to face all the challenges properly to ensure long-term success and equitable distribution of benefits.

Within this context, designing and implementing high-speed train lines requires a comprehensive approach that considers diverse factors and stakeholders' perspectives and evaluates potential alternatives effectively [9]. Such methodologies are crucial for integrating tangible and intangible criteria [10] and accommodating conflicting opinions and values among stakeholders involved in the decision-making process [11, 12]. The adoption of multidimensional support tools, i.e., Multicriteria Decision Analysis (MCDA), as demonstrated by other researchers [13–17], offers significant advantages over traditional Cost-Benefit Analysis (CBA) for evaluating complex and multi-stakeholder issues [18–20]. By enabling a holistic assessment that considers diverse criteria and stakeholder perspectives, MCDA enhances the decision-making process, leading to more informed and sustainable outcomes [21].

The present paper aims to provide a model to support decision-makers (DMs) in comparing alternative scenarios to implement the existing high-speed train network in Brescia (Italy) by considering a multidimensional perspective. The framework proposed is based on the MCDA methodology, and the criteria defined are coherent with the decision problem investigated.

The paper is divided into four sections: after the introduction (s1), the methodology is presented (s2), the evaluation framework is structured (s3), and limits and future perspectives are discussed in the conclusions (s4).

2 The Role of the Multicriteria Decision Analysis (MCDA)

MCDA serves as a systematic and robust framework for decision-making in complex environments where multiple criteria need to be considered [22]. When a mono-criterion approach cannot catch the complexity of the problem to be solved, or an economic evaluation is insufficient to analyze different values in play, the MCDA becomes a strategic approach to be adopted [23]. Among the other strengths:

- MCDA considers various factors, including economic, environmental, social, and technical aspects, ensuring a thorough analysis;
- Complex decision problems, such as those analyzed within this contribution's context, entail quantifiable metrics (e.g., cost, travel time) and qualitative considerations (e.g., social impacts, cultural heritage preservation). Multidimensional assessment tools allow for the integration of these tangible and intangible criteria into the decision-making process, ensuring a balanced evaluation [24];
- Stakeholders involved in complex problems often have divergent interests and priorities. MCDA provides a structured framework for eliciting and incorporating stakeholders' opinions and values. By facilitating transparent communication and consensus-building, these tools help understand conflicting perspectives and enhance stakeholder engagement [20].

MCDA also presents some criticalities. Compared to the stated preferred methodologies, it is not suitable to catch the preferences of individuals across the whole population [25]. Moreover, accepting qualitative information could cause uncertainty and ambiguity [26]. Also, the weighting is open to criticism, especially in interpreting the meaning of the weights [26]. In this context, the sensitivity analysis and the selection of the most appropriate weighting and aggregation procedure aim to verify the robustness of the results [26].

2.1 MCDA Main Phases

The MCDA is structured in several phases (Fig. 1), which allows for breaking down complex problems into more straightforward steps and focusing on specific tasks to obtain a more conscious understanding of the context and decide [27, 28].

In the first phase, it is possible to recognize the problem structuring, where the boundaries of the decision context are set, objectives and criteria relevant to the decision problem are identified, and feasible alternatives or courses of action available for

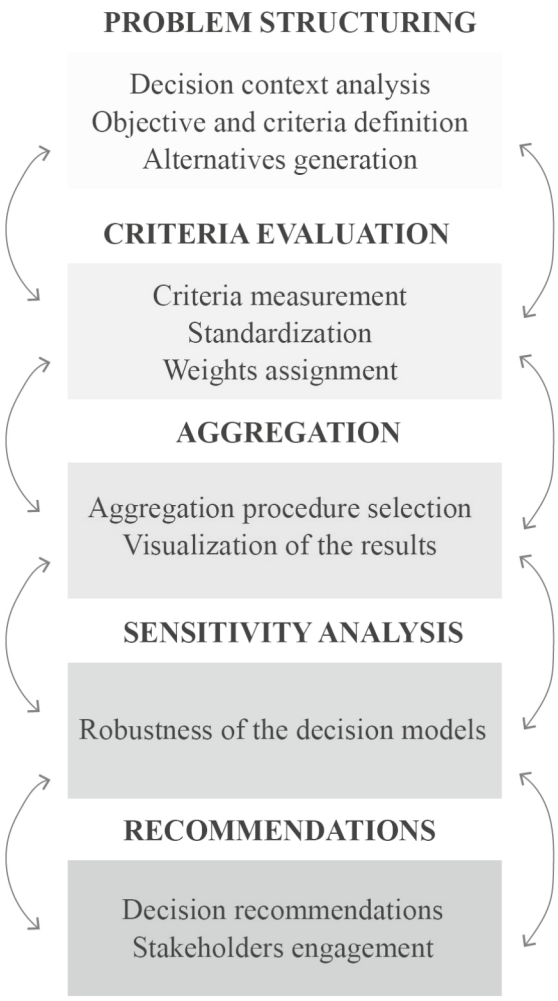

Fig. 1. Methodological framework.

addressing the decision problem are generated. The objectives should encompass all dimensions of the decision-making context and reflect the stakeholders' interests and priorities.

In the second phase, the criteria measurement is processed; once the objectives and alternatives are established, it is possible to assess the performance of each alternative against the identified criteria. This entails measuring how each alternative satisfies or achieves the specified objectives. To compare alternatives and aggregate the scores calculated, the next step involves standardization, where criteria lose their specific unit of measurement to acquire a standard a-dimensional scale, usually between 1 and 0 (where 1 represents the best performance while 0 is the worst). After that, weights can

be assigned to the criteria based on their relative importance or significance in achieving the overarching objectives [29]. The weighting process ensures the evaluation is appropriately balanced and reflects the stakeholders' preferences. In the third phase, standardized scores and assigned weights can be aggregated using the most appropriate procedure (i.e., choice, raking, and clustering) [30].

Moreover, different methodologies for addressing complex choice problems exist depending on the research objective, criteria, and the desired outcome. The main ones are i) the compensatory methodology to assess the trade-off (compensation) between criteria and ii) the non-compensatory, through which the more complex interaction between criteria can be considered. Once the most suitable aggregation procedure has been selected and the results visualized, it is possible to move to phase four, where the sensitivity analysis assesses the reliability and robustness of the decision model; this involves examining how changes in the input parameters, such as criteria weights or performance scores, affect the final decision outcomes. The last phase consists of recommendations; based on the analysis results, DMs derive recommendations or decision insights to guide the selection of the most suitable alternative. These recommendations are communicated to stakeholders to facilitate informed decision-making [31].

The model is flexible and iterative, and each phase could be reviewed if the results are unsatisfactory [32].

3 A Proposal to Assess High-Speed Train Line Alternatives

The assessment framework defined to compare design alternatives was developed based on the specific needs of the new intervention to be implemented in Brescia (Italy). The overall framework will be presented within this context since the application has yet to be concluded. Given the multidimensionality of the decision problem, fundamental objectives (thematic areas) were identified as a first step, subsequently articulated into instrumental objectives (criteria) [33], which allow the problem to be analyzed in its complexity, considering aspects of a social nature, relating to the potential change in the welfare of those affected by the infrastructure expansion projects; aspects of an environmental nature concerning acoustic impacts and on the quality of resources, such as air and soil; as well as aspects of a techno-economic nature, referring to the technical characteristics of the two expansion hypotheses, site management and production costs. The decomposition of the problem and the definition of a multidimensional value tree allow the areas to be compared and evaluated both partially, considering the thematic area of reference, and globally, thus aggregating the different performances.

The decision-making framework is the result of several meetings with key stakeholders. It, therefore, reflects interests consistent with both the goals of the municipal administration and the needs of the society and proponents of the initiative.

Analyzing the problem and considering the public perspective in detail leads to an overall objective more focused on environmental and social aspects, resulting in the *"Definition of the most suitable alternative able to maximize socio-environmental benefits."*

3.1 Potential Negative Impacts

The construction of new railway infrastructure can bring significant benefits to transportation networks, but it also poses challenges for local communities, particularly those near construction sites [34]. Railway construction activities, such as noise, dust, and vibration from heavy machinery, can disrupt residents' daily lives near construction sites. These disturbances may affect sleep patterns, increase stress levels, and diminish overall quality of life [35]. The influx of construction vehicles and temporary road closures can lead to increased traffic congestion and safety hazards for residents. Detours and traffic diversions may disrupt regular commuting routes and access to essential services [7].

Moreover, railway construction projects frequently require expropriating and demolishing properties along the route. Residents may be forced to relocate, leading to the loss of neighborhood cohesion. Property expropriation and demolition can cause economic displacement for affected residents, particularly if they cannot secure fair compensation or suitable alternative housing [36]. This displacement may exacerbate existing socioeconomic inequalities within the community [37]. Addressing these challenges requires careful planning, community engagement, and mitigation measures to minimize disruptions and ensure that affected residents are adequately supported throughout construction [38].

3.2 The Evaluation Framework

With the overall goal of supporting the choice of the solution that maximizes socio-environmental benefits, in consideration of the co-presence of different objectives, expressing the needs and expectations of the main stakeholders, and keeping in mind the potential adverse effects, the decision problem was decomposed into three thematic areas, further detailed into criteria and sub-criteria.

The evaluation framework has been conceived and structured by analyzing all the possible issues that could emerge from implementing a railway system (Table 1). Criteria, sub-criteria, and the potential indicators useful to measure the performance of the alternatives have been defined starting from workshops organized together with the main stakeholders involved in the analysis and verified with an investigation of the literature review on this topic. Mainly to check the robustness of the proposed framework, a literature review focused on the MCDA methodology and the implementation of the railway system has been developed, resulting in several existing research studies on this topic [35, 39–52]. Table 1 reflects the synthesis of the phases processed.

For each thematic area, it is essential to define the overall objective to be met and to prepare an evaluation form with three parts:

- General objective: underlying the choice of criterion;
- Performance score: describing the method of evaluation and the unit of measurement;
- Performance evaluation of alternatives: where the rating/ score for each performance is presented.

Table 1. Evaluation framework

Thematic Areas		Criteria		Sub-criteria	
1	Social	1.1	People involved/Propensity for relocation of potential people subject to expropriation	1.1.1	Socio-economic profile (age, households, family composition) of the inhabitants subject to expropriation (owners/tenants)
				1.1.2	Inhabitants subject to construction site impacts
		1.2	Properties involved	1.2.1	Type and number of housing units subject to expropriation
		1.3	Visual impact during construction and post construction	1.3.1	Assessment of the visual impacts generated on the buildings present by the 10 m buffer zone from the construction site fences
				1.3.2	Assessment of the visual impacts generated on the buildings present by the 10 m buffer zone from the railroad walls
2	Environmental	2.1	On-site and post construction vibration	2.1.1	Evaluation of vibration impacts generated on the buildings present from the 10 m buffer zone from the construction site fences (day and night)
				2.1.2	Assessment of vibration impacts generated on the buildings present from the 10 m buffer zone from the railway walls (day and night)

(*continued*)

Table 1. (*continued*)

Thematic Areas		Criteria		Sub-criteria	
		2.2	Noise at the construction site and post-work	2.2.1	Assessment of the acoustic impacts generated on the buildings present from the 10 m buffer zone from the construction site fences (diurnal)
				2.2.2	Assessment of acoustic impacts generated on buildings intersected by the 10 m band from railway walls (day and night)
		2.3	Dust	2.3.1	Evaluation of dust impacts generated on buildings present from the 10 m band from the construction site fences (day and night)
		2.4	Traffic	2.4.1	Traffic interference in accessing the units
		2.5	Land	2.5.1	Land consumption balance
3	Technical Economic	3.1	Time	3.1.1	Duration of the construction site in the reference area
				3.1.2	Impact of the construction site on the overall project
		3.2	Interference on rail service	3.2.1	Effects on the quality of rail service
		3.3	Total implementation costs	3.3.1	Estimated cost of works
				3.3.2	Estimated costs and compensation inhabitants (owners/tenants)

3.3 Evaluation Criterion

Below, some examples of an evaluation criterion form are proposed to show how the analysis will be further developed and structured.

The Criterion *"1.3 Visual impact during construction and post-construction"* considers the alteration of any natural or urban landscape with the inclusion of elements that, by their extraneousness, modify and negatively impact the reference context with effects on the population affected by such intervention. The criterion aims to minimize such effects.

The general objective of the sub-criterion *"1.3.1 Assessment of the visual impacts generated on the buildings present by the 10 m buffer zone from the construction site fences"* is to assess the impact of construction site fencing on residents living in buildings located near the project area. The performance score is assigned by considering the free-view index, which represents the distance (d) ratio of individual building façades with the construction site fences and the height of those façades (line). An average of the indices obtained between the distance of buildings and construction site fences was calculated for the evaluation. The distances of the façades to other properties were not captured as they do not change in the different alternatives due to the presence of the project. An index of 1 represents an optimal distance; conversely, an index of 0 is critical.

The Criterion *"2.5 Land"* assesses land consumption, associated with the loss of a critical environmental resource. The process is mainly due to constructing new buildings and infrastructure, expanding cities, densifying and converting land within an urban area, and land infrastructure.

The sub-criterion "2.5.1 Land consumption balance" aims to evaluate the presence of vacant areas that could be used as green areas and the enhancement of the existing bicycle and pedestrian pathways. The performance score is assigned considering a qualitative scale where:

- "high" represents the presence of vacant areas in continuity with the pedestrian-cycleway;
- "medium" is the availability of the vacant areas only;
- "low" is the absence of vacant areas.

The next step of the evaluation form consists of measuring the performances of the alternatives generated.

4 Conclusions

The present contribution highlights the strategic role of multidimensional assessment tools in designing and implementing high-speed train lines effectively. By integrating tangible and intangible criteria and accommodating stakeholders' perspectives, MCDA enhances decision-making, leading to more informed and sustainable outcomes. MCDA encompasses a structured and rigorous approach to decision-making, comprising several critical phases from problem structuring to decision support and interpretation. By systematically evaluating alternatives against multiple criteria and engaging stakeholders throughout the process, MCDA facilitates informed and transparent decision-making in complex decision environments.

The paper presents a framework based on MCDA to support DMs in evaluating alternative scenarios for high-speed train network implementation in Brescia, Italy. The framework encompasses social, environmental, and technical-economic criteria, providing a structured approach to assess the socio-environmental impacts of railway projects.

By adopting such methodologies, DMs can ensure equitable benefits distribution and address the affected communities' concerns.

From the analysis, it emerges that beyond the positive impact brought by the implementation of accessibility, several issues have to be faced. While railway construction projects may present significant challenges for local communities, proactive planning and stakeholder engagement can help mitigate adverse impacts and ensure that affected residents are adequately supported throughout the construction process. By addressing concerns related to property expropriation, noise and vibration, traffic disruption, environmental protection, and social support services, railway authorities can foster positive relationships with local communities and enhance the overall sustainability of construction projects. The proposed model can support the definition of coherent strategies to overcome those challenges and select an alternative to minimize potential criticalities.

Concerning the limitations of the contribution, the proposed model and evaluation framework are tailored to the context of high-speed train network implementation in Brescia, Italy. While it provides valuable insights into decision-making processes for this case, its applicability to other contexts or regions may be limited. Different areas may have unique socio-economic, environmental, and technical considerations that require customized approaches. Moreover, the model's effectiveness heavily relies on the availability and reliability of data for criteria measurement and evaluation. In some cases, obtaining accurate data, especially regarding social and environmental impacts, may be challenging. Data quality and consistency across different sources could affect the robustness of the evaluation outcomes.

Considering the possible future steps, after applying the methodology to the analyzed project, conducting pilot studies or case studies in different contexts can help validate the model's effectiveness and identify areas for improvement. Iterative refinement of the framework based on empirical evidence and stakeholder feedback can enhance its applicability and robustness across diverse settings. For the data issue, incorporating advanced technologies such as remote sensing, GIS mapping, and participatory sensing can provide real-time insights into social and environmental impacts, enabling more accurate assessments. Moreover, it could be successful to establish mechanisms for long-term monitoring and evaluation of implemented projects to assess their actual socio-economic, environmental, and technical outcomes. Incorporating feedback loops into the decision-making process to iteratively improve future project designs and management strategies based on lessons learned could be a keystone.

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