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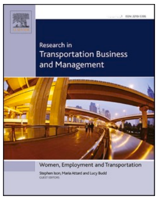

"A unifying framework for multicriteria and cost–benefit analysis in mass transit decision-making: Evidence from Italy"

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ABSTRACT

Implementing a Mass Transit System (MTS) is a complex task, as decision-makers must compare multiple technologies and route options while balancing user needs, operator requirements, and financial constraints. Therefore, a rational and transparent decision-making process is essential to identify solutions that are both technically appropriate and economically viable. However, to the best of the authors' knowledge, existing studies address only parts of this process. Some integrated Multi-Criteria Analysis (MCA) and Cost-Benefit Analysis (CBA) approaches operate only after project alternatives have already been selected. Moreover, they often require a full CBA for each option, which is impractical in early planning phases when data are limited, and the solution space remains broad. Other applications use MCA to rank predefined MTS alternatives but do not model how technology choices and route configurations are generated or how these upstream decisions influence subsequent economic feasibility. As a result, the overall evaluation of MTS alternatives remains fragmented across separate analytical stages.

This paper addresses prior gaps by proposing a structured, operational framework that unifies the overall decision-making process and supports decision-makers throughout all planning stages. It explicitly links technology selection, route definition, and economic appraisal within a single, coherent sequence of decisions. This framework is organised in three phases. The first phase selects the optimal MTS using a two-stage MCA: the Analytical Hierarchy Process (AHP) to incorporate stakeholders' preferences, followed by the Weighted Sum Method (WSM) to identify the best system. The second phase applies the WSM again to determine the optimal route among a set of different routes suitable for the system selected in the first phase. Finally, the third phase applies a comprehensive CBA to assess the economic feasibility of the solution developed in the previous two phases.

The framework is applied to a case study in the province of Brescia (Italy) to identify the optimal public transport solution for the corridor connecting the city of Brescia to the northwestern shore of Lake Garda, currently served only by a suburban bus system. The results highlight the importance of integrating MCA and CBA into a unified decision-making process to overcome fragmented planning approaches and support more transparent and robust transport decisions. Thus, the proposed framework provides decision-makers with a practical, replicable procedure for identifying MTS solutions that are not only technically and socially optimal but also economically sustainable.

List of acronyms

AHP	Analytic Hierarchy Process
BAU	Business-As-Usual
BRT	Bus Rapid Transit
CBA	Cost–Benefit Analysis
CDF	Cumulative Distribution Function
CEN/TC	European Committee for Standardisation Technical Committee
CR	Consistency Ratio
CT	Classic Tramway
EBCR	Economic Benefit–Cost Ratio
EIRR	Economic Internal Rate of Return
ENPV	Economic Net Present Value
GB	Guided Busway
GIS	Geographic Information System

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(*continued*)

ISTAT	Italian National Institute of Statistics
LM	Light Metro
MCA	Multi-Criteria Analysis
MTS	Mass Transit System
O&M	Operations and Maintenance
O-D	Origin–Destination
PTO	Public Transit Operator
RoH	Rule of Half
TA	Transit Authority
TB	Trolley Bus
TRT	Tramway Rapid Transit
TT	Tram-Train
ToR	Tram on Rubber
VOC	Vehicle Operating Cost
WGS	Weighted Global Score
WSM	Weighted Sum Method

1. Introduction

Implementing or upgrading public Mass Transit Systems (MTSs) is a key step toward more sustainable mobility, counteracting the long-term shift from collective transport to less sustainable individual motorised systems that began in the second half of the 20th century (Ortúzar & Willumsen, 2011; Ceder, 2016; Garilli et al., 2017; Tang et al., 2018). The need for this transition is underscored by evidence that the large number of vehicles currently on the road generates heavy externalities, including congestion, emissions and road crashes (Cavallaro & Nocera, 2022; Quddus et al., 2010; Stipancic et al., 2019). These latter claim numerous lives each year: for example, in Italy, during 2023, 3 k + people died along roads (Italian Ministry of Infrastructure and Transport & Italian National Institute of Statistics (ISTAT), 2024).

These externalities degrade people's quality of life and health, underscoring the urgent need to adopt policies to improve sustainable mobility, such as providing high-quality MTSs, promoting soft modes, and, more generally, encouraging alternatives to the indiscriminate use of private vehicles (Barabino et al., 2011, 2013; Barabino & Di Francesco, 2016; Boglietti, Barabino and Maternini, 2021; Comi & Polimeni, 2024; Logan et al., 2022; Raccagni et al., 2024, 2025).

To mitigate the issues outlined above, the scientific community and public transport companies have been working for many years to identify the most suitable solutions for each context. This work has led to the introduction of countless technological MTS alternatives to the market, each with distinct characteristics and functionalities, and these are still in use globally (Sinha & Labi, 2011; Vuchic, 2007).

However, the decision-making process for identifying the optimal solution is particularly complex. Building a new MTS affects the surrounding area in various ways, and a solution that is optimal with respect to one criterion may be less favourable with respect to another. Moreover, conflicting interests among stakeholders often arise, necessitating the identification of the optimal compromise through a Multi-Criteria analysis (MCA) (Assefa et al., 2024; Barbosa et al., 2017; Lee, 2018; Nassereddine & Eskandari, 2017; Zak, 2011). At the same time, assessing economic sustainability is essential to a full evaluation of feasibility, requiring a Cost-Benefit Analysis (CBA) that accounts for both the costs and benefits of the compromise solution (Carteni et al., 2019; COM - The European Commission, 2014; De Aloe et al., 2023; Ventura et al., 2022).

Nevertheless, although several studies combine MCA and CBA in transport appraisal, they generally evaluate predefined project alternatives without addressing the broader decision-making process. To the best of the authors' knowledge, no comprehensive study has operationalised the full sequence of decisions required in MTS planning within a single framework. Structuring these stages within a single process would enable a coherent progression from preference-based assessments to economic appraisal, evaluating economic feasibility only after the most promising technological and routing options have been identified (Beria et al., 2012).

Therefore, this study meets this need by proposing a framework structured into three phases: (1) Selection of the MTS technological alternative through MCA, with stakeholders' involvement to define decision-making criteria and weights; (2) Identification of the optimal route for the chosen MTS through MCA, refining parameters established in the first phase; (3) Economic evaluation of the proposed solution using CBA, including sensitivity and risk assessment for robustness. The viability of the overall framework is demonstrated through a real-world application in the Province of Brescia (Italy). As one of the most populous provinces in Italy, it serves as a significant industrial, commercial, tourist, and social hub, which results in heavy daily road traffic.

This study contributes to the existing literature primarily from a procedural and practical perspective. Procedurally, rather than introducing new decision-making methods, it demonstrates how existing MCA and CBA approaches can be sequentially linked within a unified planning framework. Practically, it provides transport planners and decision-makers with an empirical case study to assess the suitability and relevance of selected systems in comparable contexts.

The remainder of this paper is organised as follows. Section 2 reviews the state of the art regarding the use of MCA and CBA in transport contexts. Section 3 details the methodological framework that integrates these two approaches. Section 4 applies the framework to an Italian case study and discusses the results. Finally, Section 5 outlines the conclusions and directions for future research.

2. State of the art

Recent advances in transportation research have increasingly emphasised the need to improve the performance and sustainability of transport systems through data-driven approaches and the use of large-scale, high-resolution data (Shang et al., 2023; Shang et al., 2025; Shao et al., 2022; Urbano et al., 2025; Zhao et al., 2025). This growing body of work highlights the complexity of modern transport systems and reinforces the need for structured, transparent, and sequential decision-making processes to evaluate alternative solutions across multiple dimensions.

In this perspective, decision-support methodologies play a central role in structuring such complexity and guiding planning choices. The use of decision-support methodologies in transport engineering has been widely explored, and both MCA and CBA have generated extensive bodies of literature over the past decades. This section focuses on recent and operationally relevant contributions, rather than revisiting well-established fields that have already been comprehensively reviewed elsewhere (e.g., Beria et al., 2012; Donais et al., 2019; Macharis & Bernardini, 2015; Yannis et al., 2020). The aim is to situate this research within contemporary applications of MCA and CBA in transportation studies and, above all, to highlight the persistent gaps in integrating these methods into a unified decision-making process to support the full sequence of choices required for planning an MTS.

In the MCA domain, many studies have employed these techniques to support strategic and operational decisions in public transport. Much of this literature focuses on selecting, ranking, or comparing MTSs in diverse contexts. A wide variety of MCA methods is available, each grounded in different aggregation logics and suited to specific decision structures. According to Yannis et al. (2020), the most used families include: (i) value-based methods, such as the Analytic Hierarchy Process (AHP), the Weighted Sum Method (WSM), and Multi-Attribute Utility Theory or Multi-Attribute Value Theory (MAUT/MAVT), which are based on compensatory logic and are widely adopted due to their transparency and ease of interpretation; (ii) outranking methods, such as *ELimination Et Choix Traduisant la REalité* (ELECTRE) and Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), which rely on non-compensatory logic and can incorporate thresholds, veto conditions, and partial preferences; and (iii) goal- or compromise-based methods, such as the Technique for Order of

Preference by Similarity to Ideal Solution (TOPSIS) and *VIseKriterijumska Optimizacija I Kompromisno Resenje* (VIKOR), which identify solutions closest to an ideal reference point and are particularly suited to problems involving trade-offs among conflicting objectives.

This diversity has supported a wide range of applications in public transport planning, in which different MCAs have been employed depending on the decision context and the type of information available. For instance, Nassereddine & Eskandari (2017) combine the Delphi method with an integrated MCA framework to analyse public transport users' preferences in Tehran. Awasthi et al. (2018) classify urban mobility projects using different multicriteria methods and test the robustness of their results through sensitivity analyses. Comparative evaluations of Bus Rapid Transit (BRT) and Light Rail Transit (LRT) are frequent in this research stream (Lambas et al., 2017). Lee (2018) extends the previous analysis to advanced public transport modes and distinguishes between metropolitan and smaller urban contexts, thereby capturing how results vary with population size and existing rail infrastructure. Hamurcu and Eren (2020) apply MCA to identify the most suitable among alternative transport investments (including electric buses, LRT extensions, or the modernisation of existing systems). Notable studies include the feasibility checklist for tram-train systems proposed by Naegeli et al. (2012) and the user–expert-based criteria identified by Ušpalytė-Vitkūnienė et al. (2020). Further contributions broaden the analysis to journey-based user experience (e.g., Barbosa et al., 2017) or differentiate the preferences of multiple stakeholder groups, as in Ghorbanzadeh et al. (2018). Beyond system selection, MCA has also been applied in operational planning, including the evaluation of rolling stock alternatives (Żak, 2017), the choice of bus propulsion technologies (Borghetti et al., 2024; Büyüközkan et al., 2018; Teoh & Wong, 2025), and personnel planning (Zak, 2011). Overall, the MCA literature is rich, methodologically well-developed, and extensively applied to a wide range of decision problems in urban and regional transport.

The literature on CBA in the transport sector is extensive and highly consolidated. Indeed, CBA represents the dominant, and probably most institutionalised framework for the *ex-ante* evaluation of transport infrastructure globally, supported by a long tradition of applications and comprehensive guidelines from national authorities and international organisations (e.g., Beria et al., 2012; COM - The European Commission, 2014; Donais et al., 2019). Its strength lies in monetising costs and benefits, comparing scenarios on a consistent welfare basis, and providing clear, reproducible criteria for decision-making. Within this well-established tradition, several studies have applied CBA to MTS projects, including the evaluation of tram–rail integrations in Brescia (De Aloe et al., 2023), the assessment of Light Rail Transit in the Naples metropolitan area (Cartenì et al., 2019), and the comparison of BRT and LRT alternatives in Oslo (Siedler, 2014). Moreover, CBA has been widely used beyond classical infrastructure appraisal, extending to road pricing, environmental policies, cycling networks, and other sustainable mobility measures (Beria et al., 2012). This demonstrates that the method is not limited to large-scale infrastructure investments, although its application becomes more challenging when impacts are mainly intangible or long-term.

Despite the maturity of both MCA and CBA, the two bodies of literature have largely evolved in parallel. A limited but growing strand of research tried to combine multi-criteria techniques with economic appraisal in transport contexts. Tsamboulas and Mikroudis (2000) introduced the "*Evaluation Framework of Environmental impacts and Costs of Transport*" (EFECT) framework. It integrates MCA and CBA into an additive structure to evaluate transport initiatives across different regions and time horizons, with a strong emphasis on environmental and network-wide impacts. Ambrasaite et al. (2011) examine how MCA and CBA can be systematically combined in transport project appraisal, considering monetary and non-monetary effects through a composite index calibrated via a decision-maker-defined trade-off parameter. Their contribution is primarily conceptual, focusing on merging the two evaluation logics into a coherent analytical framework. In contrast, Gühnemann et al. (2012) develop an integrated appraisal framework tailored to large transport infrastructure projects, particularly for European policy evaluation. Their approach combines MCA and CBA to support strategic decision-making for complex investments, integrating both monetisable and qualitative impacts within a unified assessment process. More recent studies propose hybrid MCA–CBA frameworks for transport and infrastructure projects, focusing on methodological integration issues such as aggregation, scaling, and weighting procedures, as well as their applicability to complex decision contexts (e.g., Henke et al., 2020; Shoaei et al., 2026; Veličković et al., 2025). These works demonstrate that MCA and CBA can coexist within a single assessment architecture, typically by embedding CBA outputs as criteria in an MCA model or by aggregating heterogeneous impacts through additive functions.

Beyond these conceptual and policy-oriented contributions, which primarily focus on integrating MCA and CBA at the evaluation stage, a smaller set of studies has applied combined MCA–CBA approaches to specific transport projects. For instance, Impastato et al. (2015) evaluate tramway alternatives in Rome by applying a CBA and subsequently using a multicriteria ranking to incorporate qualitative and context-dependent aspects that are not easily monetised. Ventura et al. (2022) adopt a complementary approach by combining an MCA-based context analysis with a CBA of tram-train options in the Salento region, showing how qualitative assessments and economic feasibility can be jointly considered in early-stage project evaluation.

All previous studies have contributed to understanding the roles of MCA and CBA in decision-making through various techniques, but several research gaps remain.

First, relevant review papers strongly recommend research into integrating MCA and CBA to support the assessment of sustainable transport projects. MCA could be adopted for a broad screening of options, while CBA evaluates public expenditures and consumer surplus and advances empirical applications in real or scenario-based cases (Beria et al., 2012). Moreover, the integration of MCA and CBA appears more suitable than a specific analysis alone to support more holistic, participatory, and economically robust evaluations, in complex and uncertain environments such as sustainable transport (Donais et al., 2019).

Second, although several works demonstrate that MCA and CBA can be integrated within a common appraisal setting, no study provides a coherent, stepwise framework that explicitly links system choice, route definition, and economic appraisal within a unified operational decision process. Indeed, even within this integrated strand of literature, the nature and sequencing of the decisions involved in MTS planning are only partially addressed. Early integrated frameworks, such as EFECT (Tsamboulas & Mikroudis, 2000), Ambrasaite et al. (2011), and Gühnemann et al. (2012), mainly operate as general evaluation tools[1] once project alternatives have already been defined. As such, they do not structure the full decision chain from technology selection to route definition and economic feasibility assessment. Moreover, these approaches typically require performing a full CBA for each alternative: EFECT includes a CBA-based pre-screening and subsequently embeds CBA outputs as criteria within an MCA model, while Ambrasaite et al. (2011) rely on a composite index calibrated on complete economic appraisals of all options. More recent hybrid MCA–CBA frameworks adopt more refined aggregation, scaling, and weighting strategies and demonstrate their applicability to complex transport and infrastructure contexts (e.g., Henke et al., 2020; Shoaei et al., 2026; Veličković et al., 2025). However, their focus remains largely on improving appraisal

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[1] In this context, "general evaluation tool" refers to appraisal frameworks comparing predefined project alternatives without explicitly structuring the upstream process through which technology and route options are identified and selected.

consistency rather than on structuring the underlying decision-making sequence. Alternative generation, filtering, and selection are not formally linked to the subsequent economic appraisal, which is typically performed for all candidate alternatives. This requirement can be highly resource-consuming in early planning phases, when data are scarce, and the solution space remains broad.

Third, even if Impastato et al. (2015) and Ventura et al. (2022) integrated MCA and CBA, they address specific MTS-alternatives rather than exploring the broader decision process that precedes them. In both cases, the analysis begins once a set of predefined solutions is already available, and the role of MCA and CBA is limited to comparing or validating those options. As a result, these studies do not consider how the choice of the underlying MTS technology is made, nor how different route configurations are generated and filtered before economic appraisal. Therefore, their focus is on evaluating given alternatives, rather than structuring the upstream sequence of decisions that leads from technology identification to route definition and, ultimately, to the economic assessment of the preferred configuration.

Finally, the potential complementarity between MCA and CBA remains underexploited in existing decision-support approaches, which typically apply these methods in isolation or at disconnected stages of the planning process. The limitations of each approach could instead be systematically mitigated by the strengths of the other. On the one hand, MCA primarily focuses on effectiveness and preference consistency, while paying limited attention to public spending efficiency; on the other hand, CBA provides a rigorous assessment of economic efficiency and welfare impacts but often struggles to account for intangible effects that are central to sustainable transport and urban quality of life. As a result, the absence of a coherent process linking these tools prevents decision-makers from fully exploiting their methodological complementarity.

Addressing these shortcomings requires more than the mere integration of evaluation methods: it calls for a clearer structuring of the decision-making process they support. Therefore, in this study, the term “unifying” refers to the explicit structuring of the entire MTS planning sequence within a single stepwise framework, from the generation and multicriteria screening of alternatives to their final economic validation. In such a framework, MCA enables the stakeholder-driven identification of the most suitable MTS and route options, while CBA provides a comprehensive assessment of their economic sustainability, ensuring both preference consistency and economic soundness.

This study aims to address these gaps by proposing a structured integration and sequencing of existing methods within a single operational framework.

3. Methodological framework

This section presents the proposed framework, structured into three interdependent phases: selection of the MTS technological alternative and identification of the optimal route by MCA, and final economic appraisal through CBA. Rather than independent analytical steps, these phases form a sequential decision process in which each stage constrains and informs the next. Specifically, the first phase compares alternative transport technologies, the second evaluates feasible route options for the selected system, and the third assesses the economic sustainability of the resulting project configuration. In general terms, this sequential structure progressively reduces the solution space by filtering alternatives at each stage, allowing the final economic appraisal to focus only on the most promising configurations. Fig. 1 illustrates the overall framework and its twelve operational steps.

3.1. *Phase 1 – Selecting the MTS alternative*

Phase 1 aims to select the optimal MTS from a set of possible alternatives. It involves identifying the relevant transport systems for the context, defining the evaluation criteria, and applying MCA methods, such as AHP for criteria weighting and WSM for ranking the alternatives. This is carried out through a three-step workflow, detailed below.

STEP 1 *Defining MTS alternatives*

The first step is to identify the set of MTSs that could be implemented as competing alternatives. Formally, let S be the set of MTSs and let $s \in S$ be a generic MTS. These alternatives could differ in construction and technical characteristics, performance, implementation, operational costs, and environmental and social impacts. If no specific study is available for the context, this selection can be informed by a literature review of similar cases, thereby ensuring that the process is grounded in proven solutions and adaptable to local conditions.

STEP 2 *Defining criteria and weights*

Once the set of MTS alternatives is defined, the second step establishes the criteria for comparing these options and assigns appropriate priority to each criterion. This process requires the involvement of stakeholders, whose needs and preferences must be considered to ensure that the proposed system is both functional and acceptable to the wider community. Given the heterogeneity of stakeholders' interests and levels of technical expertise, a structured method is essential to elicit robust and representative preferences. Since these preferences may vary depending on stakeholders' familiarity with individual criteria, potentially leading to inconsistent or unstable judgments, adopting a formal weighting procedure is necessary to mitigate these effects. Accordingly, importance weights are assigned to each criterion. As noted by Zelany (1974) and Castillo and Pitfield (2010), directly eliciting weights from experts may lead to inconsistent and unstable judgments, especially when many criteria are involved. This issue is particularly relevant in participatory planning contexts, where stakeholders may exhibit preference instability and scale interpretation biases. Several alternative weighting methods have been proposed in the literature to address these challenges (e.g., Cantwell et al., 2009; Friman et al., 2001; Hassan et al., 2013; Wang & Lee, 2009). Among them, techniques such as the Best–Worst Method (BWM) aim to reduce cognitive burden and typically yield smoother, more internally consistent weight vectors (Keshavarz-Ghorabaee, Amiri, Hashemi-Tabatabaei and Ghahremanloo, 2021; Rezaei, 2015). However, despite these advantages, such methods are less commonly adopted in applied transport-planning studies. In contrast, the AHP enhances the interpretability and communicability of weighting results for planners and practitioners, making it particularly suitable for participatory and public-facing decision processes. These characteristics explain its long record of use in applied planning contexts. For these reasons, the proposed framework adopts AHP, which derives weights via pairwise comparisons and produces a ratio-scale measure while explicitly quantifying judgment consistency through a consistency ratio. Rather than eliminating inconsistency, AHP allows it to be observed and assessed, providing a transparent and diagnostically informative approach to ranking decision-making criteria (Saaty, 1980; Saaty, 1987; Saaty, 1990; Tavana et al., 2023).[2] In addition, AHP is

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[2] Despite some criticism of the method (Dyer, 1990), a substantial body of literature supports its application and highlights the benefits associated with its use (e.g., Forman & Gass, 2001; Harker & Vargas, 1990; Saaty, 1990). In particular, Harker and Vargas (1990) and Forman and Gass (2001) have discussed the theoretical foundations of AHP and examined its strengths and limitations in response to early critiques, thereby contributing to its broad methodological acceptance. Furthermore, the widespread adoption of AHP across numerous engineering disciplines has contributed to consolidating its acceptance in practice, including among bus operators (e.g., de Steiguer et al., 2003; Hamurcu & Eren, 2020; Nassereddine & Eskandari, 2017; Ventura et al., 2022). Its proven effectiveness in structuring participatory decision processes further explains its continued use in transport planning applications.

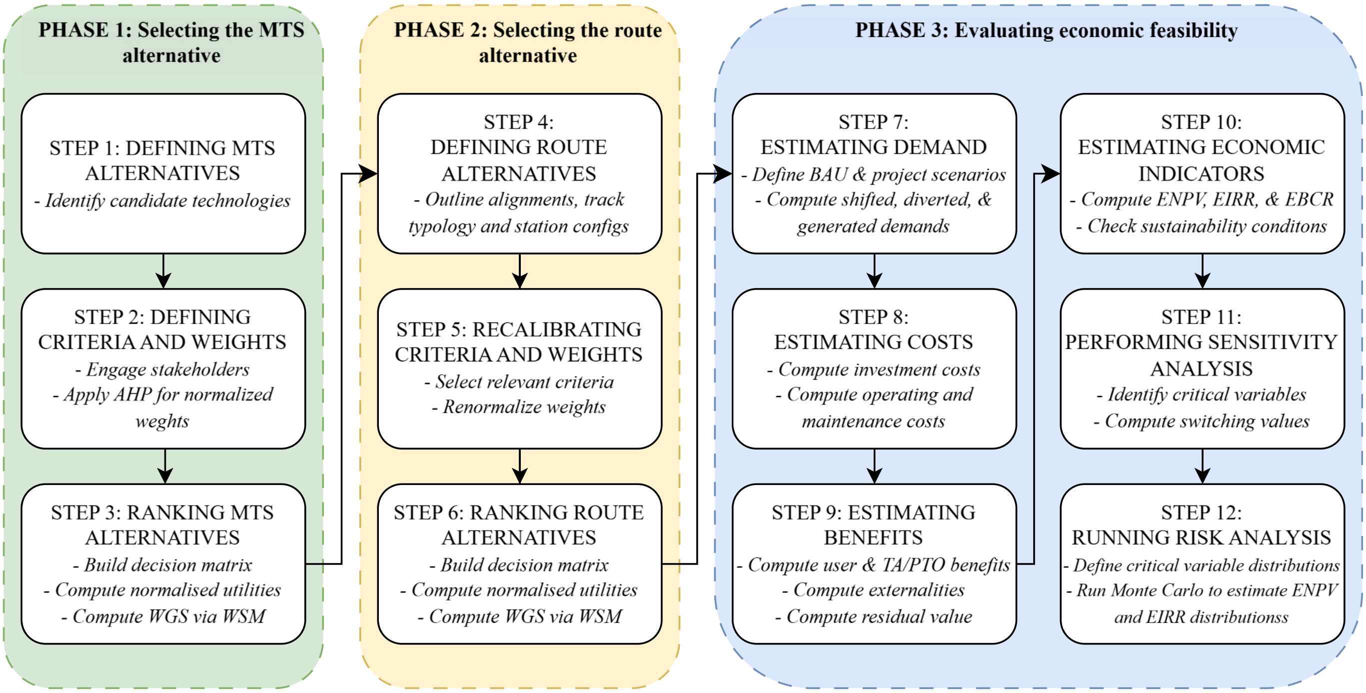


Fig. 1. Flowchart of the proposed methodology.

particularly suitable for this study because of its pairwise-comparison structure, which simplifies complex judgments by allowing stakeholders to express preferences incrementally. This is especially relevant in early-stage MTS planning, where stakeholders may have heterogeneous backgrounds and limited familiarity with formal evaluation procedures. While other weighting methods also enable preference elicitation, AHP offers a highly intuitive comparison mechanism combined with an explicit consistency check. This allows the reliability of judgments to be assessed and, if necessary, revised. Its solid mathematical foundation and widespread application in multicriteria decision analysis further contribute to its credibility and acceptance in applied transport-planning contexts. This combination of transparency, ease of use, and internal consistency control make it particularly appropriate for participatory and multi-actor decision contexts, where the credibility and acceptability of the weighting process are as important as its analytical rigour.

The AHP process begins by providing each stakeholder with a questionnaire in which they compare pairs of criteria to evaluate the relative importance of one criterion over another. This method also includes a consistency check to reduce subjectivity in the comparisons. In particular, the consistency of pairwise judgments is assessed using the Consistency Ratio (CR), which quantifies the deviation from perfect logical consistency, enabling potentially inconsistent evaluations to be identified and controlled within acceptable thresholds (Pant et al., 2022; Saaty, 1980). The acceptable threshold is traditionally set at 0.10 (10%), although values up to 0.20 (20%) may be tolerated in specific applications (e.g., Carra et al., 2023; Carrara et al., 2021; Wedley, 1993).

More formally, let Γ^{Ph1} be the set of criteria used in phase 1, and $\gamma \in \Gamma^{\mathrm{Ph1}}$ a generic criterion. The output of AHP is a vector $\overline{W}^{\mathrm{Ph1}}$ where each element $w_{\gamma}^{\mathrm{Ph1}}$ represents the normalized weight of $\gamma \in \Gamma^{\mathrm{Ph1}}$.

STEP 3 *Ranking MTS alternatives*

After obtaining the criteria weights via AHP, the third step applies the Weighted Sum Model (WSM), among the different MCA, methods to rank the MTS alternatives across multiple criteria (Alanazi & Abdullah, 2013; Broniewicz & Ogrodnik, 2020; Triantaphyllou, 2000). Its adoption is primarily motivated by its transparency, interpretability, and direct compatibility with the AHP-derived weighting structure. The method's additive formulation allows decision-makers to explicitly trace how each criterion and its associated weight contribute to the final ranking. This transparency is essential in participatory planning contexts, where the explainability of results plays a key role. Furthermore, comparative analyses with alternative MCA techniques demonstrate that additive aggregation methods, such as the WSM, exhibit relatively high stability under moderate stochastic perturbations of criteria weights (Ventura et al., under review). This resilience justifies their application as stable screening tools during early-stage decision-making. Besides, the method's low computational demands ensure high robustness and reproducibility, even under severe data constraints. Furthermore, the assumptions underlying WSM, particularly the preferential independence of criteria, are consistent with many transport planning applications. Finally, its compatibility with established weighting techniques and economic appraisal tools supports coherent integration within comprehensive decision-making frameworks.

Despite these advantages, it is acknowledged that WSM relies on a compensatory aggregation structure and may be sensitive to potential rank-reversal effects. However, in the context of this study, these limitations are mitigated by: (i) the use of a limited and carefully structured set of criteria; (ii) the prior validation of weights through AHP consistency checks, and; (iii) the presence of a subsequent CBA stage, which provides an independent and non-compensatory evaluation of the selected alternative. Therefore, WSM is used primarily as a transparent screening and ranking tool within a broader multi-stage decision process, rather than as a standalone evaluation method.

In this framework, WSM is implemented using a three-part algorithm to ensure a structured and systematic evaluation.

The first part involves completing a decision matrix by assigning performance values to each criterion and each MTS alternative. Formally, let $\overline{A}$ be the decision matrix and $a_{s\gamma} \in \overline{A}$ the generic element, representing the performance of $s \in S$ based on $\gamma \in \Gamma^{\mathrm{Ph1}}$. To populate this matrix, an analysis of the existing literature and a review of similar prior studies may be conducted. However, the resulting performance matrix contains elements that are not directly comparable. This is because, depending on the criterion considered, each performance is expressed in the unit of measurement specific to that criterion.

For this reason, the second part of WSM focuses on transforming the heterogeneous values in the decision matrix into homogeneous ones by defining appropriate utility functions. Since performance values can be quantitative o qualitative, different utility functions can be considered. For quantitative performance values, a linear utility function is assumed for ease of analysis; for qualitative performance values, following a similar logic, the corresponding utility is assigned using an evenly spaced scale, ensuring that more favourable categories receive proportionally higher utility values. More formally, let:

- $a_{\gamma \text{MAX}}$ and $a_{\gamma \text{MIN}}$ be the highest and the lowest value among the performances associated with $\gamma \in \Gamma^{\text{Ph1}}$, considering all alternatives, respectively.
- $f(a_{s\gamma})$ be the utility value related to $a_{s\gamma}$.
- $\hat{f}(a_{s\gamma})$ be the normalized value of $f(a_{s\gamma})$.

Hence, the utility function is defined as follows:

$$f(a_{s\gamma}) = \begin{cases} \dfrac{a_{s\gamma} - a_{\gamma \text{MIN}}}{a_{\gamma \text{MAX}} - a_{\gamma \text{MIN}}}, & \text{if } \gamma \text{ is a benefit criterion} \\ 1 - \dfrac{a_{s\gamma} - a_{ij \text{MIN}}}{a_{\gamma \text{MAX}} - a_{\gamma \text{MIN}}}, & \text{if } \gamma \text{ is a cost criterion} \end{cases} ; \forall s \in S; \forall \gamma \in \Gamma^{\text{Ph1}} \tag{1}$$

Applying eq. (1) to each performance yields the utility matrix, where each row refers to the MTS technological alternatives, each column refers to the criteria at hand, and each entry reports the utility value computed by eq. (1), which is assumed to range from 0 to 1. Next, to ensure comparability across criteria and avoid scale-related biases, each utility value is normalized so that, for each parameter, the sum of utility values equals 1 (eq. (2)).

$$\hat{f}(a_{s\gamma}) = \frac{f(a_{s\gamma})}{\sum_{s \in S} f(a_{s\gamma})}; \forall s \in S; \forall \gamma \in \Gamma^{\text{Ph1}} \tag{2}$$

Finally, the third part of WSM consists of aggregating all normalized utility values using the overall weight vector $\overline{W}^{\text{Ph1}}$, so that a hierarchy of alternatives can be established through the Weighted Global Score (WGS), which indicates how convenient each alternative is.

More formally, let WGS_s be the WGS of $s \in S$. It is computed as follows:

$$\text{WGS}_s = 100 \cdot \sum_{\gamma \in \Gamma^{\text{Ph1}}} w_{\gamma}^{\text{Ph1}} \cdot \hat{f}(a_{s\gamma}); \forall s \in S \tag{3}$$

Given that the utility function is designed so that a higher utility value always corresponds to a more advantageous alternative, regardless of whether the criterion is a cost or a benefit, it follows that an alternative becomes more favourable as its WGS increases. Consequently, the alternative with the highest WGS should be regarded as the best compromise MTS system.

It is worth noting that performance values in the decision matrix are not always quantifiable with high precision, particularly in the early stages of design. Consequently, the performance measure $a_{s\gamma}$ should not necessarily be interpreted as a fixed value, but rather as belonging to a plausible interval reflecting uncertainty or variability in available data. Rather than assuming a single deterministic decision matrix, this variability can be explicitly explored by defining a set of representative scenarios, each corresponding to a specific combination of performance values within the specified intervals. For each scenario, a distinct decision matrix is constructed and subsequently transformed into a utility matrix, yielding a scenario-specific WGS for each alternative. This scenario-based approach allows the analyst not only to assess the relative ranking of alternatives under different assumptions, but also to evaluate the robustness and stability of such rankings with respect to input variability. In this way, potential inconsistencies or sensitivity in the ranking results are explicitly identified and mitigated, providing a more reliable basis for decision-making under uncertainty. Moreover, comparing rankings across scenarios provides an indirect validation of the robustness of the multicriteria structure itself. If the preferred alternatives remain relatively stable under different assumptions, the resulting decision can be considered more reliable. Conversely, strong ranking variability may indicate that the decision is highly sensitive to uncertain parameters or weighting assumptions and therefore requires additional investigation before implementation.

3.2. *Phase 2 – Selecting the route alternative*

Phase 2 aims to select the optimal route from a set of alternatives for the transit system selected in Phase 1. It involves identifying route alternatives, defining evaluation criteria, and applying the WSM to rank the alternatives. This is carried out through a three-step workflow, detailed below.

STEP 4 *Defining route alternatives*

This step focuses on identifying alternative routes. Formally, let R be the set of routes, and $r \in R$ a generic route. Each $r \in R$ is characterised by its spatial configuration, including planimetric and altimetric alignments, as well as technical details such as track typology (e.g., underground, at ground level, or on a viaduct), and the location and number of stations or stops along it. Additionally, this phase considers constraints related to the urban context, environmental conditions, and potential integration with existing infrastructure, ensuring that the proposed alternatives are both feasible and aligned with operational and sustainability goals.

STEP 5 *Recalibrating criteria and weights*

Once the set of route alternatives has been defined, this step involves establishing decision criteria. Since Phase 1 already includes a list of criteria weighted by a panel of experts, Phase 2 criteria could be selected as a subset of the previously considered items, focusing only on those relevant to route selection. However, the weights of these criteria must be renormalised so that their sum equals 1. This normalisation ensures that the selected criteria remain proportionally relevant in the decision-making process, keeping their total contribution consistent and comparable. Formally, let:

- $\Gamma^{\text{Ph2}} \subseteq \Gamma^{\text{Ph1}}$ be the subset of criteria used in phase 2.
- $\overline{W}^{\text{Ph2}}$ be the vector of the weights used in phase 2, and w_{γ}^{Ph2} the element corresponding to the criterion $\gamma \in \Gamma^{\text{Ph2}}$.

Each element w_{γ}^{Ph2} is computed as follows:

$$w_{\gamma}^{\text{Ph2}} = \frac{w_{\gamma}^{\text{Ph1}}}{\sum_{\gamma \in \Gamma^{\text{Ph2}}} w_{\gamma}^{\text{Ph1}}}; \forall \gamma \in \Gamma^{\text{Ph2}} \tag{4}$$

Applying eq. (4) to each phase 2 criterion yields a normalized weight vector for use in Phase 2.

STEP 6 *Ranking route alternatives*

The final step of Phase 2 aims to rank the route alternatives using the same procedure defined in Phase 1 (STEP 3) for MTS alternatives. This involves generating a new performance matrix for the routes identified in STEP 4 and the criteria defined in STEP 5, and then applying equations from (1) to (3) once again. Consequently, the route alternative with the highest WGS should be considered the best compromise solution.

3.3. Phase 3 – Evaluating economic feasibility

Once the optimal MTS technology and its associated route have been defined, the final phase applies a CBA to assess the economic sustainability of the proposed solution. This economic appraisal is particularly efficient because the preceding MCA stages have already narrowed down the choices. By substantially reducing the solution space, this approach eliminates the need to perform full CBAs on a wide set of initial alternatives.

In line with established technical literature, the CBA includes demand forecasting, cost estimation, monetisation of user and societal benefits, calculation of economic indicators, and sensitivity and risk analyses (e.g., COM - The European Commission, 2014). This is carried out through a five-step workflow, detailed below.

STEP 7 *Estimating demand*

This step consists of analysing and forecasting transport demand to estimate the potential users of the new MTS for each year of the evaluation period. The process begins by defining the study area, including both directly affected zones and external areas that significantly influence traffic flows.

Once the study area is established, two scenarios are considered:

- The Business-As-Usual (BAU) scenario, representing the current demand on each transportation system operating within the identified area.
- The Project scenario, which introduces the new MTS into the same territorial context.

A wide range of approaches can be used to estimate travel demand in both scenarios, including transport models, dedicated surveys, existing studies, and simplified spreadsheet-based tools. This framework is designed to remain general and can accommodate any of these approaches, depending on the data and modelling capabilities available in each context. In the Project scenario, the demand on the new MTS is broken down into three components (e.g., COM - The European Commission, 2014):

(i) Diverted demand, representing users switching from private transport.
(ii) Shifted demand, representing users moving from other public transport systems.
(iii) Generated demand, which corresponds to new trips induced by the implementation of the system.

Formally, let:

- K be the set of transport systems operating in the study area, $k \in K$ a generic system, and $k_{NEW} \in K$ the new MTS in project.
- T be the set of years of analysis, including both the implementation period and the useful life of the project; $t \in T$ denote a generic year; $\widetilde{t} \in T$ denote the last year of the implementation period.
- $D_{0,k}(t)$ and $D_{1,k}(t)$ be the demand acting on $k \in K$ in BAU and Project Scenarios, respectively, at year $t \in T$.

The demand diverted or shifted from each $k \in K$ to $k_{NEW} \in K$ at year $t \in T$ (denoted as $D_{D/S,k}(t)$) can be computed as in eq. (5), if the reduction in demand acting on $k \in K$ $(k \neq k_{NEW})$ from BAU to Project Scenario entirely moves to the new MTS:

$$D_{D/S,k}(t) = D_{0,k}(t) - D_{1,k}(t); \forall k \in K : k \neq k_{NEW}; \forall t \in T : t > \widetilde{t} \tag{5}$$

The demand generated by implementing the new MTS at year $t \in T$ (denoted as $D_{G,k_{NEW}}(t)$) can be defined as the difference between the demand on k_{NEW} in the Project Scenario and the sum of the diverted and shifted demands. More formally:

$$D_{G,k_{NEW}}(t) = D_{1,k_{NEW}}(t) - \sum\nolimits_{k \in K : k \neq k_{NEW}} D_{D/S,k}(t); \forall t \in T : t > \widetilde{t} \tag{6}$$

STEP 8 *Estimating costs*

This step estimates the overall cost, that is, the economic value of the resources required to realise and manage the project. Implementing a new MTS involves two categories of costs: i) initial investment costs, and ii) operating and maintenance costs. These are detailed in what follows.

Initial investment costs

Supposing that disaggregated investment costs are not available (as it is typical in the preliminary phase of MTS design), their estimation is carried out using an aggregate parametric approach (e.g. COM - The European Commission, 2014; De Aloe et al., 2023). This method analyses the literature and past case studies to identify costs for projects with characteristics similar to those of the proposed system. After applying appropriate discounting, the average unit costs from these projects serve as a baseline for estimating the new system's investment costs (Sinha & Labi, 2011).

According to the Italian Ministry of Infrastructure and Sustainable Mobility (2022), investment costs could be divided into specific categories:

- General costs represent the expenditure incurred by the contracting authority for everything related to preliminary studies, works management, and design at the various levels required by current legislation, including any specialist studies, topographic survey campaigns, etc.
- Civil works costs represent all cost items relating to the construction of civil works for the operation of the service, such as stops, vehicle and equipment depots, as well as all urban and compensatory works required by current urban planning regulations.
- Costs for the electro-tramway systems represent all expenses related to the electrical and control infrastructure of the system, including electric substations, overhead contact line, the installation of any protective measures to secure the track, and all signalling and communication systems necessary for the safe operation.
- Vehicle purchase costs represent the cost incurred for the purchase of new vehicles or for the possible modernisation of an existing fleet.
- Other available funds represent the funds available to the contracting authority for all that is not included in the previous items. By way of example, and without limitation, this category includes safety costs, costs of any expropriations or land acquisitions, and a sum made available to cover unforeseen expenses during subsequent design or construction phases.

More formally, let:

- $INV(t)$ be the investment cost at year $t \in T$.
- I be the set of investment cost items.
- c_i be the unitary investment cost of the item $i \in I$.
- $n_i(t)$ be the overall quantity for the item $i \in I$ at year $t \in T$.

Hence, $INV(t)$ is calculated as follows:

$$INV(t) = \sum_{i \in I} c_i \cdot n_i(t); \forall t \in T : t \leq \widetilde{t} \tag{7}$$

Operating and maintenance costs

Operating and maintenance (O&M) costs are estimated using reference values derived from case studies with characteristics comparable to those of the proposed MTS. More formally, let:

- $OC(t)$ be the O&M costs at year $t \in T$.
- $\xi_{1,k_{NEW}}$ be the marginal O&M cost pursued by the Transit Authority (TA)/Public Transit Operator (PTO) for dispensing the supply of $k_{NEW} \in K$ in the Project Scenario.
- $\mu_{1,k_{NEW}}(t)$ be the supplied mileage of $k_{NEW} \in K$ at year $t \in T$ in the Project Scenario (e.g., estimated according to the exercise program).

Hence, $OC(t)$ is calculated as follows:

$$OC(t) = \xi_{1,k_{NEW}} \bullet \mu_{1,k_{NEW}}(t); \forall t \in T : t > \widetilde{t} \tag{8}$$

Finally, the overall cost for each year t, denoted as $C(t)$, is calculated as follows:

$$C(t) = \begin{cases} INV(t) \text{ if } t \leq \widetilde{t} \\ OC(t) \text{ if } t > \widetilde{t} \end{cases}; t \leq \widetilde{t} \tag{9}$$

STEP 9 *Estimating benefits*

This step estimates the expected benefits of implementing the new MTS. These can be divided into two categories: direct benefits and indirect benefits (externalities) (e.g., COM - The European Commission, 2014; Italian Ministry of Infrastructure and Sustainable Mobility, 2022; Italian Ministry of Infrastructure and Transport, 2019; Ventura et al., 2022).

Direct benefits are all the advantages enjoyed by those directly affected by the new MTS. They can be divided into two sub-categories: user benefits and TA and/or PTO benefits. Externalities, by contrast, are benefits that accrue to those who do not use the service but are indirectly affected by its effects.

All benefits are calculated by assigning a monetary value to travel time and introducing marginal costs that enable the economic quantification of benefits resulting from factors such as reduced pollution, road traffic, and crashes. Note that implementing a new MTS may, in certain respects, lead to a deterioration relative to the current situation (e.g., an increase in ticket prices would raise overall travel costs for users). In such cases, these aspects are treated in the CBA as benefits with negative values, effectively considering them as costs.

More details about benefit estimations are provided below.

User benefits

User benefits are related to changes in travel time and in the costs (fares and vehicle operating) they incur to undertake the journey. More formally, let:

- $B_{US,TIME}(t)$, $B_{US,FARES}(t)$ and $B_{US,VOC}(t)$ be users' benefits related to the change in travel time, fares, and Vehicle Operating Costs (VOC), respectively, at year $t \in T$.
- $L_{0,k}$ and $L_{1,k}$ be the average trip length for each $k \in K$ in the BAU and Project Scenarios, respectively.
- $v_{0,k}$ and $v_{1,k}$ be the commercial speed of each $k \in K$ in the BAU and Project Scenarios, respectively.
- $\tau_{0,k}$ and $\tau_{1,k}$ be the economic (marginal) value of travel time for each $k \in K$ in the BAU and Project Scenarios, respectively.
- $\varphi_{0,k}$ and $\varphi_{1,k}$ be the marginal fares paid for a trip (ticket, toll) by a user of $k \in k$ in the BAU and Project Scenarios, respectively.
- $\zeta_{0,k}$ and $\zeta_{1,k}$ be the marginal Vehicle Operating Cost (VOC) paid by a user of the private transport $k \in K$ (obviously, for public transport systems, the VOC bearing on the user is null) in the BAU and Project Scenarios, respectively.

As for $B_{US,TIME}(t)$, according to the Italian Ministry of Infrastructure and Sustainable Mobility (2022), an economic value could be attributed to the travel time saved in the Project Scenario compared to the current scenario, considering each of the three components of the project demand (shifted, diverted, and generated). Hence, the user's benefits related to the change in travel time at year $t \in T$ is calculated as follows:

$$\begin{aligned} B_{US,TIME}(t) = \sum\nolimits_{k \in K: k \neq k_{NEW}} \Bigg[& \left(\tau_{0,k} \frac{L_{0,k}}{v_{0,k}} - \tau_{1,k} \frac{L_{1,k}}{v_{1,k}} \right) D_{1,k}(t) \\ & + \frac{1}{2} \left(\tau_{0,k} \frac{L_{0,k}}{v_{0,k}} - \tau_{1,k_{NEW}} \frac{L_{1,k_{NEW}}}{v_{1,k_{NEW}}} \right) D_{D/S,k}(t) \Bigg] \\ & + \frac{1}{2} \left(\tau_{0,\tilde{k}} \frac{L_{0,\tilde{k}}}{v_{0,\tilde{k}}} - \tau_{1,k_{NEW}} \frac{L_{1,k_{NEW}}}{v_{1,k_{NEW}}} \right) D_{G,k_{NEW}}(t); \forall t \in T : t > \widetilde{t} \end{aligned} \tag{10}$$

Notably, when considering the travel time savings from diverted and generated demand, the Rule of Half (RoH) applies. Moreover, the travel time saved by generated demand is calculated as the difference between the travel time in the Project Scenario $k_{NEW} \in K$ and the time a hypothetical user would have spent travelling in the BAU scenario using a reference transit system $\widetilde{k} \in K$. This assumes that the new system $k_{NEW} \in K$ represents an improvement over $\widetilde{k} \in K$.

The benefits from overall travel cost savings are calculated as the difference between the total costs users incur in the BAU and Project Scenarios. This benefit comprises two components: $B_{US,FARES}(t)$ and $B_{US,VOC}(t)$, calculated according to Eqs. (11) and (12), respectively:

$$\begin{aligned} B_{US,FARES}(t) = \sum\nolimits_{k \in K: k \neq k_{NEW}} \Bigg[& \left(\varphi_{0,k} L_{0,k} - \varphi_{1,k} L_{1,k} \right) D_{1,k}(t) \\ & + \frac{1}{2} \left(\varphi_{0,k} L_{0,k} - \varphi_{1,k_{NEW}} L_{1,k_{NEW}} \right) D_{D/S,k}(t) \Bigg] \\ & + \frac{1}{2} \left(\varphi_{0,\tilde{k}} L_{0,\tilde{k}} - \varphi_{1,k_{NEW}} L_{0,k_{NEW}} \right) D_{G,k_{NEW}}(t); \forall t \in T : t > \widetilde{t} \end{aligned} \tag{11}$$

$$\begin{aligned} B_{US,VOC}(t) = \sum\nolimits_{k \in K: k \neq k_{NEW}} \Bigg[& \left(\zeta_{0,k} L_{0,k} - \zeta_{1,k} L_{1,k} \right) D_{1,k}(t) \\ & + \frac{1}{2} \left(\zeta_{0,k} L_{0,k} - \zeta_{1,k_{NEW}} L_{1,k_{NEW}} \right) D_{D/S,k}(t) \Bigg]; \forall t \in T : t > \widetilde{t} \end{aligned} \tag{12}$$

Note that, like eq. (10), eqs. (11) and (12) apply the RoH to the terms related to the diverted and generated demand.

TA / PTO benefits

TA and PTO can also benefit from implementing the new MTS. Specifically, these benefits pertain primarily to changes in ticket sales revenue and operating costs.

More formally, let:

- $B_{TA/PTO,FARES}(t)$ and $B_{TA/PTO,OC}(t)$ be TA/PTO benefits related to the variation in revenue from the sale of travel tickets, and operating costs, respectively, at year $t \in T$.
- $\xi_{0,k}$ and $\xi_{1,k}$ be the marginal O&M cost pursued by the TA/PTO for dispensing the supply of $k \in$ K in the BAU and project scenarios, respectively (obviously, for private mode users, these marginal costs are null).
- $\omega_{0,k}$ and $\omega_{1,k}$ be the average occupation coefficient of each $k \in K$ in the BAU and Project Scenarios, respectively.

As for $B_{TA/PTO,FARES}(t)$, it is calculated by summing the additional ticket revenues generated by the new MTS, the variation in revenues from existing public transport systems, and the revenues lost due to demand shifting to the new MTS (eq. 13).

$$\begin{aligned}B_{TA/PTO,FARES}(t) = {} & \varphi_{1,k_{NEW}} L_{1,k_{NEW}} D_{1,k_{NEW}}(t) \\ & - \sum\nolimits_{k \in K : k \neq k_{NEW}} (\varphi_{0,k} L_{0,k} - \varphi_{1,k} L_{1,k}) D_{1,k}(t) \\ & - \sum\nolimits_{k \in K : k \neq k_{NEW}} \varphi_{0,k} L_{0,k} D_{D/S,k}(t); \forall t \in T : t > \widetilde{t}\end{aligned} \tag{13}$$

Moving on $B_{TA/PTO,OC}(t)$, it is defined as the difference between the total operating cost of the public transport network in its current state (BAU) and the operating costs of all public transport systems that will be active in the Project Scenario, including the operating, management, and maintenance costs of the new MTS (eq. 14).

$$B_{TA/PTO,OC}(t) = \sum\nolimits_{k \in K : k \neq k_{NEW}} \left(\xi_{0,k} L_{0,k} \frac{D_{0,k}(t)}{\omega_{0,k}} - \xi_{1,k} L_{1,k} \frac{D_{1,k}(t)}{\omega_{1,k}} \right); \forall t \in T : t > \widetilde{t} \tag{14}$$

Non-user benefits (externalities)

The implementation of a new MTS entails benefits that affect not only users but also non-users. Indeed, the diversion of demand from private transport to the new system results in fewer vehicles on the roads, which means fewer crashes, emissions of pollutants (e.g., tyre and road wear particles), traffic noise, and greenhouse gases. These are all benefits that affect the entire community and should be considered in the CBA process.

The calculation of externalities is provided by attributing marginal costs to each externality considered and multiplying them by the corresponding variations in mileage, according to the Italian Ministry of Infrastructure and Sustainable Mobility (2022).

More formally, let:

- EXT be the set of considered externalities. These might include, e.g., road crashes, pollutant emissions, acoustic emissions, and greenhouse gases.
- $B_{ext}(t)$ be the benefit generated by the reduction of the generic externality $ext \in EXT$ at year $t \in T$.
- $\mu_{ext,0,k}$ and $\mu_{ext,1,k}$ be the marginal cost of externality $ext \in EXT$ for each $k \in K$ in the BAU and Project Scenarios, respectively.

The value of $B_{ext}(t)$ could be generalised as follows:

$$B_{ext}(t) = \sum\nolimits_{k \in K} \left(\mu_{ext,0,k} \, L_{0,k} \frac{D_{0,k}(t)}{\omega_{0,k}} - \mu_{ext,1,k} \, L_{1,k} \frac{D_{1,k}(t)}{\omega_{1,k}} \right); \forall t \in T : t > \widetilde{t}; \forall ext \in EXT \tag{15}$$

Finally, the overall benefit for each year t, denoted as $B(t)$, is calculated as follows:

$$\begin{aligned}B(t) = {} & B_{US,TIME}(t) + B_{US,FARES}(t) + B_{US,VOC}(t) + B_{TA/PTO,FARES}(t) \\ & + B_{TA/PTO,OC}(t) + \sum\nolimits_{ext \in EXT} B_{ext}(t); \forall t \in T\end{aligned} \tag{16}$$

Residual Value

The Residual Value is the last benefit considered. It is defined as the value of the project at the last year of analysis, computed using linear depreciation of the initial investment cost of each component (including renewals) based on its economic life. Each component's depreciation rate is determined by its physical life.

More formally, let:

- $RV(\sup(T))$ be the residual value of the whole project at the last year of analysis.
- $RV_i(\sup(T))$ be the residual value of the item $i \in I$ at the last year of analysis.
- ε_i be the economic life of the item $i \in I$.

Hence, the residual value is computed according to Eqs. (17) and (18).

$$RV_i(\sup(T)) = \left(\sum_{t \in T : t \leq \tilde{t}} c_i \cdot n_i(t) \right) \bullet \left(1 - \frac{\left(\sup(T) - \widetilde{t}\right) - \varepsilon_i \bullet \text{floor}\left(\frac{\sup(T) - \widetilde{t}}{\varepsilon_i} \right)}{\varepsilon_i} \right) \tag{17}$$

$$RV = \sum_{i \in I} RV_i(\sup(T)) \tag{18}$$

Specifically, in Eqs. (17), the first factor, i.e., $\sum_{t \in T : t \leq \tilde{t}} c_i \cdot n_i(t)$, represents the total investment made on item $i \in I$ during the implementation period, aggregating all initial expenditures into a single initial value before depreciation begins. This reflects the assumption that all components start their first depreciation cycle at the end of the implementation period $\widetilde{t}$.

The second factor., i.e., $1 - \frac{\left(\sup(T) - \widetilde{t}\right) - \varepsilon_i \bullet \text{floor}\left(\frac{\sup(T) - \widetilde{t}}{\varepsilon_i} \right)}{\varepsilon_i}$, determines the share of the last depreciation cycle that remains at the end of the analysis period. Specifically, the term $\left(\sup(T) - \widetilde{t}\right) - \varepsilon_i \bullet \text{floor}\left(\frac{\sup(T) - \widetilde{t}}{\varepsilon_i} \right)$ captures the “age” of the final cycle, obtained by subtracting from the total elapsed time the number of full economic-life cycles completed between $\widetilde{t}$ and $\sup(T)$. Dividing this residual age by ε_i yields the fraction of the last cycle that has already been depreciated, while the complement to one represents the remaining value.

Consequently, the residual value of item $i \in I$ is strictly positive unless the last year of analysis coincides exactly with the end of a full depreciation cycle, in which case the remaining fraction becomes zero.

Finally, Eq. (18) aggregates the residual values of all investment items, yielding the project's total Residual Value at the end of the analysis period.

STEP 10 *Estimating economic indicators*

Once the monetary values have been obtained, this step compares costs and benefits using CBA's typical indicators, namely: the Economic Net Present Value (ENPV), which represents the economic return of the investment; the Economic Internal Rate of Return (EIRR), defined as the discount rate that makes ENVP equal to zero; and the Economic Benefit – Costs Ratio (ECBR), which indicates the extent to which benefits exceed costs.

More formally, let ρ be the social discount rate, depending on social, economic and political conditions of the study area. Thus, CBA indicators are calculated as follows:

$$\begin{aligned}\text{ENPV} & = \sum_{t \in T} \frac{B(t) - C(t)}{(1+\rho)^t} \\ & = - \sum_{t \in T : t \leq \tilde{t};} \frac{I(t)}{(1+\rho)^t} + \sum_{t \in T : t > \tilde{t};} \frac{B(t) - OC(t)}{(1+\rho)^t} + \frac{RV(|T|)}{(1+\rho)^{|T|}}\end{aligned} \tag{19}$$

$$EIRR = arg\left\{\rho : \sum_{t\in T}\frac{B(t)-C(t)}{(1+\rho)^t} = -\sum_{t\in T:t\le\tilde{t};}\frac{I(t)}{(1+\rho)^t} + \sum_{t\in T:t>\tilde{t};}\frac{B(t)-OC(t)}{(1+\rho)^t} + \frac{RV(|T|)}{(1+\rho)^{|T|}} = 0\right\} \tag{20}$$

$$\mathrm{EBCR} = \left(\sum_{t\in T:t>\tilde{t};}\frac{B(t)}{(1+\rho)^t} + \frac{RV(|T|)}{(1+\rho)^{|T|}}\right)\cdot\left(\sum_{t\in T:t\le\tilde{t};}\frac{I(t)}{(1+\rho)^t} + \sum_{t\in T:t>\tilde{t};}\frac{OC(t)}{(1+\rho)^t}\right)^{-1} \tag{21}$$

According to the results of eqs. (19), (20), and (21), the project previously defined with MCA is economically sustainable if all the following conditions are simultaneously fulfilled:

$$\mathrm{ENPV} > 0$$

$$\mathrm{EIRR} > 0 \wedge \mathrm{EIRR} > \rho$$

$$\mathrm{EBCR} > 1$$

STEP 11 *Performing sensitivity analysis*

If STEP 10 confirms that the project is economically sustainable, the next step is to assess the robustness of this sustainability. To this end, a sensitivity analysis is conducted to assess how fluctuations in input variables may affect the project's economic indicators, thereby verifying the resilience and reliability of the results across different scenarios.

Formally, let:

- X be the set of input variables influencing ENPV, such as $\mathrm{ENPV} = \mathrm{ENPV}(X)$.
- $X_{crit} \subseteq X$ be the subset of project's "critical" variables.
- $switch(x)$ be the switching value of the generic variable $x \in X_{crit}$.

Sensitivity analysis examines how variations in X affect the ENPV and identifies conditions under which the project could become unprofitable. Each variable should be defined as disaggregated as possible to avoid bias and double-counting. The first task is to determine X_{crit}, i.e., the variables for which a ± 1% change from their base-case value results in a variation (in absolute value) greater than ±1% in the ENPV (COM - The European Commission, 2014). This analysis is performed by varying one input variable at a time and observing its impact on ENPV. In other words, X_{crit} is identified by evaluating the elasticity of ENPV with respect to each $x \in X$ (eq. (22)).

$$X_{crit} = \left\{x\in X : \left|\frac{\partial\mathrm{ENPV}}{\partial x}\bullet\frac{x}{ENPV(x)}\right| > 1\right\} \tag{22}$$

Subsequently, for each $x \in X_{crit}$, the switching value $switch(x)$ is computed, defined at the specific value $\tilde{x}$ that makes ENPV equal to zero (eq. 23). These switching values indicate the thresholds beyond which the project becomes economically unsustainable.

$$switch(x) = arg\{\tilde{x} : ENPV(X\backslash\{x\}\bigcup\tilde{x}) = 0\}; \forall x \in X_{crit} \tag{23}$$

Moreover, this analysis enables the contribution of each variable to the final economic performance to be explicitly quantified, thereby clarifying which assumptions most strongly influence project feasibility and which parameters require greater attention during subsequent planning stages.

STEP 12 *Running risk analysis*

This step further stresses the project's economic sustainability by conducting a risk analysis. Indeed, while sensitivity analysis helps identify which variables have the greatest impact on economic outcomes, it does not account for the likelihood or distribution of those variations. For this reason, a risk analysis is also conducted on the most critical variables to capture the probability and range of possible scenarios. This approach provides a more comprehensive understanding of potential uncertainties and supports more informed decision-making.

More formally, let:

- x_{min} and x_{max} be the lower and upper bounds of the domain of $x \in X_{crit}$.
- $\Psi_x : [x_{min}, x_{max}] \longrightarrow [0, 1]$ be the cumulative distribution function (CDF) of the variable $x \in X_{crit}$.
- Θ be the set of simulation instances for risk analysis.
- $\pi_{x,\theta} \in [0, 1]$ a random number associated with the variable $x \in X_{crit}$, sampled at instance $\theta \in \Theta$ from a uniform distribution.
- x_θ be the simulated value of $x \in X_{crit}$, generated at instance $\theta \in \Theta$.
- ENPV_θ and $EIRR_\theta$ be the simulated value of ENPV and EIRR at instance $\theta \in \Theta$, computed using all X, where non-critical variables remain at base case.

This approach assigns a proper CDF (Ψ_x) to each critical variable $x \in X_{crit}$ within a defined range around its best estimate (base case) to recalculate expected values of economic performance indicators (e.g., ENPV and EIRR). CDFs can be derived from experimental data, literature on similar cases, or expert judgment. Care is needed because if these distributions are unreliable, the risk assessment will be unreliable as well. In this respect, demand-related variables require particular attention, as transport demand is inherently influenced by macroeconomic dynamics (e.g., variations in gross domestic product), which may substantially affect mobility patterns and long-term projections (Libardo & Nocera, 2008). Nevertheless, risk analysis improves understanding of the project's strengths and weaknesses compared to the base case.

Once Ψ_x are established, the next stage is to compute the probability distribution of ENPV and EIRR for the project. Monte Carlo simulation can be applied for this purpose, to convert the deterministic values, based on actual evaluations, into stochastic evaluations, to introduce uncertainty in the estimation. The method involves repeatedly drawing random sets of values for the critical variables according to their respective CDF and calculating the resulting performance indicators for each set (eqs. 24, 25, and 26).

$$x_\theta = \Psi_x^{-1}(\pi_{x,\theta}); \forall x \in X_{crit}; \forall\theta \in \Theta \tag{24}$$

$$\mathrm{ENPV}_\theta = ENPV(\{x_\theta : x \in X_{crit}\}, X\backslash X_{crit}); \forall\theta \in \Theta \tag{25}$$

$$\mathrm{IERR}_\theta = arg\{\rho : ENPV(\{x_\theta : x \in X_{crit}\}, X\backslash X_{crit}, \rho) = 0\}; \forall\theta \in \Theta \tag{26}$$

By repeating this process a sufficiently large number of times, the simulation provides an estimate of the distribution for ENPV and EIRR. These distributions can be interpreted in probabilistic terms, for instance, by assessing the likelihood of achieving positive ENPV values or EIRR levels above reference thresholds, thereby supporting a risk-informed evaluation of the project's economic sustainability.

4. Results and discussion

4.1. Research context

To demonstrate the viability of the framework, a case study was

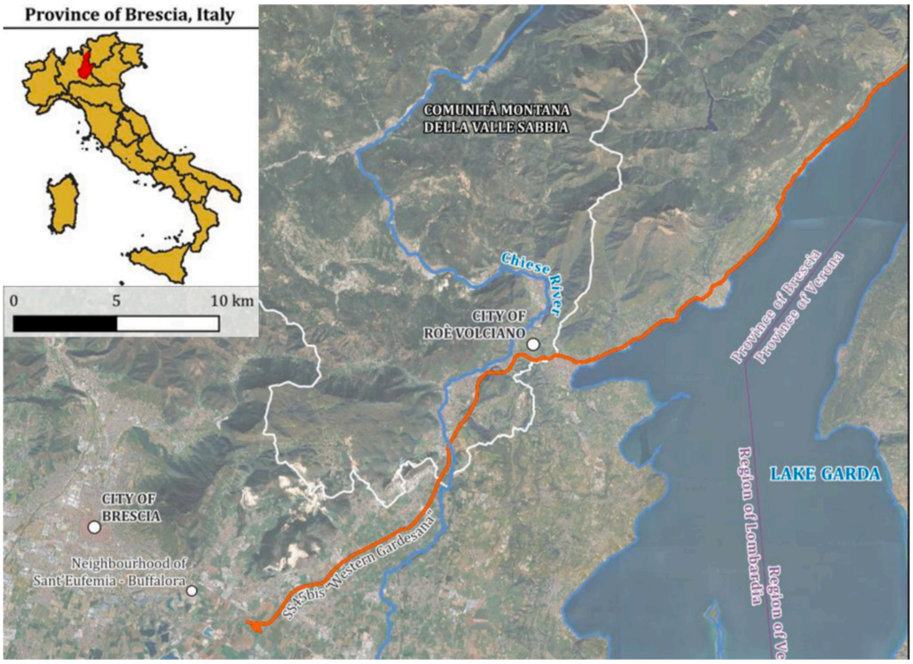
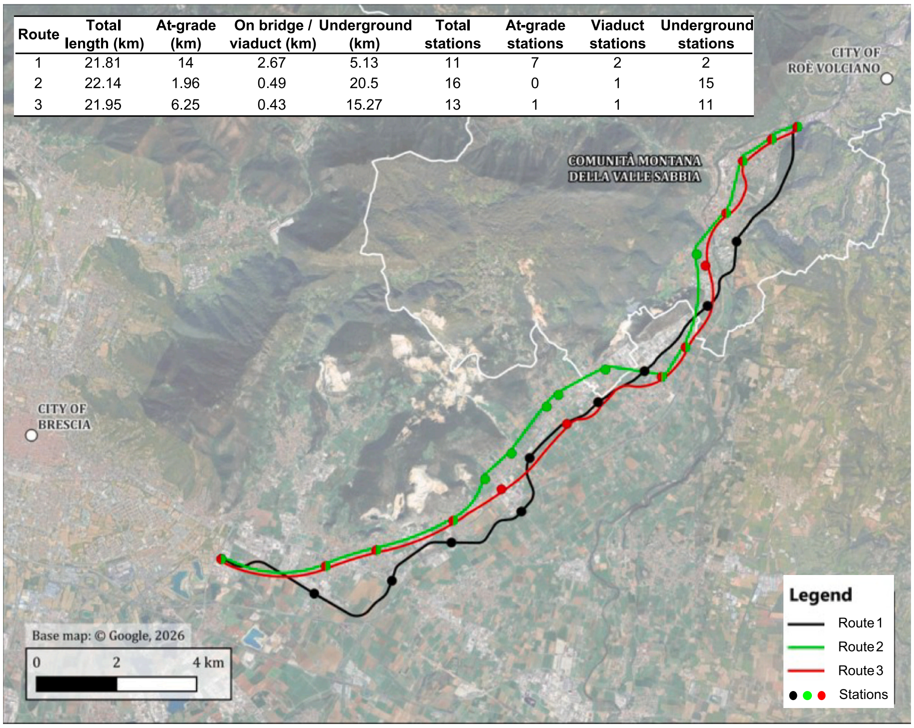


Fig. 2. Planimetry of the case study area.



Route	Total length (km)	At-grade (km)	On bridge / viaduct (km)	Underground (km)	Total stations	At-grade stations	Viaduct stations	Underground stations
1	21.81	14	2.67	5.13	11	7	2	2
2	22.14	1.96	0.49	20.5	16	0	1	15
3	21.95	6.25	0.43	15.27	13	1	1	11

Fig. 3. Planimetry of the 3 routes considered.

considered in the north-eastern suburban area of Brescia, in northern Italy (Lombardy region). The area lies between Lake Garda to the east and the city of Brescia to the west (Fig. 2). It is a densely urbanised area developed along the Chiese river, covering approximately 120′000 km^2 and hosting about 100′000 inhabitants, excluding the city of Brescia. The investigated area links the S. Eufemia neighbourhood in Brescia with the town of Roé Volciano. Brescia is the administrative and economic centre of the province, and the second most populous city in Lombardy, while Roé Volciano is a small town with fewer than 5′000 inhabitants. Despite its small population, Roé Volciano plays a strategic role in the area due to its location. The area's morphological and topographical characteristics make Roé Volciano (and, more generally, the whole corridor) the most practical access route to both the north-western shores of Lake Garda and the mountainous Valsabbia. This area serves residents commuting to Brescia for work or study, as well as tourists visiting Lake Garda's beaches and the mountains of Valsabbia. (See Fig. 3.)

Currently, there is no MTS service operating on dedicated infrastructure on a suburban bus route that shares the roadway with private vehicles. Moreover, most extra-urban traffic demand relies on a single extra-urban road: National Roadway No. 45B, known as the “Western Gardesana”. As a result, this road frequently experiences congestion, leading to increased greenhouse gas emissions, longer travel times, and reduced road safety. For these reasons, the Province of Brescia is exploring the possibility of implementing a new MTS in this area.

4.2. Optimal MTS alternative in the case study

4.2.1. MTS alternatives

According to STEP 1 and based on a review of the relevant literature, eight main MTSs were preliminarily identified as potential candidates for the study area (Abdallah, 2023; Ingvardson & Nielsen, 2018; Van Egmond et al., 2003; Vuchic, 2007). They are Busway (B), Classic Tramway (CT), Guided Busway (GB), Light Metro (LM), Tramway Rapid Transit (TRT), Tram on Rubber (ToR), Tram-Train (TT) and Trolley Bus (TB). The selection of these MTSs is based on their recurrence in contexts like the one investigated, as well as their varying capacities, levels of infrastructure integration, flexibility, and technological maturity. Together, they represent a diverse yet representative set of feasible solutions that can address the study area's specific mobility needs, spatial constraints, and operational requirements.

4.2.2. Decision criteria and weights

Next, according to STEP 2, in December 2022, a pool of 32 experts was surveyed during dedicated meetings, comprising political and technical representatives from all the local authorities and transport agencies involved.[3] The selection of stakeholders followed a purposive approach to ensure institutional representativeness and coverage of the key decision-making perspectives involved in planning the new MTS. Stakeholders were identified between public authorities and operational actors directly involved in transport planning and management within the study area. The final panel included 28 representatives from municipalities and inter-municipal authorities (14 Municipal Councillors for Public Works and Transport and 14 Heads of Technical Departments), as well as 4 managers and technical experts from local public transport agencies. The former ensures the inclusion of strategic, regulatory, and planning perspectives, the latter contribute to operational and service-oriented expertise. This composition ensures a balanced integration of strategic, technical, and managerial viewpoints.

The survey required respondents to perform pairwise comparisons of a predefined set of six criteria, further articulated into 25 parameters to capture more specific dimensions of system performance.

The definition of these criteria and parameters followed a structured selection process grounded in existing literature on public transport system evaluation (e.g., Barabino et al., 2020; Broniewicz & Ogrodnik, 2020; Keshavarz-Ghorabaee et al., 2022; Sciences, 2013; Vuchic, 2007; Zhang et al., 2022). In particular, the selection was guided by three principles:

(i) Empirical relevance, ensuring that the chosen parameters correspond to attributes consistently identified as determinants of modal choice and system attractiveness.

(ii) Measurability, understood not only as numerical quantification but also as the ability to classify each factor in a clear, reproducible, and unambiguous way, thus including both quantitative indicators (e.g., speed, frequency) and qualitative or categorical attributes (e.g., type of flooring, right-of-way configuration).

(iii) Planning alignment, guaranteeing coherence with international transport planning guidelines.

Table 1

Criteria, parameters and weights for MTSs ranking.

Criterion	Parameter	Type	Weight ($\overline{\boldsymbol{W}}^{\mathbf{Ph1}}$)
General characteristics	Served population	Numerical (Benefit)	0.070
	Net extension	Numerical (Benefit)	0.029
	Number of stations or stops	Numerical (Benefit)	0.035
	Stations or stops distance	Numerical (Benefit)	0.030
	Separation of the network from the rest of the road system	Categorical	0.029
Infrastructure	Type of flooring	Categorical	0.020
	Type of infrastructure	Categorical	0.029
	Maximum slope	Numerical (Benefit)	0.018
	Minimum curve radius	Numerical (Cost)	0.014
	Platform height	Numerical (Cost)	0.021
Functional characteristics	Maximum frequency	Numerical (Benefit)	0.051
	Maximum capacity	Numerical (Benefit)	0.029
	Commercial speed	Numerical (Benefit)	0.035
	Regularity	Numerical (Benefit)	0.068
Impacts	Visual intrusion	Numerical (Cost)	0.021
	CO_2 emissions	Numerical (Cost)	0.043
	Acoustic impact	Numerical (Cost)	0.027
	Safety	Numerical (Benefit)	0.043
	Discouraging the use of private cars	Numerical (Benefit)	0.038
Costs	Construction costs	Numerical (Cost)	0.034
	O&M	Numerical (Cost)	0.073
	Design and construction time	Numerical (Cost)	0.046
Integration with the local area	Territorial development due to the presence of the system	Numerical (Benefit)	0.051
	Accessibility	Numerical (Benefit)	0.071
	Multimodality	Numerical (Benefit)	0.073

As a result, the final set of criteria and parameters covers a comprehensive spectrum of evaluation dimensions, including general system characteristics, infrastructure features, functional performance, environmental and social impacts, and cost- and integration-related aspects. Together, they constitute the core factors for assessing the performance of each MTS alternative.

Once all surveys were completed, the AHP Analysis was performed twice, first at the criterion level and then at the parameter level, to calculate an importance weight of each item. While some individual responses exhibited CR values slightly above the 0.1 threshold, this is not uncommon in participatory contexts involving heterogeneous stakeholders with diverse backgrounds and perspectives (Frish et al., 2025; Lukinskiy et al., 2021). Rather than excluding such judgments a priori, their impact was evaluated at the aggregate level. In this case, no statistically significant differences were observed in the resulting weight distributions compared with those from subsets of more consistent responses. Therefore, all questionnaires were retained, ensuring that the final weighting reflects the full diversity of stakeholder viewpoints.

Table 1 summarises the criteria and parameters considered in the

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[3] This study was reviewed and approved by the CeSCAM ethics advisory council. All participants provided informed consent before taking part in the activity.

analysis (Γ^{Ph1}), along with their respective cost/benefit classification, and the specific AHP-derived weights ($\overline{W}^{Ph1}$).

Notably, the number of selected criteria and parameters reflects a deliberate balance between ensuring coverage of the dimensions most emphasised in the literature and keeping the pairwise-comparison task manageable for respondents. However, the framework remains general and flexible: it does not impose a fixed set of factors, and these can be readily adapted or expanded to suit the specific needs and priorities of different case studies.

The results show that O&M costs emerged as the most influential factor from the experts' perspective, followed by multimodality, accessibility, and served population. This outcome reflects a notable sensitivity to long-term financial sustainability, which is particularly relevant in contexts where operating budgets are constrained, and efficiency gains can significantly impact feasibility.

Interestingly, the leading role of O&M costs is a novelty with respect to most prior studies, which typically rank user-centric criteria such as accessibility, integration and safety as dominant (Barbosa et al., 2017; Ghorbanzadeh et al., 2018; L'Hostis et al., 2017; Naegeli et al., 2012). While some studies note the growing relevance of O&M costs in small- to medium-sized areas, they seldom emerge as the top priority (Lee, 2018). This divergence suggests that in areas with high baseline operating costs and constrained budgets, financial sustainability can take precedence over service-oriented attributes. Such context-specific weighting underlines the importance of integrating stakeholder preferences with financial considerations when applying multi-criteria frameworks to real-world transit planning.

4.2.3. MTSs ranking

Besides, according to STEP 3, the optimal MTS among the pool of eight technological alternatives was determined. The decision matrix ($\overline{A}$) was populated by considering the performance value associated with each specific alternative and criterion ($a_{s\gamma}$). Performance values for each system parameters were derived from an analysis of 112 European cases, classified by system type (see Table 14 in the Supplemental Materials). To support this process, 2800 entries were collected, describing the 25 parameters considered in the AHP for each European case. These entries were sourced from literature and web documentation (Britpave, 2004; BRTDATA, 2023; COM - The European Commission, 2019, 2023; Durkan et al., 2000; ITDP - Institute for Transportation & Development Policy, 2023; Kuhn & An, 2008; NACTO - North American cities and transit agencies, 2016; NACTO - North American cities and transit agencies, 2023; The European Union - EUROSTAT, 2023). Data collection was affected by heterogeneity in the implementation years of the European systems examined, posing challenges to ensuring temporal consistency across the sample. To address this issue, a minimum implementation year was defined, and only systems introduced from 2000 onwards were included in the analysis. As a result, several adjustments were required. First, all date-sensitive information was normalized by applying financial equivalence methods to capital-related data, ensuring comparability across systems implemented in different years. Second, within each group of cases belonging to the same system type, data validity was assessed by evaluating “attention limits” using the ±3-sigma method. This procedure established upper and lower bounds around the overall mean to exclude atypical values for each parameter considered. Following this filtering process, the final dataset consisted of 97 case studies. The average values and variability ranges for each parameter in this dataset are shown in Fig. 7 of the Supplemental Materials.

To account for the uncertainty in performance estimates induced by variability, the analysis was carried out under the following three scenarios:

- Maximum values: For each criterion, the maximum values of the range were taken, whether the criterion was a cost or a benefit.
- Favourable situation: For each criterion, the limit value of the interval that maximises the cost-effectiveness of the corresponding alternative is selected; that is, the minimum value for costs and the maximum value for benefits.
- Average scenario: For each criterion, the average value within the corresponding interval is selected.
- Unfavourable situation: For each criterion, the limit value of the interval that minimises the cost-effectiveness of the corresponding alternative is selected; that is, the minimum value for benefits and the maximum for costs.
- Minimum values: For each criterion, the minimum values of the range were taken, whether the criterion was a cost or a benefit.

The performance values for each scenario are presented in Tables 15–19 of the Supplemental Materials.

Subsequently, performance values were converted into utility values using eq. (1). However, if the performances associated with any criterion were qualitative, eq. (1) could not be applied; in such cases, the utility interval [0;1] was discretised by assigning a value 1 to the most favourable performance, 0 to the least favourable, and intermediate values to the remaining performances.

After normalising all utility values (eq. (2)), the WGS was computed for each scenario using eq. (3). Results for each scenario are shown in Table 2. Rail-based alternatives (LM, TRT, and TT) clearly dominate the ranking, consistently occupying the top positions across all five analysed scenarios (maximum, favourable, average, unfavourable, and minimum). Among these, LM achieves the highest scores in the most favourable scenarios, likely due to its strongest functional performance and the highest level of integration with the surrounding urban context; however, its substantial capital costs and lengthy construction times pose significant limitations to its overall feasibility. Conversely, TRT emerges as the preferred solution under the most constrained conditions. By recording the best values in unfavourable or minimal scenarios and never falling below the second position, the TRT demonstrates limited ranking volatility despite wide variations in input performance values. This consistency across diverse operational contexts provides a quantitative indication of ranking robustness, confirming that the relative ordering of the alternatives is highly resilient to plausible variations in input assumptions.

It should be noted that the resulting rankings are directly influenced by the weight structure derived from the AHP analysis, which reflects stakeholders' priorities. In particular, the relatively greater importance assigned to criteria related to transport–land use integration and system performance would tend to favour solutions that ensure both territorial accessibility and operational effectiveness. At the same time, criteria related to investment costs and implementation time could limit the use of more capital-intensive options, such as fully grade-separated rail systems.

Systems with characteristics comparable to LM, particularly TRT and TT, therefore, emerge as plausible alternatives, especially in suburban contexts where full metro standards may not be justified. However, it should be noted that the relatively low costs and short implementation times often associated with TT systems are largely related to the conversion of existing, disused railway or tramway corridors. Since such pre-existing infrastructure is not available in the present study context, these typical advantages of TT solutions would not be fully replicable. Given these considerations, the TRT emerges as the most appropriate and feasible solution for the study area's specific conditions.

Interestingly, the preference for TRT contrasts with findings from other MCA studies conducted in urban contexts, which typically favour bus-based or light rail systems (Awasthi et al., 2018; Hamurcu & Eren, 2020; Lambas et al., 2017; Lee, 2018). However, in this case study, the area spans both urbanised and extra-urban sections. This creates a particularly demanding configuration, as the system must simultaneously integrate with the urban fabric while meeting corridor-wide requirements for higher commercial speeds and stringent right-of-way

Table 2
Results for MTSs ranking.

System	Average scenario	Maximum values	Minimum values	Unfavourable situation	Favourable situation
Busway (B)	10.86	11.30	12.26	11.17	11.90
Classic Tramway (C)	10.56	9.94	8.84	9.27	9.52
Guided Busway (GB)	11.99	12.14	9.41	9.83	11.33
Light Metro (LM)	18.12	19.31	15.12	12.51	22.12
Tramway Rapid Transit (TRT)	14.87	15.87	15.13	15.42	15.78
Tram on Rubber (ToR)	9.45	8.65	12.09	13.82	6.24
Tram-Train (TT)	14.48	14.11	14.02	14.37	15.14
Trolley Bus (TB)	9.68	8.67	13.11	13.61	7.98

constraints. Under these combined pressures, TRT emerges as a more suitable compromise. This reinforces the idea that technology ranking is inherently context-dependent, and that adopting uncertainty-aware scoring across multiple scenarios, rather than relying on single-point estimates, might provide a more robust and reliable assessment.

Although the proposed framework is not intended to validate any specific MCA method, the results across different performance scenarios provide an initial assessment of the decision structure's robustness. Rail-based systems consistently occupy the highest-ranking positions, suggesting limited volatility under moderate variations in assumptions. At the same time, some ranking changes between LM, TRT, and TT confirm the sensitivity of results to weighting structures and performance variability. Rather than a limitation, this reflects the framework's purpose: to transparently show how stakeholder priorities and uncertain early-stage assumptions influence the decision-making process.

4.3. *Optimal route in the case study*

4.3.1. *Routes alternatives*

According to STEP 4, a set of different routes (R) compatible with a TRT was identified. These alignment options were developed through close consultation with local political decision-makers and transport authorities involved. The selection process considered key requirements, including ensuring a fully segregated, safe right-of-way; achieving competitive commercial speeds through appropriate geometric standards; siting stops to intercept major demand nodes; and controlling construction costs in the most constrained sections of the corridor.

This process led to the identification of three TRT-compatible routes (Fig. 3): Route 1, which minimises construction costs; Route 2, which maximises the directly served population; and Route 3, which represents a compromise between the previous two. Notably, the track on Route 3 runs largely underground due to the high concentration of residential and commercial buildings. This is essential to position stations as close as possible to the highest number of users.

The plans for the proposed routes are shown in greater detail in Figs. 8–10 of the Supplemental Materials.

4.3.2. *Recalibration of decision criteria and weights*

According to STEP 5, not all parameters listed in Table 1 are relevant to the route selection process. This is because some of them are specific to an MTS and do not vary with the route. Hence, in the case study, STEP 5 considers a subset of five of the twenty-five initial parameters, using the same importance weights calculated in STEP 2 but renormalised according to eq. (4). These five parameters (Γ^{Ph2}), along with respective weights ($\overline{W}^{Ph2}$), are shown in Table 3.

Table 3
Parameters and weights for route ranking.

Parameter	Weight from STEP 2	Renormalized Weight (eq. (4))
(directly) Served population (n°)	0.070	0.287
Construction cost (€)	0.034	0.139
Design and construction time (y)	0.046	0.189
O&M (€/y)	0.073	0.299
Visual intrusion [–]	0.021	0.086

Table 4
Annual service kilometrage and estimated operation and maintenance (O&M) costs for the three routes.

Route	Annual service kilometrage (train·Mkm/year)	Marginal production cost (€/train·km) (Sinha & Labi, 2011).	O&M costs (M€/year)
Route 1	1.258	7.06	8.88
Route 2	1.278	7.06	9.02
Route 3	1.266	7.06	8.94

4.3.3. *Routes ranking*

According to STEP 6, a new decision matrix was compiled to apply WSM (eqs. (1)–(3)) and determine the optimal route among the alternatives. Unlike in Phase 1, the performance values in Phase 2 can be estimated with greater accuracy because the MTS is known. This paragraph describes the procedure for defining each performance value.

The directly served population is the number of people who can reach a TRT stop within a 10-min walk, i.e., those living within a 500-m radius[4] of a stop. This estimate was based on population census data from ISTAT (2022). These data divide the territory into zones (census sections), assigning a specific population to each. By overlaying these data within a Geographic Information System (GIS) software, it was possible to calculate the population living within 500 m of the TRT stops.

Construction costs were estimated using an aggregate parametric approach. First, the projects were subdivided into 19 items, each associated with an average unit cost derived from the literature (Baumgartner, 2001; Spinosa, 2022). All unit costs were updated to 2023 using official data from the Italian National Institute of Statistics. Total construction costs for each route were then obtained by multiplying the updated unit costs by the corresponding quantities derived from the route design (e.g., track length, number of stations or stops, number of vehicles). The detailed results are reported Table 21 (Supplemental Materials). The estimated unit investment costs (33 M€/km, 92 M€/km, and 73 M€/km for Routes 1, 2, and 3, respectively) are broadly consistent with values found in the technical literature (e.g., Sinha & Labi, 2011). Although Routes 2 and 3 exhibit higher costs than the preliminary Phase-1 estimates, this difference is largely explained by their characteristics, particularly the high share of underground alignment, which makes them more comparable to a Light Rail Transit system than to a TRT.

The same procedure was applied to estimate the design and

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[4] Computed assuming a pedestrian speed of 3 km/h.

Table 5
Decision matrix for route ranking.

Criterion	Normalized Weight	Route 1	Route 2	Route 3
Construction cost [M€]	0.139	722.08	2′046.07	1′595.06
Design and construction time [y]	0.189	5	6.5	5.5
O&M costs (M€/y)	0.299	8.88	9.02	8.94
(directly) Served population [#]	0.287	4′923	27′077	21′121
Landscape Impact [−]	0.086	High	Low	Medium

construction durations according to similar and already implemented projects (Eno Center for Transportation, 2022). This required creating an operating schedule that accounted for daily demand fluctuations.

Operational and maintenance costs were estimated according to a preliminary service schedule (Table 4). The schedule was developed using key parameters, including total route length, vehicle capacity, and preliminary demand estimates derived from the directly served population parameter. For each time band, the analysis determined the required service frequency and the number of vehicles needed to maintain acceptable occupancy levels, ensuring the load factor remained below a predefined threshold (80% according to specific quality criteria, such as those proposed by the European Committee for Standardisation Technical Committee (CEN/TC 320, 2002, 2006) and by Barabino and Di Francesco (2016)). Operating hours were set from 05:00 to 24:00, with service frequencies ranging from 2 trains per hour during off-peak periods to 12 trains per hour during peak periods.

Finally, with respect to landscape impact, Route 2, which is almost entirely underground, has the least impact on the surrounding environment. Conversely, Route 1, which is predominantly above-ground, has the greatest impact, while Route 3 represents a compromise between the two, given its mixed characteristics.

Table 5 summarises the performance values.

Applying equations from (1) to (3) to Table 5, Route 1 emerged as the optimal (best compromise) solution for the case study, as shown in Table 6.

The preference for Route 1, despite serving fewer residents than other alternatives, reflects the strong weight of O&M and construction costs, and penalties associated with extensive underground works, echoing evidence that excessive tunnelling often shifts projects toward light-metro cost structures without proportional gains. Although more complex alignments could provide greater coverage and accessibility, these benefits are offset by higher implementation costs. Consequently, the chosen solution strikes a better balance between functional performance and economic feasibility and aligns with the stakeholder priorities derived from the AHP weighting process.

4.4. *Economic analysis in the case study*

According to phase 3, a CBA was conducted to assess the economic sustainability of the solution identified in the previous two phases. At this stage, the analysis benefits from the progressive reduction of the solution space achieved in phases 1 and 2. The initial problem consists of 8 technological alternatives combined with 3 route configurations (i.e., up to 24 feasible technology–route combinations). Through the two MCA stages, this space is reduced to a single technology–route solution, which is then assessed through CBA. This enables the economic appraisal to focus directly on the most robust configuration identified upstream, ensuring consistency across the sequential decision process. The CBA was performed for the new TRT system, assuming an economic life of 30 years from the start of operations (i.e., 35 years when including design and construction time).

Table 6
Utility matrix and results for route ranking.

Criterion	Weight	Route 1	Route 2	Route 3
Construction cost [M€]	0.14	1.00	0.00	0.34
Design and construction time [y]	0.19	1.00	0.00	0.50
O&M costs [M€/y]	0.30	1.00	0.00	0.57
(directly) Served population [#]	0.29	0.00	1.00	0.73
Landscape Impact [−]	0.09	0.00	1.00	0.50
WGS		**62.70**	**37.30**	**56.55**
Rank		**1**	**3**	**2**

4.4.1. *Demand analysis*

According to STEP 7, the demand analysis was carried out.

First, the study area was defined and zoned as depicted in Fig. 4, including both the municipalities directly involved in implementing the new MTS and those that indirectly gravitate toward it.

Hence, since an advanced simulation transport model was not available for the study area, mainly due to budget constraints, travel demand was estimated using existing studies and straightforward spreadsheet-based simulation transport models.

Specifically, for the BAU scenario, the transport demand $D_{0,k}(t)$ in the study area was derived from the official Origin-Destination (O—D) matrix provided by the Lombardy Region for the reference year 2020[5] (Regione Lombardia, 2020). The main transport systems considered in this scenario are the extra-urban bus service (indicated as $bus \in K$), and private cars (indicated as $car \in K$).

For the Project Scenario, these two systems were supplemented by the new TRT system (indicated as $trt \in K$). The project demand $D_{1,k}(t)$ was estimated starting from the BAU baseline using spreadsheet-based models, accounting for shifted,[6] diverted,[7] and generated[8] demand components.

For both the BAU and Project Scenarios, the demands were projected from the reference year 2020 (to which the Lombardy O—D matrix refers) to a generic year $t \in T$ by applying a variation rate of 0.27%[9] for public transport systems (bus, TRT) and 0.00%[10] for private cars.

The resulting BAU and Project demands are presented in Table 7. For the sake of synthesis, only the data for the first year of TRT operation (i.e., $t = 6$) are reported in Table 7, while the annual demand trend for the entire operating period is illustrated in Fig. 5.

4.4.2. *Costs estimates*

As for STEP 8, both construction and operating/maintenance costs were already estimated in Phase 2 (see Table 5). However, clarification

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[5] These data are unaffected by the temporary decrease in transport demand caused by the COVID-19 pandemic.

[6] This corresponded to approximately 80% of the BAU extra-urban bus demand. This value is consistent with the logic of rationalizing the extra-urban bus service by eliminating roughly 80% of the runs on lines that partially or fully overlap with the TRT corridor.

[7] This corresponded to approximately 20% of the BAU private car demand. This is in line with diversion rates suggested by previous studies conducted in comparable contexts, as well as with the potentially high propensity for modal shift from private cars to the TRT, given the strong traffic congestion in the study area (De Aloe et al., 2023; Feudo & Festa, 2012).

[8] This corresponded to approximately 3% of total shifted and diverted demand. This value aligns with the guidance provided by the European Commission (COM - The European Commission, 2014) for the “Urban Transport” case study, conservatively reduced from 5% to 3% to reflect the high building density in the area, which may partially limit the development of new residential, industrial, or commercial settlements along the proposed TRT route.

[9] The 0.27% rate was derived from the historical trend of the provincial bus fleet between 2000 and 2022 (Automobile Club d'Italia (ACI), 2024).

[10] The 0.00% rate was assumed conservatively to reflect saturation in densely urbanised areas, despite a historical growth of approximately 0.44% (Automobile Club d'Italia (ACI), 2024).

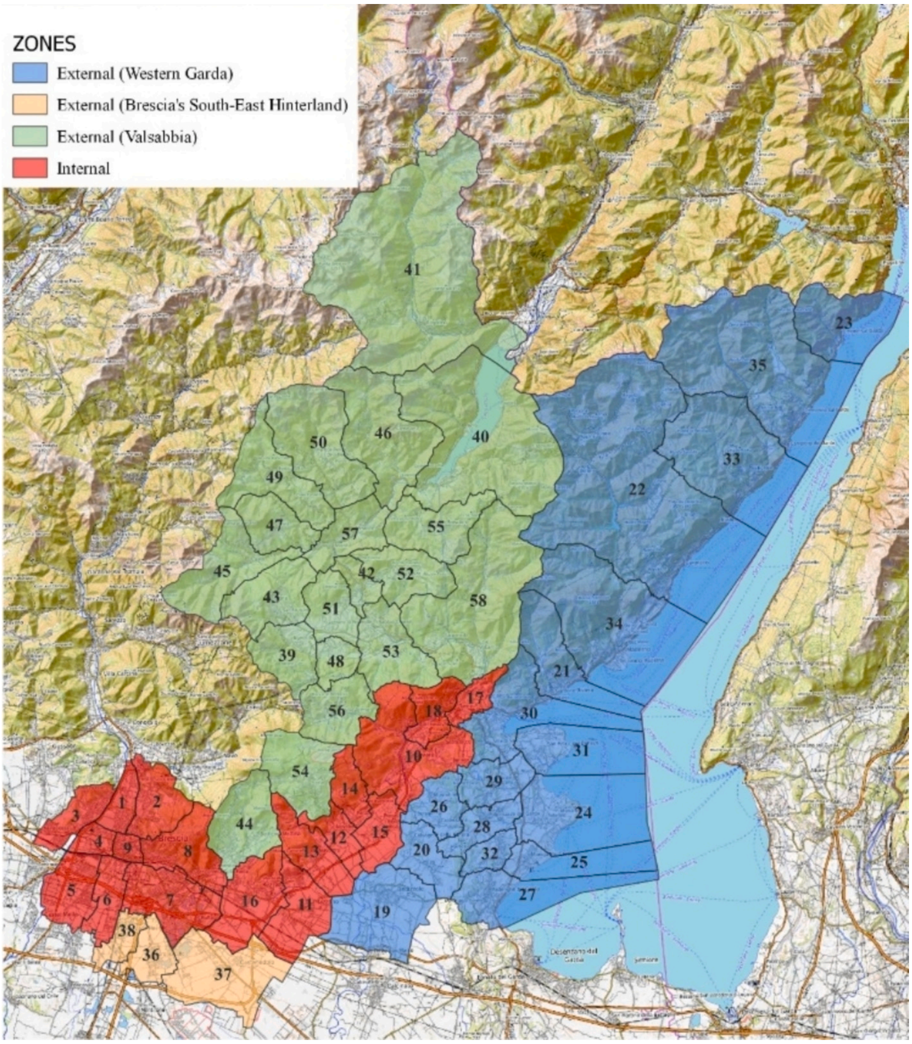


Fig. 4. Traffic Analysis Zones of the study area. The numbers inside each area represent their IDs. For more details, please refer to Table 20 in Supplemental Materials.

Table 7
Results of the demand estimation for the BAU and Project Scenarios for the first year of operation of the TRT (i.e., t = 6).

Component	Symbol	Value [pax/year]
BAU Scenario		
Demand on extra-urban bus	$D_{0,bus}(6)$	7′336’086
Demand on private car	$D_{0,car}(6)$	23′577’940
Project Scenario		
Demand on extra-urban bus	$D_{1,bus}(6)$	1′467’217
Demand on private car	$D_{1,car}(6)$	18′862’352
Demand on TRT	$D_{1,trt}(6)$	10′911’811
Of which shifted from extra-urban bus	$\boldsymbol{D_{D/S,bus}(6)}$	**5′868’869**
Of which diverted from private car	$\boldsymbol{D_{D/S,car}(6)}$	**4′715’588**
Of which generated	$\boldsymbol{D_{G,trt}(6)}$	**327’354**

Demand for each system and scenario is distributed by trip purpose as follows: systematic trips (work and study) account for 66%, while non-systematic (e.g., leisure) trips account for 34% (Regione Lombardia, 2020).

is needed in Phase 3, as outlined below.

Regarding construction costs, they are not evenly distributed over the construction period, as they depend on the chronological sequence of works. For this reason, a preliminary work schedule was hypothesised, drawing on similar projects already planned and/or implemented (e.g., Table 14 in Supplemental Materials), and construction costs were allocated accordingly (Table 8). This allocation was crucial for deriving a more accurate estimate of the discounted cost, as it accounts for the temporal distribution of expenditures and the effect of the social discount rate.

Regarding O&M costs, it was assumed that the TRT would begin operations only after construction was completed. Therefore, O&M costs were considered only from year 6 to year 35. The value of €8.88 M€/year (estimated in Phase 2), which refers to the first year of TRT operation, was progressively increased in subsequent years to account for the expected rise in service production to meet growing demand. Table 9 shows the trend of O&M costs.

4.4.3. *Benefits estimates*

According to STEP 9, the benefits were estimated as follows.

First, to estimate the benefits resulting from the implementation of the new TRT, the unit values presented in Table 10 were assumed, and all monetary values were updated to 2023 using ISTAT data.

Although Table 10 is largely self-explanatory, certain components require further clarification.

The commercial speed of the TRT was determined by analysing the motion law of vehicles along the planned alignment, accounting for its specific characteristics such as the dedicated track and the distance between stations. For simplicity, vehicle movements between two consecutive stops were modelled using a trapezoidal speed profile

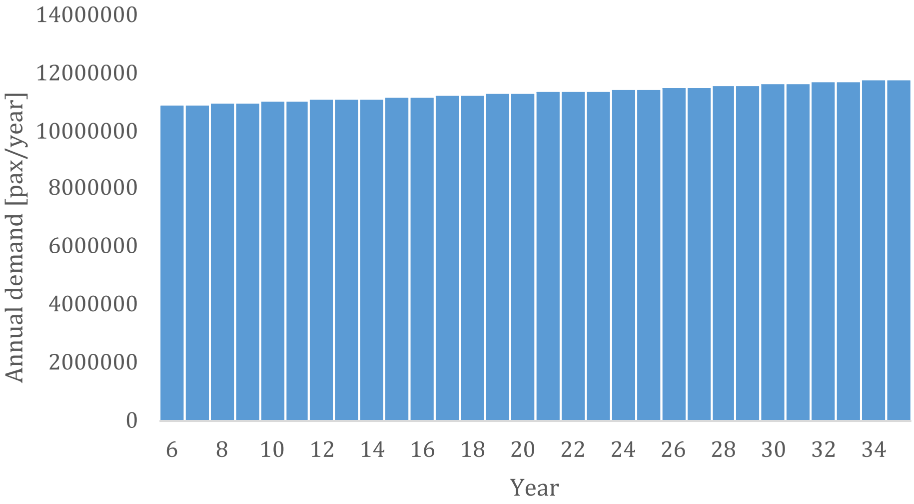


Fig. 5. Trend of the annual demand on the TRT system in the Project Scenario.

Table 8
Temporal allocation of construction costs.

	Year					
Item	1	2	3	4	5	Total
General costs [M€]	15.88	10.34	10.34	10.34	10.34	**57.22**
Civil works [M€]	0.00	73.00	174.39	174.39	60.69	**482.48**
Electro-tramway systems [M€]	0.00	0.00	2.50	24.96	24.96	**52.41**
Vehicles [M€]	0.00	0.00	0.00	0.00	37.34	**37.34**
Other available founds [M€]	25.70	16.73	16.73	16.73	16.73	**92.63**
Total [M€]	**41.58**	**100.07**	**203.96**	**226.42**	**150.05**	**722.08**
Cost allocation [%]	**5.8%**	**13.9%**	**28.2%**	**31.4%**	**20.8%**	**100.0%**

comprising three phases: acceleration, constant cruising speed, and braking. A fourth phase was then added to represent the dwell time at stations for passenger boarding and alighting. The resulting commercial speed of approximately 46 km/h may initially appear high for a TRT system. However, this outcome is a direct consequence of the large radii of curvature and high station spacing adopted during the design phase. These choices were made with the specific aim of maximising commercial speed to enhance the system's attractiveness, which primarily serves an extra-urban context.

The economic value of travel time was determined by the purpose of the trip. According to the Italian Ministry of Infrastructure and Sustainable Mobility (2022), travel time has different unit values depending on whether it relates to systematic trips such as study and work, business trips, or other purposes, with respective values of 7.823 €/(pax h), 16.688 €/(pax h), and 10.430 €/(pax h). By averaging these values according to the trip-purpose distribution shown in Table 7, the resulting average unit value of travel time is 12.604 €/(pax·h).

As for the marginal fare of the TRT, the value of 0.10 €/(pax km) was a design choice, considering that the current marginal fare for the extra-urban bus system in the study area is approximately 0.071 €/(pax h). Due to the expected higher quality of service offered by a rail system on dedicated tracks compared to a shared-road bus system, charging a slightly higher fare for TRT users was deemed reasonable. Based on an average trip length of 19.06 km, this translates to an approximate ticket price of €1.90 per passenger.

Finally, externalities from fixed electric traction systems were considered negligible, in accordance with the Italian Ministry of Infrastructure and Sustainable Mobility (2022).

Using the demand values from STEP 7 and the unit values in Table 10, eqs. (10)–(18) were applied to calculate annual benefits for each stakeholder category. A summary of these results is presented in

Table 9
Trend of O&M costs.

Year	Service production [(veh*km)/year]	Marginal cost [€/(veh*km)]	Total cost [M€/year]	Year	Service production [(veh*km)/year]	Marginal cost [€/(veh*km)]	Total cost [M€/year]
6	1’257’791	7.06	8.88	21	1’309’706	7.06	9.25
7	1’261’187	7.06	8.91	22	1’313’242	7.06	9.27
8	1’264’592	7.06	8.93	23	1’316’787	7.06	9.30
9	1’268’006	7.06	8.95	24	1’320’343	7.06	9.32
10	1’271’430	7.06	8.98	25	1’323’908	7.06	9.35
11	1’274’863	7.06	9.00	26	1’327’482	7.06	9.37
12	1’278’305	7.06	9.03	27	1’331’066	7.06	9.40
13	1’281’757	7.06	9.05	28	1’334’660	7.06	9.43
14	1’285’217	7.06	9.08	29	1’338’264	7.06	9.45
15	1’288’687	7.06	9.10	30	1’341’877	7.06	9.48
16	1’292’167	7.06	9.13	31	1’345’500	7.06	9.50
17	1’295’656	7.06	9.15	32	1’349’133	7.06	9.53
18	1’299’154	7.06	9.17	33	1’352’776	7.06	9.55
19	1’302’662	7.06	9.20	34	1’356’428	7.06	9.58
20	1’306’179	7.06	9.22	35	1’360’091	7.06	9.60

Table 10

Unit values used in the computation of benefits.

Variable	Symbol	Unit	Value	Source
Avg. trip length	$L_{0,\mathrm{k}}, L_{1,\mathrm{k}}$	Km	19.06	Estimated from Regione Lombardia, 2020
Commercial speed (extra-urban bus)	$\nu_{0,\mathrm{bus}}, \nu_{1,\mathrm{bus}}$	km/h	30	Estimated from (Brescia Local Public Transport Agency, 2019)
Commercial speed (car)	$\nu_{0,\mathrm{car}}, \nu_{1,\mathrm{car}}$	km/h	30	Google Maps® journey times for multiple routes in the study area
Commercial speed (TRT)	$\nu_{1,\mathrm{TRT}}$	km/h	46	Computed design value
Marginal value of time (all systems)	$\tau_{0,k}, \tau_{1,k}$	€/(pax · h)	12.604	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal VOC for users (car)	$\zeta_{0,\mathrm{car}}, \zeta_{1,\mathrm{car}}$	€/(pax · km)	0.276	(Italian Ministry of Infrastructure and Transport, 2019)
Marginal operating cost for TA/PTO (extra-urban bus)	$\xi_{0,\mathrm{bus}}, \xi_{1,\mathrm{bus}}$	€/(bus · km)	4.633	(Brescia Local Public Transport Agency, 2019)
Marginal operating cost for TA/PTO (TRT)	$\xi_{1,\mathrm{TRT}}$	€/(train · km)	7.062	Computed in section 4.4.2
Marginal fare (extra-urban bus)	$\varphi_{0,\mathrm{bus}}$, $\varphi_{1,\mathrm{bus}}$	€/(pax · km)	0.071	(Brescia Local Public Transport Agency, 2019)
Marginal fares (TRT)	$\varphi_{0,\mathrm{TRT}}$, $\varphi_{1,\mathrm{TRT}}$	€/(pax · km)	0.100	Design value
Avg. occupation coefficient (extra-urban bus)	$\omega_{0,\mathrm{bus}}$, $\omega_{1,\mathrm{bus}}$	pax/bus	23.11	Regione Lombardia, 2020 and (Brescia Local Public Transport Agency, 2019)
Avg. occupation coefficient (car)	$\omega_{0,\mathrm{car}}$, $\omega_{1,\mathrm{car}}$	pax/car	1.231	Regione Lombardia, 2020
Avg. occupation coefficient (TRT)	$\omega_{0,\mathrm{TRT}}$, $\omega_{1,\mathrm{TRT}}$	pax/train	189.21	Project demand and service production
Marginal cost of road crashes (extra-urban bus)	$\mu_{crash,0,bus}$, $\mu_{crash,1,bus}$	€/(bus · km)	0.050	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of road crashes (car)	$\mu_{crash,0,car}$, $\mu_{crash,1,car}$	€/(car · km)	0.008	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of road crashes (TRT)	$\mu_{crash,1,TRT}$	€/(train · km)	0.000	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of polluting emissions (extra-urban bus)	$\mu_{poll,0,bus}$, $\mu_{poll,1,bus}$	€/(bus · km)	0.053	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of polluting emissions (car)	$\mu_{poll,0,car}$, $\mu_{poll,1,car}$	€/(car · km)	0.008	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of polluting emissions (TRT)	$\mu_{poll,0,TRT}$, $\mu_{poll,1,TRT}$	€/(train · km)	0.000	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of acoustic emissions (extra-urban bus)	$\mu_{aco,0,bus}$, $\mu_{aco,1,bus}$	€/(bus · km)	0.056	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of acoustic emissions (car)	$\mu_{aco,0,car}$, $\mu_{aco,1,car}$	€/(car · km)	0.012	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of acoustic emissions (TRT)	$\mu_{aco,0,TRT}$, $\mu_{aco,1,TRT}$	€/(train · km)	0.000	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of CO2 emissions (extra-urban bus)	$\mu_{co2,0,bus}$, $\mu_{co2,1,bus}$	€/(bus · km)	0.131	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of CO2 emissions (car)	$\mu_{co2,0,car}$, $\mu_{co2,1,car}$	€/(car · km)	0.030	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)
Marginal cost of CO2 emissions (TRT)	$\mu_{co2,0,TRT}$, $\mu_{co2,1,TRT}$	€/(train · km)	0.000	(Italian Ministry of Infrastructure and Sustainable Mobility, 2022)

Table 11

Summary of annual benefits.

Beneficiary	Benefit description	Symbol	Value (M€/year)
Users	Change in travel time	$B_{US,TIME}(6)$	15.2
	Change in fares	$B_{US,FARES}(6)$	−6.43
	Change in VOC	$B_{US,VOC}(6)$	12.4
TA/PTO	Change in fares	$B_{TA/PTO,FARES}(6)$	12.86
	Change in operating costs	$B_{TA/PTO,OC}(6)$	22.43
Non-users	Reduction in road crash	$B_{CRASH}(6)$	0.84
	Reduction in polluting emissions	$B_{POLL}(6)$	0.85
	Reduction in acoustic emissions	$B_{ACO}(6)$	1.12
	Reduction in CO2 emissions	$B_{CO2}(6)$	2.83
TOTAL		$\boldsymbol{B}(\mathbf{6})$	62.10

Table 11. For conciseness, only the data for the first year of TRT operation (i.e., $t = 6$) are shown here; the benefits for the entire operating period are provided in Table 22 in the Supplemental Materials.

The benefit pattern emerging from Table 11 mirrors international evidence. The most distinctive result is that the largest benefit category concerns the reduction of TA/PTO operating costs (22.43 M€/year). This reflects the rationalisation effects of high-capacity transit systems, in which the replacement or restructuring of conventional bus services can generate substantial operating cost savings (Grimaldi et al., 2010; Guerrieri, 2019; Popovic et al., 2012; Prud'homme et al., 2011).

User-side benefits follow established patterns. Travel-time savings (15.2 M€/year) represent the main gain, driven by improvements in speed and reliability, long recognised as primary contributors to user welfare (Litman, 2009; Siciliano et al., 2016). Reductions in private-vehicle operating costs (12.4 M€/year) are consistent with expected savings under modal diversion. The negative fare effect (−6.43 M€/year) reflects the redistribution of welfare between users and operators when fare adjustments occur (e.g., Litman, 2009).

Safety-related benefits amount to 0.84 M€/year. The result is consistent with international evidence, suggesting that safety gains would generally increase with reductions in private-car travel; yet their relative weight may still appear limited when other benefit categories are substantially larger (e.g., Holtzclaw, 2002; Litman, 2009).

Environmental and acoustic externalities (pollutant emissions, noise, and CO₂) amount to approximately 4.8 M€/year. Rather than signalling negligible effects, this figure suggests that these benefits are simply overshadowed by the much larger operator- and user-side gains.

Table 12
Cost Benefit Analysis results.

Indicator	Unit	Value
ENPV	M€	+ 213.95
EIRR	%	+ 4.95
EBCR	[−]	+ 1.226

4.4.4. *Economic indicators and CBA results*

According to STEP 10, the economic indicators were computed using eqs. (19) to (21), with an analysis period T of 35 years, including 5 years for designing and construction (i.e., $\widetilde{t} = 5$) and 30 years of economic life for the system. The social discount rate ρ was assumed to be 3% (COM - The European Commission, 2014; Italian Ministry of Infrastructure and Sustainable Mobility, 2022). The initial investment costs I(t) were allocated as shown in Table 8 for years 1 to 5. Finally, the operating costs and benefits were considered, as reported in Tables 9 and 11, respectively, for years 6 to 35. The results are summarised in Table 12.

The economic indicators support the project's financial sustainability. An ENPV of about 214 M€, an EBCR well above unity, and an EIRR of 4.95%, exceeding the 3% discount rate, demonstrate that the investment is economically viable with a reasonable margin. These results comply with international guidelines for transport projects (COM - The European Commission, 2014; Sinha & Labi, 2011) and align with findings from comparable CBA studies on rail-based systems (De Aloe et al., 2023; Ventura et al., 2022).

4.4.5. *Sensitivity analysis*

Next, in accordance with STEP 11, the robustness of the project's economic sustainability was assessed using sensitivity analysis. The procedure follows the one-factor-at-a-time approach described in the methodological framework, in which each input variable is varied independently by ±1% from its base-case value while holding all other variables constant, and the corresponding change in ENPV is computed. Based on this, critical variables are identified, and for each of them, the corresponding switching value is determined, representing the threshold at which the ENPV becomes zero.

The set of variables influencing the ENPV (X) was identified in a disaggregated form. This set includes parameters related to both BAU and project demand, route characteristics (e.g., length and investment costs), and all unit values used to estimate benefits as defined in Step 9. For each variable, the percentage change in ENPV resulting from a ± 1% perturbation was compared with the ±1% threshold (eq. (22)), leading to the identification of 15 critical variables (X_{crit}) (Table 13).

The results indicate that ENPV is primarily sensitive to demand-related variables and investment cost parameters, as reflected in the magnitude of the resulting variations. Under a positive (+1%) variation in the input variable, the highest positive impacts are associated with the baseline demand for extra-urban bus and private car, as well as with the average trip length (all +4.35% on ENPV). The strongest negative influence stems from the length of the TRT route and its investment cost (both −3.35% on ENPV). Operational parameters such as commercial speed also exert a non-negligible influence, ranging from approximately −2% to +2.3% depending on the transport system, with negative effects for existing modes and positive effects for the TRT. Conversely, environmental externalities and marginal fare variations have minimal impact (consistently below 1% in absolute terms), indicating comparatively low relevance in the overall economic balance. The prominence of baseline demand, marginal investment cost, and route length as critical variables aligns with CBA guidelines and prior rail-based studies, which consistently identify demand and capital expenditure as dominant drivers of economic sensitivity (COM - The European Commission, 2014;

Table 13
Sensitivity analysis: identification of the critical variables and related switching values. The values in the column "ENPV Variation" correspond to a + 1% change in each variable. A − 1% change produces an effect of equal magnitude but opposite sign.

Variable	Symbol	Unit	ENPV Variation	Critical variable?	Switching value
BAU demand on extra-urban bus	$D_{0,bus}(\mathrm{t})$	pax/year	+4.35%	Yes	−23.00%
BAU demand on private car	$D_{0,car}(\mathrm{t})$	pax/year	+4.35%	Yes	−23.00%
Project demand on TRT (shifted from extra-urban bus)	$D_{D/S,bus}(\mathrm{t})$	pax/year	+2.36%	Yes	−42.42%
Project demand on TRT (diverted from private car)	$D_{D/S,car}(\mathrm{t})$	pax/year	+1.95%	Yes	−51.30%
Project demand on TRT (generated)	$D_{G,trt}(\mathrm{t})$	pax/year	+0.04%	No	–
Length of the TRT route	l	km	−3.35%	Yes	+29.87%
Marginal investment cost of TRT	$\left(\sum_{t\in T:t\leq\tilde{t};} I(t)\right)/l$	M€/km	−3.35%	Yes	+29.87%
Avg. trip length	$L_{0,\mathrm{k}}, L_{1,\mathrm{k}}$	km	+4.35%	Yes	−23.00%
Commercial speed (extra-urban bus)	$v_{0,\mathrm{bus}}, v_{1,\mathrm{bus}}$	km/h	−2.01%	Yes	+97.35%
Commercial speed (car)	$v_{0,\mathrm{car}}, v_{1,\mathrm{car}}$	km/h	−1.53%	Yes	+184.23%
Commercial speed (TRT)	$v_{1,\mathrm{TRT}}$	km/h	+2.31%	Yes	−30.05%
Marginal value of time (all systems)	$\tau_{0,k}, \tau_{1,k}$	€/(pax · h)	+1.24%	Yes	−80.53%
Marginal VOC for users (car)	$\zeta_{0,\mathrm{car}}, \zeta_{1,\mathrm{car}}$	€/(pax · km)	+1.01%	Yes	−98.71%
Marginal operating cost for TA/PTO (extra-urban bus)	$\xi_{0,\mathrm{bus}}, \xi_{1,\mathrm{bus}}$	€/(bus · km)	+1.83%	Yes	−54.57%
Marginal operating cost for TA/PTO (TRT)	$\xi_{1,\mathrm{TRT}}$	€/(train · km)	−0.73%	No	–
Marginal fare (extra-urban bus)	$\varphi_{0,\mathrm{bus}}, \varphi_{1,\mathrm{bus}}$	€/(pax · km)	−0.32%	No	–
Marginal fares (TRT)	$\varphi_{0,\mathrm{TRT}}, \varphi_{1,\mathrm{TRT}}$	€/(pax · km)	+0.85%	No	–
Avg. occupation coefficient (extra-urban bus)	$\omega_{0,\mathrm{bus}}, \omega_{1,\mathrm{bus}}$	pax/bus	−1.93%	Yes	+105.58%
Avg. occupation coefficient (car)	$\omega_{0,\mathrm{car}}, \omega_{1,\mathrm{car}}$	pax/car	−1.35%	Yes	+278.31%
Avg. occupation coefficient (TRT)	$\omega_{0,\mathrm{TRT}}, \omega_{1,\mathrm{TRT}}$	pax/train	+0.72%	No	–
Marginal cost of road crashes (extra-urban bus)	$\mu_{crash,0,bus}, \mu_{crash,1,bus}$	€/(bus · km)	+0.02%	No	–
Marginal cost of road crashes (car)	$\mu_{crash,0,car}, \mu_{crash,1,car}$	€/(car · km)	+0.05%	No	–
Marginal cost of road crashes (TRT)	$\mu_{crash,1,TRT}$	€/(train · km)	0.00%	No	–
Marginal cost of polluting emissions (extra-urban bus)	$\mu_{poll,0,bus}, \mu_{poll,1,bus}$	€/(bus · km)	+0.02%	No	–
Marginal cost of polluting emissions (car)	$\mu_{poll,0,car}, \mu_{poll,1,car}$	€/(car · km)	+0.05%	No	–
Marginal cost of polluting emissions (TRT)	$\mu_{poll,0,TRT}, \mu_{poll,1,TRT}$	€/(train · km)	0.00%	No	–
Marginal cost of acoustic emissions (extra-urban bus)	$\mu_{aco,0,bus}, \mu_{aco,1,bus}$	€/(bus · km)	+0.02%	No	–
Marginal cost of acoustic emissions (car)	$\mu_{aco,0,car}, \mu_{aco,1,car}$	€/(car · km)	+0.07%	No	–
Marginal cost of acoustic emissions (TRT)	$\mu_{aco,0,TRT}, \mu_{aco,1,TRT}$	€/(train · km)	0.00%	No	–
Marginal cost of CO2 emissions (extra-urban bus)	$\mu_{co2,0,bus}, \mu_{co2,1,bus}$	€/(bus · km)	+0.23%	No	–
Marginal cost of CO2 emissions (car)	$\mu_{co2,0,car}, \mu_{co2,1,car}$	€/(car · km)	+0.23%	No	–
Marginal cost of CO2 emissions (TRT)	$\mu_{co2,0,TRT}, \mu_{co2,1,TRT}$	€/(train · km)	0.00%	No	–

Ventura et al., 2022).

Despite their importance, these variables would need to deviate substantially to compromise the project's economic sustainability. This is confirmed by the corresponding switching values, which quantify the variation required to reduce ENPV to zero. As shown by the results in Table 13, all *switch*(x) associated with the critical variables (computed using eq. (23)) are all well above 20% in absolute terms, suggesting a substantial margin of robustness. This result aligns with established evidence, where switching thresholds above ±20–30% are generally interpreted as substantial robustness margins and indicators of resilience to input uncertainty (COM - The European Commission, 2014; Ventura et al., 2022).

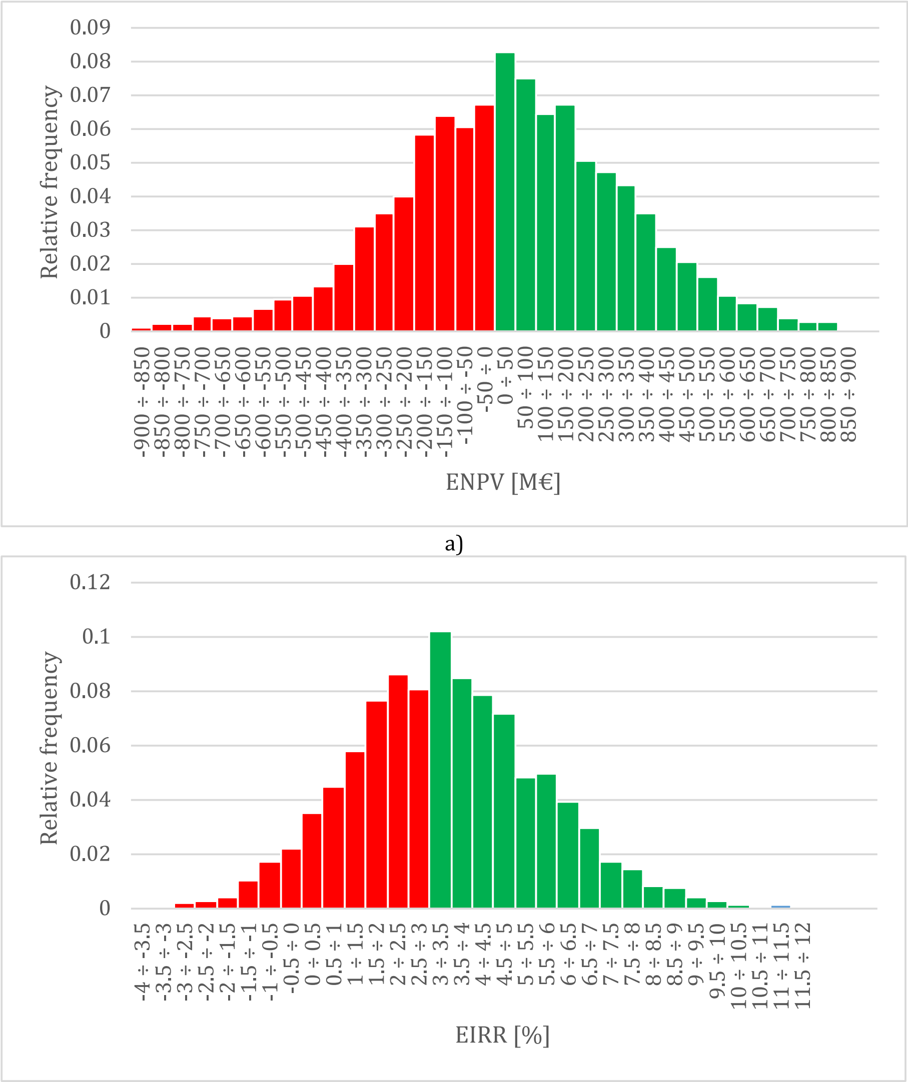
These findings help prioritise the focus of subsequent risk analysis efforts.

4.4.6. *Risk analysis*

Finally, the risk analysis (STEP 12) was performed to further assess the project's economic sustainability. Ideally, all X_{crit} variables should be included in this analysis. However, in practice (especially in a preliminary phase of MTS design), the available data often lack the granularity needed to model accurate probability distributions for every variable. Incorporating poorly defined distributions is not recommended, as it would compromise the reliability of the results. For this reason, the present case study focused on the five critical variables with the greatest impact on ENPV, namely: BAU demand for extra-urban buses, BAU demand for private cars, average trip length, marginal investment cost of TRT, and route length of TRT. This targeted selection ensured that the risk assessment remained both methodologically sound and produced robust, credible outcomes, while avoiding speculative assumptions that could have undermined decision-making.

Since, to the authors' knowledge, no studies have been conducted in Italy on the probability distributions of these variables, the required distributions (Ψ_x) were assigned as follows:

- BAU demand (bus and car): Gaussian distribution of variations around the base mean value (mean = 0%), with 99.7% of values between −50% and + 50% (std. dev. = 50%/3), following COM - The European Commission (2014) "*Railway Case Study*."
- Average trip length: Same Gaussian assumption as BAU demand (mean = 0%, std. dev. = 50%/3), by analogy with COM - The European Commission (2014) "*Railway Case Study*."
- Marginal investment cost: Empirical distribution based on Flyvbjerg et al. (2003), analysing 167 large-scale transport projects. Results



a)

b)

Fig. 6. Risk analysis. Relative frequency distributions for ENPV (a) and EIRR (b). Green bars indicate sustainable instances (ENPV > 0 and EIRR > ρ), while reed bars indicate the opposite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

show a right-skewed distribution with an average cost overrun of about +20% compared to initial estimates.

- Route length: Gaussian distribution with mean = 0% and 99.7% of values between −5% and + 5% (std. dev. = 5%/3), in analogy with demand and trip length variables, but assuming lower uncertainty due to the almost deterministic nature of such design variable.

The risk analysis was performed through 5000 Monte Carlo simulations (Θ) using equations from (24) to (26). The resulting frequency distributions of ENPV and EIRR are shown in Fig. 6. These indicate that the probability of economic sustainability (ENPV >0 and EIRR $> \rho$) is approximately 60%, confirming that the project solution coupling the TRT system with Route 1 is economically viable with a reasonable margin. These results underline the importance of incorporating stochastic analysis alongside deterministic approaches to capture variability. Ultimately, this provides decision-makers with a quantitative measure of the project's resilience under uncertainty, thereby clarifying potential risk exposure (COM - The European Commission, 2014).

5. Conclusions

Implementing a new Mass Transport System (MTS) is a complex process that requires multiple phases of preliminary planning. However, to the best of the authors' knowledge, the literature lacks empirical evidence that addresses the overall decision-making problem in all its aspects. Existing literature often treats the planning process in a fragmented manner, investigating only a single phase in isolation. Consequently, other crucial phases are either assumed or deferred to future research.

This paper addresses this gap by structuring and operationalising a unified three-phase decision-support framework. Rather than introducing new decision-making theories, the paper's main contribution is the systematic organization and integration of established evaluation methods into a sequential workflow. Specifically, multicriteria analysis (MCA) and cost–benefit analysis (CBA) are integrated into a single process to guide MTS technology and route selection and to verify their economic feasibility. Unlike approaches that rely exclusively on MCA or CBA, the proposed framework integrates the two methods, reducing the risk of selecting solutions that are technically attractive but economically unsustainable, and vice versa.

Specifically, the strength of this approach lies in the synergy between MCA and CBA. MCA enables the evaluation of heterogeneous criteria, including non-monetizable factors, while stakeholder involvement through Analytical Hierarchy Process (AHP) supports a transparent and context-sensitive weighting process. CBA complements this perspective by verifying the economic sustainability of the selected alternatives. Together, the two methods support a more comprehensive and operational evaluation process than approaches relying on a single assessment technique.

The overall framework was applied to the Brescia–Lake Garda area in Italy, where the analysis yielded several relevant findings beyond the methodological demonstration. The AHP-based weighting process highlighted the central role of long-term operational sustainability, with operation and maintenance costs emerging as the most influential criterion, followed by accessibility and multimodality. This result suggests that, in suburban and resource-constrained contexts, stakeholders tend to prioritise operational efficiency and network integration over purely technological performance. The MCA results consistently identified rail-based systems as the most competitive alternatives across the analysed scenarios. In particular, the Tramway Rapid Transit (TRT) emerged as the best compromise solution, showing strong robustness under both favourable and constrained conditions, while the Light Metro (LM), despite its superior functional performance, was penalised by higher investment costs and implementation complexity. Route 1 was identified as the preferred alignment due to its lower investment, operation and maintenance costs. Finally, the subsequent CBA confirmed the economic sustainability of the selected configuration, while sensitivity and Monte Carlo risk analyses highlighted the variables with the greatest influence on project feasibility and confirmed the relative robustness of the preferred solution under uncertainty conditions.

The framework has important practical implications for contexts where political authorities recognise the need for a new MTS but seek to identify the most suitable alternative through a systematic, objective process rather than through predefined design choices. In such cases, responsibility can be entrusted to a designated entity, whether a technical body, a consultant, or a multidisciplinary group, with the task of determining the optimal solution for the practical implementation of the project. By integrating MCA and CBA into a unified decision-making process, this approach ensures that technical, social, and economic dimensions are jointly considered, enabling decisions that are both context-sensitive and economically sustainable.

However, new challenges could be addressed in future studies. The framework requires, in both the MCA and CBA phases, a substantial amount of data, which are not always easy to retrieve from the literature, especially when considering innovative transport systems that have been recently introduced or are still poorly established. Consequently, new research aimed at building a comprehensive dataset of the technical and operational performance characteristics of a wide range of transport systems would be useful for supporting decision-making processes. In addition, the risk analysis phase highlights another critical need: defining more specific probability distributions for the most influential variables. Without robust and well-founded distributions, the accuracy of risk assessments may be reduced. Therefore, further research should focus on collecting empirical data and developing standardised approaches for modelling these distributions to strengthen the reliability of risk-based evaluations. Finally, a challenging future work should explore how to effectively integrate non-experts into transport decision-making processes, which have traditionally been dominated by experts. Attention should be given to fostering citizen participation, as it is expected to enhance transparency, legitimacy, and public acceptance that can complement expert-based evaluations (e.g., Rupprecht Consult, 2019; Cain et al., 2020; Linovski & Baker, 2023). Finally, the application to the Brescia case study also highlighted the importance of robustness analyses within the proposed framework. The combination of scenario-based MCA evaluation, sensitivity analysis, and probabilistic risk assessment enabled an examination of the stability of the preferred solution under different assumptions and levels of uncertainty. The results suggest that the framework can support not only the identification of preferred alternatives but also the assessment of how strongly such preferences depend on stakeholder priorities, performance variability, and economic assumptions. Future research may further extend this line of inquiry by systematically comparing rankings produced by alternative MCA methods within the same decision structure. In this respect, the proposed framework is modular and methodologically flexible, allowing alternative MCA techniques to be readily integrated without altering the overall decision-making logic.

Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve English language and readability. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

CRediT authorship contribution statement

Benedetto Barabino: Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization. **Davide Proserpio:** Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Roberto Ventura:** Writing – review & editing, Visualization, Validation, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors report there are no competing interests to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rtbm.2026.101730.

Data availability

The data that has been used is confidential.

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