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Prioritization of railway proximity interventions: The case of the Portuguese railway network

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ABSTRACT

The mission of a national railway administration is to provide conditions for the efficiency, competitiveness, and sustainability of rail transport. In this context, this study aims to fill a gap in rail infrastructure management through the adoption of multi-criteria decision analysis (MCDA) and quadrant analysis to obtain a priority evaluation matrix for railway proximity interventions (small-scale, medium/short-term interventions close to the customer). In order to achieve the network manager's general goals, an extensive collection of railway activities and an iterative procedure, which combines the strategic vision of different operational units, were adopted. Moreover, a multi-criteria and hierarchy process based on quadrant analysis to select the interventions with greater potential to achieve a set of objectives over five years, was defined. The proposed methodology was applied in a real case within the Infrastructures of Portugal, SA competencies and needs (Portuguese railway network manager). The identification of a set of fundamental interventions from a technical and non-technical point of view was performed and allowed a more efficient resource allocation. This allowed listing the most relevant interventions in both technical and non-technical perspectives (19–25% of total interventions) and also from an essentially technical point of view (27–31% of total interventions). These correspond to the interventions located in the two most relevant quadrants (Q1 – develop and Q2 – validate) and to more than 70% of the total investment. The presented approach and results constitute the first three iterations to be monitored and evaluated in the revision of future plans in order to increase reliability levels, safety conditions and service quality. The methodology has the potential to be adapted to different scenarios (in particular budgetary) and future proximity intervention plans, thus being an essential decision support tool for an efficient allocation of the company's resources.

1. Introduction and background

"Proximity interventions", a designation adopted by the manager of the Portuguese railway network, are small-scale interventions in the railway system with significant and immediate impact, aimed at strengthening safety conditions and improving the level of reliability and quality of the service provided to the customers of the Portuguese railway network.

The term "Proximity" is related to the scope of interventions referring to a medium/short-term plan (5 years) that defines a set of interventions aimed at overcoming difficulties close to the customer (user), complementing the major structuring interventions of railway investment plans. The Portuguese "Ferrovia 2020" (Infraestruturas de Portugal, 2016) and the 2030 National Investment Program (República Portuguesa, 2020) are examples of these plans.

These interventions are also intended to contribute to the improvement of the rail infrastructure integration in the surrounding territory, thus enhancing positive externalities and mitigating negative ones, as well as improving mobility conditions (travel times).

Bridges, tunnels, viaducts and buildings rehabilitation, slope stabilization, rehabilitation of railways tracks and the improvement of telecommunication systems are some examples of proximity interventions.

There is a considerable number of constraints (criteria) to be considered in the identification of the interventions to be performed.

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This evidences the importance of implementing a multi-criteria analysis (MCA) methodology for the definition of intervention priorities.

MCA models have a well-established record of providing robust and effective support to decision-makers working on a range of problems and circumstances overcoming obstacles with a discrete set of options (Department for Communities and Local Government, 2009).

MCA techniques usually provide an explicit relative weighting system for the different criteria considered in a given complex problem and can be used to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or to distinguish acceptable from unacceptable possibilities (Caetano et al., 2018; Department for Communities and Local Government, 2009). One of its main advantages is that it allows quantifying quantitative and qualitative criteria, not necessarily in monetary terms, in order to incorporate not only economic but also environmental, technical, spatial and social aspects (Barfod and Leleur, 2014; Caetano et al., 2018; Couto et al., 2018; Department for Communities and Local Government, 2009; Fernandes and Pacheco, 2007; Kosijer et al., 2020; Macharis and Bernardini, 2015; Stoilova et al., 2020; Yücel and Tasąbat, 2019). On the other hand, the criteria weighting and the wide variety of different data are pointed out as the two main limitations due to the subjectivity of the expert or group of experts involved in structuring the process (Aldian and Taylor, 2005). Determining each criteria weight requires much responsibility and expertise as the weights have a considerable influence on the assessment results (Barfod and Leleur, 2014).

Cost Benefit Analysis (CBA) has also been applied in the evaluation of transportation investments and is used to summarize the overall value of a project taking only into account monetary values. In this approach benefits and costs are expressed in money terms, and are adjusted for the time value of money to be expressed on a common basis in terms of their discounted present values (Morgan et al., 2012).

Specifically, a CBA measures the value of quantified and monetized benefits and costs to society, such as: travel time or delay, crashes, and externalities (e.g., emissions). This quantification and monetization of benefits and costs are complex to define and involve the definition and availability of data sources, assumptions, calculation and forecast methods, sensitivity analyses, and unit monetary values. Consequently, standardized and generally acceptable methodology to accurately validate how valuable is a rail infrastructure benefit has yet to be fully developed (Protopapas et al., 2012). According to Protopapas et al. (2012), the CBA complex nature along with the use of advanced calculations and modelling techniques can be a challenge to stakeholders, mainly to understand the process.

In CBA analysis the benefit-cost ratio often serves as a base for rating and prioritization purposes, along with legislative, project management assessment and user benefits priorities (Marcelo et al., 2016; Washington State Department of Transportation, 2008).

According to Yannis et al. (2020) and Yücel and Tasąbat (2019), MCA techniques lead to better-considered, justifiable and explainable decisions when compared to traditional Cost-Benefit Analysis since they allow conflicting and contradictory views and non-economic criteria to be addressed simultaneously and transparently. They also help to organize, manage and simplify the amount of available technical information and allow process modifications at a further stage, if the options considered or the data provided, are not adequate.

When MCA techniques are used for the assessment of different alternatives, in which several points of view and priorities are taken into account to produce a common output for individuals or groups, to rank, select and/or compare the alternatives considered (e.g., products, technologies, policies or, in this case, railway interventions), the MCA can be considered as Multi-criteria Decision Analysis (MCDA) (Barfod and Leleur, 2014; Belton and Stewart, 2002).

Numerous techniques can be applied to conduct a MCDA. According to several authors (Barfod and Leleur, 2014; Broniewicz and Ogrodnik, 2020; Caetano et al., 2018; Department for Communities and Local Government, 2009; Macharis and Bernardini, 2015; Morfoulaki and Papathanasiou, 2021; Yannis et al., 2020), the most widespread methods used in the field of transport are simple additive weighting (SAW), multi-attribute theory variants (AHP - Analytic hierarchy process, ANP - Analytic network process, MAUT – Multi-attribute utility theory, MAVT – Multi-attribute value theory, SMART - Simple Multi-Attribute Rating Technique, SMARTER - Simple Multi-attribute rating technique exploiting ranks) and outranking methods (PROMETHEE - Preference Ranking Organization METHod for Enrichment of Evaluations, ELECTRE - ELimination Et Choix Traduisant la REalité, REGIME analysis).

Among the techniques used to aggregate or combine different criteria, linear additive models are considered the basis of the MCDA, being the simplest, the most easily understood by decision-makers from different backgrounds and the most widely used form of value function method (Barfod and Leleur, 2014; Department for Communities and Local Government, 2009; Yannis et al., 2020). This procedure assumes that criteria are preferentially independent (Department for Communities and Local Government, 2009). A MCDA based in a linear additive model can be adopted to provide an overall ordering of options, from the most preferred to the least preferred option, serving as an aid to decision making, but not to take the decision (Barfod and Leleur, 2014; Department for Communities and Local Government, 2009).

To improve the outcome and support strategic decision making, the MCDA can incorporate a quadrant analysis to compare sets of conflicting interests. The axis representing the conflicting interests can be defined by the aggregation of criteria or sub-criteria (e.g., economic and non-economic, technical and non-technical, etc.), thus resulting in a 2×2 matrix or quadrants that can be designed with different goals and for different scenarios. By conducting an average split based on the criteria aggregation ratings, the vertical and horizontal axis can be established in the quadrant chart and the conflicting interests can be classified based on their relative urgency of intervention. This approach has been used to prioritize improvement actions based on users' perceptions (Machado-León et al., 2017), and in the analysis of passengers' satisfaction (Currie and Muir, 2017; Shen et al., 2016; Yuan et al., 2021), transport project investment (Marcelo et al., 2016) and sustainable urban mobility policies (Morfoulaki and Papathanasiou, 2021).

The main objective of this study is the definition of a methodology to obtain a priority matrix for proximity interventions (perceptible to users/customers) based on MCDA and quadrant analysis to define priority levels for different investments to support the management of the railway network infrastructure. As a secondary objective, it is also intended to provide the infrastructure manager with a medium-term vision (5 years) "portfolio" of projects/interventions, thus establishing priority rules for those that must be developed and identifying the ones that should be rethought, re-analysed or suspended. Such methodology will constitute a valuable contribution to the strategic objectives of the company that performs the management of the Portuguese rail infrastructures (Infrastructures of Portugal, SA – IP, SA), and must be flexible enough to be applied to other networks and scenarios.

This paper is organized as follows: after a background review about MCDA and quadrant analysis approaches, section 2 presents the methodological approach where the concept of "Proximity Plan" is framed in the business planning cycle of the railway network manager, and the criteria, the assessment process of sub-criteria weight and the algorithm used to compute the technical, non-technical and global scores are identified. Section 2 also introduces the quadrant approach used for the selection of the most relevant activities to be suggested to the decision-makers for approval. The Portuguese railway network case study is presented in section 3. In this section, the proposed methodology is applied to three annual proximity plans (2017–2021, 2018–2022 and 2019–2023) for a financial analysis of a real case and the results are compared to the outcomes of an average split quadrant analysis. The study main conclusions and some final remarks about future iterations are presented in section 4.

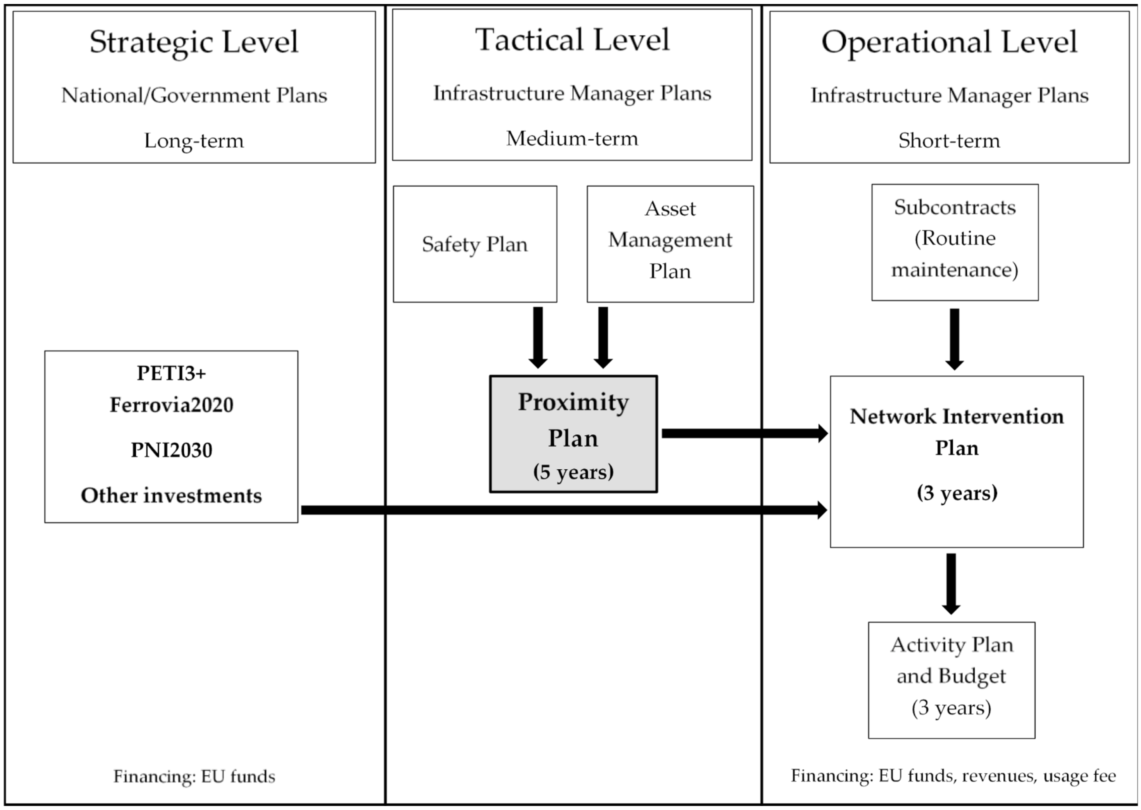

Fig. 1. IP, SA Business Planning Cycle Note: PETI3+ is the Portuguese Strategic Plan for Transport and Infrastructure 2014–2020; Ferrovia 2020 is the Railway Investment Plan and PNI2030 is the 2030 National Investment Program.

2. Methodology

2.1. Integration in the business planning cycle

Management entities need to define planning instruments, properly framed with the service that is intended to be provided and allocate adequate resources to the tactical planning that will result in the definition of concrete actions executed at the operational level. The involvement of the entities' operational units in the preparation of these tactical instruments should be promoted to achieve better results (Oliveira, 2016).

In the presented study, tactical planning is accomplished through the implementation of a proximity interventions prioritization approach to national railway networks. The intended "Proximity Plan" can only be achieved with an iterative, participatory, and engaging process involving several departments of the company (the process is managed by the planning unit and has inputs from financial, asset management, network maintenance, telecommunications and telematics, safety and environment units).

In Portugal, the Proximity Plan of the IP, SA is an integral part of the medium/short-term business planning cycle at a tactical level and has contributions from the IP, SA's Safety and Asset Management Plans (see Fig. 1). Subsequently, the Proximity Plan supports, along with other strategic investments plans such as PETI 3+, and the derivative Ferrovia 2020, and more recently, the 2030 National Investment Program (Governo de Portugal, 2015; Infraestruturas de Portugal, 2016; Official Journal of the European Union, 2019; República Portuguesa, 2020), at the operational planning level, the Network Intervention Plan for a 3-year-period resulting in the Activity Plan and Budget.

At the investment level, as manager of the Portuguese railway network, the IP, SA supports the implementation of the Proximity Plan, thus complementing the investments considered at the strategic level in Ferrovia 2020 (aligned with European funds eligibility).

The effectiveness of this decision support tool depends fundamentally on the criteria defined by all stakeholders, directly or indirectly involved, to support the decision. It may also be an instrument for evaluating investment projects by integrating complex socio-economic analyses involving not only stakeholders, such as operators and/or the system's beneficiaries but also those indirectly involved, as the civil society represented by the State.

2.2. Criteria identification

Based on the literature and the company needs, a set of criteria and sub-criteria were identified as relevant to assess the prioritization of railway proximity interventions (Couto et al., 2018; Kosijer et al., 2020; Macura et al., 2020; Mandic et al., 2014; Pamucar et al., 2022; Stoilova et al., 2020; Yücel and Taşabat, 2019).

In the applied methodology, it was chosen to distinguish and group the identified sub-criteria, according to their impact, into four general thematic criteria, giving greater importance to technical and operational aspects:

- Legal criteria: obligations, safety, and environment.
- Operational criteria: classification, quality, and conservation status.
- Financial criteria: investments and financing.
- Political criteria: commitment and impact.

Legal criteria aim to assess the legal and institutional weight in the implementation of each proposed intervention. They present a greater focus on the safe transport of people and goods, but also a strong impact on the environment, especially on climate change, air pollution, noise, and land use.

Operational criteria assess the potential effects of the proposed intervention on improving railway operating conditions, but also the obsolescence of materials or technology, both with implications in

Table 1
Defined criteria and sub-criteria (Oliveira, 2016; Oliveira et al., 2017).

Criteria	Sub-criteria	Weights	% by Criteria
Legal	Grantor authority's instruction/court/ other (Obligations)	2	23%
	Railway safety (railway crossing, action plan) (Regulatory)	6	
	Reduces operational safety risks (Regulatory)	10	
	Crossing type (Regulatory)	2	
	Noise reduction (Regulatory)	2	
	Fauna (Regulatory)	1	
Operational	Network segmentation	10	55%
	Implemented speed limitation, Lv (km/h)	10	
	Reduces maintenance costs	8	
	Improves maintenance conditions (obsolescence)	4	
	Improves conservation state	4	
	Improves interoperability conditions	2	
	Integration with contiguous sections	2	
	Non-conforming conservation state (asset)	10	
	Suggested intervention year (by the management system)	3	
	Proposed intervention year (by the organic unit)	2	
Financial	Enhancer of performed investments	3	18%
	Intended investments	4	
	EU funds	6	
	European investment bank	3	
	Trans-European transport network	2	
Political	Specific territorial impact	1	4%
	Number of municipalities	1	
	Number of residents	1	
	Protocols / other commitment (Administrative council, Government)	1	

maintenance actions.

Financial criteria are a factor of concern in any activity of the Government sector, including the one related to the management of road and railway infrastructures. The financial criteria intend to assess whether the execution of an activity will allow financing and if it can result in medium/long term financial advantages for the company. In addition to a cost/benefit evaluation for different interventions, the inclusion of the infrastructure in the Trans-European Transport Network (TEN-T) is also considered. TEN-T materializes an ambitious program of construction, modernization, and interconnection of the main European transport infrastructures, aiming to develop a single market by strengthening economic competitiveness and social cohesion in the European area (European Parliament and the Council of the European Union, 2013).

Transport services are essential for the efficient and competitive functioning of society and the economy, ensuring inter and intra-regional mobility of people and goods. The political criteria are intended to assess the impact of the implementation of an activity in terms of potential effects on the socio-economic development of a region.

It was possible to verify that the four groups of selected criteria are in line with the most common criteria and proved to be relevant. They were also able to influence the hierarchy of interventions and sufficiently comprehensive and representative of all stakeholders, both internal and external to the company.

Regarding the criteria weight, Cadena and Magro (2015) point out that the definition of weight is one of the MCDA issues that require further research and state that the use of weights is the main unresolved matter due to the lack of transparency of judgements and their influence on the final results. Approaches for criteria weighting usually require complex mathematical tools which are not easy to manage or suffer from problems in modelling the subjectiveness of human decision processes (Cadena and Magro, 2015). Several authors mention the importance of integrating decision-makers and/or experts in the process of obtaining criteria weights (Cadena and Magro, 2015; Mandic et al., 2014; Marcelo et al., 2016; Pamucar et al., 2022; Quadros and Nassi, 2015). Considering that standardized and practical methods for evaluating the trade-offs among economic, environmental and social aspects in transport projects are still in need, it is important to include experts from specific areas to provide their estimates of criteria weights for which no exact data exists or could not be defined (Cadena and Magro, 2015). The literature review also revealed that the sub-criteria specification does not follow a clear trend and that they are selected based on the specificity of each analysis.

In the proposed methodology, the general criteria weights were defined by the infrastructure's manager, being closely related to the road model in use by the company (Infrastructures of Portugal, SA), so that results could be presented in a joint road-rail view. To reflect the relative importance of each criterion in the final score, each weight was defined as a percentage of the overall evaluation, therefore, the total weight is set equal to 100. The weight scale initially defined can be adjusted, if necessary, in accordance with the specifications or criteria changes introduced at each analysis period.

For the railway intervention prioritization model, the defined and adopted sub-criteria and criteria weights are presented in Table 1.

The list of sub-criteria, the level of impact of each attribute and the classification scales resulted from an internal iterative process based on the professional experience and expertise of the IP, SA staff and on the recommendations from an advisory panel. Similar processes are described in the literature (Cadena and Magro, 2015; Couto et al., 2018). Table 1 also shows the result of the described process.

In the identification of sub-criteria to compare infrastructure intervention proposals, the following restrictions were considered:

- Degradation of the existing infrastructure resulting in capacity limitation and speed reductions.
- End of life approaching and technical obsolescence of part of the network, namely regarding the circulation control systems.
- Lack of rail electrification in a significant part of the network.
- Safety at non-suppressed level crossings.
- Heterogeneous gauge, signalling, and power feeding systems.

It was also a concern that the impact descriptor should be as unambiguous as possible so that it is easily understood by all actors and does not cause disruption when assessing activities, particularly where quantitative descriptors could not be established, and qualitative descriptors are used.

The procedure was concluded with the definition of a partial preferences scale from the most attractive level of impact to the least attractive.

The weights defined for each of the sub-criteria were initially based on a scale of five values (very bad, bad, reasonable, good, and very good). However, given the high number of sub-criteria considered, the weights were adjusted to a ten values scale for a more comprehensive and balanced analysis (Bana e Costa and Beinat, 2010; Oliveira, 2016) (see Table 1).

Table 1 presents the initial set of sub-criteria and weights adopted. Over the planning cycles, after analysis of results, slight adjustments were made to this initial approach to attend the infrastructure manager's perception, needs and priorities.

2.3. Activities

After defining the analysis criteria, all possible activities for evaluation were identified. This procedure resulted from an inventory of the intervention proposals identified by the organic units responsible for the various company areas associated with the management of the railway infrastructure. For this purpose, a template and respective guidelines were made available to assist in providing contributions and to

Table 2
Characterization of activities (Oliveira, 2016).

Feature	Description
Activity ID	Depends on the year of registration.
Organic Unit (OU)	Identification of the Organic Unit that lists the activity.
Office in charge	Office in charge of the activity implementation.
Activity No.	Activity code, designated by the Organic Unit.
Activity designation	Identification of the contract designation.
Line N°. (IET 50)	Identification number of the railway line where the activity is located (according to the Technical Exploration Instruction (IET) N°. 50 (Infraestruturas de Portugal, 2005)).
Line	Railway line identification (name) where the activity is located (according to IET 50 (Infraestruturas de Portugal, 2005)).
Segment	Identification of the railway segment where the activity is located (according to IET 50 (Infraestruturas de Portugal, 2005)).
Initial km	km identification of the beginning of contract/ service provision according to the Portuguese railway network line where the activity is located.
Final km	km identification of the end of contract/service provision according to the Portuguese railway network line where the activity is located.
km (track) / No. (Bridges, Tunnels and Viaducts)	Identifies the total number of km (track) to intervene and/or the number of bridges/tunnels/ viaducts that the activity includes.
District	Identification of the Districts covered by the activity. If the activity covers more than one District, the % of activity affecting each District should be specified.
Municipality	Identification of the Municipalities covered by the activity.
Base Value (without VAT) (€)	Indication of the amount to be provided.
Materials value (estimate without VAT) (€)	Indication of the amount to be provided.
Phase	Identification of the activity phase: launch, tender phase, signed contract, granted.
Proposed release year (by OU)	Indication of the year proposed by the Organic Unit to launch the contract: 2017, 2018, 2019, 2020, 2021, etc.
Speciality	Railway crossing, bridges, tunnels and viaducts, stations, other buildings and constructions, catenary, railway track, railway signalization, telecommunications, power lines.
Intervention typology	Accident reduction, bridges/tunnels/viaducts rehabilitation, building rehabilitation, implementation of normative RCT + TP (RCT - Traction Current Return, TP – Protection Lands), slope stabilization, rehabilitation of railways tracks, improvement of telecommunications systems, implementation of the Global System for Mobile Communications – Railway (GSM-R) in the Portuguese railway network, noise reduction.
Asset class	Indication of the asset to be intervened: railway crossings, land, infrastructure and track platform, track superstructure, catenary and traction energy, infrastructure of bridges/tunnels/viaducts, buildings, telecommunications, signalization systems or operation safety.
Action type	Activity arising from conditioned preventive maintenance, systematic preventive maintenance, corrective maintenance, integral rehabilitation of assets.

guarantee the standardization of correct responses. To apply the algorithm, and after identifying the intervention needs, their characterization was completed and standardized, as exhaustively as possible, as described in Table 2.

2.4. Algorithm

The individual intervention characterization and impact classification allowed to quantify the activity impact by applying impact weighting factors. The impact weights were defined through an internal participatory process involving the main organic units responsible for the management of various aspects of the Portuguese railway infrastructure. It should be noted that interventions that result in an effective reduction in operational safety risk are the most valued (e.g., railway rehabilitation, telecommunication systems improvement and slope stabilization). As an example, the impact weights defined for the legal sub-criteria are presented in Table 3.

Table 3
Impact of legal sub-criteria.

Sub-criteria	Impact weight	Sub-criteria weight
Grantor authority’s instruction / court / other	Yes = 100 No = 0	2
Railway safety (railway crossing, action plan)	Yes = 100 No = 0	6
Reduces operational safety risks	Yes = 100 No = 0	10
Crossing type	Level crossing = 100 Lane crossing = 75 Crossing in unauthorized locations = 50 Not applicable = 0	2
Noise reduction	Level 0 = 0 Level 1 = 60 Level 2 = 80 Level 3 = 100	2
Fauna	Yes = 100 No = 0	1

Table 4
Calculation of partial and global values.

Code	Parameters	Calculation
A	Total value of legal criteria - Obligations	Weighted sum of all legal criteria related to obligations
B	Total value of legal criteria - Regulatory	Weighted sum of all legal criteria related to regulations
C	Total value of operational criteria	Weighted sum of all operational criteria
D	Total value of financial criteria	Weighted sum of all financial criteria
E	Total value of political criteria	Weighted sum of all political criteria
F	Global value	F = A + B + C + D + E
G	Order number	RANK.EQ (number;array;order) (Returns the rank of a number in a list)
H	Technical criteria value	H = B + C
I	Non-technical criteria value	I = A + D + E

The product of the classification score by the sub-criteria weighting coefficient quantifies the impact of the intervention execution for each sub-criterion. The sum of all sub-criteria impacts is determined to obtain an intervention global value.

The scores obtained are also aggregated into two groups (see Table 4), one including the criteria considered as more technical and objective, referred to as “technical criteria”, and another with the criteria related to political and financial matters, the “non-technical criteria”, thus resulting in two partial values.

As a result, by applying the additive method, for each intervention proposal identified and considered in the analysis, global and partial values are obtained using a spreadsheet duly automated to achieve these results. The instructions considered in the calculation are summarized in Table 4.

To evaluate the relation between the technical and non-technical criteria values, a quadrant analysis approach was adopted which allowed considering the two values even if their range is significantly different.

As shown in Fig. 2, the quadrants, designated as Q1, Q2, Q3 and Q4, are defined to represent four possible outcomes in the decision support

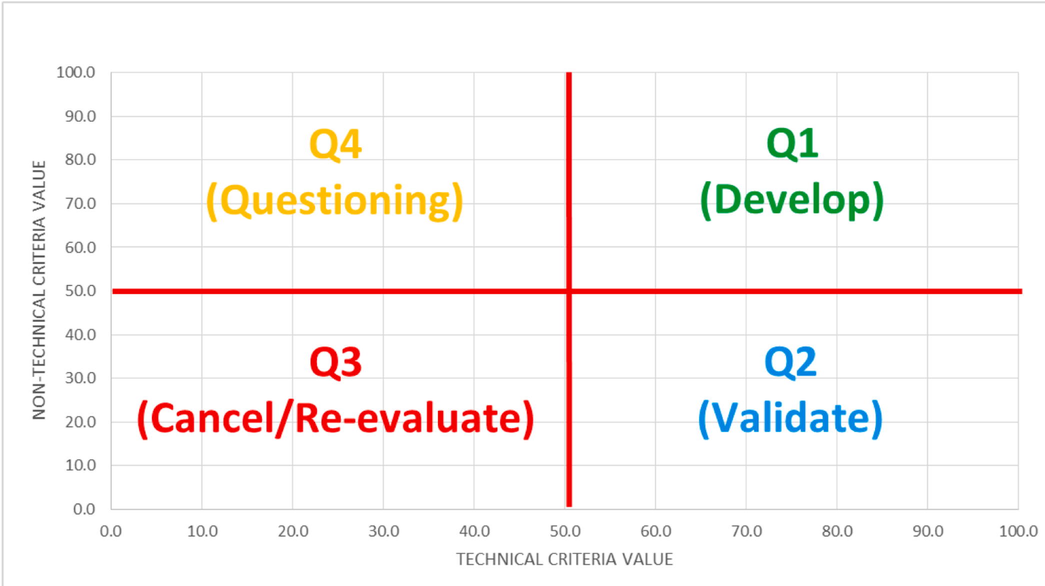

Fig. 2. Example of quadrant analysis considering an average split based on the normalization of technical and non-technical criteria.

Table 5
Quadrant description.

Quadrant	Result	Description
Q1	Develop	Activities whose implementation is unambiguous since they present high partial values (technical and non-technical). Technical criteria values > x and non-technical criteria values > y.
Q2	Validate	Activities that, given the available investment/ financing, require further confirmation. Technical criteria values > x and non-technical criteria values < y.
Q3	Cancel / Re-evaluate	Activities to be verified on a case-by-case basis. Interventions with low values of both technical and non-technical criteria. Technical criteria values < x and non-technical criteria values < y.
Q4	Questioning	Activities to be considered in relation to the available investment and identified urgency, with values of technical criteria < x and non-technical criteria > y. Interventions with low technical criteria values and high non-technical criteria.

Note: x and y are respectively the assumed technical and non-technical criteria quadrant limit values adopted in the analysis.

process: Develop (Q1), Validate (Q2), Cancel/Re-evaluate (Q3) and Question (Q4) (see Table 5).

The limits of the quadrants can be defined considering an average split based on the normalization of criteria aggregation ratings (technical and non-technical), on the median, on the difference between the mean and the standard deviation of values or on the difference between the median and the median absolute deviation, depending on the normality of data and desired degree of maximization for Q1 activities. Other quadrant limits can be defined by the infrastructure manager, supported in the previous analyses.

Within each quadrant, interventions are prioritized according to their global value.

3. Case study: Portuguese railway network

3.1. Priority matrix and quadrant analysis

For the application of the proposed methodology, three annual five-year periods of analysis were considered: 2017–2021, 2018–2022 and 2019–2023. The 2017–2021 proximity plan included 930 activities proposed by the different organic units. Only about two-thirds were considered due to the rejection of about 28% of the sample. This rejection was due to several reasons, of which the following should be

Table 6
Extract of the calculation matrix 2017–2021 (values not normalized).

Activity ID	Legal criteria (Obligations)	Legal criteria (Regulations)	Operational criteria	Financial criteria	Political criteria	Global value	Order number	Technical criteria	Non-technical criteria
1	0	1120	2230	400	110	3860	523	3350	510
2	0	1000	2980	800	200	4980	137	3980	1000
3	0	1000	2920	800	150	4870	171	3920	950
4	0	1000	2860	800	150	4810	181	3860	950
5	0	1120	2170	300	155	3745	538	3290	455
6	0	1120	2110	300	155	3685	556	3230	455
7	0	1120	2230	300	155	3805	531	3350	455
8	0	1000	2610	600	110	4320	387	3610	710
9	0	1000	2610	500	110	4220	419	3610	610
10	0	1000	2520	500	140	4160	440	3520	640
11	0	0	2680	800	80	3560	581	2680	880
12	200	0	2030	400	120	2750	646	2030	720
13	0	0	2660	600	115	3375	601	2660	715
14	0	1000	2940	900	85	4925	152	3940	985
103	0	0	2030	300	90	2420	659	2030	390

Table 7
Descriptive statistics.

Statistics	Technical criteria		Non-technical criteria	
	Not normalized	Normalized	Not normalized	Normalized
2017–2021	Number of activities		672	
Normality test	Kolmogorov-Smirnov	p_{value} = 0.000*	Kolmogorov-Smirnov	p_{value} = 0.000*
	Shapiro-Wilk	p_{value} = 0.000*	Shapiro-Wilk	p_{value} = 0.000*
Maximum score	5740	100.0	1110	100.0
Minimum score	310	0.0	105	0.0
Mean	3735	63.1	655	54.7
Median	3780	63.9	630	52.2
Standard deviation	823	15.2	215	21.4
$Q_{25\%}$	3305	55.1	510	40.3
$Q_{75\%}$	4150	70.7	800	69.2
Interquartile range ($Q_{75\%}$-$Q_{25\%}$)	848	15.6	290	28.9
Median absolute deviation	440	8.1	140	13.9
2018–2022	Number of activities		865	
Normality test	Kolmogorov-Smirnov	p_{value} = 0.000*	Kolmogorov-Smirnov	p_{value} = 0.000*
	Shapiro-Wilk	p_{value} = 0.000*	Shapiro-Wilk	p_{value} = 0.000*
Maximum score	5750	100.0	1470	100.0
Minimum score	250	0.0	230	0.0
Mean	3228	54.1	732	40.5
Median	3200	53.6	710	38.7
Standard deviation	857	15.6	213	17.2
$Q_{25\%}$	2550	41.8	585	28.6
$Q_{75\%}$	3850	65.4	830	48.4
Interquartile range ($Q_{75\%}$-$Q_{25\%}$)	1300	23.6	245	19.8
Median absolute deviation	650	11.8	125	10.1
2019–2023	Number of activities		838	
Normality test	Kolmogorov-Smirnov	p_{value} = 0.000*	Kolmogorov-Smirnov	p_{value} = 0.000*
	Shapiro-Wilk	p_{value} = 0.000*	Shapiro-Wilk	p_{value} = 0.000*
Maximum score	6020	100.0	1810	100.0
Minimum score	800	0.0	230	0.0
Mean	3329	48.4	750	32.9
Median	3335	48.6	720	31.0
Standard deviation	990	18.9	259	16.4
$Q_{25\%}$	2565	33.8	580	22.2
$Q_{75\%}$	4076	62.8	830	38.0
Interquartile range ($Q_{75\%}$-$Q_{25\%}$)	1511	29.0	250	15.8
Median absolute deviation	753	14.4	125	7.9
Note: * Non-normal distribution				

highlighted: activity release out of the planned time span; work adjudicated or abandoned by the tenderer; activities whose investment falls out of the "proximity" concept, such as full track renovations; current actions essential to basic functional needs, such as, maintenance interventions on heating, ventilation and air conditioning systems (HVAC), equipment for passengers' safety, etc. The assessment of these particular cases resulted in a final sample of 672 activities. The final sample for the periods 2018–2022 and 2019–2023 were respectively 865 and 838.

Table 6 presents an extract of the calculation matrix used to obtain intervention partial and global values. The order number of each activity corresponds to its global value position in the overall ranked list. Lower order numbers indicate activities with higher priority.

In the periods under analysis, the maximum scores found for technical criteria were 5740, 5750 and 6020, and for the non-technical criteria 1110, 1470 and 1810, respectively for 2017–2021, 2018–2022 and 2019–2023. The descriptive statistics values listed in Table 7 were obtained based on the scoring values of each sample. The corresponding normalized values (0–100 scale), obtained using Eq. (1), are also presented.

$$x_i = \frac{(R_i - R_{min})}{(R_{max} - R_{min})} \quad (1)$$

Where:

i is the criteria type (technical or non-technical).

x_i is the normalized criteria i value.

R_i is the non-normalized criteria i value (value to be normalized).

R_{min} and R_{max} are the minimum and maximum non-normalized criteria values.

According to several authors (Abu-Shawie, 2008; Habibzadeh, 2017; Lydersen, 2020; Madadizadeh et al., 2015; Yang et al., 2021; Arachchige and Prendergast, 2019), for normally distributed continuous numerical data, mean and standard deviation (SD) are reported to present the centre and dispersion of data. For non-normally distributed data, the median is a more appropriate average indicator and interquartile range (IQR = $Q_{75\%}$-$Q_{25\%}$) and median absolute deviation (MAD) are better dispersion indicators. Based on the non-normal distribution of the technical and non-technical criteria values obtained, the limits adopted in the quadrant analysis were established as being equal to the median criteria values. Figs. 3–5 show the plot of technical and non-technical normalized criteria values considering the median quadrant limits definition and the median absolute deviation range.

Fig. 6 presents data distribution analysis using histogram and boxplot representations.

With the application of the reference limits adopted (median), it is possible to classify each activity in one of the quadrants, obtaining an overall evaluation to assists decision making.

Activities included in quadrant Q1 will have priority over all others and have (theoretically) a better justification to be financed. These are activities that, both technically and not technically, present an evaluation above the median. Within each quadrant, the activities can be sorted in ascending order according to their order number.

Activities included in quadrant Q2, which present a score above the median for technical criteria and below the median for non-technical criteria, will be the activities to be considered next if there is an available budget after consideration of Q1 activities.

The activities in quadrant Q4, with a score above the median for non-technical criteria and below the median for technical criteria, will be the activities to be considered after those in quadrant Q2. The last activities to be considered will be those in quadrant Q3, whose assessment is below the median for both technical and non-technical criteria.

This methodology allows the assessment of the relevance of the activities, not only considering their global value but also considering the best combination between technical and non-technical criteria evaluation.

When adopting other values for quadrant limits (inside the median absolute deviation range), the interpretation of results and prioritization of interventions is performed similarly.

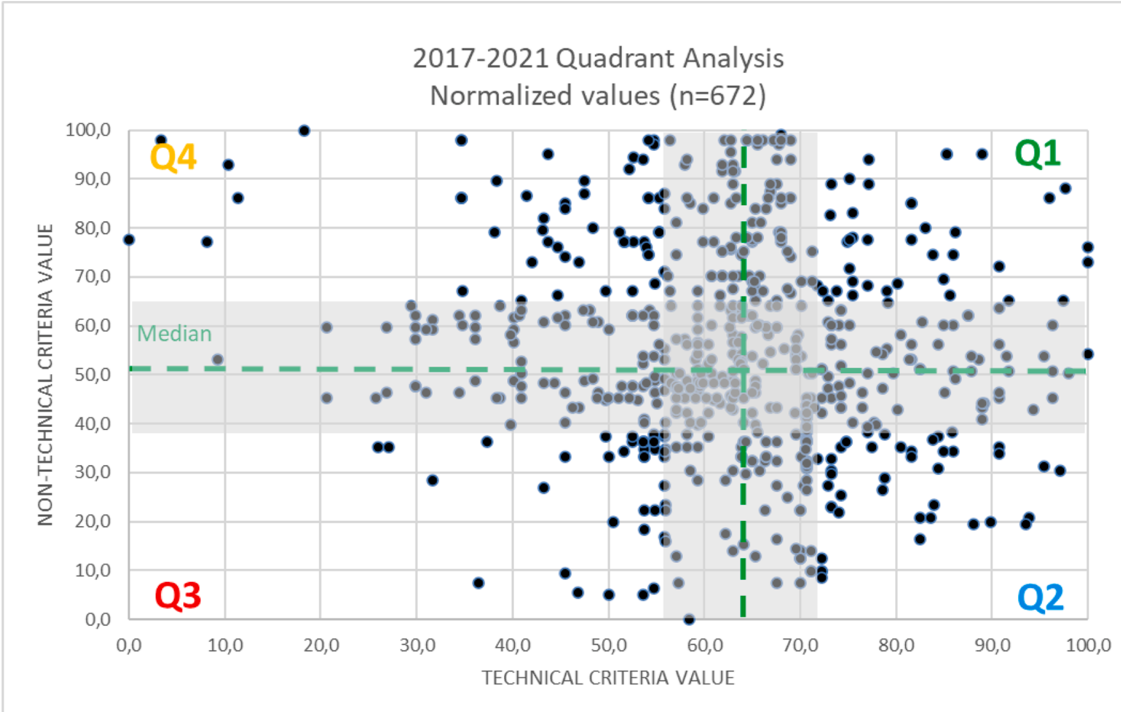

Fig. 3. 2017–2021 analysis with median quadrant limits and median absolute deviations range.

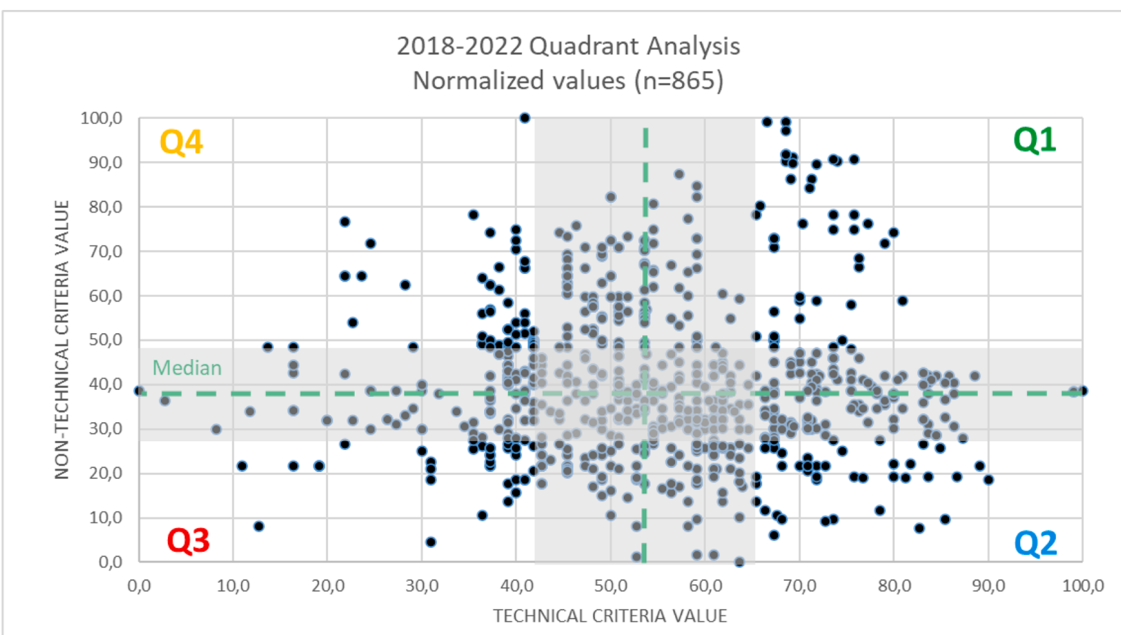

Fig. 4. 2018–2022 analysis with median quadrant limits and median absolute deviations range.

3.2. Results and discussion

The application of the designed algorithm resulted in the distribution of the selected activities by quadrant according to the information presented in Table 8. The quadrant distribution of the activities is presented considering the average split (score of 50 for both technical and non-technical criteria) and the median split. The latter was the one adopted in the analysis.

From Table 8 it is possible to verify that Q1 activities proportion range from 3.8% to 45.2% considering the average split, and from 19.3% to 25.2% for the median split. On the other hand, the Q3 activities range from 5.5% to 41.3% considering the average split, and from 18.7% to 22.6% for the median split. The results allow to conclude that the average split distribution presents a greater variation over the different years. The median split gives a more balanced activities distribution over the different periods under analysis with around 20 to 30% of activities distributed per quadrant, showing more stable and independent outcomes.

From a financial point of view, an investment analysis was also considered. More than 90% of the activities were considered by the

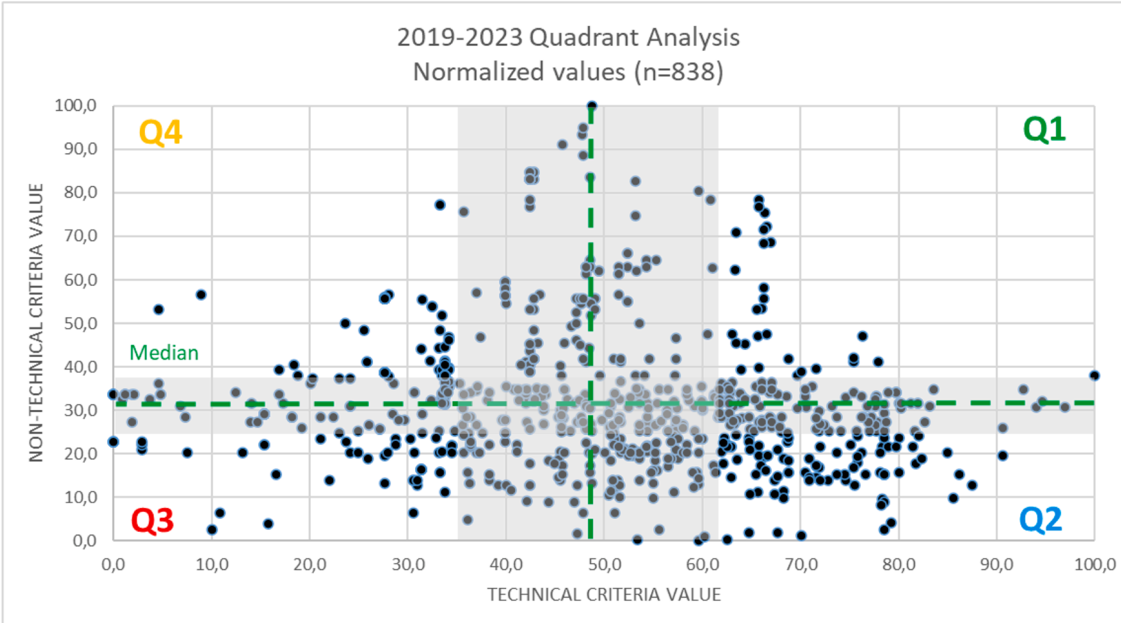

Fig. 5. 2019–2023 analysis with median quadrant limits and median absolute deviations range.

network manager (decision maker) for analysis. The activities taken from the analysis represent 1.2% of Q1 activities and 15.1% of Q2 activities for the 2017–2021 period, but no Q1 or Q2 activities were removed in the 2018–2022 and 2019–2023 plans.

The average split outcomes show the allocation of more than 62% of the investment on Q2 activities in all analysed periods.

Applying the median algorithm outcomes to the investment analysis, 20.7% to 37.9% of the necessary investment to complete the analysed set of activities fall in quadrant Q1 and 13.4% to 16.0% in Q3 (activities to potentially dismiss). The model presents fairly stable outcomes through the analysed cycles with greater proportion of the investment in the Q2 quadrant (42.0 to 53.1%).

These results are in line with the assumption of higher weights for technical criteria compared to the non-technical ones. The model shows a tendency for the most relevant activities (Q1 and Q2 represent about 50% of the activities) being the more expensive ones (more than 70% of costs).

3.3. Plan implementation

The proposed methodology constitutes an approach to evaluate technical and non-technical criteria and to support decision making for the development of railway network interventions aiming to maximize safety conditions, reliability levels and the quality of the service provided to customers, for a five-year period (to be reviewed and adjusted annually).

2017 marked the introduction of the developed methodology as a tactical planning tool in the IP, SA management process. Its implementation was carried out under a rigorous monitoring and control process. The outcome of the proposed evaluation is one of the company's main performance indicators, as well as of all Organic Units that manage the recommended activities. The practical applicability of the proximity plan is translated into the Network Interventions Plan, which will operationalize the portfolio of the selected activities.

The defined methodology allows the decision-maker to obtain a clear and transparent comparative analysis between alternatives and a first iteration for a priority list. The methodology is also flexible, allowing adjustments in various parts of the process. The procedure's first phase, which corresponds to the criteria, sub-criteria and their impact weights definition, is an internal participatory process involving the main organic units and it is reviewed annually. The quadrant limits can also be adjusted considering the data distribution, centre and dispersion indicators to attend annual overall budget specificities and quadrant intervention distribution (for example, for interventions close to quadrant limits). In years with higher budgets, it is possible to reduce the thresholds below the mean or median to include more Q1 activities, as well as increase the selection requirements by raising thresholds above the mean or median, when more demanding budgets exist.

The methodology's outcome allows the company to anticipate the contracts launching rate, and to set a launching works schedule for each year of the 5-year-period under review, in a balanced, financially sustainable, and operationally rational manner.

The results obtained, namely, the ordered list of activities to be developed, is annually and internally disseminated, so that the management tools of each organic unit can adjust their planning mechanisms to the defined strategy. Results are also represented in the company's Geographic Information System (GIS IP). This system allows to visualize the location of the prioritized activities and to obtain all the relevant information related to each: designation, year of launch, investment value and typology.

It is important to point out that the proposed procedure constitutes an evolving working tool, reviewed, and adjusted annually.

An example of these adjustments are the changes in sub-criteria and their weights performed in the second and third cycle. In the 2018–2022 planning cycle, the network manager considered that the legal sub-criteria "Fauna" was no longer relevant and dismissed it. On the other hand, the legal sub-criteria "Grantor authority's instruction/court/other" had its relevance increased from 2 to 5 points. The manager also dismissed the operational sub-criteria "Proposed intervention year (by the organic unit)" based on the consideration that the "Suggested intervention year" sub-criterion is sufficient to include the intervention year variable in the model. These adjustments meant an increase from 23% to 25% of the legal criteria weight, and a decrease from 55% to 53% of the operational criteria weight. Compared to the results with the 2017–2021 cycle conditions, the changes resulted in a quadrant exchange of 11 interventions (1.2% of the total number of intervention).

Considering the 2019–2023 planning cycle, the network manager kept the same adjustments mentioned for 2018–2022 legal sub-criteria. For the operational sub-criteria, besides keeping the adjustment considered in 2018–2022, five new sub-criteria were considered

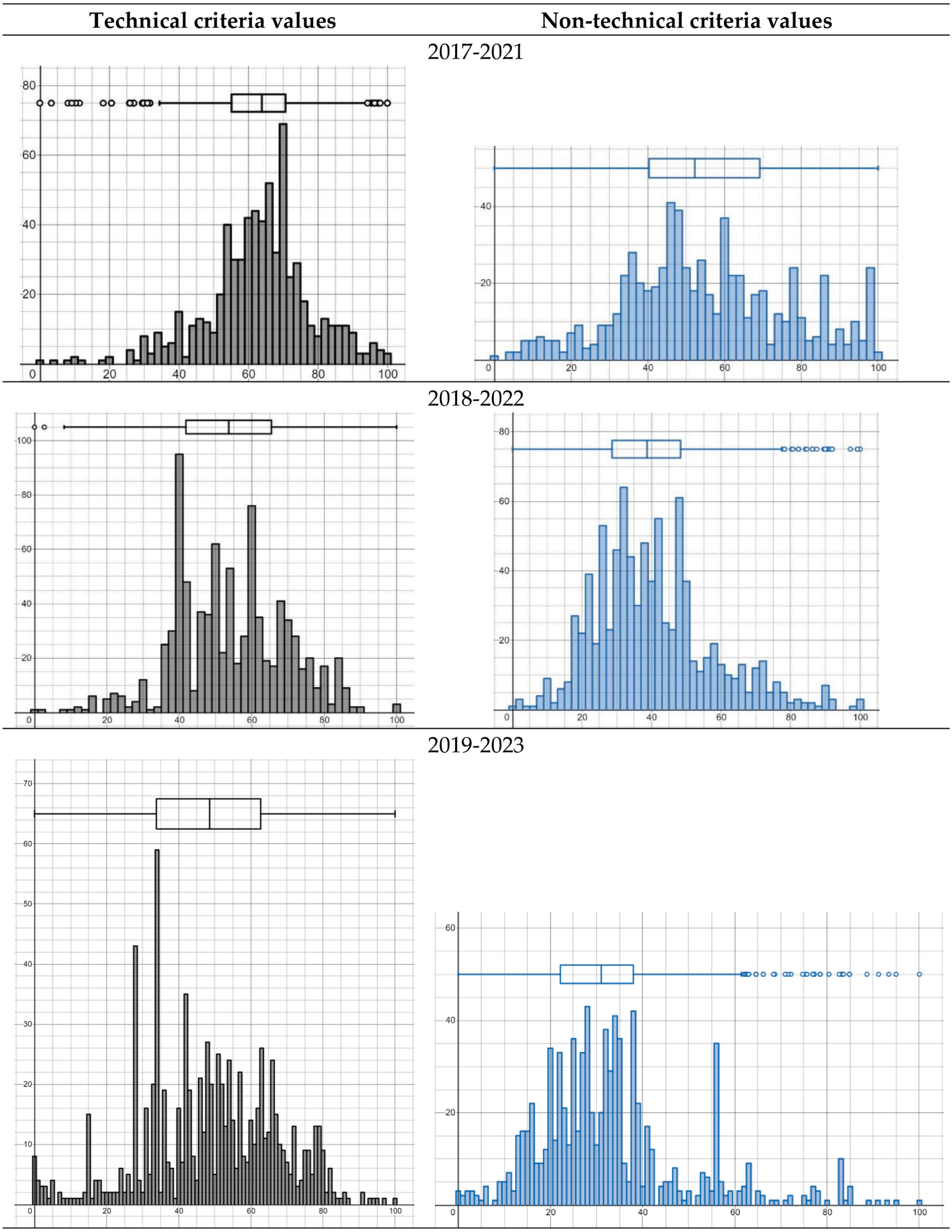

Fig. 6. Data distribution analysis: histogram and boxplot.

relevant and introduced:

- Contribution to the implementation of Technical Specifications for Interoperability (TSI) (weight = 1): the intervention aims the implementation of a system, or component, within the scope of the TSI.
- Compliance with the principle of co-modality (weight = 1): the intervention will contribute to the networks' integration (railway and road), enhancing efficiency and competitiveness.
- Contribution to improving the offered level of service (weight = 1).
- Contribution to improve user satisfaction (weight = 1): evaluating whether the intervention minimizes the clients' complaints.

Table 8
Distributions obtained by applying the algorithm (normalized values).

	2017–2021				2018–2022				2019–2023			
	Activities (%)		Investment (%)		Activities (%)		Investment (%)		Activities (%)		Investment (%)	
Quadrant	AV	MDN	AV	MDN	AV	MDN	AV	MDN	AV	MDN	AV	MDN
Q1	45.2	**25.2**	32.9	**20.7**	12.5	**21.5**	18.8	**37.9**	3.8	**19.3**	11.9	**34.0**
Q2	39.6	**26.6**	62.2	**53.1**	47.2	**30.5**	65.6	**42.0**	44.0	**31.1**	65.5	**44.1**
Q3	5.5	**22.6**	2.8	**16.0**	30.6	**19.4**	12.8	**13.4**	41.3	**18.7**	20.1	**15.3**
Q4	9.7	**25.6**	2.1	**10.2**	9.7	**28.6**	2.7	**6.7**	10.9	**30.8**	2.5	**6.6**
Unfunded (% activities)	–	–	8.5	8.5	–	–	5.4	5.4	–	–	3.6	3.6

Note 1: AV – average split, MDN – median split. Note 2: Unfunded activities were selected by the network manager.

Table 9
Intervention quadrant exchanges due to the 2018–2022 and 2019–2023 sub-criteria adjustments.

		2018–2022 conditions					2019–2023 conditions				
		Q1	Q2	Q3	Q4	Total	Q1	Q2	Q3	Q4	Total
2017–2021 conditions	Q1	–	5	0	0	5	–	4	0	5	9
	Q2	3	–	0	0	3	5	–	9	0	14
	Q3	0	0	–	2	2	0	2	–	0	2
	Q4	0	0	1	–	1	12	0	0	–	12
	Total	3	5	1	2	11	17	6	9	5	37

- Railway usage (weight = 1): most recent data on the number of trains/day/section by year (passengers and freight).

The weights of "Network segmentation" and "Implemented speed limitation" were decreased from 10 to 9 points, reflecting the interventions already carried out within the scope of these sub-criteria. The "European Investment Bank" sub-criteria from the financial criteria was also removed because the proximity plan railway interventions did not fall within its scope.

These adjustments increased the operational criteria weight from 55% to 56% and decreased the financial criteria weight from 18% to 15%. Comparing the results with the 2017–2021 cycle conditions, the changes resulted in a quadrant exchange of 37 interventions (4.4% of the total proposed interventions). The quadrant exchange due to the 2018–2022 and 2019–2023 sub-criteria adjustments can be seen in Table 9.

These results show that a 1 to 3% change in the sub-criteria weights, with an overall change between 3% and 6% in the criteria weights, has a low impact in quadrant assignment (1 to 4%).

4. Conclusions

MCDA methodologies have been widely applied for setting investment priorities in various transport-related problems. Its application, however, has been mainly at the strategic level for the selection of investment alternatives and comparison between systems (national and international). Similarly, quadrant analysis has been applied to assess transport project investment, as well as transport problems based on the users' perception. The approach presented combines these two methodologies with enormous potential to support decision making at the tactical and operational level to efficiently and effectively achieve the commitments assumed in concession contracts.

The developed methodology based on MCDA and quadrant analysis overcomes the lack of an internal decision support tool for evaluating proximity interventions in national railway networks. The methodology increases the process transparency since it allows an objective response to the need of setting priorities for actions, through standardization and clear identification of multidisciplinary, measurable, traceable, and inclusive criteria, incorporating internal perspectives of the different organic units which are part of the railway company.

The main benefits of the approach proposed are the availability of a proximity intervention prioritization process centred in an algorithm based on weights (MCDA) and the incorporation of both technical and non-technical criteria simultaneously (quadrant analysis); the standardization of work typologies and specialities; a timely survey and record of short/medium-term intervention needs; the flexibility of the process that allows decision-makers to adjust the tool outcomes in a sustained way; the replicability to other scenarios, and the definition of future conservation level for each network asset. No similar railway proximity intervention prioritization approach was found in the literature.

The approach clearly benefited from the experience and knowledge of the company's staff, stakeholders, and scholars, which allowed the development of an adequate tool for the management and financial resources allocation in railways infrastructures.

The applicability of the tool was demonstrated in a real-case study, the Portuguese railway network, having been applied to three planning cycles (2017–2021, 2018–2022 and 2019–2023). Considering the medians as limits for the quadrant analysis, it was possible to identify:

- The most relevant interventions (simultaneously from a technical and non-technical perspective – Q1), corresponding to around 19 to 25% of the total number of interventions considered in the analysis and to 21 to 38% of the total annual intervention investment.

- The less relevant interventions (with low scores on technical and non-technical criteria – Q3) corresponding to approximately 19 to 23% of the total interventions and around 13 to 16% of the total investment needs.

- The technically relevant activities (Q2) representing 27 to 31% of all activities and 42 to 53% of the investment.

- And the non-technical relevant activities (Q4) representing 26 to 31% of the activities and 7 to 10% of the investment.

The methodology also allowed ordering the proposals within each quadrant.

The decision support tool does not exclude any proposed intervention but supports the decision-maker to select where to invest each year. The Q1 activities present technical and non-technical scores that justify their inclusion in the budget and the ranked list of Q2, Q4 and Q3 interventions can be used to assist the selection of the remaining activities to be considered attending the budget.

The methodology adequacy was also measured by the percentage of the interventions actually carried out, which according to the Portuguese rail network manager was 50 to 60% of all analysed interventions for the years of 2017, 2018 and 2019, corresponding to the most highly ranked. Further, an impact quadrant assignment study was performed considering the sub-criteria changes proposed by the manager for the 2018–2022 and 2019–2023 cycles. These changes, corresponding to 3% to 6% of the criteria weights, had a low impact in the quadrant assignment (1% to 4%).

In the Portuguese real-case study, the priority action plan (Proximity Plan) as part of the strategy for optimized planning of Infrastructures of Portugal, SA interventions, also allows a greater interconnection with the sector's supply companies. As such, the implementation of this tool in the planning cycle can significantly reduce costs, services and products' acquisition times and become a fundamental element in the interactions with local authorities.

As in any new decision-support tool, there are methodological aspects to be improved in the upcoming planning cycles. These improvements can result from monitoring the interventions implementation accessing their impact on the "real world" to support adjustments to aspects valued by the manager and advisory panel, motivating stakeholders to critically analyse the relevance of the chosen sub-criteria and their weights and impacts. Other possible improvements are related to motivating all organic units to provide accurate information for analysis, and to evaluate how to re-introduce in the following planning cycles previously selected activities that were not implemented due to budget restrictions or decision-maker's choice.

In future approach iterations, the inclusion and definition of minimum acceptable thresholds for both technical and non-technical scores can also be assessed by presenting and discussing this aspect with all stakeholders; a more detailed study on the operational safety intervention impacts quantification can be performed; and a formal sensitivity analysis of the criteria and sub-criteria weights is recommended.

CRediT authorship contribution statement

Jorge Gonçalves: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. **Bertha Santos:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. **Alexandra Oliveira:** Conceptualization, Formal analysis, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abu-Shawie, M.O.A., 2008. A simple robust control chart based on MAD. J. Math. Stat. 4 (2), 102–107. https://doi.org/10.3844/jmssp.2008.102.107.

Aldian, A., Taylor, M.A.P., 2005. A consistent method to determine flexible criteria weights for multicriteria transport project evaluation in developing countries, Journal of the Eastern Asia Society for Transportation Studies. Eastern Asia Society for Transportation Studies. 10.11175/EASTS.6.3948.

Arachchige, C.N.P.G., Prendergast, L.A., 2019. Confidence intervals for median absolute deviations 2, 1–13.

Bana e Costa, C.A., Beinat, E., 2010. Estruturação de Modelos de Análise Multicritério de Problemas de Decisão Pública. Cent. Manag. Stud. IST 1–30.

Barfod, M.B., Leleur, S., 2014. Multi-criteria decision analysis for use in transport decision making. DTU Transp, Compend, p. 75.

Belton, V., Stewart, T.J., 2002. Multiple Criteria Decision Analysis: an integrated approach, Multiple Criteria Decision Analysis. Springer US. 10.1007/978-1-4615-1495-4.

Broniewicz, E., Ogrodnik, K., 2020. Multi-criteria analysis of transport infrastructure projects. Transp. Res. Part D Transp. Environ. 83, 102351. https://doi.org/10.1016/j.trd.2020.102351.

Cadena, P.C.B., Magro, J.M.V., 2015. Setting the weights of sustainability criteria for the appraisal of transport projects. Vilnius Gedim. Tech. Univ. 30, 298–306. https://doi.org/10.3846/16484142.2015.1086890.

Caetano, V., Couto, P., Fontul, S., João Falcão Silva, M., Maia, N., Dimitrovová, Z., 2018. Multi-criteria analysis applied to railway rehabilitation. MATEC Web Conf. 211, 12007. https://doi.org/10.1051/matecconf/201821112007.

Couto, P., Salvado, F., Silva, M.J.F., Maia, N., Dimitrovová, Z., 2018. Optimization of railway infrastructures rehabilitation based on multicriteria analysis. MATEC Web Conf. 211, 12003. https://doi.org/10.1051/matecconf/201821112003.

Currie, G., Muir, C., 2017. Understanding passenger perceptions and behaviors during unplanned rail disruptions. Transp. Res. Procedia 25, 4392–4402. https://doi.org/10.1016/j.trpro.2017.05.322.

Department for Communities and Local Government, 2009. Multi-criteria analysis: a manual. London.

European Parliament and the Council of the European Union, 2013. Regulation (EU) 1315/2013 of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU. Off. J. Eur. Union.

Fernandes, E., Pacheco, R.R., 2007. Airport management: A strategic approach. Transportation (Amst). 34 (1), 129–142. https://doi.org/10.1007/s11116-006-9102-8.

de Portugal, G., 2015. PETI 3+ Plano Estratégico dos Transportes e Infraestruturas 2014–2020. Portuguese Strategic Plan for Transport and Infrastructure 2014–2020.

Infraestruturas de Portugal, 2016. Plano de investimentos em infraestruturas Ferrovia 2020 (Railway Investment Plan).

Infraestruturas de Portugal, 2005. Instrução de exploração Técnica n.º 50 - Rede Ferroviária Nacional.

Kosijer, M., Ivic, M., Beloševic, I., Pavlovic, N., Opricovic, M., 2020. Fuzzy multicriteria decision-making in railway infrastructure planning and design. Gradjevinar 72, 323–334. 10.14256/JCE.2459.2018.

Habibzadeh, F., 2017. How to report the results of public health research. J. Public Heal. Emerg. 1, 90. https://doi.org/10.21037/jphe.2017.12.02.

Lydersen, S., 2020. Mean and standard deviation or median and quartiles? J. Nor. Med. Assoc. 1–3.

Machado-León, J.L., de Oña, R., Baouni, T., de Oña, J., 2017. Railway transit services in Algiers: priority improvement actions based on users perceptions. Transp. Policy 53, 175–185. https://doi.org/10.1016/j.tranpol.2016.10.004.

Macharis, C., Bernardini, A., 2015. Reviewing the use of multi-criteria decision analysis for the evaluation of transport projects: Time for a multi-actor approach. Transp. Policy 37, 177–186. https://doi.org/10.1016/j.tranpol.2014.11.002.

Macura, D., Saaty, R., Prokić, M., Jerković, V., 2020. Resource constrained projects prioritization with Mcdm method case study: serbian railway infrastructure projects, in: Quantitative Methods in Logistics. pp. 7–24. 10.37528/ftte/9786673954196.001.

Madadizadeh, F., Asar, M.E., Hosseini, M., 2015. Common statistical mistakes in descriptive statistics reports of normal and non-normal variables in biomedical sciences research. Iran. J. Public Health 44, 1557.

Mandic, D., Jovanovic, P., Bugarinovic, M., 2014. Two-phase model for multi-criteria project ranking: Serbian Railways case study. Transp. Policy 36, 88–104. https://doi.org/10.1016/j.tranpol.2014.08.002.

Marcelo, D., Mandri-Perrott, C., House, S., Schwartz, J., 2016. Prioritizing Infrastructure Investment. Prioritizing Infrastruct. Invest. A Framew. Gov. Decis. Mak. 10.1596/1813-9450-7674.

Morfoulaki, M., Papathanasiou, J., 2021. Use of promethee mcda method for ranking alternative measures of sustainable urban mobility planning. Mathematics 9 (6), 602. https://doi.org/10.3390/math9060602.

Morgan, C.A., Protopapas, A., Warner, J.E., Carlson, T.B., Huang, J. (Jade), Li, Y. (Sabrina), Olson, L.E., 2012. Identification of priority rail projects for Texas-initial methodology/User Manual and Guidebook.

Official Journal of the European Union, 2019. Directive (EU) 2019/1936 of the European Parliament and of the Council.

Oliveira, A., 2016. Priority Definition for Railway Activities (in Portuguese). University of Beira Interior.

Oliveira, A., Gonçalves, J., Santos, B., 2017. Priorização de intervenções de proximidade na Rede Ferroviária Nacional (Priority definition for railway activities). ICEUBI2017 – International Congress on Engineering. University of Beira Interior, Covilhã.

Pamucar, D., Macura, D., Tavana, M., Božanić, D., Knežević, N., 2022. An integrated rough group multicriteria decision-making model for the ex-ante prioritization of infrastructure projects: the Serbian Railways case. Socioecon. Plann. Sci. 79, 101098.

Protopapas, A., Warner, J.E., Morgan, C.A., 2012. Evaluation of methodologies in benefit-cost and economic impact analyses for freight rail projects. Transp. Res. Rec. 2288 (1), 83–90. https://doi.org/10.3141/2288-10.

Quadros, S.G., Nassi, C.D., 2015. An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil. Transp. Policy 40, 8–16. https://doi.org/10.1016/j.tranpol.2015.02.002.

República Portuguesa, 2020. Programa Nacional de Investimentos 2030 (2030 National Investment Program).

Shen, W., Xiao, W., Wang, X., 2016. Passenger satisfaction evaluation model for Urban rail transit: a structural equation modeling based on partial least squares. Transp. Policy 46, 20–31. https://doi.org/10.1016/j.tranpol.2015.10.006.

Stoilova, S., Munier, N., Kendra, M., Skrúcaný, T., 2020. Multi-criteria evaluation of railway network performance in countries of the TEN-T orient-east med corridor. Sustain. 12 (4), 1482. https://doi.org/10.3390/su12041482.

Washington State Department of Transportation, 2008. Rail benefit/impact evaluation methodology.

Yang, D., Li, J., Gao, P., Chen, T., Cheng, Z., Cheng, K., Deng, H., Fang, Q., Yi, C., Fan, H., Wu, Y., Li, L., Fang, Y., Tian, G., Pan, W., Zhang, F., 2021. The prognostic significance of electrocardiography findings in patients with coronavirus disease 2019: A retrospective study. Clin. Cardiol. 44 (7), 963–970. https://doi.org/10.1002/clc.23628.

Yannis, G., Kopsacheili, A., Dragomanovits, A., Petraki, V., 2020. State-of-the-art review on multi-criteria decision-making in the transport sector. J. Traffic Transport. Eng. (English Edition) 7 (4), 413–431.

Yuan, Y., Yang, M., Feng, T., Rasouli, S., Li, D., Ruan, X., 2021. Heterogeneity in passenger satisfaction with air-rail integration services: results of a finite mixture partial least squares model. Transp. Res. Part A Policy Pract. 147, 133–158. https://doi.org/10.1016/j.tra.2021.03.003.

Yücel, N., Tasąbat, S.E., 2019. The selection of railway system projects with multi creteria decision making methods: a case study for Istanbul. Procedia Comput. Sci. 158, 382–393. https://doi.org/10.1016/j.procs.2019.09.066.