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Selection of maintenance, renewal and improvement projects in rail lines using the Analytic Network Process

Jesús Montesinos-Valera[a], Pablo Aragonés-Beltrán[b*], Juan-Pascual Pastor-Ferrando[b]

a Operations and Engineering Department, Administrador de Infraestructuras Ferroviarias (ADIF). Bailén 5.46007 Valencia, Spain

b Department of Engineering Projects. Universitat Politècnica de València. Camino de Vera s/n. 46022 Valencia, Spain

***Corresponding Author:**
Pablo Aragonés-Beltrán; aragones@dpi.upv.es;
Tel. +34 963879860:
Fax: +34 963879869

Email addresses: jemontesinos@adif.es (Jesús Montesinos-Valera), aragones@dpi.upv.es (Pablo Aragonés-Beltrán), jppastor@dpi.upv.es (Juan-Pascual Pastor-Ferrando)

Abstract

This paper addresses one of the most common problems that a railway infrastructure manager has to face: to prioritize a portfolio of maintenance, renewal and improvement (MR&I) projects in a railway network. This decision making problem is complex due to the large number of MR&I projects in the portfolio and the different criteria to take into consideration, most of which are influenced and interrelated to each other. To address this problem, the use of the Analytic Network Process (ANP) is proposed. The method is applied to a case study in which the Local Manager of the public company, who is responsible for the MR&I of Spanish Rail Lines, has to select the MR&I projects which have to be executed first. Based on the results, it becomes evident that, for this case study, the main factor of preference for a project is the location of application rather than the type of project. The main contributions of this work are: the deep analysis done to identify and weigh the decision criteria, how to assess the alternatives and provide a rigorous and systematic decision-making process, based on an exhaustive revision of the literature and expertise.

Keywords: Maintenance, renewal & improvement; rail line projects; analytic network process; project portfolio management; project management.

1 Introduction

The construction of railway infrastructure networks requires heavy investment, long execution time and life cycles. Once constructed, the basic elements in the railway (track design, railway curve radii, bridges, tunnels and platform type) are difficult to modify. These elements are located in areas with different environmental conditions and have different deterioration processes (Furuya & Madanat, 2013).

Maintenance, Renewal and Improvement (MR&I) of railway lines are essential actions to maintain railway infrastructures in good condition and to adapt them to environmental changes and new operating conditions and needs. Grimes and Barkan (2006) differentiate between ordinary maintenance and renewal maintenance techniques. The first one includes the renewal of small quantities of infrastructure components, and the second one includes the replacement of larger quantities of components, more sophisticated, and more expensive equipment. Improvement measures refers to actions aimed at improving infrastructure performance beyond the current optimal level by improving functionality and reducing operation and maintenance costs (ADIF, 2010).

MR&I project plans have a great impact in the short term because they affect the performance of already operating facilities. A critical issue for public infrastructure managers and planners is the effective allocation of the scarce resources available for maintenance and repair of railway infrastructures (Durango-Cohen & Madanat, 2008). According to Nyström and Söderholm (2010) the manager of a rail network area (local manager) is faced with different MR&I needs and a limited budget to satisfy them. This is materialized in projects to be executed with different levels of urgency, different levels of investment and different improvement measures on the railway network.

Therefore, the problem for the local manager is to prioritize the portfolio of MR&I projects. This decision problem is complex due to the large number of MR&I projects in the portfolio and the different criteria to take into consideration. The fundamental questions to be answered by the local manager are:

1. What specific MR&I projects have to be considered in the portfolio (alternatives of the decision making problem)?
2. What criteria must be taken into account in the analysis and what is their relevance?
3. How is each MR&I project evaluated against each criterion?
4. How to set priorities among all MR&I projects to be taken?

The overall objective of this work is to "Provide the infrastructure manager of a methodological tool, which has a solid scientific basis, in order to establish a priority among the many MR&I projects, taking into account multiple technical and economic criteria that the manager knows that will influence the decision"

In this paper, Multi-Criteria Decision Analysis (MCDA) is proposed as a tool for helping the manager to prioritize the MR&I projects. The use of the Analytic Network Process (ANP) with Benefits, Opportunities, Costs and Risks (BOCR), a well-known MCDA technique, is proposed to model this complex decision making problem (Saaty, 1980, 2001, 2005). The method is applied to a case study to select the MR&I projects which will be executed in a specific Spanish railway network area. The rest of this paper is organized as follows: in Section 2 a literature review is presented; in Section 3 a brief overview of AHP/ANP is given; in Section 4 the proposed decision model is described in details; in Section 5 the results are presented and discussed; finally, a brief closure is presented in Section 6.

2 Literature review

Transportation infrastructure management is a decision making process concerning the allocation of resources for maintenance, rehabilitation, and reconstruction of facilities composing transportation systems (Furuya & Madanat, 2013). The high costs of maintenance of civil infrastructures and the budget limitations, make infrastructure maintenance investment decision making a complex task (Arif, Bayraktar, & Chowdhury, 2016).

There are different approaches described in the literature to support MR&I decisions. The first one is a family of discrete-time maintenance optimization models which are formulated as finite (state and action) Markov Decision Processes (MDP). These models consider the management of facilities over a planning horizon of time. The objective is to choose a set of MR&I actions or policies, that minimizes the expected discounted sum of agency and user costs incurred over planning horizon. A review and evolution of these models can be seen in (Durango-Cohen & Madanat, 2008) (Durango-Cohen & Sarutipand, 2009). Seyedshohadaie, Damnjanovic, and Butenko (2010) used this framework and the Conditional Value at Risk to take into account risk associated with deterioration uncertainty in risk measurement in maintenance and rehabilitation planning. Gao, Guo, and Zhang (2011) formulate a multistage linear stochastic programming model for MR&I scheduling problems, given budget uncertainty, to optimize the system's condition, solved by means of Augmented Lagrangian Decomposition. Medury and Madanat (2013) introduces Approximate Dynamic Programming in a MDP-based framework to incorporate network-based considerations into MR&I decision-making. Furuya and Madanat (2013) suggest that decision makers have to consider not only the physical condition of the infrastructure, but also other multiple parameters, such as infrastructure's strategic importance, socioeconomic contribution and utilization. They develop a two-stage optimization model capturing interdependency between facilities' maintenance activities.

Another approach widely used to assist with decision making in civil engineering is Multi Criteria Decision Analysis (MCDA), which "is a term that includes a set of concepts, methods and techniques that seek to help individuals or groups to make decisions, which involve several points of view in conflict and multiple stakeholders" (Belton & Stewart, 2002). MCDA concepts, methods and applications have been largely studied in the Operational Research Literature (Figueira, Greco, & Ehrgott, 2005), (Bouyssou, Marchant, Pirlot, Tsoukias, & Vincke, 2006), (Ishizaka & Nemery, 2013). Among the better known models are those based on Multiple Attribute Utility Theory (MAUT) (Keeney & Raiffa, 1976), Analytic Hierarchy Process (AHP) (Saaty, 1980) and Analytic Network Process (ANP) (Saaty, 2001), Outranking Methods such as ELECTRE (Roy, 1991) or PROMETHEE (Brans, Vincke, & Mareschal, 1986) or the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang & Yoon, 1981).

Selection of the mathematical model based on discrete MCDA is not easy. All MCDA techniques have their advantages and drawbacks. According to Bouyssou et al. (2000) there is no best model. Using a technique or another depends on the type of decision problem and its context. Wallenius et al. (2008) made a thorough bibliometric analysis on the development of MCDA techniques for the period 1992-2007, which is an update of a similar previous analysis. These authors concluded that the MCDA field has made great progress in both theoretical and practical applications. The growth of publications related to AHP stands out from the other techniques mentioned.

The cost-benefit analysis (CBA) is one of the most widely used approaches for evaluating public investment, particularly for the analysis of both general and specific rail investment projects. Damart and Roy (2009) suggests that CBA does not capture the full complexity of the problem and recommend using multicriteria approaches. Olsson, Økland, and Halvorsen (2012) have used CBA to compare railway projects in several EU countries and show that the results obtained by this method are strongly dependent on the data used in each country. This high variability can be explained by the use of a previous multi-criteria analysis (formal or informal) for the application of the CBA model to each country.

Recent studies suggest a more comprehensive view of the problem. Famurewa, Stenström, Asplund, Galar, and Kumar (2014) applies Fuzzy Inference System for aggregating selected railway infrastructure performance indicators to relate maintenance and renewal function to capacity situation and also to enhance strategic decision making and long term infrastructure management. Famurewa, Asplund, Rantatalo, Parida, and Kumar (2015) applies risk matrix as a maintenance analysis method for the classification of railway systems into risk categories and present an adapted criticality analysis method for the generation of an improved list for assemblies and systems based on the weakest link theory. Pardo-Bosch and Aguado (2015) present a Prioritization Index for the Management of Hydraulic Structures which is based on multi-criteria decision making to prioritize non-similar maintenance investments in hydraulic structures considering three axioms of sustainability (social, environmental and economic).

Arif, Bayraktar, and Chowdhury (2016) suggest that decision makers have to consider not only the physical condition of the infrastructure, but also other multiple parameters, such as infrastructure's strategic importance, socioeconomic contribution and utilization. These authors, after reviewing existing decision making frameworks, propose a prototype decision support framework for allocating infrastructure maintenance investments by integrating multiple decision parameters, considering budget constraints and taking a portfolio management approach. This framework integrates Multiattribute Utility Theory (MAUT), Markov Decision Process (MDP), and Portfolio Management Approach. These authors also say that "there is a need for a decision support framework that can considerer multiple decision parameters, be used at a local level, and adopt a portfolio management approach while making infrastructure maintenance decisions under budgetary constraints" (Arif et al., 2016).

Based on these ideas, in this work, the use of Analytic Network Process is proposed as an alternative to address the problem. The reasons for using an ANP-based decision analysis approach in the present work are: (i) they allow decision makers to analyze complex decision-making problems using a systematic approach that decomposes the main problem into simpler and affordable subproblems, (ii) it incorporates both qualitative and quantitative factors, (iii) if there are interdependencies among groups of elements (criteria and alternatives) ANP should be used, (iv) the detailed analysis of priorities and interdependencies between clusters' elements, forces the DM to carefully reflect on his/her project priority approach and on the decision-making problem itself, which results in a better knowledge of the problem and a more reliable final decision.

3 Overview of AHP/ANP

The Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP) are theories of relative measurement of intangible criteria (Saaty & Sagir, 2009), proposed by Saaty (Saaty, 1980, 2001, 2005). AHP breaks down a decision problem into several levels in such a way that they form a hierarchy with unidirectional hierarchical relationships between levels. The top level of the hierarchy is the main goal of the decision problem. The lower levels are the tangible and/or intangible criteria and sub-criteria that contribute to the goal. The bottom level is formed by the alternatives to evaluate relative to the criteria. AHP uses pairwise comparison to allocate weights to the elements of each level, measuring their relative importance with Saaty's 1-to-9 scale, and finally calculates overall weights for evaluation at the bottom level. The method also calculates a consistency ratio (CR) to verify the coherence of the judgments, which must be about 0.10 or less to be acceptable. Mathematical foundations of AHP can be found in (Saaty, 1994, 2008).

AHP is conceptually easy to use; however, its strict hierarchical structure, based on the independence among the elements of the hierarchy, cannot handle the complexities of many real world problems. ANP allows to model decision making problems with dependence and feedback among elements of the problem (criteria and alternatives). ANP represents a decision-making problem as a network of criteria and alternatives (all called elements), grouped into clusters. All the elements in the network can be related in any possible way, i.e., a network can incorporate feedback and interdependence relationships within and between clusters. This provides a more accurate model of complex settings. The influence of the elements in the network on other elements in that network can be represented in a supermatrix. This concept consists of a two-dimensional element-by-element matrix which adjusts the relative importance weights in individual pairwise comparison matrices to build a new overall supermatrix with the eigenvectors of the adjusted relative importance weights.

Figure 1: ANP steps scheme

According to Saaty (2001), the ANP model comprises the steps shown in Figure 1:

1) Given a decision problem with $x_1, x_2, \ldots, x_N$ elements, the first step consists of building a model grouping the elements into $c_1, c_2, \ldots, c_G$ clusters. Let x_i^c the i element of the model, which belongs to cluster c, with $i = 1,\ldots,N$, $c = 1,\ldots,G$. Let x^{c_a} the elements of cluster c_a , $\{x_i^c : c = c_a\}$. Let n_{c_a} the number of elements of cluster c_a.

2) Identify the elements' relationships, ask the DM, and obtain the (NxN) Elements' Relationships matrix, $= [r_{i,j}] = [r_{i,j}^{c_a,c_b}]$. $r_{i,j}^{c_a,c_b} \in \{0,1\}$ where $c_a, c_b = 1 \ldots$ G and $i,j = 1 \ldots$ N:

   - $r_{i,j}^{c_a,c_b} = 0$ indicates that the element $x_i^{c_a}$ has no influence on the element $x_j^{c_b}$, and in the graphical model there isn't an edge between $x_i^{c_a}$ and $x_j^{c_b}$.
   - $r_{i,j}^{c_a,c_b} = 1$ indicates that the element $x_i^{c_a}$ has some influence on the element $x_j^{c_b}$, and in the graphical model there is an arc from $x_j^{c_a}$ to $x_i^{c_b}$.

3) Obtain the (GxG) Clusters' Relationships matrix, $\widehat{\boldsymbol{R}} = [\hat{r}_{c_a,c_b}]$. $\hat{r}_{c_a,c_b} = \{0,1\}$ where $c_a, c_b = 1 \ldots$ G:

   - $\hat{r}_{c_a,c_b} = 0$ indicates that any element of cluster c_a has influence on any element of cluster c_b:

$$\hat{r}_{c_a,c_b} = 0 \ \rightarrow \forall\, i,j \ \ i,j = 1,\ldots,N : \ r_{i,j}^{c_a,c_b} = 0$$

   - $\hat{r}_{c_a,c_b} = 1$ indicates that some element of cluster c_a has influence on some (at least one) elements of cluster c_b:

$$\hat{r}_{c_a,c_b} = 1 \ \rightarrow \exists\, i,j \ \ i,j = 1,\ldots,N : \ r_{i,j}^{c_a,c_b} = 1$$

4) Use usual AHP pairwise matrices to compare the influence of the elements belonging to each cluster on any element, and derive a priority vector, and obtain the (NxN) Unweigthed Supermatrix, $\boldsymbol{U} = [u_{i,j}^{c_a,c_b}]$, with $u_{i,j}^{c_a,c_b} \in [0,1]$, $c_a, c_b = 1,\ldots$,G

and $i, j = 1, \ldots, \mathrm{N}$, where $u_{i,j}^{c_a,c_b}$ is the influence of element i, which belongs to cluster c_a, on element j, which belong to cluster c_b:

- $u_{i,j}^{c_a,c_b} = 0$ indicates that element i which belongs to cluster c_a has no influence on element j which belongs to cluster c_b.

$$u_{i,j}^{c_a,c_b} = 0 \;\leftrightarrow\; r_{i,j}^{c_a,c_b} = 0$$

- $u_{i,j}^{c_a,c_b} = 1$ indicates that element i which belongs to cluster c_a is the unique element of cluster c_a which has influence on element j which belongs to cluster c_b:

$$u_{i,j}^{c_a,c_b} = 1 \;\Rightarrow \forall\, k \neq i,\; k = 1 \ldots N : x_k \in x^{c_a} \rightarrow r_{k,j}^{c_a,c_b} = 0$$

- Given a cluster, c_a, and an element j that belongs to cluster c_b, $x_j^{c_b}$, the sum of the unweighted values of the elements which belong to c_a, that have influence on x_j is 1. If any element of c_a has influence on x_j then the sum is 0:

$$\text{Given } c_a, x_j^{c_b}$$

$$\sum_{\substack{k=1 \\ k:\, x_k \in x^{c_a}}}^{N} \left(u_{k,j}^{c_a,c_b}\right) \in \{0,1\}$$

Columns sum, $\sum_{i=1}^{N}\left(u_{i,j}\right)$, indicates how many clusters have influence on the column element. Identify the components and elements of the network and their relationships.

5) Conduct pairwise comparisons on the clusters, obtaining $\widehat{\boldsymbol{U}} = [\hat{u}_{c_a,c_b}]$ the (GxG) Cluster Weights matrix, with $\hat{u}_{c_a,c_b} \in [0,1]$, $c_a, c_b = 1, \ldots$,G, where $\hat{u}_{c_a,c_b}$is the influence of cluster c_a on cluster c_b.

   - $\hat{u}_{c_a,c_b} = 0$, shows that any element of cluster c_a has influence on any element of cluster c_b.
   - $\sum_{c_a=1}^{G}(\hat{u}_{c_a,c_b}) = 1$.

6) Calculate $\boldsymbol{W} = \left[w_{i,j}^{c_a,c_b}\right]$ the (NxN) Weigthed Supermatrix , with $w_{i,j}^{c_a,c_b} \in [0,1]$, $c_a, c_b = 1, \ldots$,G and $i, j = 1, \ldots$,N, where $w_{i,j}^{c_a,c_b} = u_{i,j}^{c_a,c_b} \cdot \hat{u}_{c_a,c_b}$:

   - $w_{i,j}^{c_a,c_b}$ is the weighted influence of element *i*, which belongs to cluster c_a, on element *j*, which belongs to cluster c_b.
   - $\sum_{i=1}^{N}\left(w_{i,j}^{c_a,c_b}\right) \in]0,1]$

7) Calculate $\boldsymbol{Q} = \left[q_{i,j}^{c_a,c_b}\right]$ the (NxN) Normalized and Weigthed Supermatrix, with: $q_{i,j}^{c_a,c_b} \in [0,1]$, $c_a, c_b = 1, \ldots$,G and $i, j = 1, \ldots$,N , where $q_{i,j}^{c_a,c_b} = \frac{w_{i,j}^{c_a,c_b}}{\sum_i\left(w_{i,j}^{c_a,c_b}\right)}$.

   - $q_{i,j}^{c_a,c_b}$ is the normalized weighted influence of element *i*, which belongs to cluster c_a, on element *j*, which belongs to cluster c_b.
   - $\sum_i\left(q_{i,j}^{c_a,c_b}\right) = 1$. $\boldsymbol{Q}$ is a left-stochastic matrix.

8) Raise the weighted supermatrix to limiting powers until the weights converge and remain stable (limit supermatrix), $= \lim_{k\to\infty} \boldsymbol{Q}^k$; l_i is the final priority of element x_i. If x_i is an alternative, l_i is the rating of the alternative. If x_i is a criterion, l_i is the weight of the criterion.

The design of the network in a decision problem is a key factor to find an appropriate solution, although there are no clear directions in the literature on how to design the network (Saaty & Shih, 2009). Network design is usually the first and one of the most important steps of the method. It forces the decision maker and his/her team to conduct a thorough analysis of the problem. It is common practice to develop a complex network model, after analyzing a problem with simpler models (type, hierarchy, single network or costs and benefits subnets). When the decision problem is complex, a model based on Benefits, Opportunities, Costs and Risks (BOCR) subnets is used (Saaty, 2005). Benefits are criteria to evaluate immediate advantages, Opportunities are criteria to evaluate future advantages, Costs are criteria to evaluate immediate disadvantages and Risks are criteria to evaluate future disadvantages.

AHP and ANP, like the rest of MCDA methods, have weaknesses that are under debate in the scientific community. The main points of discussion are the rank reversal problem and the method proposed to derive priorities from the pairwise (Dyer, 1990) (Harker & Vargas, 1990), (Bana e Costa & Vansnick, 2008) (Bouyssou et al., 2006), (Ishizaka & Labib, 2011), (Kulakowski, 2015), (Karanik, Wanderer, Gomez-Ruiz, & Pelaez, 2016). Other point of debate is how AHP and ANP manage the vagueness and ambiguity of the judgements of decision makers. Among decision theorists, ambiguity usually refers to imprecision in an individual's probabilistic judgements, in the sense that the available evidence is consistent with more than one probability distribution over possible states of the world (Shattuck & Wagner, 2016).

AHP and ANP assume that the decision maker has certain level of knowledge about the alternatives and about the consequences of the choice. Ambiguity is not considered in this method. Vagueness is referred to the imprecision in making judgements. Numerous studies to manage the vagueness have been published which use fuzzy logic applied to MCDA techniques (Mardani et al., 2015) and, particularly, to AHP and ANP (C: H. Cheng, 1997) (Özkır & Demirel, 2012). Although this approach may be useful, Saaty and Tran (2007) considers that its application adds complexity to the problem. These discussions are not the subject of this work.

AHP and its most developed version, ANP, have been extensively used in the field of project portfolio prioritization: Karydas and Gifun (2006) applied both AHP and Multi-Attribute Utility Theory for prioritization of infrastructure renewal. Cheng and Li (2005), Aragonés-Beltrán, Chaparro-González, Pastor-Ferrando, and Rodríguez-Pozo (2010), Aragonés-Beltrán, Chaparro-González, Pastor-Ferrando, and Pla-Rubio (2014) applied ANP for project selection. Ivanović, Grujičić, Macura, Jović, and Bojović (2013) concluded that ANP as a multicriteria decision making approach is suitable for making a correct decision related to selection of transport infrastructure projects. In the maintenance field, Arunraj and Maiti (2010) used AHP combined with Goal Programming for maintenance policy selection. Kumar and Maiti (2012) used fuzzy ANP for maintenance policy selection. Salem, Miller, Deshpande, and Arurkar (2013) used AHP for selecting an effective plan for bridge rehabilitation.

AHP has been used in the field of railway management and other similar projects: for selection of urban rail transit networks proposals (Gerçek, Karpak, & Kilinçaslan, 2004), to assess the feasibility for adding new railway stations (Baek, Chung, Song, & Kim, 2005), for prioritization of railway lines to reconstruct (Baric, Radacic, & Danko, 2006), selection of maintenance actions in railway infrastructure (Nyström & Söderholm, 2010) or for the elimination of useless line crossings (Sohn, 2008).

ANP with Benefits, Opportunities, Costs and Risks (BOCR model), has been used by Liang and Li (2008) for enterprise resource planning (ERP) and manufacturing executive system (MES) projects selection in a Chinese undershirt manufacturer, by Lee, Chen, and Kang (2009) to compare the performance of different feeder management systems (FMS) projects in China or by Lee, Kang, and Chang (2011) to select the most appropriate technology. A review of the main developments in the AHP and ANP can be found in (Al-Harbi, 2001), (Vaidya & Kumar, 2006), (Ishizaka & Labib, 2011), (Sipahi & Timor, 2010). A review of the use of MCDA methods in transport projects can be found in (Macharis & Bernardini, 2015) and for infrastructure Management in (Kabir, Sadiq, & Tesfamariam, 2013).

4 Proposed decision model

4.1 Formulation of the problem

The Spanish railway sector is regulated by the Railway Sector Act 39/2003 of 17 December and by Railway Regulation, Royal Degree 2387/2004 of 30 December. This act formally separated between railway infrastructure operators and railway services companies that at that time was played only by a public company (RENFE). It formed a new public company, ADIF (Railway Infrastructure Manager), which is responsible for the management and construction of railway infrastructure in Spain. As a result, ADIF manages and operates the Spanish railway network, keeping it in the best possible condition.

ADIF has divided the Spanish railway network in six Territorial Management Areas (ADIF, 2015). This case study focuses on the East Area located in Valencia (Spain). The Maintenance Manager of Valencia (Local Manager) is responsible for the management of the rail network of this area. The problem that local managers have to face is selecting the MR&I projects that should be executed first. The rail network section selected for the case study is extensive including different train lines and infrastructures of all types, from non-electrified lines and mechanical-electrical signals to high-speed rail lines (220 km/h) with high performance and variable traffic levels. The lack of homogeneity among the possible actions makes the decision analysis much more complex (See Annex 1 for the scheme of the East Area Network).

The present study was carried out by the Local Manager of the Valencia Department along with one of the technicians of his Department (and coauthor of this paper) that acted as Decision Maker (DM) by consensus, assisted by two members of the research team of the Department of Engineering Projects of the Polytechnic University of Valencia, who played the role of Analysis Team (AT). The local manager was interested in improving the procedure used so far, and having scientifically proven methodological tools to help them to ground and justify their recommendations. Figure 2 illustrates the decision-making process followed in this study.

Figure 2: Decision Making Process

In the first two meetings between the Analysis Team and the Decision Maker the decision problem was formulated and the main goal of the analysis process was identified as follows: "*Establishing priorities among the MR&I projects to be implemented by the Local Manager of the Valencia Unit*"

4.2 Identification of the MR&I projects

The railway network in the Valencia area is divided in 34 rail lines (Table 1). The Company technicians identified about 24 different standard actions to be performed on each line of the railway network (Table 2). Taking the Cartesian Product of these two sets 816 potential MR&I projects are obtained. Some of these projects are not feasible, as example, if a potential project consists of removing the level crossing in a rail line, and the rail line has no level crossings, this MR&I project is unreal. After an exhaustive analysis, 419 MR&I projects were identified (e.g., projects in Figure 3). In parallel to the identification and analysis of the alternatives, the next step was to identify the evaluation criteria, as described in the next section.

Table 1: List of standard actions

Table 2: List of rail lines in the East Area Network

Figure 3: Examples of feasible projects

4.3 Criteria analysis

All multicriteria methods call for the identification of key factors (values, objectives, criteria, points of view) which will form the basis of a decision making process (Belton & Stewart, 2002) and which must be (as far as possible) well defined (Figueira et al., 2005). According to Keeney and Raiffa (1976), "*in many instances it may be useful to have a group of knowledgeable experts identify the objectives in a problem area*". The DMs should identify criteria that: i) have value relevance, that is to say, the DMs has to be able to link criteria to the goal identified (Belton & Stewart, 2002), ii) they balance completeness and conciseness, i.e., all important aspects of the problem are captured and keeping the level of detail to the minimum (Keeney & Raiffa, 1976), and iii) they are relevant in the context of a particular decision making problem.

In this case study, the identification and analysis of the criteria was based on the:

- Experience of the DM.
- Quality Management Manual of ADIF (ADIF, 2010) based upon the key maintenance indicators defined by ADIF. These indicators are according to

EN 15341 and RAMS (Reliability, Availability, Maintainability and Safety) proposed in IEC 62278. RAMS defines safety management and life cycle of the elements and is a common technique, adapted to railway specific problems in EN-50126 and its derived family of norms (50128, 50129, etc), used in railway analysis to quantify changes in maintainability, safety and operation parameters (IEC, 2002).

- Common safety indicators defined by European Directive 88/2014 are used to create safety related criteria.
- Review of existing literature about decision making on transportation infrastructure projects and maintenance management.

Tsamboulas (2007) analyzed economic cost, return on investment, removal of bottlenecks, and environmental, political and interoperability effects. Gerçek, Karpak, and Kilinçaslan (2004) proposed 4 groups of criteria: financial (operating and maintenance costs, infrastructure costs and cost of the trains), economic (operation cost of road vehicles, purchase of road vehicles, road accidents cost, accidents cost, travel times and environmental costs), planning (system capacity, accessibility, integration and compliance with the general plan) and political (expropriation costs, construction time, etc). Ahern and Anandarajah (2007) studied users' benefits resulting from improving public transport services, connections between the main population centers, balanced regional development, reduced environmental impact and transparency in project selection using goal programming.

In a first stage of this work, a hierarchical model based on AHP was developed, according to Nyström and Söderholm (2010). The DM identified influence relationships among the criteria, so it was changed to an ANP model. This model evolved from one single network model, to a model with two subnets (Benefits and Costs), until current BOCR model which is presented in this article. In addition, the criteria were modified. The final model is the result of a deep reflection on the problem developed over three years, while the DM was applying each of the models.

4.3.1 The ANP-BOCR model

The following paragraphs describe the decision model based on BOCR subnets in order to weigh the criteria. As the number of alternatives was very high, the alternatives cannot be included in the ANP supermatrices because the alternatives cannot be compared for each criterion. That is, the weight of the criteria is not dependent on the proposed alternatives, but on their influence relationships. In this case, the alternatives were evaluated using Ratings.

Table 3 presents the four subnets with the groups of criteria that have been identified in each subnet. The cluster "Rail Line Characteristics" (RLC) appears in all subnets because these affect the Benefits, Costs, Opportunities and Risks. Criterion "Future maintenance costs" appears in the Costs (EEC.C25) and in the Risks (CUF.C28) subnets. Criterion "Reduction in the number of incidents" is a criterion of Technical Efficiency in the Benefits subnet (TEC.C08) and of Performance Improvement in the Opportunities subnet (PIC.C16). Following is a list of criteria grouped into their clusters.

Table 3. The ANP-BOCR Model

Cluster 1. (RSC) Rail Safety Criteria. This set of criteria assesses the effect of the MR&I projects on rail safety in the rail section under study. Rail safety is divided into two groups, rail and train operation safety and people safety. Operation safety comprises the actions taken to reduce the likelihood or severity of a malfunction that could cause a train derailment or a collision between trains. People safety refers to actions that prevent people from being run over by a train; actions taken to reduce train accidents will increase the priority of this action in the cluster. The criteria in this cluster are based upon the common safety indicators defined by the European rail agency.

- *RSC.C01: Reduction in the number of level crossings*. This criterion evaluates the reduction in the number of level crossings, which in turn reduces the number of accidents (Thomas, Rhind, & Robinson, 2006).
- *RSC.C02: Improvement of railway crossing signalling.* Any improvement in the level crossings signalling reduces the number of accidents.
- *RSC.C03: Improvement of driving support systems*. These systems prevent human error and facilitate the detection of system failures. This criterion evaluates how each MR&I project contributes to this improvement.
- *RSC.C04: Automatic control of lines and blocking systems*. The setting up of automation systems facilitate traffic management and reduce human intervention, increasing safety. This criterion evaluates the contribution of each MR&I action to the improvement of these systems.

Cluster 2. (PEC) *Performance efficiency criteria*. These criteria describe the effect of the actions that will increase the number of trains or passengers that will use the rail system as a result of technical or management improvements, as well as reductions in train power costs. These improvements are easily perceived by the users and train operators companies.

- PEC.C05: *Travel time reduction*. This criterion assesses the reduction in travel time due to the implementation of MR&I actions. Transport demand and traveller satisfaction increase with decreasing travel times (Fitzroy, Smith, & Germany, 1995), (Ieda, Kanayama, Ota, Yamazaki, & Okamura, 2001).
- *PEC.C06: Critical block reduction*. The capacity of a rail section is limited by the capacity of the weaker line section, which becomes a bottleneck and sets the maximum number of trains that can use a given section of the rail network (Abril et al., 2008). This criterion evaluates the contribution of the MR&I project to the improvement in capacity in bottlenecks.
- *PEC.C07: Improvement of operations systems*. All rail systems have some maximum theoretical operating specifications, which determine the maximum speed at which a train can run and the minimum headway between trains (slopes, curve radii, rail line conditions, etc.). Any changes in the operations system that approach real operation to theoretical maximum values help increase system capacity and reduce delays caused by the accumulation of trains. This criterion evaluates the changes that bring about a more efficient exploitation of the rail line and approach it to its theoretical capacity.

Cluster 3. (TEC) ***Technical Efficiency Criteria***. This set of criteria includes all factors that enable a more efficient performance of the system; for example, projects that extend the life of existing equipment, facilitate preventive maintenance of the system, improve system reliability, and in general, any project that improves service quality for as long as possible at the lowest cost.

- CET.C8: *Reduction in the number of incidents*. This criterion assesses the reduction in the number of annual incidents as a consequence of the implementation of the project. It evaluates how the project changes the future number of incidents. A reduction in the number of incidents increases system efficiency and facilitates preventive maintenance.

- CET.C9: *Reduction in train delays*. Train delays are useful indicators of system failures and general performance of the rail system, because they affect system capacity and expected punctuality (Huisman & Boucherie, 2001). This criterion evaluates each MR&I project in terms of reduction in train delays. The reduction in train delays is one of the main objectives of the company's management policy and they are usually independent from travel duration (Goverde, 2010).

Cluster 4. (SUC) *Social Utility Criteria*. This group of criteria evaluates the effect of projects on the overall urban communications and the effects of railway on urban structure.

- SUC.C10: *Improvement in road safety*. This criterion evaluates the effects of the project on the accidents occurring in the urban area outside the railway infrastructure but close to it. How rail lines are integrated in their surrounding urban areas is important to road safety.

Cluster 5. (RLC) *Rail line characteristics*. The effects of the improvement measures depend on the characteristics of the rail line. For example, the automated signalling of a rail line with little traffic is much less efficient than the same action performed on a heavy-traffic line, such as a commuter line. This group of criteria evaluates each MR&I project taking into account the previous characteristics of the line.

- RLC.C11: *Kmtrain/km*. This criterion assesses the number of kilometers run by a train on a section of a rail line, divided by the number of kilometers of that rail section. It is an indirect measure, since the value of km-train is a known value and is calculated in order to estimate train maintenance costs and operator's fees. The combination of these two variables shows the real use of the system.
- RLC.C12: *Level crossings in the line*. The presence of level crossings (PaN) affects the performance of the rail system and is a common source of incidents. On the one hand the interaction between road and rail traffic always generates breakdowns and interference, and on the other hand, it is a very sensitive safety system generating multiple system failures. Lines with many level crossings should be given preference when performing MR&I projects.
- RLC.C13: *Line speed.* The nominal line speed is the maximum speed on this rail section regardless of specific limitations due to the presence of singular points (curves, bridges, poorly maintained line sections). Line speed affects the maximum capacity of the system and recovery time after an incident. Rail sections with speeds lower than specified affect system performance and recovery time. As Ieda et al. (2001) described, traffic congestion and travel time are strongly associated with service dissatisfaction.
- RLC.C14: *Signalling level*. This criterion assesses the type of line-blocking system. The blocking system is the traffic management system between two railway stations. The type of blocking system marks the practical limit of the capacity of the line. The more efficient the blocking system is, the greater the capacity of the line and the more robust against incidents (Abril et al., 2008).

Cluster 6. (PIC) *Performance improvement criteria*. This set of criteria evaluates to what extent MR&I projects improve line use possibilities and reduce rail traffic congestion.

- PIC.C15: *Increase in the number of trains*. Improvement measures to increase the number of trains per line. Fitzroy et al. (1995) suggest that train frequency, traffic density and population density can explain most of the differences in transport demand in the countries under study.
- PIC.C16: *Reduction in the number of incidents*. This criterion has been described in the cluster Technical efficiency. This criterion generates direct benefits and opportunities for future improvement.

Cluster 7. (CIC) *Cost improvement criteria*. This group of criteria evaluates the reductions in costs that each project can generate.

- CIC.C17: *Reduction in maintenance costs*. This criterion assesses reduction in operation and maintenance costs as a result of implementing MR&I projects. The factors used in this paper to estimate reductions in maintenance costs were analyzed qualitatively to describe non-realized reductions that were found probable for the specific circmustances (Bouch, Roberts, & Amoore, 2010), (Johansson & Nilsson, 2004).
- CIC.C18: *Cost of further improvement*. This criterion assesses to which extent an MR&I project helps or affects the implementation of future projects. There are projects that can solve a current problem, but can involve very high additional extra costs in future projects or even prevent the

implementation of further projects, becoming a major constraint for the future use of the rail system.

Cluster 8. (LIC) ***Line improvement criteria***. This group of criteria evaluates how each MR&I project contributes to improving the capability of the railway line in which it is implemented. The criteria included in this group describe the performance of a railway line from a maintenance point of view.

- LIC.C19: *Delays/km*. The delays in the trains are one of the main quality factors perceived by train users (Asensio & Matas, 2008).This criterion refers to the number of delays due to the bad conditions of the line. It is measured in minutes of train delays, divided by the number of kilometers of the line section so as to compare delays between sections.
- LIC.C20: *Delays/kmtrain*. This criterion reflects train delays due to line saturation (number of trains running per line) and how a project can help reduce delays.
- LIC.C21: *Incidents/km*. This criterion is another key indicator of the performance of the line. This indicator is also used by ADIF as a management indicator. This criterion indicates wearing rate and quality of the line. It evaluates the actual number of incidents in the line. A project that produces an improvement in a bad line is better than a project that produces the same improvement in a good line.
- LIC.C22: *Incidents/km train*. This criterion considers the number of incidents associated with the number of trains running along each rail section. The higher the number of trains running in one-line section, the larger the number of incidents usually is. This criterion is used to discriminate heavy-

traffic sections with small number of incidents and low-traffic sections with many incidents. This parameter and the previous one are independent, since one measures incidents due to poor line conditions and the latter due to train traffic density.

Cluster 9. (EEC). ***Economic Efficiency criteria***. This group of criteria evaluates the cost of the proposed projects and the changes in general costs of operations before and after.

- EEC.C23: *Project cost*. This criterion assesses the cost of implementing the proposed MR&I projects, considering that, according to the DM's experience, it is not worth implementing neither very cheap nor very expensive projects. Thus MR&I projects of about € 25M should be better rated.
- EEC.C24: *Future operating costs*. This criterion assesses the effect of the project on the cost of future operation of the line section after project implementation, compared with the cost of current operation. The inclusion of this factor is important because it is not common practice to assess MR&I projects based on future operating costs. Usually very complex and advanced solutions have high operating costs, according to ADIF's experience. These costs include everything needed to keep the system under operation. This criterion is estimated calculating a percentage of future operation costs relative to current estimated costs. For example, Higher than 120% indicates an estimated future operating cost 120% higher than current cost.
- EEC.C25: *Future maintenance costs*. This criterion allows us to evaluate how line maintenance conditions change after project execution. It is different

from the former criterion because some projects may not affect operation costs but may affect maintenance.

Cluster 10. (CPC) ***Changes in project criteria***. This set of criteria assesses project maturity and likelihood of significant project deviations, according to the experience of the decision maker.

- CPC.C26: *Cost deviation*. This criterion estimates expected cost deviation in the implementation of the projects against budgeted costs. It measures uncertainty of project execution. This criterion has been analyzed by several authors (Cantarelli, van Wee, Molin, & Flyvbjerg, 2012), (Özgür, 2011).
- CPC.C27: *Results deviation*. This criterion analyzes the complexity of getting the desired results. The more complex a project is the more it depends on uncontrolled or external factors, the greater the expected deviation.

Cluster 11. (CUF) ***Criteria for future use***. This group belongs to the Risks Subnet. It includes criterion CUF.C28: Future maintenance cost.

- CUF.C28: *Future maintenance cost*. This criterion has been described in the Economic Efficiency cluster. This criterion helps to analyze costs, though it also generates risks. Experience tells us that maintenance costs can evolve over time to a reduction or an increase over the expected value. If over time, the implementation of a project has achieved a reduction of maintenance costs (future benefits), it becomes an opportunity. However, if this cost increases (future cost), then it is a risk. This criterion in this cluster, assesses the risk of a project to increase maintenance costs in the future.

4.3.2 Analysis of the relationships among criteria

After the identification and clustering the criteria (elements of the network), the next step was to determine the influence relationships among them. To identify which elements have some influence on the others within each subnet, Elements' Relationships matrices, was used (see steps 2 of ANP steps). The rows and columns of the matrix are formed by all the elements of each subnet. Table 4 shows the elements' relationship of Benefits subnet (see in Annex 2 the elements' relationships matrices of Opportunities, Costs and Risk subnets).

Table 4: Relationships between elements of the Benefits subnet

4.3.3 ANP supermatrices

The next step consists of assigning priorities to related elements in order to build the unweighted supermatrix. For this end, each criterion is analyzed in terms of which other criteria exert some kind of influence upon it; then the corresponding pairwise comparison matrices of each criteria group are generated in order to obtain the corresponding eigenvectors. For this end, the DM answered a questionnaire (an illustration is shown in Table 5) and the unweighted supermatrices were obtained. For these calculus Superdecisions software has been used. Unweighted supermatrix for Benefits is shown in Table 6 (see in Annex 3 the unweighted supermatrices of the Opportunities, Costs and Risks subnets).

The Analysis Team checked the CR of all pairwise comparison matrices. Most of them had a CR admissible, except for a few matrices that showed a CR slightly exceeding admissible. In such cases, the DM, assisted by AT and with the aid of Superdecisions software, returned to reformulate their judgments. It became apparent that small adjustments in judgements affected very little to the previous priority obtained through the eigenvector and however improved the CR to the allowable limits.

Table 5: Example of the questionnaire about prioritization of elements

Table 6: Subnet Benefits. Unweighted Supermatrix

In each subnet, different elements from different clusters have influences on one element and the corresponding unweighted matrix is non-stochastic by columns. Thus, according to (Saaty, 2001), all clusters that exert any kind of influence upon each group have to be prioritized using the corresponding cluster pairwise comparison matrices. The value corresponding to the priority associated with a certain cluster weights the priorities of the elements of the cluster on which it acts (in the corresponding unweighted supermatrix), and thus, the weighted supermatrix can be generated. Weighted supermatrix for Benefits is shown in Table 7 (see in Annex 4 the weighted supermatrices of the Opportunities, Costs and Risks subnets).

Table 7: Subnet Benefits. Weighted Supermatrix

From weighted supermatrices the limit supermatrix of each subnet is calculated. As a final step, the BOCR control hierarchy was assessed. In this case, the DM decided to give equal weight to all subnets. The weights of the criteria for each subnet are shown in the Results section.

4.4 Alternatives assessment

As aforementioned, the alternatives were evaluated using Ratings. The Ratings technique is recommended when a large number of alternatives are analyzed. Ratings are categories for each criterion whose values are obtained by pairwise comparison. The values are used to associate each alternative with a category (Saaty, 1990, 2006). In this way, a large number of alternatives can be evaluated without comparing them to each other. The alternatives are assumed to be independent of each other.

The DM identified the categories corresponding to each criterion and set their priorities using their respective pairwise comparisons. The rating values were selected taking into consideration whether the preference was of minimization or maximization. The scores were normalized in ideal mode to avoid rank reversal (Millet & Saaty, 2000), (Saaty & Vargas, 1993) (see Tables 8 and 9).

Table 8: Rating categories and ideal weights (I)

Table 9: Rating categories and ideal weights (II)

Most of the relationships between the categories are linear. However, there are criteria with nonlinear categories, for example, CEE.C22 Cost of the project plans. In this criterion, the decision maker considered that too expensive or too cheap projects usually are not beneficial projects either because they do not undertake major reforms or because they require spending many financial resources in a small area.

5 Results and Discussion

5.1Criteria weights

Tables 10, 11, 12 and 13 present the weights of the criteria organized by subnets. In the Benefits subnet, the most important criterion is criterion RLC.C12: *Level crossings in* *the line*, followed though by far by criteria RLC.C14 *Signalling level* and RSC.C03 *Improvement of driving support systems*. It is worth mentioning the little importance of those criteria associated with specific line performance factors. This shows that the DM considers project benefits to be more strongly related to the type of rail line than to the projects. This is logical because when a line has a poor performance (mainly defined by the number of level crossings and a poor signalling system) any project performed on this line will have a high priority.

(Tables 10 to 13: Criteria weights)

In the Opportunities subnet, the criterion with the highest weight is RLC.C14: *Signalling level*, followed by TEC.C08: *Reduction in the number of incidents*, LIC.C21: *Incidents/km* and RLC.C11: *Kmtrain/km* . The Signalling level is critical to determine whether a section of the rail line requires project on it. The Signalling level defines the actual capacity of the rail section under study, its robustness against incidents and its safety level. In general, the more intensive the use of a line (more *kmtrain/km*) and the greater the number of incidents, the more effective the measures taken will be. In the field of transport systems, a common problem is the adjustment of the infrastructure capacity to demand, because if demand is much lower than line capacity, operating costs will be too high. However, if demand gets too close to the maximum capacity of the line, service quality is greatly reduced, a factor which can be indirectly measured by the number of incidents.

Regarding the Costs subnet, criterion EEC.C24 *Future operating costs* is of great importance compared to the other criteria, clearly dominating the subnet. Behind this criterion, the use of the network (RLC.C11 *kmtrain/km*) is also very important, the two criteria together accounting for about 50% of the total weight. In other studies on maintenance costs of railway infrastructures (Johansson & Nilsson, 2004), one of the most important factors is the use of the line, because maintenance costs and needs increase with increasing use of the line.

In the Risks subnet, the criteria with highest priorities are RLC.C13 *Line Speed* and RLC.C14 *Signalling level*. Both have similar weights, much higher than the other criteria. The higher the speed and signalling level are, the higher the risk of a project of affecting the railway line negatively. The worst sections of the line are less likely to affect line capacity.

5.2 Priorities of the alternatives

Once the criteria weights and ratings were obtained, the DM evaluated each of the 419 alternatives for each criterion associating them with their corresponding category. By applying the BOCR multiplicative aggregation rule (BO/CR), the overall priorities of the alternatives were obtained. Given the large number of alternatives evaluated, in Table 14 only the 23 best alternatives are shown, being the last alternative the one whose priority is 60% compared to the best.

Table 14: Best scored alternatives

Almost all projects in the top 10 positions act on two very specific line sections, section 31300 L'Aldea-Salou and 32300 Buñol-Utiel. The former is an anomaly in the network, as it is a single-track line in the Mediterranean corridor, with heavy railway traffic and train links with two-way sections. Its conditions are much worse than the nearby rail line, because it has worse facilities and it is a single-track line section with level crossings. The Utiel-Buñol section has relatively heavy traffic for a line of low performance. Any project on these lines will substantially improve network performance.

Figure 4 depicts the results by section of the railway line. Each column shows the distribution of priority (in distributed mode) of each proposed project on the railway line section. The sum of the priorities of the projects of the line sections 31300, 32300 and 33800 stand out over the rest. The most highly recommended general projects are replacement of telephone blocking systems for automatic blocking systems, elimination of level crossings and the use of land-train radio. The less favourable projects are the construction of new substations (M). The construction of additional substations involves little additional benefits and high maintenance costs.

Figure 4: Projects grouped by railway line sections

5.3 Sensitivity analysis

A sensitivity analysis was performed to test the robustness of the priorities of the alternatives. In the multiplicative model BOCR makes no sense to modify the weights of the subnets because this does not produce alterations in the ranking. Doing this is equivalent to multiplying by a factor the result (Wijnmalen, 2007). In this case, the required sensitivity analysis is modified in a systematic way, regarding the weight of the criteria in each subnet and in the sequence it is presented how those changes affect the results.

It was considered in the model used that the weights of the criteria obtained through network models are independent of the alternatives. In this case, the systematic way to perform the sensitivity analysis is the following: 1) In each subnet, select a criterion and change successively its weight (redistributing each change proportionately among the other criteria in the subnet), calculating in every change the results in the subnet and in the final BOCR aggregation. 2) Repeat the step 1 for every criterion in the subnet, 3) Repeat steps 1 and 2 for every subnet.

As an illustration of this process, Figure 5 presents the sensitivity analysis for the most important criterion in the model, RLC.C12 in Benefits subnet, for the top ten alternatives. The weight of this criterion has been successively changed from 0 to 1 in twelve steps and, for each change, the final priorities for the top ten alternatives have been calculated (only these ten alternatives have been selected for simplicity). The horizontal axis shows the weight of the criterion RLC.C12 and the vertical axis shows the BOCR priority corresponding to the alternatives classified in the top 10 positions of the original ranking. The vertical dot line shows the original weight of this criterion. A detailed view is shown in Figure 6, which describes the changes in the ranking when the weight of the criterion is modified ±25%.

After the sensitivity analysis performed for all subnets, it was observed that when variations in the weights did not exceed 25% of its original weight, neither significant changes occurred in the alternatives classified in the top positions nor, in general, in the positions in which the original BOCR priorities were clearly differentiated. Only changes were seen in the ranking of the alternatives whose original priorities had similar values. Figure 7 displays the same sensitivity analysis for the alternatives ranked in positions 41 to 45.

Figure 5: Top ten alternatives sensitivity analysis for RLC.C12 weight in Benefits subnet

Figure 6: Detail of top ten alternatives sensitivity analysis for RLC.C12 weight in Benefits subnet

Figure 7: Alternatives ranked 41 to 45 sensitivity analysis for RLC.C12 weight in Benefits subnet

5.4 MR&I projects incompatility

Model analysis was based on the initial assumption that each of the 419 alternatives are independent. In this way, the results described above were obtained using certin common criteria set by ADIF maintenance division. However, there are projects that, if implemented in a particular line section, may cause other projects to be unnecessary. To solve this fact, a *projects-incompatibility matrix* was developed. Since the way to generate the alternatives is to apply all types of projects to all lines, incompatibilities only occur within a given rail line. The projects performed on different lines are independent of each other.

The projects incompatibility matrix was developed by the DM based on his experience. Project incompatibilities are grouped into five clusters of related projects, based on the standard actions (see Table 1):

- Projects for the replacement of line sections with different types of tracks (standard actions A, B, C), which are incompatible with each other as they involve different technical solutions for the same purpose but different cost and performance.
- New rail diversions. Partial actions included in the projects for track replacement.
- Projects for the replacement of the catenary (standard actions I and J), incompatible with each other, similar to track replacement.

• Type standard actions O (replacement of the electric blocking system for an electronic system), are unnecessary if standard actions Q or R have already been executed (replacement of ADB for BAB).

• The family of projects of replacement of telephone blocking systems for any of the standard actions S, T, U, and V which provide different technical solutions to the same problem with different results.

The incompatibility algorithm used is:

1. A priority rank of projects is generated.
2. The best rated project is selected.
3. The projects that are incompatible with the highest priority project in the same rail line are removed from the list.
4. The second best rated project in the new list is taken.
5. The projects that are incompatible with the second best ranked project are eliminated from the list
6. Step 3 and forth are repeated until the last project from the list, which does not eliminate any project.

As expected, the elimination of projects is not equal in all lines. The order of application of the elimination algorithm results in the elimination of different projects depending on the line under analysis, especially because there are non-symmetrical incompatibilities between projects (A eliminates B, but B does not eliminate A).

5.5Discussion of the results

With these results, it becomes evident that the main factor of preference for a project is the location of application rather than the type of project. The worst rated projects of the most interesting locations (lines in worse conditions and/or heavy traffic) are better ranked than the best projects of the less interesting locations. This result indicates that the MR&I projects must be selected taking into account the effects they have on current operating conditions of the lines. There is no "always better" project to blindly apply in any railway line, but depends on the specific condition of each line. Therefore, railway managers must not only consider the technical aspects and costs of projects. It is essential to consider how the network is improved as a whole. This result agrees with the previous intuitions of the DM, in the sense that the most advanced technical solution is not always the right one.

Priority rank obtained is a first step in deciding which projects to execute. According to (Phillips & Bana e Costa, 2007) the final decision not only have to consider the budget available, but other factors such as changes in company strategy, high level decisions, local council grants, manpower availability and others. Another issue to consider, in addition to the incompatibility between projects is that some of them can be executed following a factor of synergy between them, as suggested Bana e Costa and Oliveira (2002). These two issues are not considered in this work and remain for future development.

From a technical point of view, the results also indicate how to improve the projects to change their assessment and make them more attractive for the maintainer. For example, a complete replacement of a rail track between Vara de Quart and Buñol is very expensive, greatly affects traffic during execution and hardly brings any benefits once implemented, but projects focused on the weakest points of the line, with more broken tracks, longitudinal wear etc., would get a much better score as this would maintain or increase benefits and reduce costs and risks. These modified projects would be included in a new iteration of the selection process.

6 Conclusions

This paper presents a real case study in railway management field to prioritize a huge portfolio of MR&I projects using an ANP based approach. The analysis of this type of projects is very complex because of the large number of qualitative factors that are difficult to quantify. This method allows the local managers to take into consideration and weigh all these factors, analysing its dependencies and feedbacks between them. In a second stage, each MR&I project has been assessed taking into account each of the criteria. Ratings technique is useful when the number of alternatives is high because, once the Decision Maker has assessed the priorities of the ratings, he can assess each project independently of the others.

This work has considered rail safety criteria; performance, technical and economic efficiency criteria; social utility; rail line characteristics and performance, cost and line improvement criteria; all of them grouped in a BOCR decision making framework. To the best of author's knowledge, this is a novel approach which tries to organize, in a systematic way, all of the parameters that a local manager has to consider to prioritize the huge MR&I portfolio.

Although this work does not make any fundamental or theoretical contribution to the MCDA field, the practical application of these methods to real-world decision making problems contribute, in our opinion, to make the theoretical models more compatible with the reality of decision makers. ANP is difficult to apply to real cases not because the technique is difficult to understand, but because the reality is complex in itself. For this reason, authors believe that it is useful for the scientific community to know how MCDA theories and models are able to collect this complexity and to produce good results.

The study allowed the DM to review the MR&I projects and to improve his perception of improvement needs, changing his decision approach for new projects and re-adapting it in the case of ongoing projects. The DM also found that technological improvements without adequate analysis do not necessarily result in improvements in the rail network. As a limitation to this study it should be mentioned that it focuses on a specific region (ADIF East Area located in Valencia, Spain). As future development it could be very interesting to extend this analysis to other regions adapting the criteria proposed in this work to the other local areas and to the experience and knowledge of their Line Managers and their technical teams. Other work could be to design a compatibility algorithm that would allow to group different projects in clusters in order to reduce the number of alternatives.

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Annex 1. East Area Railway network

Annex 2 Elements relationships matrices

(Table 15. Relationships between elements of the Opportunities subnet)

(Table 16. Relationships between elements of the Costs subnet)

(Table 17. Relationships between elements of the Risks subnet)

Annex 3 Unweighted supermatrices

(Table 18. Subnet Opportunities. Unweighted Supermatrix)

(Table 19. Subnet Costs. Unweighted Supermatrix)

(Table 20. Subnet Risks. Unweighted Supermatrix)

Annex 4 Weighted supermatrices

Table 21. Subnet Opportunities. Weighted Supermatrix

Table 22. Subnet Costs. Weighted Supermatrix

Table 23. Subnet Risks.Weighted Supermatrix

FIGURES AND TABLES

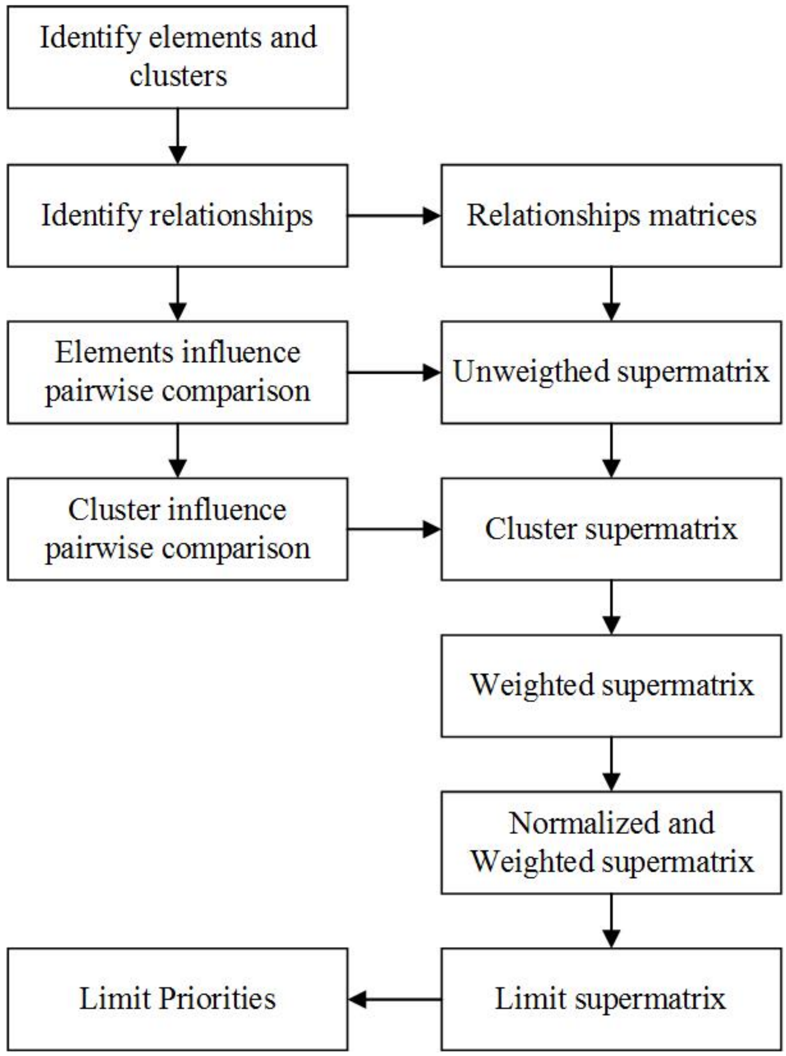


Figure 1: ANP steps scheme

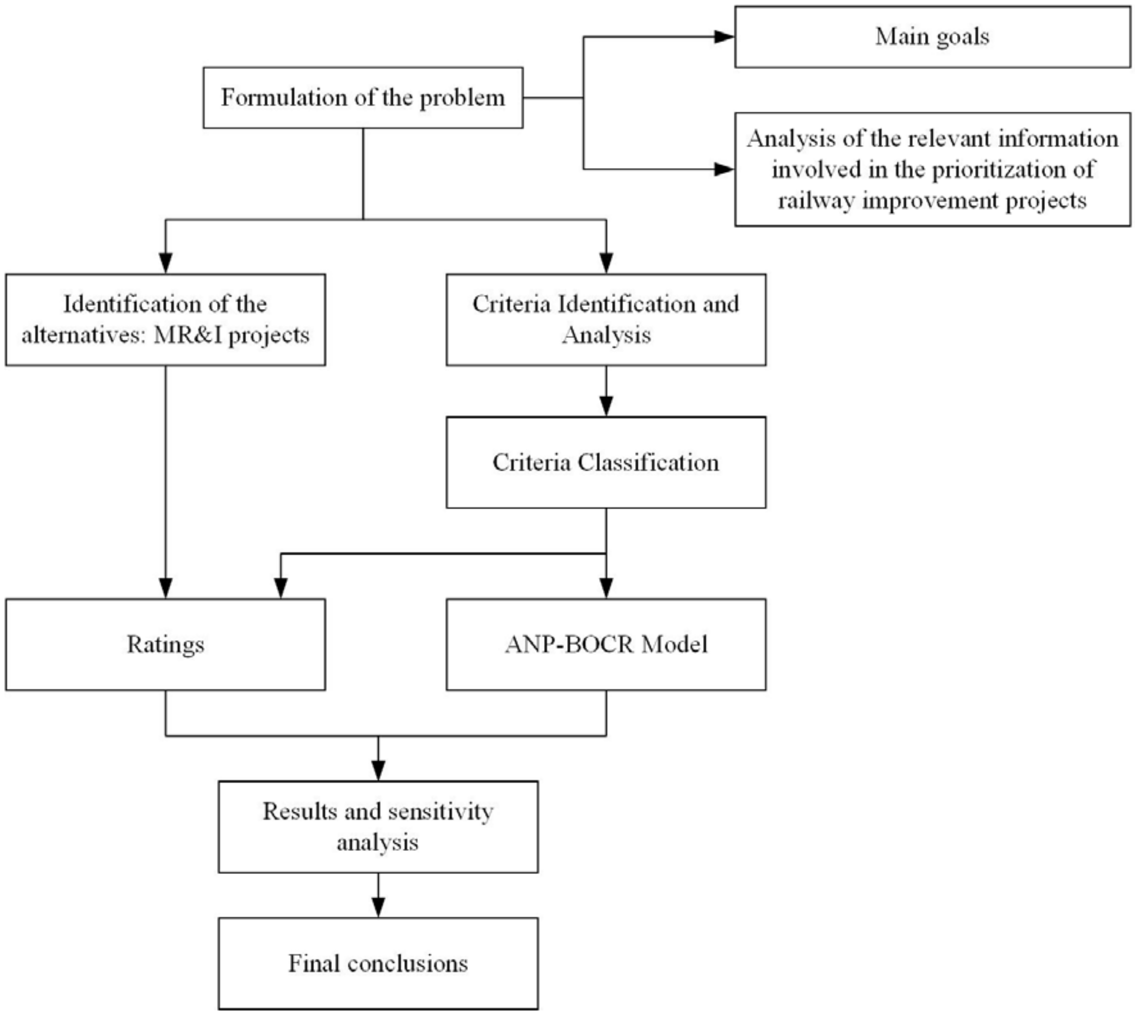


Figure 2: Decision Making Process

Action code	Action description
A	Track renewal with UIC 60 and concrete sleeper
B	Track renewal with UIC 54 and RS Sleeper
C	Track renewal with UIC 54 and Concrete Sleeper
D	Change to Double track from single track
E	Switch change from A to B
F	Switch change from B to C
G	Switch change from A to C
H	Infraestructure Treatment
I	Overhead contact Line Renewal with CR220
J	Overhead contactt Line renewal with CR160
K	Distributed control in Substations
L	Substation Remote control
M	Substation Construction
N	Interlocking renewal with SSI and Jointless track circuits
O	Blocking change from electric to electronic
P	Blocking station construction and critical block reduction
Q	Blocking change from BLAU to BAU
R	Blocking change from BAD to BAB
S	Blocking change from BT to BLAU
T	Blocking change from BT to BAU
U	Blocking change from BT to BAD
V	Blocking change from BT to BAB
X	Railroad crossing elimination
Y	Train Land comunications installation

Table 1: List of standard actions

Line code	Line
30750	FUENTE DE LA HIGUERA - MOGENTE
30800	MOGENTE - JATIVA
30802	BIF.VALLADA - BIF.L ALCUDIA
30850	JATIVA - SILLA
30851	SILLA - FACTORIA FORD
30900	SILLA - VALENCIA TERMINO
30902	ALFAFAR-BENETUSSER - VALENCIA-FUENTE SAN LUIS
30950	VALENCIA TERMINO - SAGUNTO
30951	VALENCIA-FUENTE SAN LUIS - CLASIF.VALENCIA FTE.S.LUIS
30953	BIF.CLAS.VALENCIA FTE.S.LUIS - CLASIF.VALENCIA FTE.S.LUIS
30957	SAGUNTO - PUERTO DE SAGUNTO
31000	SAGUNTO - ALMENARA
31050	ALMENARA - CASTELLON DE LA PLANA
31100	CASTELLON DE LA PLANA - OROPESA DEL MAR
31101	LAS PALMAS - CASTELLON PUERTO
31150	OROPESA DEL MAR - VINAROZ
31200	VINAROZ - ULLDECONA
31250	ULLDECONA - L ALDEA AMPOSTA
31251	L ALDEA AMPOSTA - TORTOSA
31300	L ALDEA AMPOSTA - SALOU
32150	CAMPORROBLES - UTIEL
32300	UTIEL - BUNOL
32350	BUNOL - VARA DE QUART
32500	VARA DE QUART - QUART DE POBLET
33600	JATIVA - ONTENIENTE
33650	ONTENIENTE - ALCOY
33800	SILLA - GANDIA
33801	GANDIA MERCANCIAS - GANDIA PUERTO
34200	SAGUNT - SONEJA
34250	SONEJA - CAUDIEL
22400	BADULES - SANTA EULALIA DEL CAMPO
22450	SANTA EULALIA DEL CAMPO - TERUEL
22500	TERUEL - BARRACAS
22550	BARRACAS - CAUDIEL

Table 2: List of rail lines in the East Area Network

LINE CODE	LINE
30750	FUENTE DE LA HIGUERA - MOGENTE
30800	MOGENTE - JATIVA
30802	BIF.VALLADA - BIF.L ALCUDIA
30850	JATIVA - SILLA
30851	SILLA - FACTORIA FORD
…	…
22450	SANTA EULALIA DEL CAMPO - TERUEL
22500	TERUEL - BARRACAS
22550	BARRACAS - CAUDIEL

30750	**FUENTE DE LA HIGUERA - MOGENTE**
Project Code	**Standard action available**
30750A	Track renewal with UIC 60 and concrete sleeper
30750H	Infraestructure Treatment
30750I	Overhead contact Line Renewal with CR220
30750K	Distributed control in Substations
30750L	Substation Remote control
30750M	Substation Construction
30750P	Blocking station construction and critical block reduction

30800	**MOGENTE - JATIVA**
Project Code	**Standard action available**
30800A	Track renewal with UIC 60 and concrete sleeper
30800H	Infraestructure Treatment
30800I	Overhead contact Line Renewal with CR220
30800J	Overhead contactt Line renewal with CR160
30800K	Distributed control in Substations
30800L	Substation Remote control
30800M	Substation Construction
30800P	Blocking station construction and critical block reduction
30800R	Blocking change from BAD to BAB

Figure 3: Example of feasible projects

SUBNET BENEFITS	Cluster 1. (RSC) Rail safety criteria
	Cluster 2. (PEC) Performance efficiency criteria
	Cluster 3. (TEC) Technical efficiency criteria
	Cluster 4. (SUC) Social Utility Criteria
	Cluster 5. (RLC) Rail line characteristics
SUBNET OPPORTUNITIES	Cluster 6. (PIC) Performance improvement criteria
	Cluster 7. (CIC) Cost improvement criteria
	Cluster 8. (LIC) Line improvement criteria
	Cluster 5. (RLC) Rail line characteristics
SUBNET COSTS	Cluster 9. (EEC). Economic efficiency criteria
	Cluster 5. (RLC) Rail line characteristics
CLUSTER RISKS	Cluster 10. (CPC) Changes in project criteria
	Cluster 11. (CUF) Criteria for future use
	Cluster 5. (RLC) Rail line characteristics

Table 3: The ANP-BOCR Model

	RSC.C01	RSC.C02	RSC.C03	RSC.C04	PEC.C05	PEC.C06	PEC.C07	TEC.C08	TEC.C09	SUC.C10	RLC.C11	RLC.C12	RLC.C13	RLC.C14
RSC.C01	0	0	0	0	0	0	0	1	1	1	0	0	0	0
RSC.C02	0	0	0	0	0	0	0	0	1	1	0	1	0	0
RSC.C03	0	0	0	1	1	1	1	1	1	1	1	1	1	1
RSC.C04	0	0	0	0	1	1	1	1	1	0	1	0	1	1
PEC.C05	0	0	0	0	0	1	1	0	1	0	1	0	0	0
PEC.C06	0	0	0	0	1	0	1	0	1	0	1	0	0	0
PEC.C07	0	0	1	1	1	0	0	1	1	0	0	0	1	1
TEC.C08	0	0	0	0	1	1	0	0	1	0	0	0	0	0
TEC.C09	0	0	0	0	1	1	0	0	0	0	1	0	0	0
SUC.C10	1	1	0	0	0	0	0	0	0	0	0	1	0	0
RLC.C11	1	1	1	1	1	1	1	1	1	1	1	0	0	0
RLC.C12	1	1	1	1	1	1	1	1	1	1	0	1	0	0
RLC.C13	1	1	1	1	1	1	1	1	1	1	0	0	1	0
RLC.C14	1	1	1	1	1	1	1	1	1	1	0	0	1	1

Table 4: Relationships between elements of the Benefits subnet

Compare the following elements (Benefits Subnetwork) in the group RSC *Rail Safety Criteria* according to their influence upon *TEC.C08.- Reduction in the number of incidents* in the cluster (TEC) *Technical Efficiency Criteria*

RSC.C01.- Reduction in the number of level crossings
RSC.C03.- Improvement of driving support systems

Which has the greatest importance or influence?	☒ A	☐ B	☐ Equally important	
To what extent?	☐ Moderately	☒ Strongly	☐ Very strongly	☐ Extreme

Table 5: Example of the questionnaire about prioritization of elements

	RSC.C01	RSC.C02	RSC.C03	RSC.C04	PEC.C05	PEC.C06	PEC.C07	TEC.C08	TEC.C09	SUC.C10	RLC.C11	RLC.C12	RLC.C13	RLC.C14
RSC.C01	0	0	0	0	0	0	0	0.685	0.689	0.772	0	0	0	0
RSC.C02	0	0	0	0	0	0	0	0	0.058	0.173	0	0.250	0	0
RSC.C03	0	0	0	1	0.500	0.167	0.125	0.080	0.126	0.055	0.500	0.750	0.500	0.250
RSC.C04	0	0	0	0	0.500	0.833	0.875	0.234	0.126	0	0.500	0	0.500	0.750
PEC.C05	0	0	0	0	0	1	0.250	0	0.388	0	0.250	0	0	0
PEC.C06	0	0	0	0	0.833	0	0.750	0	0.515	0	0.750	0	0	0
PEC.C07	0	0	1	1	0.167	0	0	1	0.098	0	0	0	1	1
TEC.C08	0	0	0	0	0.125	0.750	0	0	1	0	0	0	0	0
TEC.C09	0	0	0	0	0.875	0.250	0	0	0	0	1	0	0	0
SUC.C10	1	1	0	0	0	0	0	0	0	0	0	1	0	0
RLC.C11	0.065	0.065	0.194	0.262	0.063	0.410	0.209	0.322	0.116	0.059	1	0	0	0
RLC.C12	0.571	0.592	0.536	0.565	0.063	0.060	0.643	0.558	0.523	0.564	0	1	0	0
RLC.C13	0.241	0.162	0.178	0.055	0.438	0.232	0.097	0.054	0.099	0.059	0	0	0.500	0
RLC.C14	0.124	0.181	0.093	0.118	0.438	0.298	0.051	0.066	0.263	0.319	0	0	0.500	1

Table 6: Subnet Benefits. Unweighted Supermatrix

	RSC.C01	RSC.C02	RSC.C03	RSC.C04	PEC.C05	PEC.C06	PEC.C07	TEC.C08	TEC.C09	SUC.C10	RLC.C11	RLC.C12	RLC.C13	RLC.C14
RSC.C01	0	0	0	0	0	0	0	0.142	0.132	0.579	0	0	0	0
RSC.C02	0	0	0	0	0	0	0	0	0.011	0.130	0	0.070	0	0
RSC.C03	0	0	0	0.239	0.068	0.023	0.018	0.017	0.024	0.041	0.112	0.211	0.133	0.066
RSC.C04	0	0	0	0	0.068	0.114	0.126	0.048	0.024	0	0.112	0	0.133	0.199
PEC.C05	0	0	0	0	0	0.541	0.143	0	0.029	0	0.020	0	0	0
PEC.C06	0	0	0	0	0.451	0	0.428	0	0.039	0	0.060	0	0	0
PEC.C07	0	0	0.282	0.214	0.090	0	0	0.082	0.007	0	0	0	0.095	0.095
TEC.C08	0	0	0	0	0.006	0.038	0	0	0.076	0	0	0	0	0
TEC.C09	0	0	0	0	0.045	0.013	0	0	0	0	0.158	0	0	0
SUC.C10	0.083	0.083	0	0	0	0	0	0	0	0	0	0.042	0	0
RLC.C11	0.059	0.060	0.140	0.143	0.017	0.111	0.060	0.229	0.076	0.015	0.538	0	0	0
RLC.C12	0.523	0.542	0.385	0.309	0.017	0.016	0.184	0.397	0.344	0.141	0	0.677	0	0
RLC.C13	0.221	0.148	0.128	0.030	0.119	0.063	0.028	0.039	0.065	0.015	0	0	0.320	0
RLC.C14	0.113	0.166	0.067	0.064	0.119	0.081	0.015	0.047	0.172	0.080	0	0	0.320	0.639

Table 7: Subnet Benefits. Weighted Supermatrix

RSC.C01.- Reduction in the number of level crossings				
Total (1)	Significant (0.401)	Partial (0.172)	Indifferent (0.074)	Increase (0.027)
RSC.C02.- Improvement of railroad crossing signalling				
Very High (1)	High (0.637)	Significant (0.222)	Negligible (0.112)	Reduction (0.06)
RSC.C03.- Improvement of driving support systems				
Very High (1)	High (0.513)	Significant (0.254)	Negligible (0.145)	Reduction (0.06)
RSC.C04.- Automatic control of lines and blocking systems				
Very High (1)	High (0.486)	Significant (0.493)	Negligible (0.059)	
PEC.C05.- Travel time reduction				
Higher than 20% (1)	Higher than 10% (0.509)	Higher than 5% (0.251)	Lower than 1% (0.124)	Reduction (0.065)
PEC.C06.- Critical block reduction				
Higher than 20% (1)	Higher than 10% (0.517)	Higher than 5% (0.256)	Lower than 1% (0.164)	Reduction (0.057)
PEC.C07.- Improvement of operations systems				
Very High (1)	High (0.464)	Significant (0.208)	Negligible (0.098)	
TEC.C08.- Reduction in the number of incidents (Subnet benefits)				
Higher than 50% (1)	Higher than 20% (0.509)	Higher than 10% (0.251)	Lower than 1% (0.123)	Increase (0.065)
TEC.C09.- Reduction in train delays				
Higher than 50% (1)	Higher than 25% (0.572)	Higher than 10% (0.52)	Lower than 5% (0.08)	Increase (0.059)
SUC.C10.- Improvement in road safety				
Very High (1)	High (0.51)	Significant (0.251)	Negligible (0.123)	Reduction (0.065)
RLC.C11.- Kmtrain/km				
Very High (1)	High (0.511)	Medium (0.206)	Low (0.106)	Very low (0.088)
RLC.C12.- Level crossings in the line				
More than 5 (1)	More than 3 (0.376)	At least 1 (0.092)	None (0.079)	
RLC.C13.- Line speed				
Higher than 200 km/h (0.153)	Higher than 160 km/h (0.271)	Higher than 140 km/h (0.318)	Higher than 120 km/h (0.609)	100 km/h or less (1)
RLC.C14.-Signalling level				
ERTMS y ASFA (0.108)	BAB/BAU (0.108)	BAD (0.219)	BLAU (0.389)	None (1)

Table 8: Rating categories and ideal weights (I)

PIC.C15.- Increase in the number of trains				
Higher than 100% (1)	Higher than 50% (0.51)	Higher than 20% (0.251)	Higher than 10% (0.123)	Reduction (0.065)

PIC.C16.- Reduction in the number of incidents (Subnet oportunities)				
Higher than 50% (1)	Higher than 20% (0.459)	Higher than 10% (0.155)	Lower than 1% (0.076)	Increase (0.076)

CIC.C17.- Reduction in maintenance costs					
Higher than 50% (1)	Higher than 25% (0.795)	Higher than 10% (0.426)	Less than 1% (0.218)	Incrase 10% (0.113)	incrase 20% (0.064)

CIC.C18.- Cost of further improvement			
Very High (0.075)	High (0.156)	Significant (0.293)	Negligible (1)

LIC.C19.- Delays/km				
Very High (1)	High (0.618)	Medium (0.254)	Low (0.082)	Very Low (0,076)

LIC.C20.- Delays/kmtrain				
Very High (1)	High (0.604)	Medium (0.214)	Low (0.101)	Very Low (0,094)

LIC.C21.- Incidents/km				
Very High (1)	High (0.744)	Medium (0.361)	Low (0.216)	Very Low (0,202)

LIC.C22.- Incidents/km train				
Very High (1)	High (0.529)	Medium (0.294)	Low (0.092)	Very Low (0,086)

EEC.C23.- Project cost				
Higher than 20M€ (0.100)	Higher than 10 M€ (0.245)	Higher than 7 M€ (0.458)	Higher than 3 M€ (1)	Less than 3 M€ (0.403)

EEC.C24.- Future operating costs					
Higher than 120% (1)	Higher tan 110% (0.670)	Higher tan 100% (0.564)	Higher tan 80% (0.262)	Higher tan 60% (0.132)	Lower tan 50% (0.073)

EEC.C25.- Future maintenance costs (Subnet Costs)			
Higher than 120% (0.109)	Higher than 100% (0.234)	Higher than 80% (0.569)	Less than 80% (1)

CPC.C26.- Cost deviation				
Higher than 100% (1)	Higher than 70% (0.446)	Higher than 50% (0.174)	Higher than 20% (0.199)	Less than 20% (0.199)

CPC.C27.- Results deviation				
Higher than 75% (1)	Higher than 50% (0.539)	Higher than 25% (0.193)	Higher than 10% (0.130)	Less than 10% (0.099)

CUF.C28.- Future maintenance cost (Subnet Risks)				
Higher than 150% (1)	Higher than 120% (0.824)	Higher than 100% (0.354)	Higher than 80% (0.249)	Less than 80% (0.203)

Table 9: Rating categories and ideal weights (II)

BENEFITS	Normalized By Cluster	Limiting
RSC.C01.- Reduction in the number of level crossings	0.058	0.012
RSC.C02.- Improvement of railroad crossing signalling	0.120	0.025
RSC.C03.- Improvement of driving support systems	0.540	0.114
RSC.C04.- Automatic control of lines and blocking systems	0.282	0.060
PEC.C05.- Travel time reduction	0.252	0.040
PEC.C06.- Critical block reduction	0.329	0.052
PEC.C07.- Improvement of operations systems	0.419	0.066
TEC.C08.- Reduction in the number of incidents	0.178	0.003
TEC.C09.- Reduction in train delays	0.822	0.016
SUC.C10.- Improvement in road safety	1.000	0.017
RLC.C11.- Kmtrain/km	0.144	0.085
RLC.C12.- Level crossings in the line	0.551	0.327
RLC.C13.- Line speed	0.085	0.050
RLC.C14.-Signalling level	0.221	0.131

Table 10: Criteria Weights Subnet Benefits

OPPORTUNITIES	Normalized By Cluster	Limiting
RLC.C11.- Kmtrain/km	0.256	0.122
RLC.C12.- Level crossings in the line	0.170	0.080
RLC.C13.- Line speed	0.165	0.078
RLC.C14.-Signalling level	0.409	0.194
LIC.C19.- Delays/km	0.045	0.009
LIC.C20.- Delays/kmtrain	0.098	0.020
LIC.C21.- Incidents/km	0.579	0.121
LIC.C22.- Incidents/km train	0.279	0.058
PIC.C15.- Increase in the number of trains	0.226	0.042
PIC.C16.- Reduction in the number of incidents	0.774	0.142
CIC.C17.- Reduction in maintenance costs	0.761	0.101
CIC.C18.- Cost of further improvement	0.239	0.032

Table 11: Criteria Weights Subnet Opportunities

COSTS	Normalized By Cluster	Limiting
RLC.C11.- Kmtrain/km	0.515	0.309
RLC.C12.- Level crossings in the line	0.138	0.083
RLC.C13.- Line speed	0.187	0.112
RLC.C14.-Signalling level	0.159	0.095
EEC.C23.- Project costs	0.065	0.026
EEC.C24.- Future operating costs	0.700	0.280
EEC.C25.- Future maintenance costs	0.236	0.094

Table 12: Criteria Weights Subnet Costs

RISKS	Normalized By Cluster	Limiting
RLC.C11.- Kmtrain/km	0.100	0.072
RLC.C12.- Level crossings in the line	0.052	0.037
RLC.C13.- Line speed	0.425	0.305
RLC.C14.-Signalling level	0.423	0.304
CUF.C28.- Future maintenance cost	1.000	0.121
CPC.C26.- Cost deviation	0.479	0.077
CPC.C27.- Results deviation	0.521	0.084

Table 13: Criteria Weights Subnet Risks

Order	Project code	Priority	Ideal
1	31300I	5.13825	1.00000
2	31300X	4.53172	0.88196
3	32300X	4.29250	0.83540
4	31300A	4.14763	0.80721
5	32300S	4.06328	0.79079
6	31300J	4.04263	0.78677
7	32300G	3.98047	0.77467
8	33800I	3.94600	0.76797
9	32300T	3.94161	0.76711
10	31300N	3.91370	0.76168
11	32300U	3.90135	0.75928
12	32300V	3.90135	0.75928
13	32300N	3.69515	0.71915
14	31300O	3.66120	0.71254
15	31300C	3.63356	0.70716
16	32300A	3.61158	0.70288
17	32300C	3.58326	0.69737
18	31300K	3.44705	0.67086
19	32300B	3.38435	0.65866
20	31300L	3.38013	0.65784
21	31300B	3.29590	0.64144
22	31300P	3.10058	0.60343
23	32300E	3.08665	0.60072

Table 14: Best scored alternatives

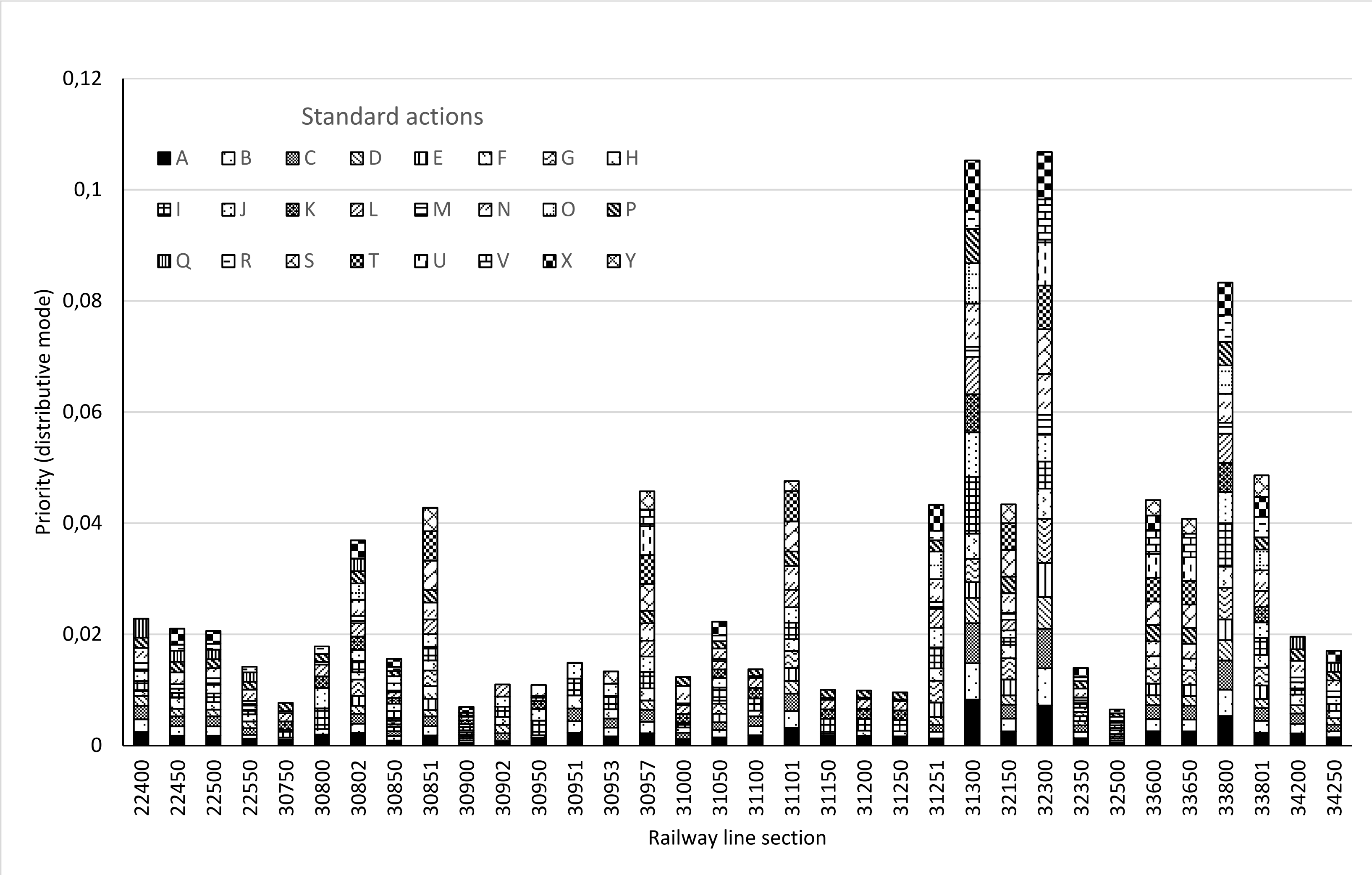


Figure 4: Projects grouped by line sections

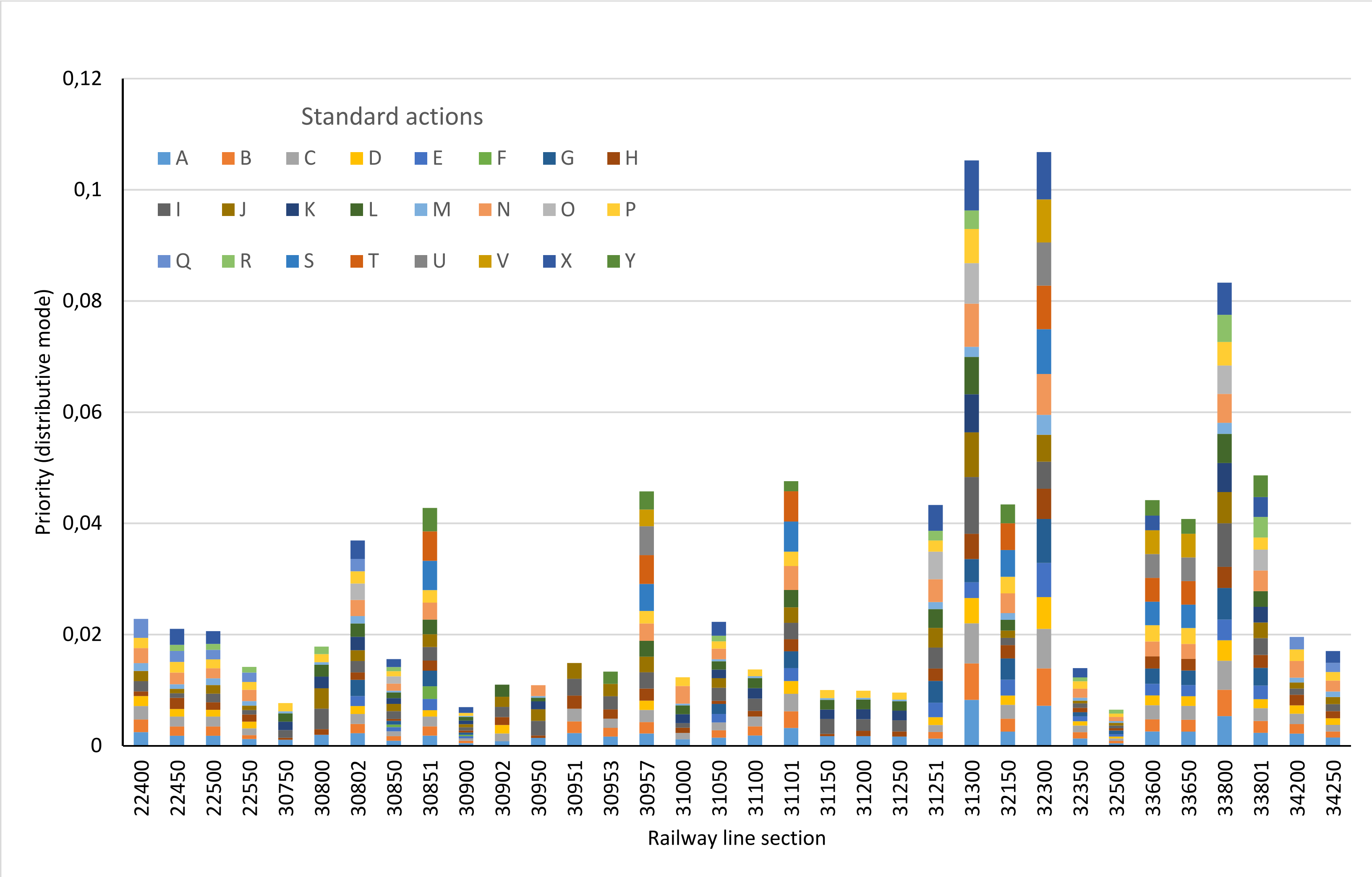


Figure 4: Projects grouped by line sections

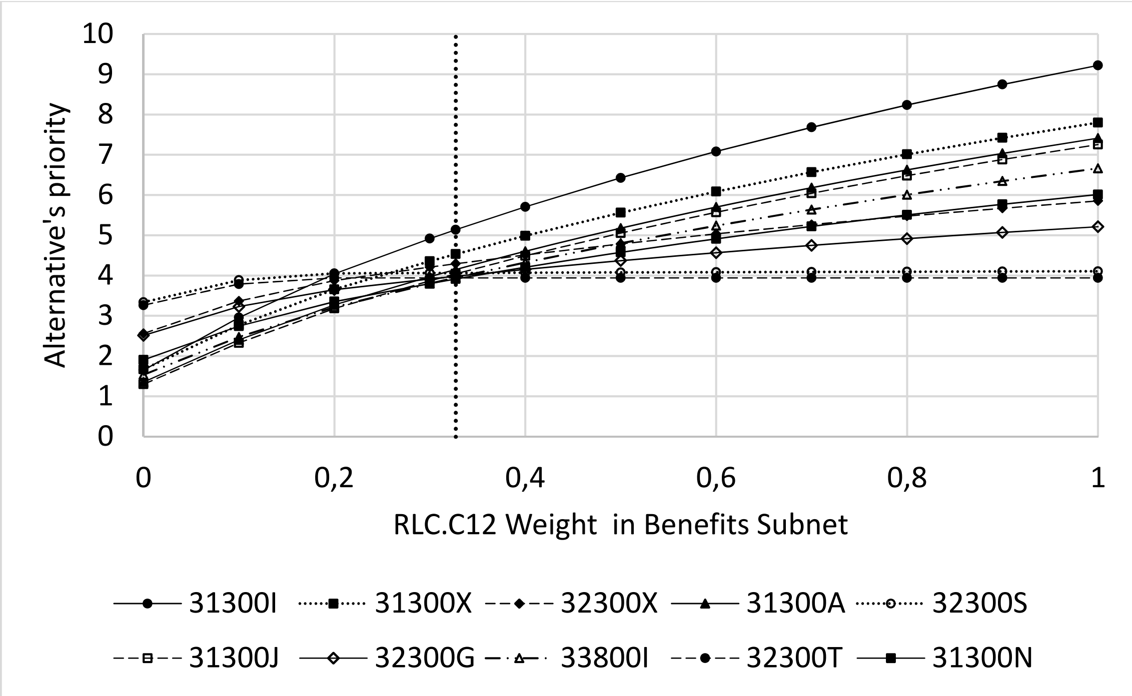


Figure 5: Top ten alternatives sensitivity analysis for RLC.C12 weight in Benefits subnet

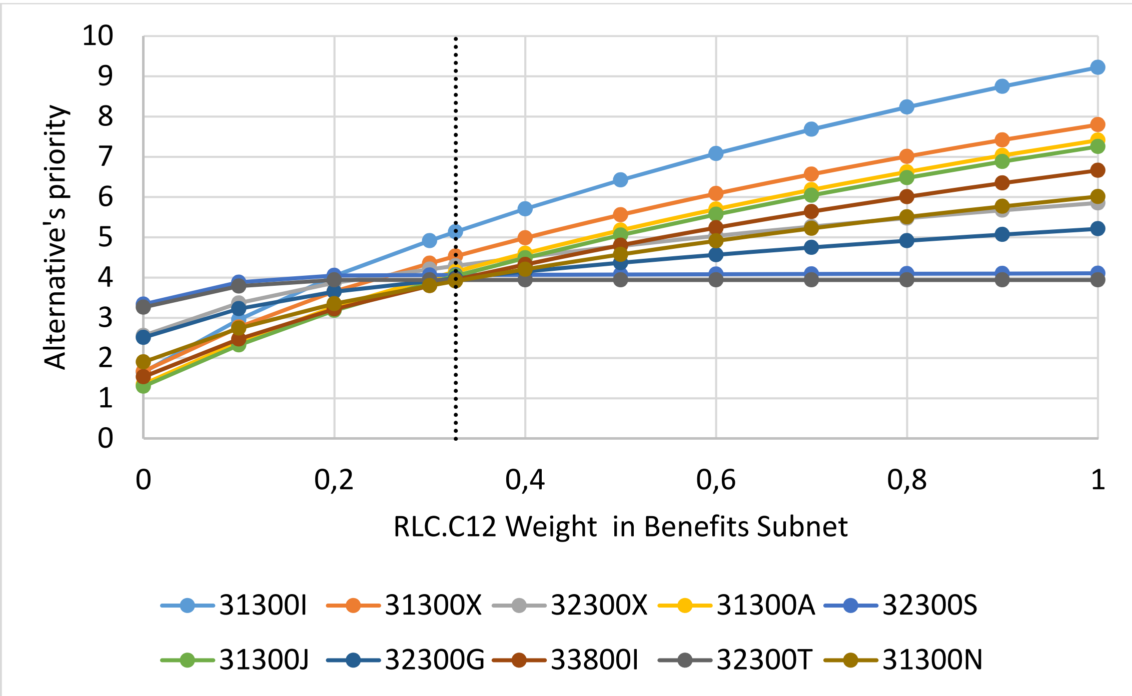


Figure 5: Top ten alternatives sensitivity analysis for RLC.C12 weight in Benefits subnet

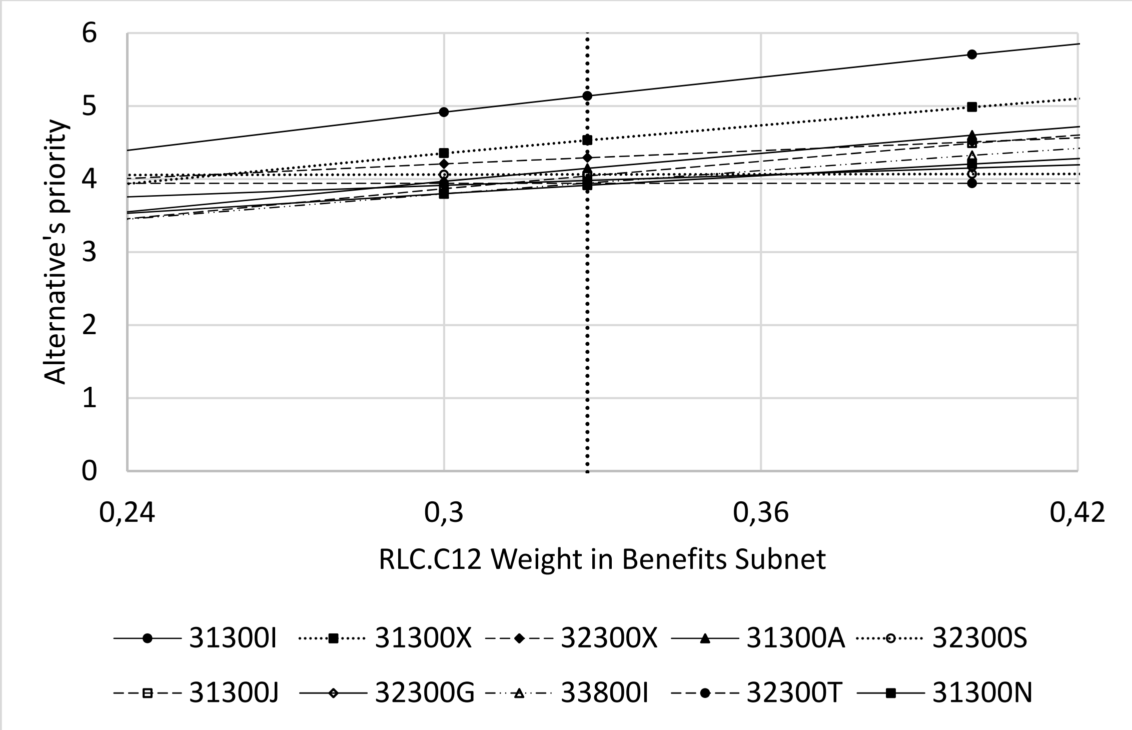


Figure 6: Detail of top ten alternatives sensitivity analysis for RLC.C12 weight in Benefits subnet

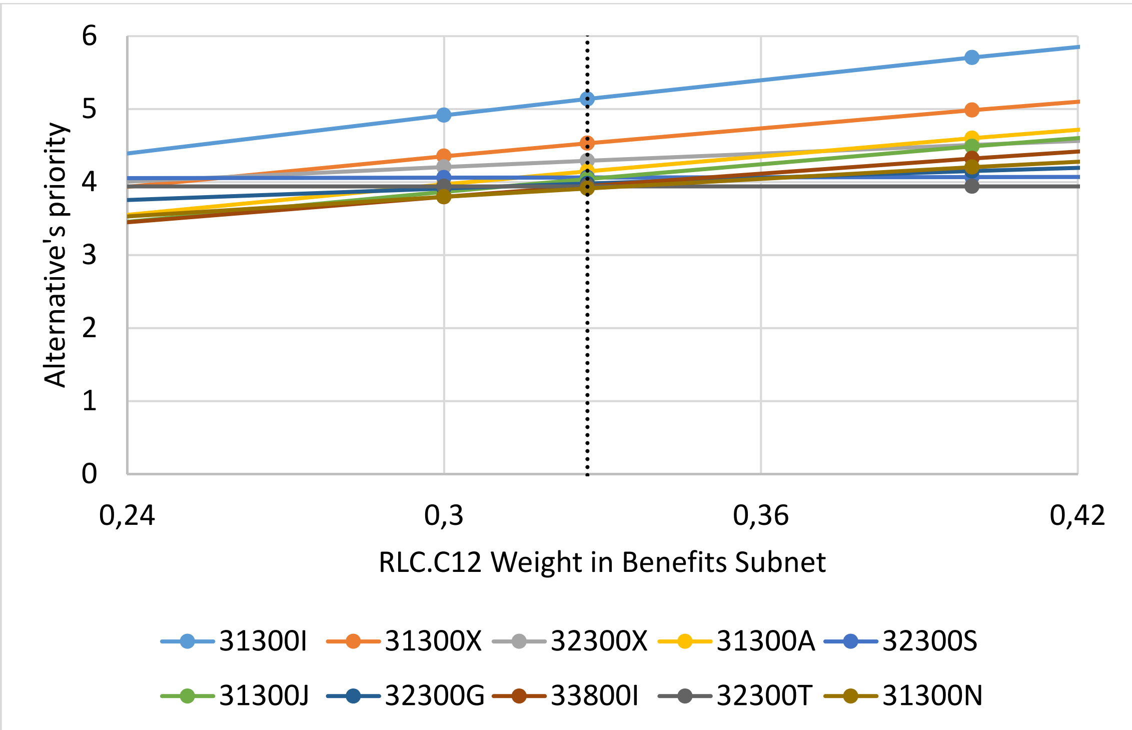


Figure 6: Detail of top ten alternatives sensitivity analysis for RLC.C12 weight in Benefits subnet

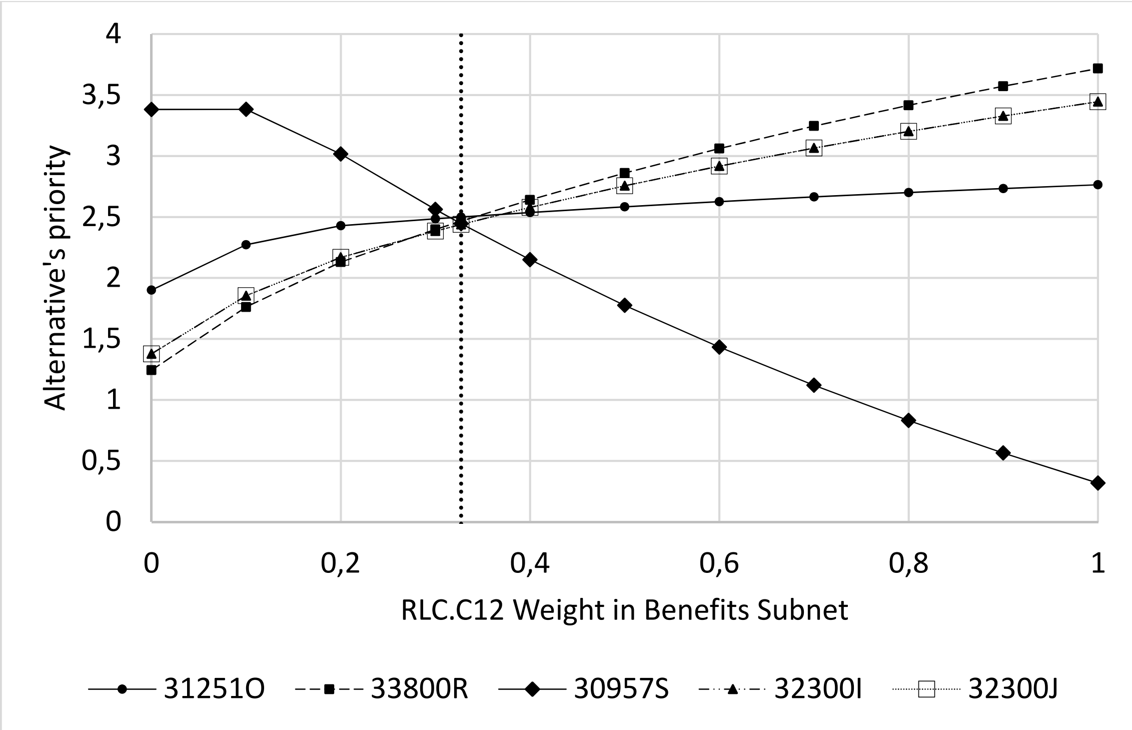


Figure 7: Alternatives ranked 41 to 45 sensitivity analysis for RLC.C12 weight in Benefits subnet

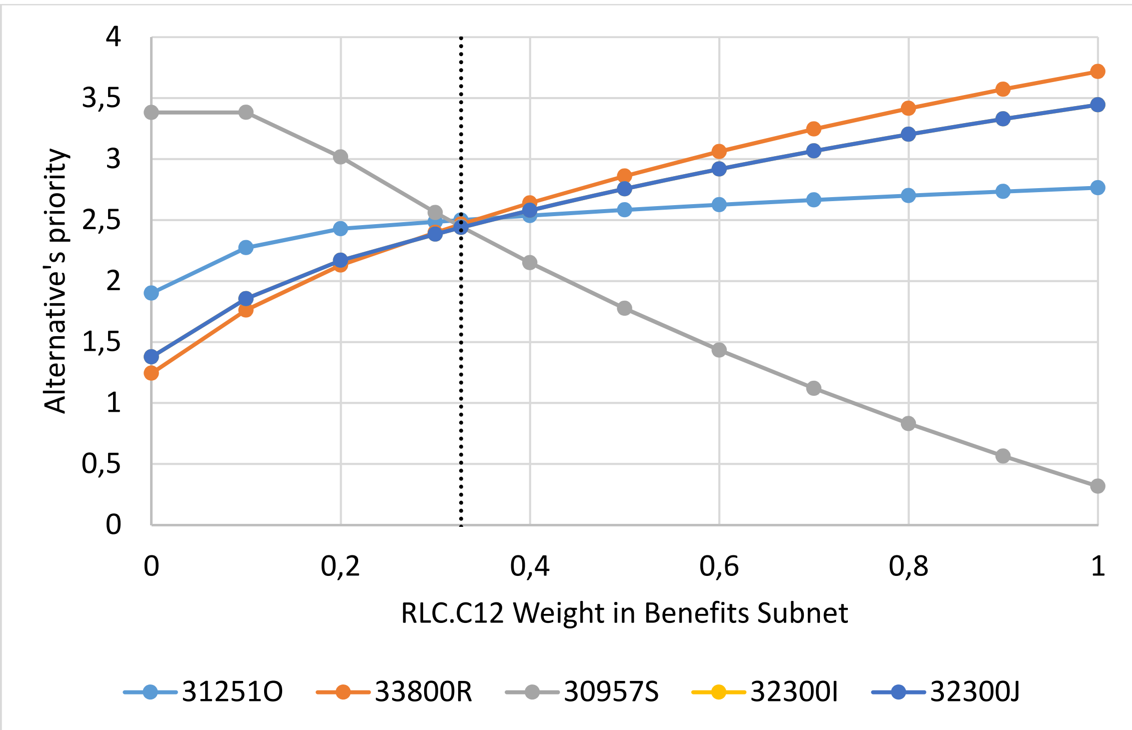
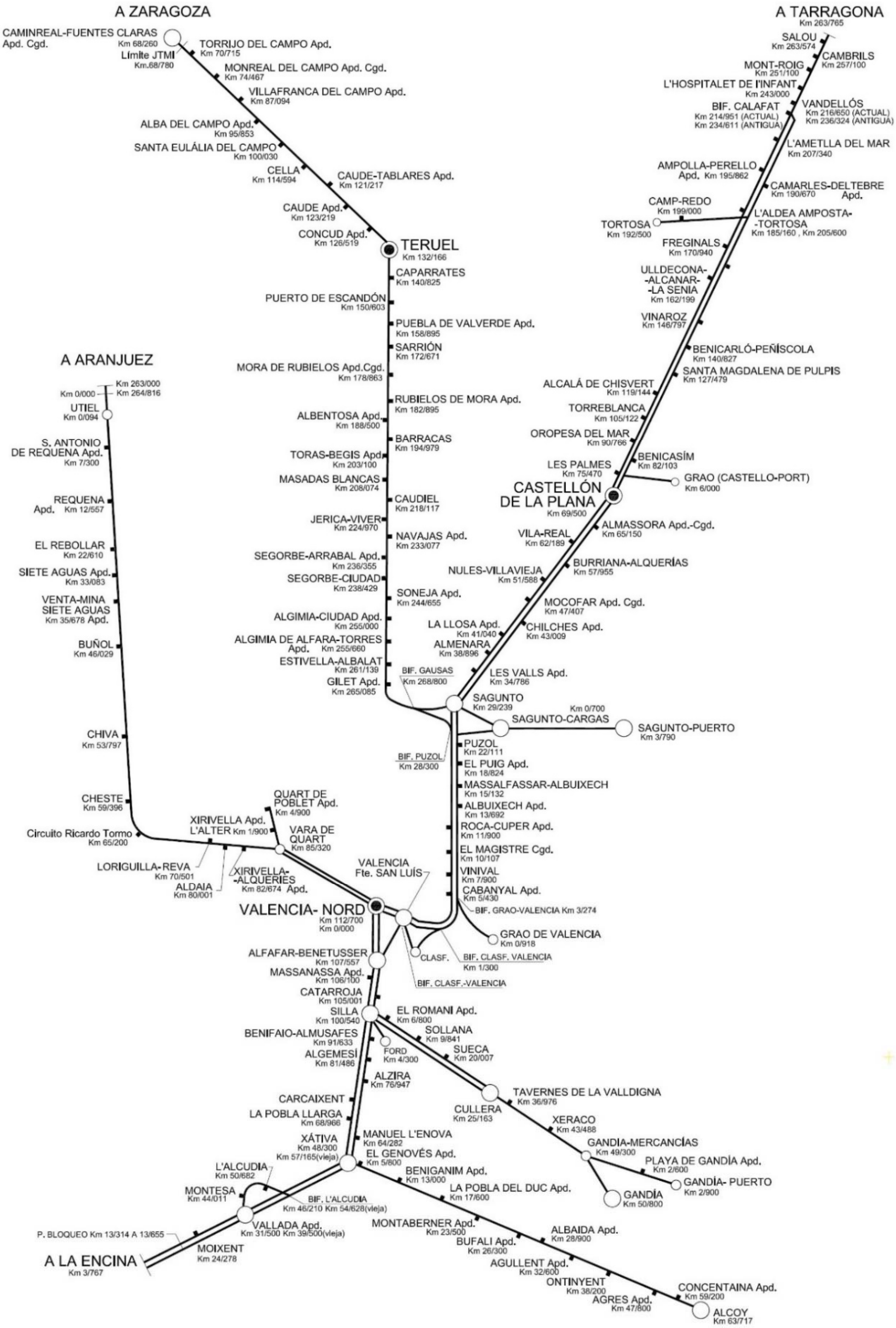


Figure 7: Alternatives ranked 41 to 45 sensitivity analysis for RLC.C12 weight in Benefits subnet

Annex 1.- East Area Railway network



Scheme of the East Area Network

Annex 2 Elements relationships matrices

	RLC.C11	RLC.C12	RLC.C13	RLC.C14	PIC.C15	PIC.C16	CIC.C17	CIC.C18	LIC.C19	LIC.C20	LIC.C21	LIC.C22
RLC.C11	1	0	0	0	1	1	1	1	0	0	0	0
RLC.C12	0	1	0	0	1	1	1	1	1	1	0	0
RLC.C13	0	0	1	0	1	1	0	1	1	1	0	0
RLC.C14	0	0	1	1	1	1	1	1	1	1	0	0
PIC.C15	0	0	0	0	1	1	0	0	1	1	1	1
PIC.C16	0	1	0	0	1	1	1	0	1	1	1	1
CIC.C17	0	0	0	0	0	0	0	0	1	1	1	1
CIC.C18	0	0	0	0	0	0	0	0	1	1	1	1
LIC.C19	1	1	0	0	1	0	0	0	0	1	0	0
LIC.C20	1	1	0	0	1	0	0	0	0	0	0	0
LIC.C21	1	1	0	1	0	1	1	1	0	0	1	1
LIC.C22	1	1	0	1	0	1	1	1	0	0	0	0

Table 15: Relationships between elements of the Opportunities subnet

	RLC.C11	RLC.C12	RLC.C13	RLC.C14	EEC.C23	EEC.C24	EEC.C25
RLC.C11	1	0	0	0	1	1	1
RLC.C12	0	1	0	0	1	1	1
RLC.C13	0	0	1	1	1	1	1
RLC.C14	0	0	1	1	1	1	1
EEC.C23	0	0	0	0	0	1	1
EEC.C24	1	1	0	0	1	1	1
EEC.C25	0	1	1	1	1	1	0

Table 16: Relationships between elements of the Costs subnet

	RLC.C11	RLC.C12	RLC.C13	RLC.C14	CPC.C26	CPC.C27	CUF.C28
RLC.C11	1	0	0	0	1	1	1
RLC.C12	0	1	0	0	1	1	1
RLC.C13	0	0	1	0	1	1	1
RLC.C14	0	0	1	1	1	1	1
CPC.C26	0	1	0	1	0	1	0
CPC.C27	1	0	0	1	1	0	1
CUF.C28	1	1	0	1	0	1	0

Table 17: Relationships between elements of the Risks subnet

Annex 3 Unweighted supermatrices

	RLC.C11	RLC.C12	RLC.C13	RLC.C14	PIC.C15	PIC.C16	CIC.C17	CIC.C18	LIC.C19	LIC.C20	LIC.C21	LIC.C22
RLC.C11	1	0	0	0	0.522	0.25	0.156	0.234	0	0	0	0
RLC.C12	0	1	0	0	0.078	0.25	0.659	0.072	0.637	0.714	0	0
RLC.C13	0	0	0.75	0	0.200	0.25	0	0.1161	0.105	0.143	0	0
RLC.C14	0	0	0.25	1	0.200	0.25	0.185	0.578	0.258	0.143	0	0
PIC.C15	0	0	0	0	0.75	0.25	0	0	0.125	0.125	0.167	0.5
PIC.C16	0	1	0	0	0.25	0.75	1	0	0.875	0.875	0.833	0.5
CIC.C17	0	0	0	0	0	0	0	0	0.5	0.75	0.75	0.833
CIC.C18	0	0	0	0	0	0	0	0	0.5	0.25	0.25	0.167
LIC.C19	0.078	0.125	0	0	0.5	0	0	0	0	1	0	0
LIC.C20	0.417	0.375	0	0	0.5	0	0	0	0	0	0	0
LIC.C21	0.408	0.375	0	0.833	0	0.5	0.5	0.5	0	0	1	1
LIC.C22	0.097	0.125	0	0.167	0	0.5	0.5	0.5	0	0	0	0

Table 18: Subnet Opportunities. Unweighted Supermatrix

	RLC.C11	RLC.C12	RLC.C13	RLC.C14	EEC.C23	EEC.C24	EEC.C25
RLC.C11	1	0	0	0	0.051	0.526	0.613
RLC.C12	0	1	0	0	0.104	0.158	0.089
RLC.C13	0	0	0.75	0.25	0.423	0.210	0.208
RLC.C14	0	0	0.25	0.75	0.423	0.107	0.089
EEC.C23	0	0	0	0	0	0.081	0.125
EEC.C24	1	0.25	0	0	0.5	0.731	0.875
EEC.C25	0	0.75	1	1	0.5	0.188	0

Table 19: Subnet Cost. Unweighted Supermatrix

	RLC.C11	RLC.C12	RLC.C13	RLC.C14	CPC.C26	CPC.C27	CUF.C28
RLC.C11	1	0	0	0	0.125	0.125	0.217
RLC.C12	0	1	0	0	0.125	0.125	0.060
RLC.C13	0	0	0.75	0	0.375	0.375	0.507
RLC.C14	0	0	0.25	1	0.375	0.375	0.217
CPC.C26	0	1	0	0.833	0	1	0
CPC.C27	1	0	0	0.167	1	0	1
CUF.C28	1	1	0	1	0	1	0

Table 20: Subnet Risk. Unweighted Supermatrix

Annex 4 Weighted supermatrices

	RLC.C11	RLC.C12	RLC.C13	RLC.C14	PIC.C15	PIC.C16	CIC.C17	CIC.C18	LIC.C19	LIC.C20	LIC.C21	LIC.C22
RLC.C11	0.776	0	0	0	0.224	0.107	0.014	0.039	0	0	0	0
RLC.C12	0	0.701	0	0	0.033	0.107	0.060	0.012	0.034	0.034	0	0
RLC.C13	0	0	0.75	0	0.086	0.107	0	0.019	0.006	0.007	0	0
RLC.C14	0	0	0.25	0.776	0.086	0.107	0.017	0.096	0.014	0.007	0	0
PIC.C15	0	0	0	0	0.321	0.107	0	0	0.033	0.029	0.041	0.122
PIC.C16	0	0.097	0	0	0.107	0.321	0.455	0	0.230	0.204	0.204	0.122
CIC.C17	0	0	0	0	0	0	0	0	0.342	0.455	0.477	0.530
CIC.C18	0	0	0	0	0	0	0	0	0.342	0.152	0.159	0.106
LIC.C19	0.017	0.025	0	0	0.071	0	0	0	0	0.1134	0	0
LIC.C20	0.093	0.076	0	0	0.071	0	0	0	0	0	0	0
LIC.C21	0.091	0.076	0	0.187	0	0.071	0.227	0.417	0	0	0.119	0.119
LIC.C22	0.022	0.025	0	0.037	0	0.071	0.227	0.417	0	0	0	0

Table 21: Subnet Opportunities. Weighted Supermatrix

	CTV.C11	CTV.C12	CTV.C13	CTV.C14	CEE.C23	CEE.C24	CEE.C22
CTV.C11	0.833	0	0	0	0.013	0.131	0.153
CTV.C12	0	0.833	0	0	0.026	0.039	0.022
CTV.C13	0	0	0.625	0.208	0.106	0.052	0.052
CTV.C14	0	0	0.208	0.625	0.106	0.027	0.022
CEE.C23	0	0	0	0	0	0.061	0.094
CEE.C24	0.167	0.042	0	0	0.375	0.548	0.656
CEE.C22	0	0.125	0.167	0.167	0.375	0.141	0

Table 22: Subnet Costs. Weighted Supermatrix

	RLC.C11	RLC.C12	RLC.C13	RLC.C14	CPC.C26	CPC.C27	CUF.C28
RLC.C11	0.584	0	0	0	0.065	0.061	0.163
RLC.C12	0	0.584	0	0	0.065	0.061	0.045
RLC.C13	0	0	0.75	0	0.195	0.184	0.380
RLC.C14	0	0	0.25	0.584	0.195	0.184	0.163
CPC.C26	0	0.135	0	0.113	0	0.451	0
CPC.C27	0.135	0	0	0.023	0.479	0	0.25
CUF.C28	0.281	0.281	0	0.281	0	0.059	0

Table 23: Subnet Risks. Weighted Supermatrix