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A METHODOLOGY FOR THE OPTIMIZATION AND EVALUATION OF RAILWAY CAPACITY IN A MULTI-ACTOR CONTEXT: THE CASE STUDY OF THE PORT OF TRIESTE

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Abstract

The advent of globalization and containerization in the second half of the last century has substantially affected previous trade patterns, putting a remarkable pression on ports. The role of such intermodal transport systems has become even more crucial due to the need of port customers for the provision of both maritime and logistics services, leading ports to assume an active part within the whole distribution channel. This condition has certainly augmented their complexity, because of the larger variety of performed activities and of involved stakeholders. Great attention has been then drawn to the establishment of solid hinterland connections, given their potential in rising port competitiveness. In this regard, the railway mode has revealed to be a financially and environmentally sustainable solution, especially on long hauls, and it is intended to be further embraced for freight transfers in the future. Nevertheless, the expected growth of train volumes poses a serious challenge to the quite limited residual capacity that characterizes many railway networks and nodes, requiring a prompt and coordinated action by the involved actors. To this end, existing railway infrastructures should be managed more efficiently and possibly complemented by new ones, according to a strategic vision for port advancements.

In the light of such demanding task, the objective of this dissertation represents the development of a methodology to determine the optimal railway capacity, which has been applied to the case study of the Port of Trieste. The proposed approach consists of the integration of different techniques that have been used to model, simulate and optimize port railway processes. The combination with a multi-actor multi-criteria evaluation procedure has addressed the aim of prioritizing the main port railway operational features and of selecting the best scenario of intervention to enhance port railway capacity. Insights coming from process optimization have proved that the maximum annual amount of train flows largely depends on the availability of tracks at the Trieste Campo Marzio station, whereas it becomes almost stable beyond a certain quantity of deployed shunting locomotives. The results obtained through the optimization procedure have been confirmed by both the assessment applications, pointing out the relevance of infrastructural resources and of implementing infrastructural interventions to accommodate additional railway traffic volumes.

Abstract

L'avvento della globalizzazione e della containerizzazione nella seconda metà del secolo scorso ha profondamente alterato la precedente struttura degli scambi commerciali, ponendo una rilevante pressione sui porti. Il ruolo di tali sistemi di trasporto intermodale si è fatto ancor più cruciale a seguito della richiesta dei clienti di fornir loro sia servizi marittimi che logistici, facendo così assumere ai porti una parte attiva all'interno dell'intera catena di distribuzione. Questa condizione ha indubbiamente comportato un aumento nella complessità di quei sistemi, vista la molteplicità delle attività svolte e degli attori coinvolti. Maggiore attenzione è stata dunque posta sulla definizione di validi collegamenti con l'entroterra, dato il loro potenziale nell'accrescimento della competitività dei porti. In tal senso, il trasporto su ferrovia si è dimostrato essere una soluzione sostenibile dal punto di vista finanziario ed ambientale, soprattutto sulle lunghe distanze, e si prevede venga adottato ulteriormente in futuro. Tuttavia, l'incremento atteso nei volumi di traffico ferroviario costituisce una sfida per la limitata capacità residua che caratterizza numerose reti e nodi ferroviari e, dunque, richiede di intraprendere un'azione pronta e coordinata tra gli attori interessati. A questo proposito, risulterebbe preferibile innanzitutto gestire in maniera più efficace le infrastrutture ferroviarie esistenti ed eventualmente integrarle con delle nuove opere, sulla base di una prospettiva strategica per lo sviluppo dei porti.

Alla luce di ciò, l'obiettivo di questa tesi è rappresentato dallo sviluppo di una metodologia atta a determinare il valore ottimale della capacità ferroviaria portuale, con un'applicazione al caso studio del Porto di Trieste. L'approccio proposto consiste nell'integrazione di diverse tecniche, che sono state usate per modellare, simulare ed ottimizzare i processi ferroviari portuali. La loro combinazione con un processo di valutazione multiattoriale e multicriterio ha permesso di stabilire le priorità dei principali aspetti ferroviari in ambito portuale e di selezionare il miglior scenario di intervento volto ad aumentare la capacità ferroviaria. Le evidenze suggerite dall'ottimizzazione dei processi hanno dimostrato che il valore del massimo numero di treni annui dipende largamente dalla disponibilità di binari nella stazione di Trieste Campo Marzio, mentre risulta piuttosto stazionario oltre una certa quantità delle locomotive di manovra impiegate. I risultati ottenuti dalla procedura di ottimizzazione sono stati confermati da entrambi i processi valutativi eseguiti, evidenziando l'importanza delle risorse infrastrutturali e della realizzazione di interventi di tale natura, al fine di soddisfare volumi di traffico aggiuntivi.

1. Introduction

Major developments in trade exchanges generated by globalization and containerization have enhanced the role of seaports, turning them into relevant intermodal transport hubs. The complexity of such transport systems has consequently increased due to the performing of a larger variety of activities, which have entailed the engagement of multiple actors. In face of that, the provision of an augmented offer including both maritime and logistics services has permitted to meet the ever-demanding needs of port customers, conferring an added value to port operations. The adoption of containerised transfer units has certainly brought to light the importance of establishing solid hinterland connections, extending the potential catchment area of ports and, thus, rising the competitiveness among them. In this regard, driven mainly by the urgency of addressing environmental issues, ports are intended to embrace intermodality even more in the future, especially with reference to the railway mode. Besides, this transport solution demonstrates to be more financially sustainable on long hauls, as against the road mode. However, the expected growth in freight railway traffic is largely challenged by the quite limited residual capacity which currently characterizes railway networks in many countries. Therefore, given also the long-lasting procedures for the realization of infrastructural interventions, a prompt and coordinated action by part of the main involved stakeholders is vital to define the most adequate strategy to overcome such physical barrier. Furthermore, the actualization of organizational and technological initiatives is necessary to enable a more efficient usage of existing capacity, possibly leading to a seamless transfer of goods not only inside ports, but along the whole transport chain.

In light of the articulation of port systems and their pressing need of accommodating future additional traffic flows, the objective of this thesis consists in delivering a methodology for the optimization of port railway capacity, in combination with the evaluation of features and interventions aimed at achieving that increase. The goal scope has been focused on intermodal transport nodes given the fact that the performances of these facilities remarkably affect the entire freight distribution system.

The innovation of the developed methodology is represented by the integration of different consolidated techniques, that have been applied in the various implementation stages of the approach allowing an effective and comprehensive examination of the problem at hand. More in detail, the proposed methodology first considers the modelling of railway processes to facilitate the analysis of their execution and, thus, to suggest possible hindering factors. In analogy with the management of industrial business processes, railway operations are

graphically displayed using a standardized modelling language, which enables the exchange of process models with tools dedicated to parametrization and simulation. The former serves the function of setting the entity of modelled elements in different simulation scenarios, which correspond to diverse operational conditions both at infrastructural and organizational level. Other than model validation, the latter permits then to efficiently identify process bottlenecks, highlighting the aspects on which interventions are required to improve railway capacity. Finally, process optimization assists the estimation of the maximum annual number of trains when changing some input variables related to infrastructural resources and the equipment for shunting activities. The outcomes descending from these stages of the methodology are accompanied by a multi-actor multi-criteria evaluation procedure, which aims of assessing, on one hand, the priorities of a few key port railway operational features and, on the other hand, the best design alternative to increase railway capacity.
The validity of the suggested methodology is proven by its application to the case study of the Port of Trieste, Italy, for which the identification of the optimal railway capacity value turns out to be particularly significant because of the expected increase in train traffic, the presence of competing terminal operators and the complexity of administrative procedures due to the Free Port regime. The innovative contribution of the thesis is reflected also in the application of the methodology to such context, since the interaction with the main port actors has fostered the creation of a framework which combines various aspects of railway processes. Indeed, this result permits to integrate in a comprehensive solution the train management systems of individual terminal operators and, as such, it is intended to constitute the future decision support system for railway operations in the Port of Trieste.

In summary, the thesis has been structured as described hereafter, following the approach which guided the development of the proposed integrated methodology.
Chapter 2 introduces the main factors which determine the complexity of modern seaports and underlines the great impact of hinterland connections on port competitiveness. A brief explanation of the operations which unfold specifically at railway terminals concludes the chapter, highlighting the need of a holistic strategy to carry out efficient freight transfers.
Chapter 3 illustrates in depth the various phases of integrated methodology proposed to optimize railway processes and, at a larger scale, port capacity. Indeed, a description of the techniques and instruments employed for process modelling, parametrization, simulation and optimization is reported, together with a literature review concerning existing approaches for such implementation stages.

Chapter 4 sets out the methods and the relative underlying principles which enable to support decision makers in decision-making processes, especially in cases in which multiple criteria and actors are involved. In this regard, an overview of the available scientific contributions is included, pointing out the importance of formulating inclusive and participated recommendations when evaluating transport-related issues.

Chapter 5 and **Chapter 6** outline, respectively, the application of the suggested methodology and of the assessment procedure to the case study of the Port of Trieste. In the former, details of the context as well as the main assumptions are given, while in the latter insights of the performed appraisals are provided according to their level of analysis.

Finally, **Chapter 7** presents and discusses the results of both the optimization procedure and of the multi-actor multi-criteria evaluation, which are then summed up in **Chapter 8**, along with possible future advancements.

2. The complexity of ports

In modern times, maritime ports represent intermodal transport hubs, which for their configuration are referable to the concept of a "system of systems", i.e. to a group of different systems aiming at specific goals, but sharing common resources and capabilities for the functioning of the whole system [1]. As such, seaports are characterized by a significant level of inherent complexity which, due to their condition of being the interface among diverse transport services, is primarily given by the involvement of many actors and by the performing of various activities. Indeed, dynamic interactions occur among port operational units in the effort to accomplish the objective of enhancing intermodality, by the seamless transfer of freight between sea and land transport modes [2], [3]. Analogously to all other transport systems, the nature of port complexity can be declined according to a twofold perspective, since it is related to both technical and social aspects. The former encompass problems whose resolution is faced mainly using methods and instruments typical of the engineering and economics fields, in order to develop technically and financially sustainable interventions. On the contrary, the latter regard social concerns with controversial blurred features and, thus, they require the adoption of a holistic planning approach, in which the standpoint of different stakeholders is reflected [4]. In this regard, the great relevance of ports within the regional, national, or even international, reference context is widely acknowledged, because of their influence on the economic growth of countries and on citizens' life quality, in terms of both employment and health [5]. Therefore, the current multi-purpose nature of ports implicates articulated organizational and regulatory issues, that broaden the scope of planning and management activities beyond the mere balance between traffic demand and supply based on infrastructural requirements. As a matter of fact, the definition of the objectives of ports is influenced not only by their mission statement and catchment market, but also by their institutional framework, which depends on the relationship among the engaged actors [6].

Referring to the variety of industrial and logistics services provided in addition to conventional intermodal transport operations, in the long run ports are expected to play a fundamental role in achieving the harmonisation among all their facilities and surrounding interacting parts, especially in developing nations [7]. To this end, the resorting to approaches able to integrate several aspects through inclusive and participatory procedures, reveals to be essential to produce effective and shared recommendations for the definition of specific strategic actions and, to a broader extent, of policies for port advancements.

Figure 1 synthetically captures the complexity of port systems, showing the multiplicity of elements that should be considered in planning activities according to a long-term perspective.

More to the point, it is evident that the main factors actually contributing to the determination of port capacity are demand forecasting, market strategy, environmental considerations, technology application, infrastructure and superstructure, and physical aspects. For that purpose, different alternative options should be technically evaluated, together with the performing of an analysis of their relative economic impact.

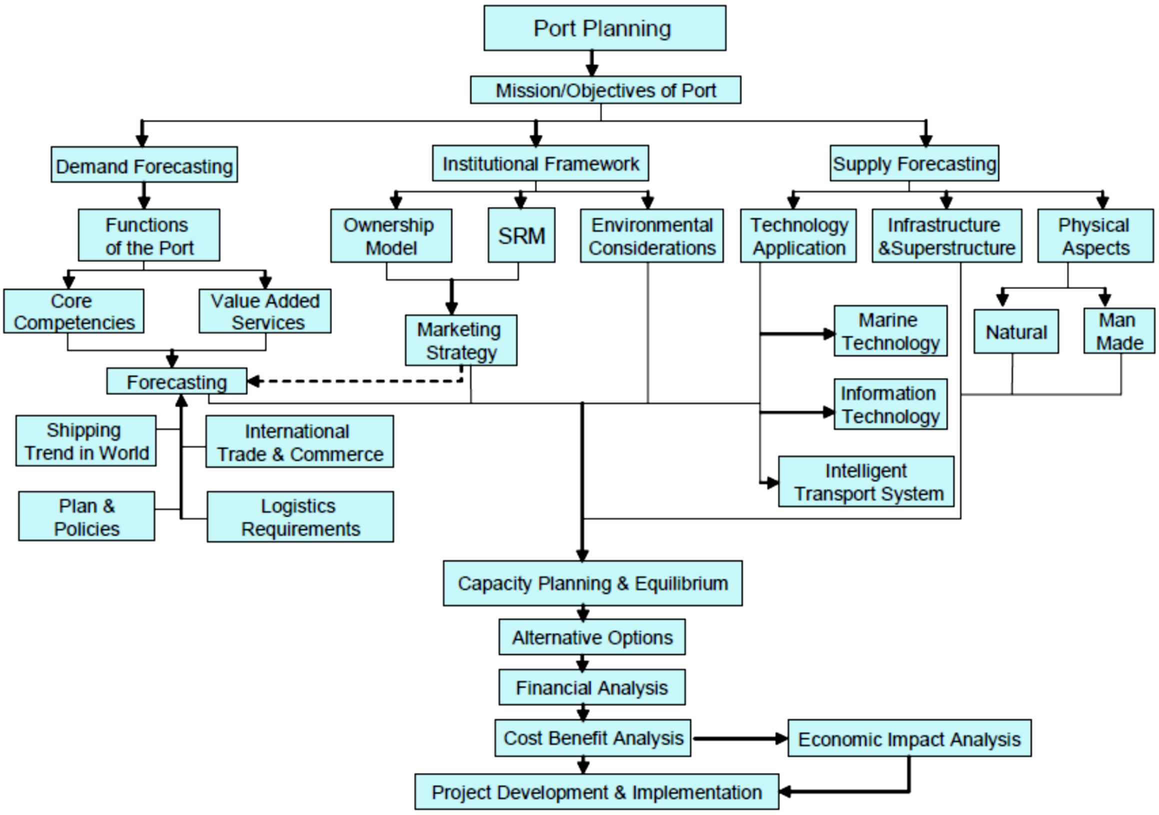

Figure 1 - Approach to port planning [6]

2.1 The role of ports

Globalization has deeply affected world's trade dynamics reshaping the role assumed by maritime transport at international level, given the massive share of freight volumes transferred through the sea mode. Such phenomenon has consequently impacted on the economic function of ports, that has undergone significant changes over the years due to the introduction of innovations in technologies, infrastructure and governance [8]. The evolution process of ports has followed the development of the global supply chain and occurred at different stages, each of them marking a diverse port generation with peculiar features. According to a set of parameters regarding port development position, structure and productive activities, three main distinct port generations have been identified to outline the transformation of ports from

conventional intermodal interfaces for transhipment to an active component of a wide distribution channel [6], [9]. Indeed, in their current configuration, major ports are assimilable to logistics hubs, where the provision of value-added logistics services is considered as vital as the performing of traditional cargo-handling operations, in order to gain competitive advantage and, thus, to ensure the long-lasting port financial sustainability [10]. In addition to adequate superstructures and infrastructures, an effective integration in carrying out core competence activities and logistics services (like storing, labelling, assemble, semi-manufacturing and customizing) is essential to attract shippers and port users, and to satisfy their more and more demanding needs. The combination of these two offer components represents one of the fundamental decisional leverages influencing customers' port selection and, consequently, the development of ports economic growth. In this regard, nowadays, high performances in port productivity are obtained benefitting from the adoption of the principles characterizing the economies of scale and the economies of scope, with the aim of reducing costs through the efficient management of port operations [6], [7].
Given the great relevance of ports in the logistics sector, and more broadly of this latter on trade exchanges profitability of countries, systematic strategic actions should be developed not only referring to historical tendencies of a specific port, but also examining the performances of other ports. To this end, while concentrating on the definition of indicators to estimate port efficiency, more attention is expected to be paid on sharing data to collect useful information regarding best practices, which can outline directions about promising investment areas to increase competitiveness against rival ports [5].

Bearing in mind the social implications which complement port planning, previous research studies, e.g. [11], has discussed the role of ports also with respect to the relationship with the city where they are settled in, because of the close interaction in many aspects. Such bond has transformed along with the development of maritime technology that, according to a spatial approach, has determined the detachment or, by contrast, the integration of the two parts. As a matter of fact, evolutionary stages in the port-city connection depict the occurrence of a substantial reversal trend, which means from an initial distancing caused by the request of more space to expand port activities, until a mutual cooperation thanks to the latest urban renewal projects considering the regeneration of waterfronts. At present, the port-city link is influenced principally by the three following factors [12]:

- the institutional relation and the role of port authorities, since the type of port organization system directly impacts on the control of economic decisions concerning port operations;

- the physical interaction, for which the negotiation among involved stakeholders is fundamental to elaborate initiatives that successfully consider harbour and city needs at the same time;
- the social relation between ports and cities, which requires the realization of communication activities with inhabitants, in order to increase their awareness of the port potential and, thus, their acceptance of the port infrastructure.

The importance of strengthening the port-city interrelationship has been highlighted also in a few Communications of the European Commission, where solutions to face problems caused by the increasing international traffic demand in European ports are proposed, suggesting to focus on two main issues, namely environmental safeguard and citizens' safety. Reaching the objectives of, on one hand, establishing sustainable inland connections through alternative itineraries and transport modes and, on the other hand, of efficiently controlling port accesses, would turn ports into facilitators for multimodality and growth [13], [14].

2.2 The importance of inland connections – The rail mode

The advent of globalization and, more in particular, the emergence of containerisation in the 1960s have caused a strong pressure on ports, which have been called to improve their performances in order to keep pace with the growth in traffic demand. Efficiency requirements coming from such trade acceleration have challenged ports to undertake significant changes in the management of activities according to different perspectives, i.e. from regulatory and organizational aspects, to technological and environmental factors [15]. Other than simplifying transport operations, the increase in freight standardization has enabled the implementation of intermodal transport systems, facilitating the transfer of materials by rail, truck or sea [16]. A further effect of containerisation consists in the fact that it has enlarged the geographic market coverage of seaports, whose hinterlands have extended from captive to contestable regions, rising the competition among ports. This phenomenon has consequently highlighted the relevance of establishing efficient hinterland chains and, in that regard, of the active role of the engaged public and private actors in solving possible coordination problems. Indeed, port hinterland accessibility encompasses not only infrastructural and market issues, but also organisational needs related to the arrangement of interdependent operational activities [17].

Forced by the demand of customers to provide an augmented and differentiated offer, the evolution of ports towards logistics hubs has definitely entailed a modification in the priority of the decision variables for port selection. The evaluation focus has moved from prices, e.g.

the expenditures for taxes or port operations, to products, intended in terms of supplied services and their quality characteristics [6]. With this respect, many research studies, inter alia [18], [19] and [20], prove the great relevance attributed to port connectivity over other critical parameters, like port location, port productivity, customer satisfaction, flexibility in providing services, and capacity. This latter results to have little influence in guiding users in the context of port choice, which is motivated by the fact that, in some cases, past trends show a non-proportional growth of traffic flows against the enhancement of port capacity [21]. In [22], the acknowledged significance of intermodal connectivity is suggested to be assumed as a key performance indicator to evaluate port competitiveness. Indeed, in contrast to the usual ranking criterion related to the throughput volume handled by individual terminals, port capacity is deemed to reflect the complexity of the port as a whole, i.e. a cluster of economic activities providing products and services.

Like mentioned, the logistical progression of ports has changed the positioning of bottlenecks from the ship/port interface to the port/land interface, making the connection between ports and hinterlands the main potential barrier hindering the productivity of such intermodal transport systems [23]. In line with this shift, as regards the total transport cost, more emphasis has been assumed by costs related to the landside part of the shipping operations. As a matter of fact, these latter have then become the main financial source on which carriers expect to have the highest potential for savings. In the face of the challenges posed by containerisation and, subsequently, by naval gigantism, such financial sparing can be accomplished enhancing intermodal access, besides realizing technological interventions to improve terminal facilities for the performing of berth activities [7].

Regarding land transport modes, in the recent past railway has gained more consideration as compared to the road mode, especially due to the increasingly pressing environmental concerns. Despite the well-known greater convenience of rail transport on long distances, such mode, as well as inland navigation, is characterized by the major limitation that no freight door-to-door services can be carried out, entailing more time-consuming transfers if compared to road haulage. In the framework of a dynamic logistics sector, this drawback definitely contributes to threaten the competitiveness of the rail mode, together with poor connection and congestion. Therefore, with specific reference to the European context, the implementation of reorganizational initiatives considering principally the optimal use of the existing railway capacity is recommended at international level, in order to fully exploit the advantages of rail transfer solutions. Furthermore, the allocation of efficient dedicated train paths to freight is advised in terms of both physical resources and time slots. This includes, respectively, the upgrading and rehabilitation of infrastructures along alternative low-traffic itineraries, and the adoption of traffic management systems to better separate train flows. Like saying, the success of priority transport corridors in transferring freights certainly depends also on the quality of rail access to ports and on the transhipment equipment at intermodal terminals [24].

Consistently with the principle of limiting the building of new infrastructures, the actualization of the suggested interventions requires a high level of coordination among stakeholders to succeed in the aim of integrating the port system in a transport network composed by multimodal trade corridors and, in turn, of increasing port competitiveness. To this end, port decision makers should resort to a multi-faceted approach, like the one reported in Figure 2, which is essential to develop coherent mobility strategies. In confirmation of the proposed line of action for port advancements, Figure 2 highlights that, within a demand-driven market environment, the infrastructural layer is functional to the transport and logistical ones. Furthermore, cooperation between actors is supposed to act in a twofold direction. On one hand, it addresses the compensation between the slow responsiveness related to the long-term perspective of the planning and realization phases of infrastructural works, and the ever-changing dynamics of the business and economic cycles. On the other hand, unlike in the past, a synergic working approach enables the smoothness of port-hinterland connections to stay ahead of the improvements on several fronts related to the maritime sector. In response to these challenging issues, also the introduction of information technology (IT) solutions can contribute to manage inland freight traffic more efficiently, optimizing the infrastructure use, especially thanks to powerful and fast data communication systems [25].

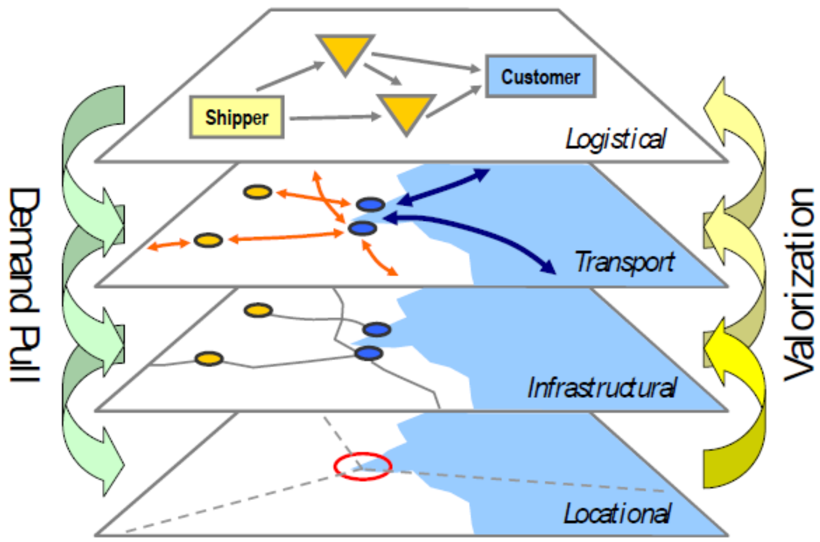

Figure 2 - Multi-layer approach to develop port-hinterland freight mobility strategies [25]

Finally, bearing in mind the wide-ranging impact of port operations, close collaboration between port managers and other public entities, such as community planners, is necessary when elaborating port investment plans, in order to draw up port development interventions that minimize conflicts. Indeed, the formulation of initiatives should seek for the maximization of port productivity and of the positive economic returns of surrounding areas, while reducing lessened the negative externalities [26], [27]. In this sense, with regard to inland connections, fostering railway intermodal transport certainly represents a sustainable measure to limit the environmental detriment caused by freight transfers.

2.2.1 Seaport railway terminals

Generally, even though seaport terminals can significantly differ in size, function and geometric configuration, they comprise a few main common and connected sub-systems, as reported in Figure 3. Considering containers when referring to the movement of intermodal transport units, quayside operations consist of loading and unloading vessels by means of quay cranes installed in the berthing area. Both import and export containers are placed in different blocks of the yard, depending on the characteristics of the goods that they contain, e.g. refrigerated or hazardous products. Other parts of the yard are reserved for stocking empty units or for the establishment of warehouses, in which specific operations on containers or additional logistics services are performed. Finally, at the opposite end of the seaport terminal, hinterland operations are carried out to deliver freights to outside transport systems using trucks or trains [28].

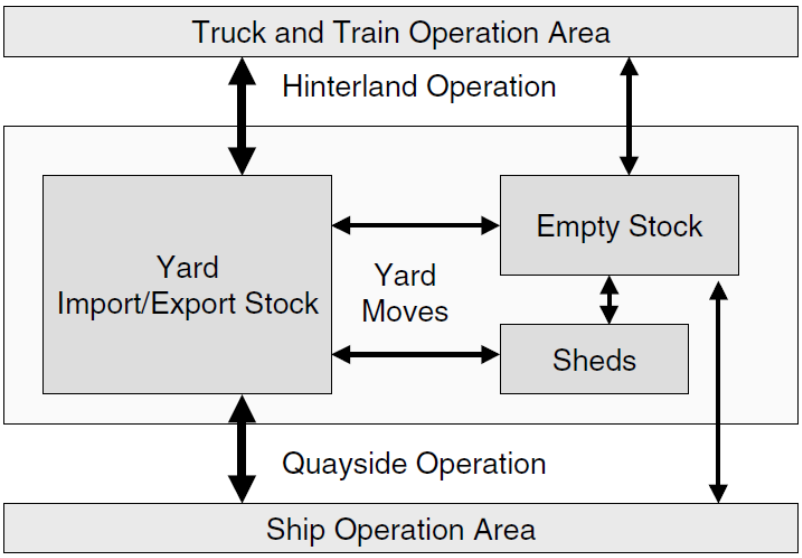

Figure 3 - Main sub-systems of a seaport terminal [29]

Concentrating the attention on the rail mode, different approaches can be adopted when carrying out planning activities related to seaport terminals. Indeed, available planning techniques and models cover a multitude of aspects regarding such components of the transport network and can be classified according to various decision levels, namely terminal design, operative planning and real-time control, or to specific logistics processes [30]. Focusing on the overall role of seaport railway terminals as multi-modal transport interfaces, decision problems regarding those facilities fall under the first listed category, since the integration of diverse modes of transport definitely impacts on the design of terminals [28]. In this regard, Figure 4 illustrates the import flow in the rail port cycle of a generic seaport terminal, indicating the main infrastructural and operational features.

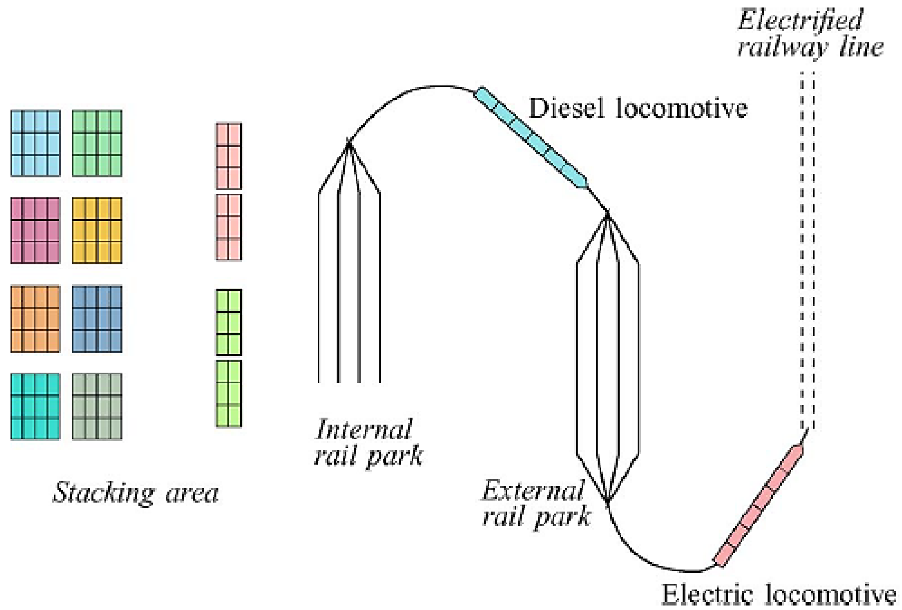

Figure 4 - Import flow in the rail port cycle [30]

It can be noticed that the import railway process displayed in Figure 4, just like the export one, unfolds on a few fundamental infrastructural parts, which are the stacking area, the internal rail park, the external rail park, and the electrified railway line. Firstly, intermodal transport units stored in the yard are brought to a collection of tracks present inside the terminal, where freight is loaded on trains using dedicated cranes. Subsequently, trains are moved to an interchange park outside the terminal by means of a diesel shunting locomotive, which is then substituted with an electric one, enabling trains to leave the port. Alternatively, inbound as well as outbound containers can be immediately loaded on or unloaded from trains, without being temporarily stacked in the yard. Of course, variations in the layout and in the handling equipment from a terminal to another can entail some differences in the operational cycle.

Irrespective of the fact that container transhipment is performed in a direct or indirect mode, an efficient alignment between the train schedule template and the transhipment plan is necessary to limit the train service time and, thus, to shorten the dwell time of goods at terminals. Since the mutual influence between rail- and sea-side activities has great consequences on terminal operations in practice, adopting a joint planning approach is essential to carry out seamless freight transfers and, based on a more holistic view, to enhance port capacity [31].

Furthermore, railway processes in a seaport terminal are usually affected by some delays, which are generated by the need of performing both physical and informative control activities that are required to move freight trains. The former consist of checking the correctness of units loaded on wagons and of verifying the train braking system after the change of traction between the port and the external railway network. On the contrary, the latter consider the check of the administrative documents accompanying inbound and outbound trains [30].

Although at different level of detail, Figures 3 and 4 highlight once again the abovementioned complexity of seaports, particularly in their meaning of intermodal transport systems, therefore requiring a comprehensive and coordinated planning approach.

2.3 Conclusions

The great complexity of modern ports, in terms of performed activities and engaged actors, is the result of the evolution of the role of such transport systems from interfaces for transhipment to fundamental parts of the overall distribution chain, given by globalization and containerisation. The increasingly demanding request of port customers for the provision of additional logistical value-added services has contributed to this change in port configuration, shedding light on the relevance of hinterland connectivity to enhance port competitiveness. As regard inland transport modes, railway definitely represents a suitable transport solution to tackle road congestion and to promote the use of environmental-friendly mobility alternatives for freight transfers. The successful accomplishment of these purposes necessitates the adoption of a multi-faceted approach, in which the cooperation of the various involved stakeholders is an essential factor. According to a technical perspective, the development of multimodal trade corridors should firstly consider the implementation of traffic management measures enabling a more efficient use of existing capacity, and secondly the realization of new infrastructures. In general terms, due to the close relation of ports with their surrounding areas, interventions should aim to balance at best port productivity and the consequent urban economic growth with the negative external effects. The great articulation of seaports is undoubtedly reflected also at more detailed level of railway terminals, confirming that adequate infrastructural and operational features prove to be of utmost importance to efficiently integrate the two different transport modes at those facilities.

3. Integrated methodology for port railway capacity optimization

Thanks to its advantage of enabling to transport high volumes of goods, the rail mode has been largely used to faster drain the increased demand of freight transfers in ports, beneficially affecting their competitiveness [1]. Therefore, despite the great relevance attributed to hinterland connectivity to assess port performances based on a systemic perspective, capacity still remains a meaningful indicator to evaluate the efficiency of any transport network in economical and safety terms [32]. As regards train transport, the consequences of the mentioned raise in traffic flows has largely impacted on such feature, whose usage has become a pressing issue in light of the expected growth in railway share [33]. Referring specifically to railway nodes, since their configuration and management can constrain operability, the identification of critical infrastructural elements and the definition of effective interventions to exploit capacity represent two common problems of railway engineering [34]. For instance, latest trends in the intermodal development framework consider the extension of the transport chain to inland terminals, as a possible alternative to accelerate freight distribution to end-users and, thus, to enhance port productivity. Indeed, the inclusion of such terminals actively contributes to the integration process between maritime and inland freight transport systems, called port regionalization, disburdening port capacity in an environmentally and economically sustainable way [35], [36], [37].

In line with the usefulness of measuring capacity to express the efficiency of transport systems, this parameter has been assumed as the key performance indicator to assess the quality of port railway processes through an integrated approach covering several aspects. As depicted in Figure 5 at a high level of detail, the developed methodology combines the modelling, simulation and optimization of railway processes, in order to estimate the maximum number of train flows under varying operational conditions. Based on a multi-faceted graphical representation of the considered processes, the creation of what-if scenarios using simulation and optimization instruments allows to examine the effects of possible infrastructural and organizational interventions on port railway capacity. The analysis definitely serves to sustain decision makers in the functional design and planning of the initiatives to be implemented. Furthermore, a multi-actor multi-criteria evaluation procedure accompanies the integrated methodology, so as to support optimization results with insights that come from a comprehensive and participatory appraisal process enabling to provide shared recommendations. Each step of the developed approach for the optimization and evaluation of port railway capacity has required the adoption of appropriate methods and tools, whose selection is motivated in the following sections.

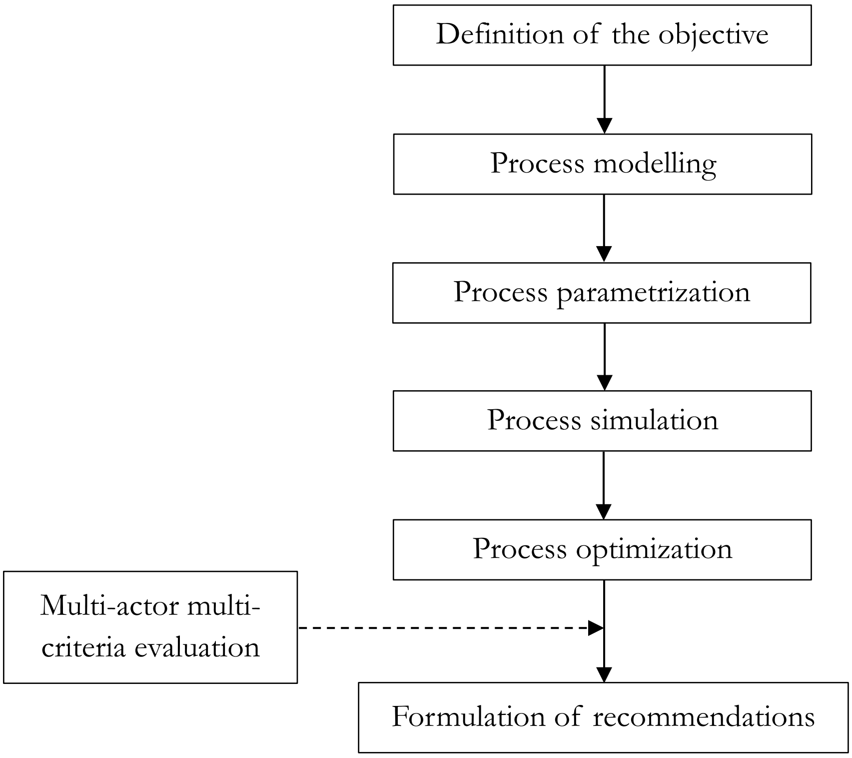

Figure 5 - Workflow of the adopted approach

3.1 Process modelling

3.1.1 The analogy with business processes

In analogy with the running of industries, also intermodal transport systems need to be conveniently managed through an efficient organization of processes, in order to gain competitiveness within the reference marketplace. Indeed, regardless of the activity sector, companies strive for the identification of strategies to enhance their productivity, product and/or service quality, and operations, which strictly depend on how business processes are carried out. In this regard, Business Process Management (BPM) represents a solution to assess potential advancements, since it consists of "a systematic approach to analyse, improve, control and manage processes with the aim of improving the quality of products and services" [38]. Consistently to the principle of the process approach for optimising process activities, the resorting to BPM helps employees to better concentrate on process bottlenecks, to more effectively use resources and to limit overcapacity. The redesign of business processes, which is referred to as Business Process Reengineering (BPR), can be faced according to two perspectives entailing a different extent of modifications to be made. On one hand, radical reengineering considers a substantial variation of existing business processes, which is generated by discontinuous thinking and aims at a breakthrough in a company organization system. The adoption of a cross-functional point of view required by such reengineering approach permits the integration of fundamental business processes and, thus, the enlargement of the goal scope. On the other hand, in the form of Business Process Improvement, BPR implicates more modest changes of current business processes, in order to accomplish gradual but continuous improvements [39], [40]. In general, thanks to its potential of optimising process productivity while reducing costs, BPM has recently gained more and more attention by companies, becoming a shared practice. This growing trend has been revealed, for instance, by the surveys conducted in [41] and [42], where the adoption of BPM techniques by various enterprises has been investigated together with its relative impacts over the general organization performances.

In spite of their common goal of attaining multi-system and component interoperability, a functional classification of the different available BPM methods can be made [43]. The categorization proposed in [44] suggests the distinction of the three following types of standards for the process design and enactment phases of the BPM life cycle: graphical standards, execution standards and interchange standards. The first ones allow users to express the characteristics of business processes, like decision points, roles and information flows, in a diagrammatic way, while the second category of standards enable to computerize the deployment of business processes and their automation. Nevertheless, the latter typology results not to be as human-readable and understandable as the previous one. The third type of standards permit not only to translate graphical standards into execution ones and vice versa, but also to exchange business process designs modelled through different graphical standards across diverse software (data portability).

3.1.2 Modelling languages

The actual activity of describing business processes in a manual and/or automated way is called Business Process Modelling (BPMo) and is usually performed by business analysts and managers committed to enhance process efficiency and quality. As a matter of fact, such task allows the representation of business processes to define and analyse their current ("as is") configuration in view of possible future improvements, which can be captured in a modified ("to be") asset of the considered processes [45]. Since the developed models can serve numerous stakeholders for different purposes, their understandability is a key feature that modelers definitely need to take into account [46]. Indeed, the usability of process models strictly depends on the ease of comprehension of their structural characteristics [47].

BPM requires the support of IT tools able to facilitate process analysis, which consist of

software solutions to monitoring quality throughout the whole examined business process. In this respect, the increasing implementation of a process-oriented approach in the transport and logistics sector has boosted the search for efficient instruments for process modelling and analysis. Such investigation has been motivated by the primary need of providing transport services with integrated planning and process organization, which are essential features to meet customers' needs [39], [48]. As a result, many BPMo techniques and corresponding IT alternatives have been created, allowing to reflect different aspects of business processes. However, as highlighted in [49], the definition of process modelling objectives represents the initial fundamental step to select the most adequate BPMo method.
In this thesis, the modelling of railway processes has been carried out to deeply understand the transport phenomenon at hand and it constitutes the starting phase of the proposed integrated methodology. Along with simulation, the analysis of the considered processes has been functional mainly to the identification of process bottlenecks that can potentially hinder an increase in port railway capacity.

Focusing on the design stage of the BPM life cycle, the following graphical standards are the most widespread BPMo techniques among the various existing methods: Unified Modelling Language Activity Diagrams (UML AD), Business Process Model and Notation (BPMN), Event-driven Process Chains (EPC), Role-Activity Diagrams (RADs), and flow charts [44]. A further popular modelling standard, called ArchiMate, has been considered in the survey performed within this thesis. A brief description of each of them is reported below, underlining their main weak and strong points.

3.1.2.1 UML AD

UML AD is one of the thirteen diagrams that have been created by the Object Management Group (OMG) principally to model object-oriented software. This particular diagram proves to be suitable exactly for the representation of business processes, thanks to the possibility of assigning modelled activities to different responsibility roles, of supporting signal sending and receiving, and of implementing waiting and processing states. Notwithstanding the maturity shown by this modelling language in designing single-level processes, it presents limitations when modelling sub-processes and resource-related or organizational aspects, like for example the interaction with the operational environment [44], [50].

3.1.2.2 BPMN

BPMN is a standard originally developed by the Business Process Management Initiative (BPMI), which has then joined the OMG to deliver a new BPMN Specification document [51]. BPMN rapidly became the *de facto* standard thanks to both its intuitive and expressive look, and to the provision of the base for process implementation. The flowchart-based graphical representation used in BPMN to model business processes considers the following main elements:

- Tasks, visualized as rectangles with rounded corners and indicating the activities to be carried out within business processes;
- Gateways, visualized as diamond shapes and representing decision points where the divergence or convergence of the business process flow is controlled;
- Events, visualized as circles and used to display different kinds of events (i.e. Start, Intermediate and End event) affecting the business process flow;
- Sequence flows, visualized as arrowed lines and used to order the execution of the activities modelled in the business process flow;
- Subprocesses, visualized similarly to single tasks but used to gather a collection of tasks, in order to facilitate the readability and understandability of the business process flow;
- Data objects, visualized as small rectangular sheets and providing information about the requirements to perform activities or about their produced results;
- Pools, visualized as big rectangles and serving the organization of the elements represented in the business process flow;
- Lanes, composing sub-parts of the pools and used to arrange the modelled elements according to specific criteria, e.g. on the basis of the responsible process stakeholders.

By way of example, some of the abovementioned BPMN graphical elements are reported in Figure 6.

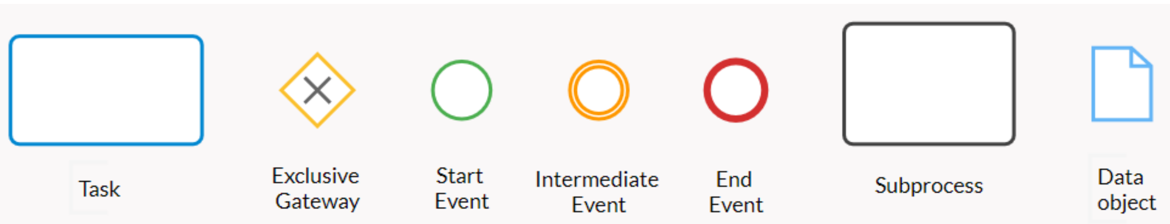

Figure 6 - Example of some BPMN graphical elements [52]

BPMN combines graphical representation with a rigorous XML encoding of processes by translating each graphical element into the corresponding XML one; both elements are accurately described in the standard. In addition, the XML code includes hidden attributes, in the form of technical details necessary for execution, that are not displayed in diagrams to preserve their readability. Therefore, BPMN models are deployed not only to communicate and interchange the requirements of business processes, but also to execute them on enterprise engines.

3.1.2.3 EPC

EPC is a modelling standard developed by the Institute for Information Systems at the University of Saarland, German, whose fundamental elements consist of functions and events. The former correspond to the activities performed in a business process which are able to trigger events, just like external actors. Despite its ease of use even by non-technical users and the possibility of executing parallel processes, the main drawback of EPC lies in the fact that its semantics and syntax seem to be poorly defined [44], [53].

3.1.2.4 RADs

RADs are used to model the interactions occurring among different subjects of an organization for the attainment of a certain goal. The activities (process steps) carried out by the considered interdependent entities are graphed in columns, one for each involved role. The vertical dimension of columns suggests the temporal sequential ordering for the execution of activities. However, as focused on a role-centric perspective of business processes, the RAD technique does not offer a detailed explanation of activities and objects [49].

3.1.2.5 Flow charts

Flowcharts consist in a formalised graphic representation of a sequential flow of actions and are characterized by a great communication ability that makes such models easy to use. The notation provided for flowcharts enables to model the properties of processes of various nature, also with a high level of detail. By contrast, this modelling method presents a few disadvantages, which are the excessive flexibility, the lack of differing between main and sub-activities and the inability to assign responsibilities or performers to the described activities [54].

3.1.2.6 ArchiMate

ArchiMate is an open and independent modelling language which has been developed by The Open Group to represent Enterprise Architectures. It provides a default iconography to model a set of entities and relationships, that are used to represent business processes, organizational structures, information flows, IT systems, and technical infrastructure. The core framework of ArchiMate is constituted by three layers, i.e. the business, application and technology ones, which are in turn combined with three aspects, namely passive structure, behaviour and active structure. The integration of these features permits to model the various points of view of enterprise stakeholders [55], [56].

Due to a lack in the standardization process, EPC, RADs and flow charts are actually considered only as supporting tools to graphically visualize the chronological implementation of activities. On the contrary, the remaining languages described above represent proper standards to model business processes. Notably, UML AD and BPMN appear to be very similar modelling languages, since they provide analogous symbols and control flow patterns. The evident likeliness in the modelling approach of these two BPMo techniques is illustrated in [57], where the comparability of their major elements is pointed out.

In this thesis, the approach adopted to choose the appropriate modelling language has referred to the framework for selecting BPMo methods proposed in [49]. Starting from the objective that guides the performing of process modelling, the goal of such task has consisted in the analyses of the current situation of port railway processes under examination, in order to identify possible improvements. The established objective has consequently influenced the perspective reflected by the modelling method and its characteristics: more specifically, the activity perspective has been considered. Such viewpoint enables to represent both carried out activities and the relationship between them. Furthermore, the selected BPMo method was required to possess peculiar characteristics, like scalability and enactability, to permit an effective investigation of the process at hand. In this respect, the preferred modelling method should be able to manage large processes, possibly sustained by multi-level representations, and to provide automated tools for process simulation. In light of these three constructs, i.e. the aim of the process modelling procedure, the perspective and the properties of the modelling method, BPMN has been selected as the most adequate standardized language to model the examined railway processes. Indeed, aside from the fact that it represents the *de facto* modelling standard, the adoption of such BPMo method has been motivated mainly by its capability of representing business processes at diverse levels of granularity and by the opportunity of mapping the developed graphical models into execution code.

In building BPMN models, great effort has been put to attain a good level of understandability which, as highlighted in [58], mostly depends on graphical readability and pattern recognition. Besides, attention has been paid principally to three categories of features, i.e. structure, layout and labelling, because, based on the analysis conducted in [59], they can often entail quality issues. In this regard, some of the recommendations suggested in [60] about BPMN method and style have been followed, like for example the collection of related activities into subprocesses, the precise positioning of certain elements in the model, and the arrangement of split flows exiting decision points. Other than that, process modelling has been performed considering the peculiar features characterizing the considered transport processes, so as to build context-sensitive models. Among the various properties outlined in [61], the operating systems, the cultural context, regulations, and operational policies represent some of the specific aspects that contribute to properly define the environment under analysis. Lastly, as stressed in [62], stakeholders' engagement, information resources and modeler's expertise have played a significant role in facilitating process modelling.

The graphical representation of BPMN models has been performed using the online editor called Cardanit, developed by Esteco S.p.A. [52], which automatically provides the XML format of created models. Cardanit also offers the opportunity to generate a report containing descriptions, screenshots and links referred to each element represented in the workflows. Such documentation can be downloaded and shared, in order to have available a comprehensive offline overview of developed models.

3.1.3 Literature review in the intermodal transport sector

Since in this thesis BPMN has been assumed as the preferred standard to model railway processes, the literature review concerning applications of BPMo techniques to the seaport context has been limited only to that method. In support of this choice, the presence of many scientific contributions regarding that modelling language in the transport and logistics sectors confirms its large embracement on part of both researchers and practitioners. However, a great amount of such papers discusses peculiar maritime-related issues, such as berthing activities, whereas just a few of them address more systemic aspects of the port system, like intermodal transport operations and logistics. In line with the scope of the integrated methodology proposed in the present dissertation, attention has been limited to contributions dealing with those latter cited topics.

In some previous articles, intermodality and port logistics have been faced in terms of the relevance of information exchange between the engaged actors, in order to smooth the overall freight transfer process. For instance, in [63], BPMN has been used to model business processes and information flows related to incoming container traffic via the port of Hamburg, underlining involved activities, events and IT systems. Notably, the communication among a deep-sea carrier, terminal operator, railway operator and railway company has been examined to assess the coordination of their processes, since it directly impacts on the potential increase in the customer value of port logistics processes. The created models have been then analysed with respect to standardization and integration, in order to detect significant junctures in the transport chain where a seamless information flow would enhance the efficiency in the utilization of existing infrastructures. In this regard, the port of Hamburg constitutes a meaningful case study, since it represents a high-performing urban-based port with shortages in space for infrastructural expansion. Indeed, this condition constitutes a common configuration also for other European ports. Finally, the authors of [63] point out the scarcity of further investigations that specifically discuss information flows in the framework of rail hinterland transport, in spite of the importance of this transport solution.

In [64], BPMN has been adopted as the modelling language to deeply examine the Port Community System (PCS) of Salerno, Italy, not only in terms of the organizational procedure of each engaged actor, but also of the inter-organizational routines between them. Rather than on the exchange of physical and financial components, the authors have focused on the information flows leading the relationships among the local actors of the considered port network, because of their crucial role in improving the coordination of operations. Starting from a thorough understanding of the current state of port logistics (as-is analysis), the implementation of possible future advancements has been investigated (to-be analysis), in order to enhance their reliability and efficiency. Furthermore, existing and potential performances of the PCS have been compared, outlining a transition plan to shift from the past process scenario to the improved one. Such analyses have been referred to the administrative activities of an export process, showing the relevance of creating an integrated information and communication platform to ensure the performing of intelligent logistics services. Indeed, the provision of such freight transport solutions enables the growth of port competitiveness and efficiency, thanks to a reduction in both costs and time necessary to pass through the port.

According to the developed integrated methodology, the static representation of business processes has been then followed by their animation using a simulation tool. Insights coming from process modelling have undoubtedly facilitated the comprehension of simulation results.

3.2 Parametrization of modelled elements

Prior to the actual simulation of processes, modelled elements have been parametrized in order to set their properties and, thus, to define the simulation scenario. This task has been accomplished using BPSim (Business Process Simulation), a standard developed by the Workflow Management Coalition (WfMC) which defines a specification for the parametrization and interchange of process analysis data. It allows to perform both structural and capacity analysis of business processes, in the view of pre-execution and post-execution optimization. In general terms, structural analysis consists in examining structural aspects of business process models, such as their configuration, and it usually considers statistical analysis by means of static methods. On the contrary, capacity analysis investigates capacity aspects of business process models, as for example their limitations, and it is normally based on dynamic analysis using discrete simulation techniques. The performing of such analyses requires the enhancement of business process models through the implementation of process analysis data, that can correspond to estimated values or historical execution values. Both types of information are suitable to be deployed as input parameters when analysing "what-if" scenarios, respectively in the context of pre-execution optimization and post-execution optimization procedures.

More in detail, the standardized specification provided by the BPSim framework permits to augment with information the business process models created using BPMN. In this regard, one of the main objectives of the BPSim specification consists exactly in being complementary to already existing languages for business process modelling. The specification is constituted by a meta-model, in the form of an underlying computer-interpretable representation, and by an interchange format, i.e. a coupled electronic file format for the protection and transfer of data between different instruments (modelling tools, simulators, results analysis or representation tools). The meta model is captured by means of the UML, while the interchange format is defined via an XML Schema Definition (XSD). A drawing of the conceptual model of BPSim is reported in Figure 7.

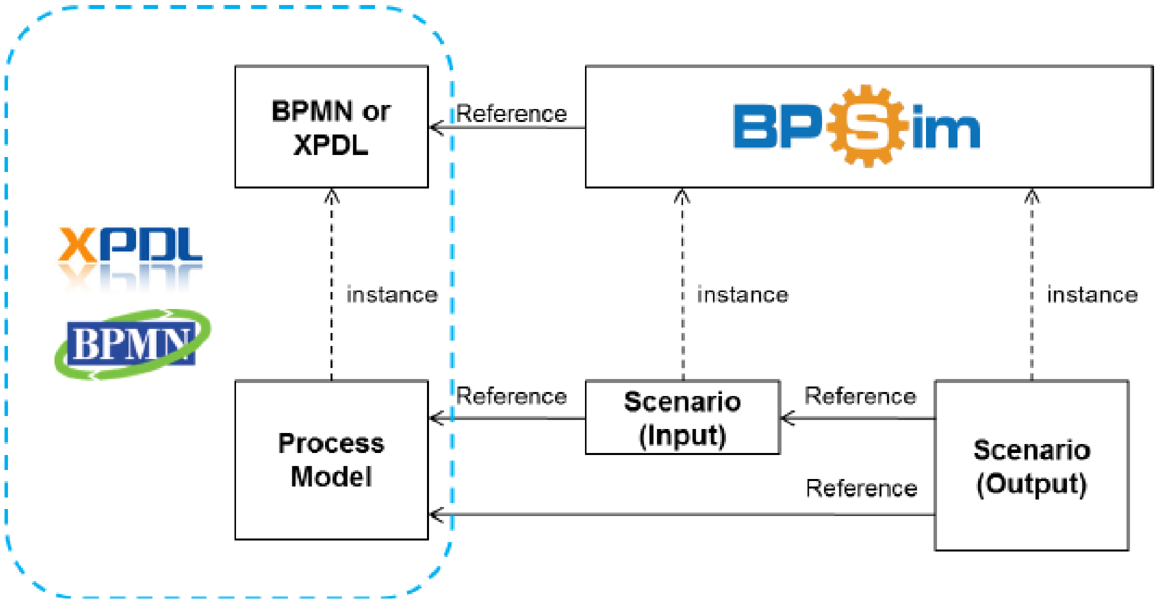

Figure 7 - Conceptual model of BPSim [65]

The interchange format is characterized by the possibility of transporting input and output scenarios, within or outside the process model file, and by the ability of producing a human-consumable XML. Interchange represents a key aspect which a variety of both vendors and end users can benefit from and it allows to reduce costs. Indeed, on one hand, it stimulates competitiveness in the marketplaces related to modelling, execution, simulation, and analysis, and on the other hand, it primarily offers flexibility and agility to business analysts, business people, business partners, and technical developers.

In the BPSim specification, parametrization is faced according to the different following perspectives: property, time, control, resource, cost, and priority. All these points of view correspond to diverse parameters, that reference to a certain process element within the considered business process models and that can be in turn detailed by additional features. Besides, the values of parameters can be distinguished in different types and their attachment to a fixed calendar permits to determine the applicability period.

The collection of a set of parameter values for process elements composes a specific scenario related to a single business process model, which is separately defined. As a matter of fact, business process models and their relative elements represent external sources that cannot be modified. According to the established purpose, different kinds of information are captured when using scenarios: input parameters identified for analysis, simulation and optimization; outcomes obtained from analysis, simulation and optimization; and historical data from past real-world execution of the business process model. Possible variations of the scenario setting can be performed based on an existing scenario, in order to assess the consequences of potential alterations. In that case, further specifications in the inheriting scenario are needed only to express the changes to the element parameter values, or to define the added parameters and their corresponding values. As well as elements, each scenario may possess scenario parameters, to characterize, for instance, its time duration.

Finally, the document concerning the BPSim specification delivers an overview of the BPSim parameters applicability, i.e. it illustrates which of them can be assigned to BPMN-modelled elements. Referring to input scenarios, BPSim also enables users to request the desired result type of a specific BPSim parameter related to a certain process model element, selecting that feature from a defined attribute set.

Through the adoption of a standard approach for data specification, BPSim promotes the use of simulation within the BPM context, highlighting its relevant role to accomplish various goals, like supporting business process design and validation, estimating business process performances to reduce risk of change and improve organization efficiency, and finally, addressing resource allocation and management [65], [66].

3.3 Simulation of modelled processes

Referring to intermodal transport systems, simulation is acknowledged as an appropriate instrument to evaluate the impacts of proposed solutions, thanks to its ability of capturing the intrinsic complexity of freight transport chains. As such, it supports decision-making processes in addressing troublesome issues related to various aspects of those transport systems, i.e. their dynamical and extensive nature, the hierarchical framework of decisions, the multiplicity of involved actors, and the randomness of different inputs and operations. Indeed, embedding practical decision-making approaches, simulation models enable the assessment of the implementation of interventions and policies at different planning decision levels, namely from the operational to the tactical and strategic one. More in detail, from a methodological perspective, the operations of intermodal transport systems can be successfully modelled by the dynamics characterizing discrete event systems, which are based on the interaction of discrete events. The concurrent happening of events, like demands, departures and arrivals of means of transport at terminals, and the acquisition and release of resources, are all intended as discrete events reflecting decision-making processes in intermodal transport networks [67], [68], [69].

In line with the "transaction-flow world view", Discrete-Event Simulation (DES) is adopted to visualize systems composed by discrete units of traffic (sometimes denominated "transactions"), that flow from one point to another of the network competing for the use of scarce resources. Such modelling approach is suitable to describe the running of queuing systems in general, in which even transport systems are included [70]. As a matter of fact, DES systems are typically meant as networks of queues and servers, where changes in the states of modelled processes are considered to occur only at discrete time points, called event times [71]. Each traffic unit, which is referred also to as an entity, triggers and responds to internal or external events, i.e. to the happenings that modify the system state. During simulation, entities move between different states before leaving the system (or model). Entities can represent physical, conceptual (information flows) or mathematical objects, and they can be characterized by parameters and/or variables, which consist respectively of stationary and dynamic state-related properties. Resources correspond to those system elements providing entities with services and are usually capacity-limited: this feature makes entities experiencing some delays while waiting for the use of resources. Control elements, like switches and counters, can be implemented in the model in order to consider other kinds of delay or logical alternatives based on the system state. When flowing through the system according to rules defined in the logical architecture, entities can perform or are affected by operations (active or passive entities), that constitute the steps to be modelled in the process. Simulation runs are managed by an internal clock that tracks the passage of simulated time, which advances in discrete steps. Time data values concerning simulation events are automatically recorded and stored [70], [72].

In the present thesis, DES has been adopted in order to estimate port railway capacity at strategic level, exploiting its ability of supporting not only the analysis of infrastructure utilization but also the assessment of the consequences of alternative interventions, thanks to the identification of potential bottlenecks [73]. Besides, initial simulation results have been used to calibrate and validate the parametrization of the developed railway process models, so as to verify their adherence to reality. Since simulation models always constitute a simplified representation of real systems, data validation is a task of utmost importance to ensure the correctness of input data, especially for crucial parameters. Indeed, the early detection of possible mistakes, often caused by miscalculations in the analysis and preparation activity of the model, allows to reduce the need for late additional data gathering [74]. The mutual influence between simulation and validation is depicted in Figure 8, which illustrates the traditional phases of a simulation study.

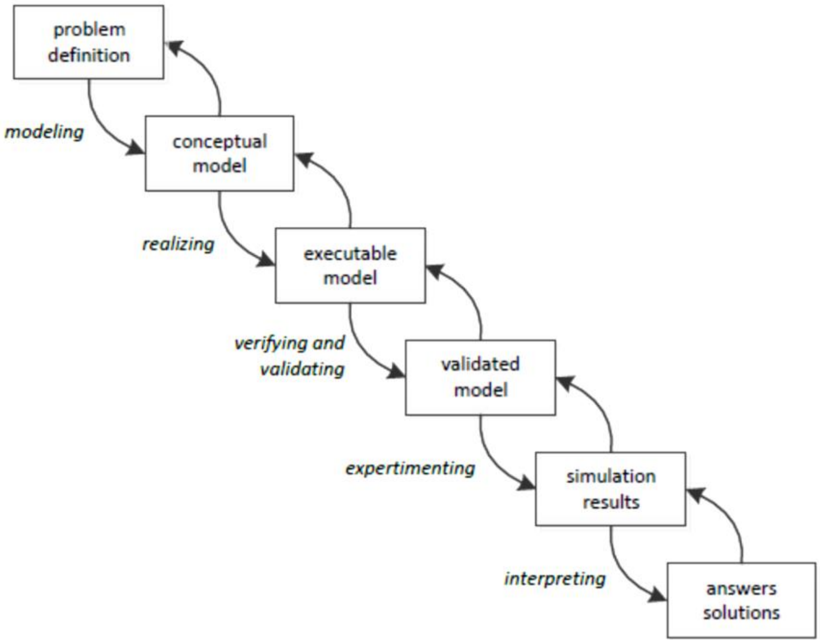

Figure 8 - Traditional phases of a simulation study [75]

Nowadays, different solutions for DES are present in terms of both simulation packages and simulation tools based on business process modelling languages. The first ones possess a more user-friendly graphical interface, in support to an easier comprehension of process animation. Besides, they offer dedicated libraries containing the essential elements necessary for the creation of simulation models for specific application fields, including the transport-related one. In this way, also non-expert users can rapidly compose simulation models via visual notation, employing the drag-and-drop functionality to insert ready-made building blocks. In face of these advantages, the scope of the area of application characterizing simulation packages proves to be quite limited, severely restricting the opportunity of modelling complex system logic functioning. To overcome this drawback, many tools with features of both a simulation language and a simulation package have been released. As such, in combination to a graphical design environment, those software enable the representation of more articulated and customized behaviours using scripting languages. Nevertheless, the resorting to programming language makes modelling a quite time-consuming task that is typically performed by a less extended and specialized target group, without providing straight insights of the developed model. Moreover, the use of proprietary building blocks to model systems constitutes one of the principal disadvantages of such simulation tools, because it implicates difficulties in exchanging simulation models between packages.

On the contrary, simulation tools based on business process modelling notations provide more flexibility and allow an easy interchange of process models with different analysis tools [75].

Among the various existing modelling languages, the majority of BPM tools and Business Suites have been developed either to natively support BPMN or to ensure the conversion to that standard, in order to be compatible and stay updated [76].

For the methodology proposed in this dissertation, a preliminary market analysis of the main simulation packages has been carried out, concentrating on the ones providing libraries dedicated specifically to the transport and logistics sector, or even to the actual rail transport mode. However, in continuity with the first phase of the methodology, i.e. business process modelling, a tool belonging to the other category of simulation instruments has been preferred over simulation packages to animate the examined system. More particularly, a technology developed by the Lanner Group, called L-Sim[1], has been adopted. It consists of a comprehensive standard-based simulation engine that can be embedded within various BPM software platforms and solutions, facilitating the exchange of models and analysis data. It supports BPMN 2.0 Interchange format and the BPSim standard, since it contains objects directly mapping BPMN elements, also in relation to specific features such as calendars and resource modelling. L-Sim offers users an overall sustain to perform the simulation of BPMN based models and diagrams, thanks to an extensive Application Programming Interface (API), visualization options and the ability of operating entirely through the exchange of XML files. Furthermore, L-Sim provides structured statistical outcomes which enable the identification of the best KPIs (Key Performance Indicators) and other beneficial effects granted by the use of predictive simulation in BPM strategies, like effective process design and the prioritization of investments. A schematization of the L-Sim architecture is reported in Figure 9, highlighting its flexible and powerful BPMN 2.0 compliant simulation capabilities [77].

[1] Esteco S.p.A. signed a commercial agreement with the Lanner Group in order to integrate L-Sim and the Cardanit editor, even for research purposes

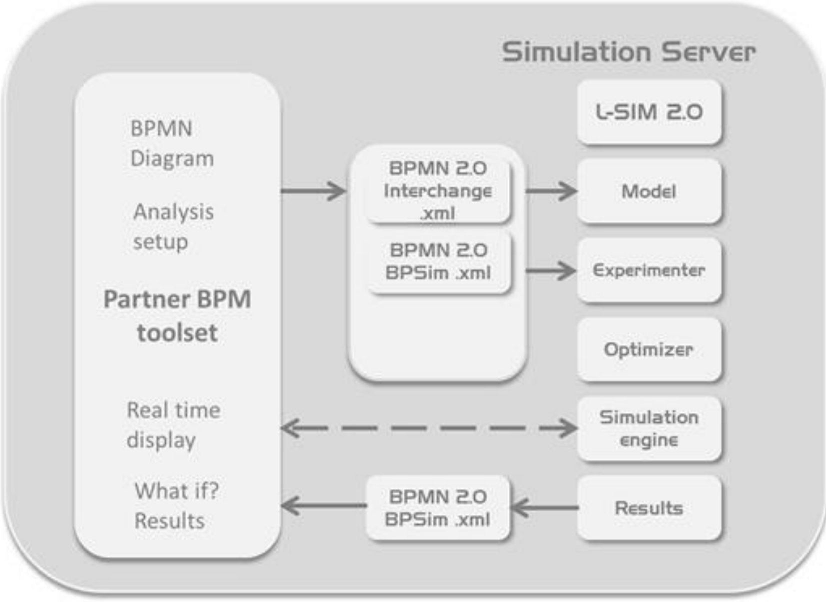

Figure 9 - L-Sim architecture [77]

3.3.1 Literature review

Since the related literature shows that modern simulation studies concerning the port logistics context are based on BPMN [76], a few examples of research contributions using such modelling standard are briefly described in the following. In [76], BPMN modelling and simulation have served the evaluation of possible improvements given by the implementation of smart Information and Communication Technologies (ICT) on maritime container terminals, considering the influence of the large-scale integration of those solutions on the framework of organization, planning and management models. In this regard, BPMN has been selected because, allowing to combine and capture several workflow patterns, it is functional to the establishment of a consistent environment for the integration of complex interaction behaviour. Indeed, other than the choice of the most appropriate technological devices, the authors stress the importance of adopting a process perspective to define the relationships among work activities, in the view of developing an enhanced integrated scenario. By creating BPMN models referred to the as-is and to-be configuration of the examined process, the evaluation of ICT impacts on the performances of the overall work flow has been carried out for a pilot container terminal in the Port of Leghorn, Italy, with respect to the dwell time of cargo in port. Benefitting from the automatic conversion of BPMN diagrams into executable models, the study demonstrates the potential of ICT in enabling the emergence of alternative design paradigms of port logistics, which are aimed at strengthening port efficiency through a better integration of the land and sea segments.

Prompted by the economic and engineering considerations characterizing the issue of modelling and simulating logistics processes, in [78] the BPMN formalism has been employed to visualize the multimodal transport chain from Hong Kong to Narvik, through Shanghai and Rotterdam, considering both the involved transport nodes and their connections. The developed BPMN representation has been then translated into the discrete event modelling and simulation language called Petri Nets, thanks to the matching of state and event elements between the two techniques. According to a hierarchical structure, the transport net has been divided into levels corresponding to single phases of the logistics chain, which have been properly linked to create the simulation model. Promising results in terms of mean transfer time of containers have been obtained in the study, but they necessitate to be verified through an accurate data gathering for every analysed transport mode.

Another attempt of converting graphical models into simulation processes has been performed in [79], in order to monitor the collaboration among resources and the occurrence of expected and unexpected events in a complex logistics process. To this end, in reference to the real scenario of an intermodal logistics chain from Austria to Romania, BPMN has been integrated with the functionality of Complex Event Processing (CEP) engines. First of all, the continuous movement of objects performed in transport operations has been represented by discrete state transitions in the business process, identifying those events related to information of interest for the track and trace of process execution. In addition, two other accomplishments have been attained in this work, namely the aggregation of fine-granular event sets to corresponding activities and the correlation of events regarding the same cargo unit. In that regard, the authors discuss the lack of an available approach to face these challenging tasks in an integrated way.

3.4 Optimization of processes

According to the proposed methodology, the simulation of the examined railway process models has been followed by an optimization procedure, in order to determine the maximum port railway capacity. Concerning the engineering field, the spread of multi-objective optimization (MOO) approaches has been historically motivated by the increasing adoption of complex simulation in design processes, which in turn has been boosted by the greater availability of computing resources. Furthermore, the need of embracing a multidisciplinary perspective to deal with real-life design problems has certainly contributed to grow interest for MOO techniques, especially in the case of applications with poorly defined targets and constrains to be satisfied. Indeed, MOO methods permit to consider different and usually conflicting goals, even when the obtainable compromise level is not known a priori. As opposed to the more restricted scope of results provided by traditional single-objective optimization (SOO) methods, the possibility of investigating a set of potential optimal solutions offered by MOO approaches efficiently supports decision makers in the selection of the most suitable one [80]. Referring to the transport sector in general, the appropriateness of adopting MOO methods is confirmed by the request of explicitly consider criteria other than costs to reflect the complexity of the social and economic environment [81]. A typical transport-related problem solved using MOO approaches consists in the design of multimodal transport networks, since the alternative scenarios to be developed involve more than one objective which pertain to different interacting design levels, i.e. both to the overall system and to the individual user behaviour [82]. In this regard, in presence of multimodal facilities, MOO methods are able to sustain the planning of network loads addressing also sustainability issues, because, taking into account various objectives simultaneously, they produce solutions with a higher level of equity [83].

More in detail, the optimization procedure has been carried out through a Multi-Disciplinary Optimization (MDO) framework, that enables to optimize engineering design processes thanks to the deployment of innovative algorithms and to the integration with major simulation tools. An engineering design process can be described as a series of stages that engineers should finalise to solve a certain design problem. To that end, the MDO framework allows to define the details of engineering design processes by means of an intuitive workflow, which contains not only the logical steps of the examined process, but also input and output variables. In doing so, the MDO framework manages to combine both the Data Flow and the Process Flow. The former indicates the data to be transferred from one process step to the other, whereas the latter illustrates the sequence of actions to be undertaken and the conditions to be evaluated. Acting as a Black Box, specific nodes in the MDO framework workflow permit the integration between external simulation tools. Indeed, the Black Box includes the necessary procedures to compute the values of output variables, based on the input variables of the engineering design process. The Black Box can contain different computational elements, such as a calculator, a script, or a specific external procedure or tool, like Computer-Aided Engineering (CAE), Computer-Aided Design (CAD) and Finite Element Methods (FEM) tools [84]. Referring to the first two elements, the former is composed by a series of instructions to produce different types of outputs, while the latter consists of a particular programming language used to automate the execution of certain program activities.

A schematic visualization of the MDO framework integration concept is reported in Figure 10. As it can be noticed, a given set of input variables feed the Black Box, i.e. the simulation engine, that provides the corresponding output variables expressed in terms of goals or constraints. Subsequently, DOE and optimization algorithms are applied to find the optimal and feasible solutions. Notably, the MDO framework used in the proposed methodology consists of the multi-disciplinary software called modeFRONTIER (mF), which has been developed by Esteco S.p.A. [85].

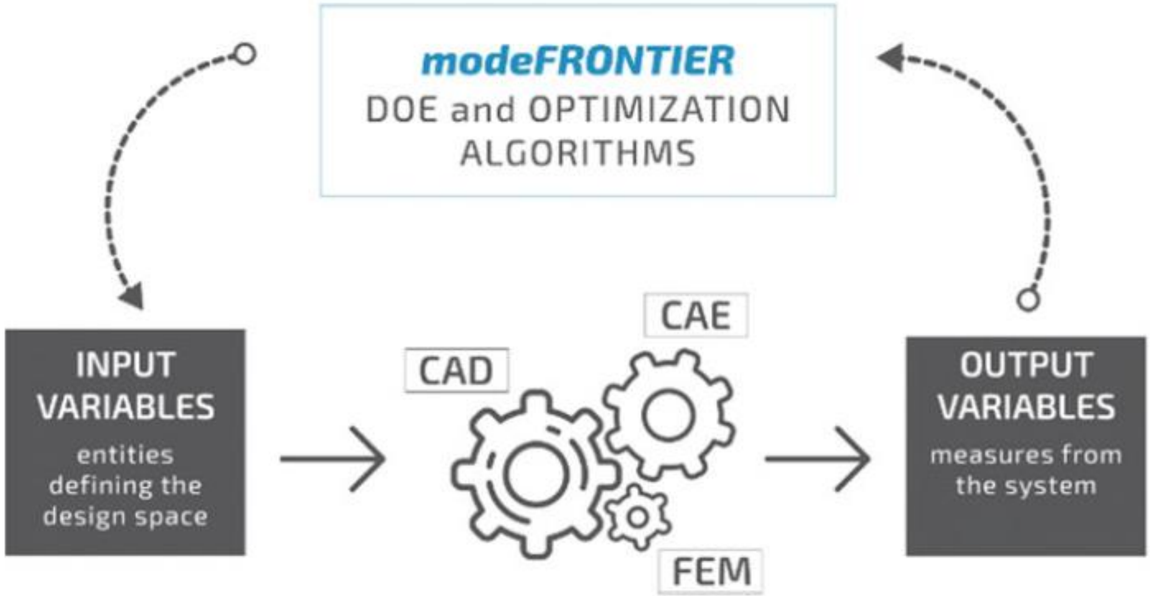

Figure 10 - The modeFRONTIER framework integration concept [84]

3.4.1 Genetic algorithms

The mF framework includes several iterative optimization algorithms for single- and multi-objective optimization problems: some of them belong to the family of Genetic Algorithms (GAs), which have been first developed by Holland in the 1970s [86]. GAs are inspired by the theory of Charles Darwin on natural evolution in the origin of species, whereby biological organisms evolve based on the principle of natural selection that considers the "survival of the fittest" in the accomplishment of particular remarkable tasks. In nature, evidence of such fundamentals can be observed in the competition among the individuals of a population for the acquisition of resources and for the attraction of mates for reproduction purposes. Indeed, because of the selection, poorly performing individuals possess less chances to survive, while the most adapted or "fit" ones are able to produce a quite large number of offspring. Based on a probabilistic approach, in the reproduction process a recombination of the good characteristics coming from each parent allows the generation of "best fit" offspring, which are supposed to be characterized by a greater fitness with respect to their ancestors. Consequently, by preserving favourable variations and rejecting unfavourable ones, the spontaneous evolution of species over generations is expected to make them ever more adapted to the surrounding environment. Embedding the Darwinian mechanism which underlies the natural evolution phenomenon, GAs have revealed to be a useful tool for search and optimization problems. As a matter of fact, GAs handle a population of possible solutions, constituting the so-called search space, to which determined reproduction operators are applied in order to mimic mutations and recombinations. While the former rarely contribute to improve algorithms, the latter perform a crossover of partial solutions that actually enhances the capability of the algorithm to approach, and eventually find, the optimal solution. Like saying, the assortment of the characteristics from two diverse parents entails the creation of new solutions with beneficial effects on their fitness, which is evaluated using a fitness function during the selection process of solutions. After the appropriate definition of the reproduction and fitness functions, the evolution of a GA begins with the random generation of an initial population and then continues by looping over an iteration process to make such population progress. At every iteration, the following steps are carried out:

- The selection of solutions for reproduction according to their relative fitness value: the best solutions are more likely to be chosen than the less suitable ones;
- The reproduction of selected solutions to produce offspring, using both recombination and mutation;
- The evaluation of the offspring's fitness;
- The replacement of solutions from the old population with the new ones.

It must be noted that, similarly to selection, also reproduction consists of a random procedure. Over successive generations, the just outlined basic operations performed by GAs enables the convergence towards the global, or near global, optimum, making a fast and robust technique to face optimization problems [87].

Among the various algorithms contained in the mF framework, the following two GAs are present: MOGA-II and NSGA-II. MOGA-II represents an improved version of MOGA developed by Poloni and it is based on the concept of Pareto optimality [88]. Such notion identifies the feasible criterion space (i.e. the Pareto front) as the set of optimal points representing trade-off solutions among the objectives of the problem at hand. By providing a wide range of options, the Pareto set proves to contain optimal solutions from a comprehensive point of view and, thus, it allows decision makers to make a more informed final decision. Indeed, according to a systemic perspective, the generation of the Pareto front enables the exploration of the effects of decisions on the examined system, with respect to all the considered objectives. The introduction by part of decision makers of further criteria, either before or after the investigation of acceptable solutions, contributes to guide, refine or narrow the search for the preferred solution [89]. In this regard, in MOGA-II the fitness of possible solutions depends on the Pareto dominance criteria, according to the definition of dominance. MOGA-II encodes the population of solutions as in traditional GAs and uses a smart multi-search elitism for robustness and directional crossover. Elitism consists in the preservation process of high performing candidates from one generation to the next, increasing the convergence speed of algorithms. When using elitism in multi-objective GAs, the populations resulting from subsequent iterations of the algorithm correspond to the combination of new solutions with current elite solutions, in which currently non-dominated solutions can be identified. The inclusion of an elitist element represents a significant feature in MOO procedures, because it contributes to enhance the effectiveness of the genetic algorithm both in terms of closeness and diversity. The former performance measure expresses the nearness of the obtained non-dominate solutions to the front, while the latter indicates their coverage of the trade-off surface. Dispersion, intended as the suitable distribution of candidate solutions in the regions of interest to decision makers, constitutes one of the goals of multi-objective GAs and it is influenced also by the selected genetic operator [90]. For reproduction purposes, the following four operators are implemented in MOGA-II: two-point crossover, directional crossover, mutation and selection. During the reproduction process, one of them is chosen according to established operator probabilities and it is applied to a certain solution.

The other considered GA, namely NSGA-II, was developed by Deb [91] and differs from MOGA-II, because it works not only with discrete variables coded in binary format, but also with continuous variables. In this latter case, a peculiar crossover and mutation operation for reproduction is carried out on the basis of a Deb probability function. NSGA-II uses a fast and smart non-dominated sorting approach and elitism for the multi-objective search. More in detail, elitism is employed by gathering all non-dominated solutions discovered so far, starting from the initial population. Besides, as well as the spread of solutions, the diversity preservation mechanism adopted in NSGA-II involves a suitable parameter-less niching approach, avoiding the use of sharing parameters. This technique considers the formation of sub-population clusters, called niches, within the global population, without being sensitive to the choice of the niche size parameter. Indeed, using a discrimination metric different from closeness, parameter-less methods do not require the determination of the niche size value, whose estimation can be quite difficult [90]. The ranking of the population in the objective space is performed according to a defined crowding distance criterion, which implies that the points with a higher average distance to the other are placed in the higher rankings.

3.4.2 Design of Experiments algorithms

Even Design of Experiments (DOE) algorithms are included in the mF framework and they are typically used to define the initial population serving optimization algorithms [88]. DOE represents a multivariate approach to experimenting, which aims at quantitatively defining the cause and effect relationship among the factors of the considered process, in support to the process optimization goal [92]. According to such methodology, input variables are referred to as controllable factors, since control can be exerted on them during an experiment. On the contrary, output variables correspond to process responses which are modified by changes in controllable factors. Usually, a certain variability of responses due to uncontrollable external factors is captured at each process run, although an identical setting of input variables is implemented. Therefore, an experiment is meant to be a set of experimental runs, during which tests are performed on the so-called experimental units. In line with this denomination, an experimental design is composed by a collection of test values for the controllable factors, which are determined beforehand in the planning of a designed experiment [93]. As a matter of fact, DOE does not suggest which input factors should be considered in tests and/or the variation of their quantitative values, but rather it is used to select combinations of value levels for the examined factors to be simulated through experiments. The combination of factors and of their quantities strictly depends on the behaviour of the input and output variables analysed in the modelled process [94]. DOE is a useful approach particularly in case of models with multiple variables, as it enables to simultaneously consider the entire space of variables, thus enabling to verify the mutual effects between the factors of interest. In this way, experimental design reduces the number of experiments or repetitions and improves the quality of the information obtained from the outcomes, lessening labour time and costs. Furthermore, the experimental error can be calculated, facilitating the analysis of results and the estimation of their reproducibility, based on the level of statistical confidence [95].

Other than the statistical approach described above, a specific DOE algorithm called Full Factorial can be used to study interactions between variables by measuring the response of every possible combination of factors. Such technique has been adopted in the proposed methodology to create the initial set of data for the optimization problem.

3.5 Conclusions

The proposed combination of methods and techniques to estimate the maximum port railway capacity underlines the complexity of accomplishing such task, due to the multiplicity of aspects to be considered. Indeed, approaching the modelling of railway processes in analogy with the BPM strategies adopted in product industries, highlights the relevance of organizational issues characterizing intermodal transport operations. Other than facilitating the comprehension of the examined phenomenon, in a certain sense the graphical visualization of processes provides insights for the selection of the appropriate methodological framework to simulate the performing of the sequence of modelled activities. In this regard, DES proves to be the most suitable approach to realistically animate transport-related processes, thanks to its ability of representing transport systems as networks of queues and servers. Simulation results turn out to be useful not only to identify process bottlenecks, but also to validate the developed models, testing the correctness of the previous parametrization phase. More in detail, the resorting to simulation tools compliant to modelling language standards enables greater flexibility, in terms of both model building and of the possibility of exchanging coding files among diverse simulation instruments. Finally, optimization procedures efficiently operate in function of the identification of a set of possible optimal solutions, even in case of design problems with conflicting goals and constrains for which the compromise level is not known in advance. Specifically, GAs constitute a fast and robust technique for search and optimization problems.

4. Multi-actor multi-criteria evaluation

Decision making (DM) constitutes a pervading activity which affects individuals on a daily basis, but most importantly, organizations and governments, that are often challenged to make decisions implicating far-reaching consequences. DM encompasses tasks like making reasoned judgements, selecting preferred options and assessing evolving situations to rapidly choose appropriate strategies, with the aim of leading agents to achieve specific goals. Based on a normative approach, DM involves a series of steps, starting from the detection and understanding of the decision problem and its environment. This initial stage is then followed by the identification of the decision maker and his/her objectives and preferences, ending up with the development of alternatives to choose among. However, it is acknowledged that the rationality guiding towards optimal decisions in the normative stream of DM can be difficult to apply in complex systems, because of problematic issues such as interconnected systems, peculiar dynamics, multiple objectives, constraints and decision makers, uncertainties, and incomplete sharing of information. To this end, support is given by adopting the prescriptive approach of DM, which includes techniques and aids to improve human DM compensating possible biases [96]. Despite the remarkable contribution provided by decision support tools, computation represents the simplest and least important of all DM components and functions, since decision quality is highly influenced by how the decision process is unfold. Indeed, when proceeding in the definition of criteria, information and alternatives to be considered, every partial decision made in relation to those individual aspects definitely impacts on the context of successive decisions and, lastly, on the final outcome of the whole decision process [97].

In the light of the articulated framework characterizing decision processes, in [97] a paradigm for which no DM takes place with respect to a single dimension is asserted, motivated by the fact that human DM actually occurs under multiple criteria only. According to this perspective, decision problems evaluated as against to a single criterion are considered just problems of analysis, measurement and search. As such, it is therefore deemed that DM exclusively refers to Multiple Criteria Decision Making (MCDM).

As regard DM methodologies enabling to consider a variety of criteria, different approaches are available to assess projects and plans based not only on financial aspects, but also on social features, in order to capture even the community standpoint. In proof of their wider adaptability compared to single-dimension evaluation methods, such techniques have been gaining an ever-increasing interest among evaluators and have been applied to several sectors [98]. One of them is represented by the Social Cost-Benefit Analysis (SCBA), i.e. an extension of the conventional Cost-Benefit Analysis (CBA) which permits to integrate the assessment procedure with non-

market effects by transforming them into economic values. Analogously to other monetary evaluation approaches, SCBA is characterized by a main limitation consisting in the fact that difficulties are often encountered when measuring certain impacts of projects or plans in financial terms. Indeed, notwithstanding the efforts made to estimate values for intangibles and externalities, a solid and agreed monetary quantification of those effects is practically unattainable, like in the case of accounting for political priorities. Consequently, such drawback entails that, at times, applying SCBA does not permit to fully determine the feasibility of the examined interventions from a societal point of view [99], [100], [101].
A useful alternative to efficiently manage non-market dimensions in appraisal processes stems from Multi-Criteria Decision Analysis (MCDA) techniques, as they allow to consider both quantitative and qualitative criteria to identify the properties of decision problems [102], [103]. These methods suit particularly well transport evaluation, since it basically consists of a conflict analysis in which technical, socioeconomic, environmental, and political value judgements are engaged. Such complexity makes transport planning a multirelated process, in which straightforward and unambiguous solutions are hard to achieve. Therefore, by providing a flexible approach to handle qualitative multidimensional effects, MCDA techniques turn out to constitute an adequate assessment methodology to appraise transport initiatives. Besides, to a general extent, and specifically in case of transport problems, an evaluation methodology is required to present the following four main features: transparency, simplicity, robustness, and accountability [99]. The achievement of these characteristics is facilitated by the adoption of MCDA methods, if properly applied. More in detail, being ease understandability a crucial aspect of assessment processes, the first two characteristics are of utmost importance especially when different stakeholders are actively involved in the evaluation exercise [104].

4.1 MCDA methods

Although a variety of MCDA methods have been developed to support decision makers, they all provide a structured framework that permits to carry out a thorough assessment of troublesome issues, even in complex contexts [105]. The selection of the most adequate multicriteria decision model strictly depends on the initial definition of the problem under study, which precedes the identification of appraisal criteria. Notably, according to [106], the following four types of problems can be addressed by the application of MCDA methods: choice, sorting, ranking, and description. Choice consists in the selection of a subset of actions, among which a single measure can be eventually chosen, whilst sorting considers the classification of actions, by assigning them to certain pre-established categories. Ranking represents the task of totally or partially ordering actions based on preferences, with the aim of determining the most attractive ones and, finally, description entails the explanation of actions and their consequences in appropriate terms. For each type of problem, diverse MCDA methods are available but, like saying, meeting the conditions and needs of the problem of interest is the leading principle that should guide what multi-criteria evaluation model to opt for [107]. In line with the objective of the methodology presented in this thesis, i.e. the strategic estimation of the optimal port railway capacity, attention has been drawn to ranking problems, so as to identify the most valuable intervention enabling the attainment of such goal.

Limiting the scope of the application field of MCDA methods to the transport sector, the most widespread techniques are multi-attribute theory variants, outranking methods and regime analysis. For instance, techniques belonging to the first family are the "Analytic Hierarchy Process" (AHP) and its alternative version called the "Analytic Network Process" (ANP), the "Multi-Attribute Utility Theory" (MAUT) and the "Multi-Attribute Value Theory" (MAVT), the "Simple Multi-Attribute Rating Technique" (SMART), and its simplified variant denominated the "Simple Multi-Attribute Rating Technique Exploiting Ranks" (SMARTER). Instead, the second category of MCDA techniques listed above includes the "Preference Ranking Organization METHod for Enrichment of Evaluations" (PROMETHEE) and the "ELimination Et Choix Traduisant la REalité" (ELECTRE - ELimination Et Choice Translating REality) method [108]. Founded on the notion of the compensation of performances, they mainly differ from how priorities are attributed to evaluation criteria and how the global effectiveness of actions is determined, which impacts on the identification of dominant solutions within the set of considered alternatives. According to the review reported in [109] and aimed at outlining the increasing adoption of MCDA methods for the evaluation of transport projects, the AHP method and its declination represented by the ANP method have turned out to be the most used techniques in the retrieved articles. Indeed, referring to the time period between 1985 and 2012, more than a third of the examined scientific contributions have proved to resort to one of the hierarchical-structured DM processes developed by professor T. L. Saaty in the 1970's [110]. Besides, such literature analysis has also shown that the selection of a specific MCDA method is often geographically determined, in the sense that the application of a certain technique is more frequent in the country where the respective school of thought has grown.
In light of the evidences suggesting the predominant use of Saaty's techniques, in this dissertation the AHP method has been selected as the preferred method to carry out the

evaluation procedure. Furthermore, it is characterized by the capability of considering both quantitative and qualitative criteria, and by a great flexibility to be integrated with diverse evaluation methods [111].

4.1.1 The AHP method: main principles

The AHP method is a quite easy analytical and synthetic MCDA approach, whose application consists of the following three main stages: hierarchy construction, priority analysis and consistency verification [112]. As illustrated in Figure 11, in the first phase decision makers need to break down complex decision problems into simpler parts, which are then organized according to a multi-level hierarchical structure. The definition of such arrangement for the overall goal, criteria and their relative attributes allows decision makers to analyse more rationally and efficiently the decision problem at hand. After the creation of the DM framework, in the second stage pairwise comparisons are performed among components belonging to the same level of the hierarchy, based on decision makers' experience and knowledge or on data provided by surveys. Notably, two elements of the same level are compared to one in the upper level, which represents the parent node. Judgments on comparative attractiveness of criteria and their attributes are expressed according to Saaty's 1-9 fundamental scale, which is reported in Figure 12. Under this preference scale, an element characterized by a higher mark is intended to have more significance than another one associated to a lower value [111]. A variety of application examples demonstrate that such rating approach makes the AHP method a valid technique to generate accurate weights, even when the insights of the person answering pairwise comparison questions are not clearly defined [113]. Since comparisons reflect subjective judgements, a certain degree of inconsistency in stated preferences can be observed, especially for decision systems presenting five or more factors for each level. In this regard, the third phase of the AHP involves checking inconsistency through the confrontation of data resulting from decision makers' judgements and a set of random outcomes obtained by random evaluations [112]. The measure developed by Saaty to estimate inconsistency is called the "Inconsistency Ratio" (IR) and its value can range between zero, when there is a perfect consistency of input data, and a large positive number. Analogously, also a "Consistency Ratio" (CR) can be calculated. In the context of the AHP theory, Saaty suggested that an IR which equals 0.1 or less is acceptable, while higher values implicate the need of reviewing input data or comparisons, or even reconsidering the effectiveness of the whole structure of the multi-criteria decision problem. Two common mistakes causing a high IR can possibly occur, i.e. when decision makers state an intransitive relationship in pairwise comparisons, or in the event that comparative judgments are inadvertently inverted [113].

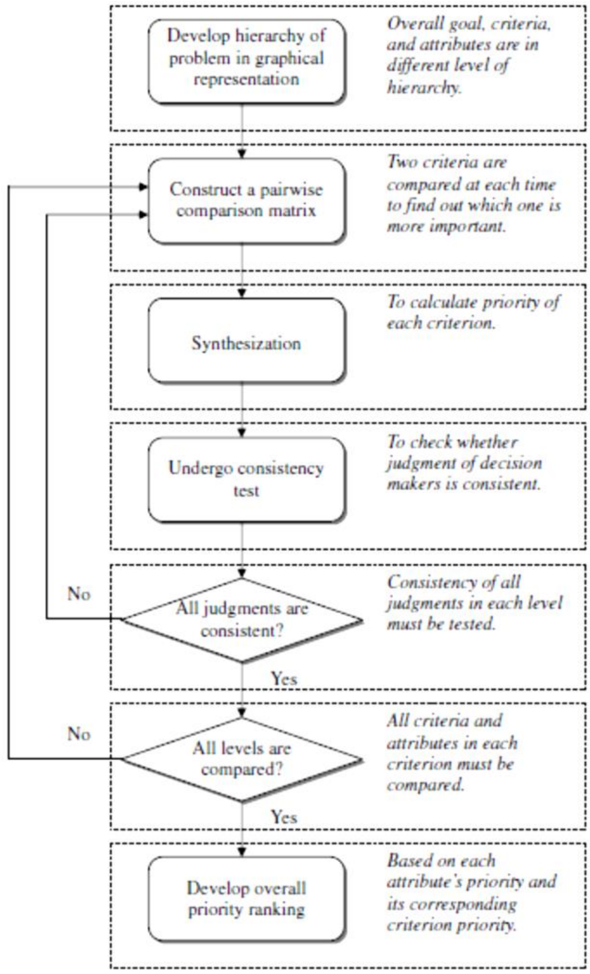

Figure 11 - The AHP flowchart [112]

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another.
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another.
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance is demonstrated in practice.
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
1.1–1.9	When activities are very close a decimal is added to 1 to show their difference as appropriate.	A better alternative way to assigning the small decimals is to compare two close activities with other widely contrasting ones, favoring the larger one a little over the smaller one when using the 1–9 values.
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	This is logical assumption.
Measurements from ratio scales		When it is desired to use such numbers in physical applications; alternatively, often one estimates the ratios of such magnitudes by using judgment.

Figure 12 - Saaty's fundamental pairwise comparison scale [110]

Notwithstanding the importance of complying to consistency principles, an excessive review and improvement of judgements could be counterproductive for the definition of weights, because the preferences of decision makers could be altered [114].

Finally, on the basis of the relative priorities of attributes and criteria, the AHP concludes with a synthesis of judgements, aimed at developing the overall priority ranking [112]. This result is functional to the selection of the most valuable alternative among the ones included in the last level of the hierarchical model, whose performances are assessed relative to the identified evaluation criteria.

At analytical level, the AHP method considers at least two approaches to estimate the priorities of decision elements that have been pairwise compared. One technique consists in solving the following homogenous system of equations (1):

$$\sum_{j=1}^{n} a_{ij} w_j = \lambda_{max} w_i \qquad i = 1, \dots \dots, n \tag{1}$$

Where a_{ij} contains the judgement assigned in the comparison between element a_i and element a_j with respect to an element of the upper level, using the 1-9 Saaty's rating scale, λ_{max} represents the principal or largest eigenvalue of the matrix of judgements and, lastly, w_i is the corresponding vector, called the principal eigenvector.

An alternative technique entails to raise the matrix of judgements to the power a large number of times, until the values of all its columns resulting from two consequent iterations are nearly the same, with reference to an established accuracy threshold [110].

In addition to accounting multiple evaluation criteria, even the consideration of multiple stakeholders proves to be necessary to accurately perform assessment procedures and, thus, to provide decision makers with reliable recommendations. This need is motivated by the fact that, on one hand, stakeholder participation enables to compensate the possible lack of information at the disposal of a single analysist and, on the other hand, it enhances the acceptability of the final decision, especially when dealing with highly controversial issues [115].

4.2 Inclusion of the stakeholder concept

With reference to the business world, "a stakeholder is by definition any individual or group of individuals that can influence or are influenced by the achievement of the organisation's objectives" [116]. The inclusion of the stakeholder concept into MCDA techniques has marked the emergence of a second generation of those methods, which differs from the previous one for the fact that the final decision obtained by performing evaluation processes does not reflect the standpoint of only a single decision maker. Indeed, in these latest methods the accounting of various stakeholders in the assessment procedure enables to generate recommendations which reflect a group ranking of the analysed decision problem components [115]. Such recent category of multi-criteria appraisal techniques encompasses several approaches, which are referred to as Group Decision Support Methods (GDSMs). For instance, the Multi-Actor Multi-Criteria Analysis (MAMCA) method developed by Macharis, represents one of the methodologies embracing the modern evolution of MCDA methods. Even though GDSMs are distinguished for the way in which the group decision process is carried out, in all of them the advanced contribution given by actors' participation to the appraisal stands out [117]. Actually, the added value provided by stakeholders' engagement in the assessment process had already been acknowledged in the past, leading to the adaptation of some traditional MCDA techniques, like e.g. the AHP, the PROMETHEE and the ELECTRE methods, to GDSMs [115]. With specific reference to the AHP, stakeholders are usually included in the second level of the hierarchical structure, right after the main goal of the decision problem, to assess their level of influence for the attainment of such objective.
The multi-actor variant of MCDA methods requires an initial fundamental stage consisting of the stakeholder analysis, i.e. an approach to gain knowledge about the actors involved in the decision problem, which is aimed at understanding their behaviour, intentions, interrelations,

and interests. Especially in complex environments, the acquisition of such information permits to assess the influence and the resources that actors are expected to assert in the DM process. Based on the examined temporal perspective (past, present or future), a few key dimensions have to be considered when investigating on stakeholders, in order to effectively capture useful insights about them. As a matter of fact, the stakeholder analysis should be declined, for example, according to its purpose, focus, scope, and time frame [118].

When it comes to the actual involvement of stakeholders in the assessment process, the determination of the evaluation group, in terms of size and arrangement, really covers a meaningful role. Reason for this is because the selected actors directly influence the problem structure, the definition of goals and the consequent achievement of decision recommendations. In this regard, to warrant the reliability of the appraisal procedure, two relevant factors, namely inclusiveness and balance, should guide the choice of group members. Indeed, depending on the analysed topic, all relevant interested parties should be properly included, avoiding disproportional circumstances in which some stakeholders are under or overrepresented [105]. Besides, accomplishing an accurate stakeholder mapping allows to develop actions that suit at best the stake of each engaged actor [119]. In addition to the properties of comprehensiveness and equity, the involvement of stakeholders should be established according to the attributes of power, legitimacy and urgency. The possession of these characteristics defines, respectively, the leverage of actors on the final evaluation outcome, the attention they deserve and the pressure of their claim with respect to time sensitivity or level of criticality [120]. The individuals forming the evaluation panel can participate to the assessment process playing diverse roles, in line with their position in the decision problem at hand. More specifically, they can take part as decision makers, source of expertise or representative of stakeholder groups. Possible complications in the development of the evaluation process may be entailed by differences among the involved actors with regard to their knowledge level of the analysed issue and to the interest they represent. Nevertheless, such barriers can be overcome thanks to the support of an external facilitator [105].

In many application sectors, including the transport-related one, the active engagement of community within the involved stakeholders has recently turned out to be a very pressing topic, due to the relevant societal impacts generated by policies and, on a broader scale, by plans and projects. Driven by the importance of considering not only scientific knowledge, but also knowledge based on experience and values, deliberation has become an ordinary approach to public participation in the development and evaluation of strategies [121]. As for the case of EU regulations, despite the importance of science in making collective decisions, the strong presence of experts in evaluation panels is likely to transform the policy definition process into a mere technical problem solving, neglecting the standpoint of the democratic representation. For this reason, the activity of evaluation groups is suggested to result in "a co-production of policy, not in a scientification of decisions" [122].

The inclusion of a variety of stakeholders into the evaluation panel brings to light another critical topic discussed in DM processes, which consists in the attribution of the relative influence of actors for the achievement of the main goal of the decision problem. To this end, different approaches can be adopted to prioritize the importance of the engaged members, ranging from the association of an equal weight to all of them, to a more or less detailed specification of their relevance considering diversified influence values. Of course, the technique used to define actors' priorities proves to have a certain impact on the final outcome of the evaluation process, since this latter descends directly from actors' preferences on the elements of the decision problem framework. Alternatively, single stakeholders' opinions can be aggregated prior to the actual appraisal procedure, using different consensus-building methods. However, in the simplest cases, the collective opinion obtained applying such methods results to be an "average" insight of the examined aspects of the decision problem, which might be not satisfactory or representative of individual judgements [123].

4.3 Literature review on multi-actor MCDA methods

As reported in [124], in recent years efforts made to turn MCDA methods into participatory approaches have been principally led by the need of solving environmental conflicts. Such endeavour has resulted in the development of various methods, like participatory multi-criteria evaluation, social multi-criteria evaluation, multi-criteria mapping, deliberative multi-criteria evaluation, and MAMCA. By involving stakeholders in multi-criteria analysis, all these methodologies address the aim to provide help in building consensus and in facing more efficiently the inherent complexity of modern social and technological systems. Besides, they contribute to enhance the transparency of DM processes [125] and, ultimately, the legitimacy of decisions. Except for MAMCA, the authors of [124] suggest that the main drawbacks of those methods are in the agreement of stakeholders on a common set of evaluation criteria and on the weights attributed to such elements. On the contrary, MAMCA considers the assessment of alternatives with respect to criteria which vary for each involved stakeholder, and that have been previously identified based on actors' objectives. Therefore, the outcome of MAMCA consists of distinct preference rankings, one for every stakeholder, which are then compared to analyse possible synergies and conflicts in the actors' preferences. In conclusion, the best scenario of intervention, or a combination of scenarios, is determined by carrying out a consensus-building process, which is intended to come to a decision that meets the interest of the majority of the engaged actors without relevant detriment for the others.

In the context of the present thesis, a few features characterizing the MAMCA methodology have been deemed not to be in line with the aim of the adopted evaluation approach. Notably, the principles of such technique that have been questioned are the use of the arithmetic mean to define criteria priorities, the association of equal values for all stakeholders' level of influence and the supply of disaggregated results. Despite these potentially hindering factors, the MAMCA method has been considered as a reference for comparison in the performing of the literature analysis, not only because it explicitly accounts for stakeholders in the decision framework, but also because it is often integrated with the AHP for the construction of the evaluation matrix. In that event, the definition of criteria priorities and the evaluation of scenarios on stakeholders' criteria are accomplished using Saaty's 1-9 rating scale for pair-wise comparisons. Besides, MAMCA has been widely applied to assess several aspects of the transport sector, i.e. infrastructures, technologies and policy measures, even in reference to intermodal transport. In this regard, recourse to such method has been made, for instance, in [126] to appraise long-term decisions on mobility and logistics in the Flemish region.
However, the assignment of diverse levels of influence to engaged stakeholders and the generation of an aggregated result directly from the evaluation procedure, rather than produced by the application of consensus-building techniques, have corresponded to the two crucial parameters marking the scientific contributions described below. Finally, although sharing the same common value tree for all the involved actors, the following research both concern the assessment of projects focusing on intermodal transport, which is the field of study of the present dissertation.
The first considered application of the AHP method [127] is part of the feasibility study that was performed within the North Adriatic Port Association (NAPA) Studies project [128] for the Port of Trieste, Italy, to assess future developments of the container traffic. Indeed, just like in the other ports involved in the NAPA, a market analysis on the potential container handling capacity was carried out, with the intention of evaluating the practicability of forming a multi-port gateway for the Asian and Central and Eastern European economies. In regard to the Port of Trieste, both the infrastructure layout and the operations were examined in depth, highlighting the bottlenecks that could compromise its role within the established port network. With the aim of enhancing the efficiency of port activities, some feasible solutions were

identified: albeit to a different extent, they all included a rearrangement of railway infrastructures and operations to enable the composition and transfer of longer trains. Such improvements proved to be necessary also to meet the requirements imposed by the European Union for the advancement of whole European transport network. Three stakeholders, namely the Port Authority, the national railway infrastructure manager and the main regional administrative entity, were engaged in the evaluation procedure, in order to account different perspectives on the decision problem at hand. As a matter of fact, even if pursuing diverse goals, they all cover a significant role for the attainment of port advancements. Besides, evaluation criteria were defined so as to appraise the considered alternatives as against specific aspects, like cohesion, efficiency, sustainability, and users' benefits.

The second application of the AHP method [129] still concerns the Port of Trieste and it is related to the objective of improving freight movements according to a different perspective, which focuses mainly on the integration of port operations within an urban context. Indeed, the evaluated scenarios of intervention consist of two measures developed in the framework of the European project called CIVITAS PORTIS (PORT-cities Integrating Sustainability) [130], which was aimed at enhancing the port-city integration in various European port cities by the implementation of sustainable mobility solutions. More in detail, the assessed initiatives considered both technological and governance initiatives that were expected to beneficially impact not only on process efficiency, but also on safety and the environment. Even the combination of the two investigated measures was accounted among the alternatives, in order to capture possible advantageous mutual effects. The stakeholders explicitly included in the decision model, and actively engaged in the evaluation procedure, were the Port Authority, terminal operators, the Municipality, and the main regional administrative entity. This latter was involved to represent citizens' interest on mobility issues. Evaluation criteria were identified based on a previous analysis by indicators of the potential impacts of measures and regarded costs, environmental sustainability, safety, transport improvements, and innovation in management.

4.4 Conclusions

In the light of the importance of making decisions in relation to different aspects, the resorting to MCDA methods is crucial to perform a sound evaluation of initiatives according to a variety of parameters. Besides, thanks to the accounting for both quantitative and qualitative criteria, they allow to overcome the main limitation of traditional monetary approaches, enabling to evaluate also intangibles. Several techniques of this kind have been developed and applied in many sectors to face different types of decision problems. Especially in complex contexts, the engagement of stakeholders into assessment procedures results to be fundamental in order to consider various perspectives, including the one of citizens', and thus, to attain shared recommendations. To this end, MCDA methods have evolved to comprise the notion of stakeholder, giving birth to a new generation of approaches that permit to carry out group DM processes. A proper application of GDSMs requires, at an early stage, the conducting of a stakeholder analysis, which is finalized to collect insights on the position, interest and network of the primary actors taking part to the evaluation process. Therefore, it can be concluded that assessment procedures represent a powerful tool to efficiently evaluate both the potential effectiveness of measures and their implementation process, when they encompass the analysis of performances in relation to individual aspects, the aggregation of those diverse estimations and the involvement of several stakeholders [131].

Concerning the transport sector, the AHP method has proved to be the most used technique to appraise projects and plans, with reference to various features of such field. In its multi-actor variant, it enables to determine actors' level of influence with respect to the main goal of the decision problem and the priorities of criteria through pair-wise comparisons between the elements of the hierarchical decision framework. Finally, the AHP provides an aggregated result, which corresponds to a recommendation supporting decision makers in the selection of the best alternative. The participatory process taking place in such circumstances enhances the transparency of the evaluation procedure and, lastly, the acceptability of the final decision.

5. Case study - The optimization procedure

Together with evaluation, the proposed methodology integrating modelling, simulation and optimization has been applied to the case study of the Port of Trieste, which is the first Italian port with respect to both the total annual throughput and the railway share for freight transfers to/from the hinterland. The resorting to appropriate analysis and evaluation tools has proved to be essential to assess its potential capacity in different scenarios of intervention, considering operational requirements and infrastructural availability. Notably, attention has been drawn to the railway mode since, based on statistical evidences, the Port of Trieste has been increasingly relying on such transport solution, also due to its relevance in contributing to environmental sustainability. In this regard, with reference to the Italian logistics context, in recent years the Port of Trieste has shown itself to be particularly virtuous, adopting policies which address that issue. The support given by the suggested methodology in estimating railway capacity is perfectly in line with the sustainable trend embraced by the Port of Trieste, as it enables to further boost the supply of intermodal transport services. Finally, given the time-consuming procedure needed to actually implement port infrastructural developments, an accurate and prompt quantification of railway capacity at strategic level is crucial to improve the functional design and planning of port advancements.

5.1 Overview of the Port of Trieste

Situated in the Northern Eastern part of the country, the Port of Trieste lies in a strategic position in the heart of Europe and represents the crossroads of various maritime routes and transport corridors. Indeed, it constitutes an important international hub for the land-sea flows concerning the marketplaces of Central and Eastern Europe, and more lately also of Far East. Thanks to its location along the Silk Road and to its great water depth, reaching until 18 meters, in the latest years the Port of Trieste has recorded a significant increase in traffic volumes, which are expected to grow even further in the future. Besides, it is characterized by the Free Port regime, which entails that customers can benefit from special regulations with respect to customs procedures and the fiscal regime. This unconventional favourable legislation guarantees the exemption from duty payments for customers and regards import, export and transit operations [132]. Proof of this, a wall marks such different legal framework, physically separating the Free Port zone from the other surrounding port areas. However, in face of the described commercial advantages, in practical terms this condition implies more complex administrative procedures for the functioning of the port system, because it requires the engagement of a larger group of stakeholders for the actual freight movement.

At infrastructural level, the Port of Trieste has available an internal railway network which is efficiently connected with the national and international ones. The development of intermodal transport in the Port of Trieste is sustained also by the presence of two of the nine TEN-T (Trans-European Transport Network) Corridors in the territory of the Friuli Venezia Giulia region, which is the area it belongs to. More in detail, as illustrated in Figures 13 and 14, the Port of Trieste is engaged by traffic flows transferring freight along the Baltic-Adriatic and the Mediterranean Corridors, which connect, respectively, the Northern and the Southern areas of Eastern Europe and South-Western Europe with Eastern Europe. The ultimate goal of the TEN-T network aims at implementing and developing a Europe-wide network including a multiplicity of routes and facilities for all transport modes, in order to not only eliminate bottlenecks and technical barriers, but also to strengthen the social, economic and territorial cohesion in the European Union. In addition to the backbone Core Network which the nine main Corridors pertain to, TEN-T encompasses a Comprehensive Network composed by a series of secondary transport connections to cover all European regions [133]. To further foster intermodality in freight transport, for each Corridor some financial investments have been planned considering the realization of new links and of infrastructural and technological modernization interventions, on both railway line sections and nodes.

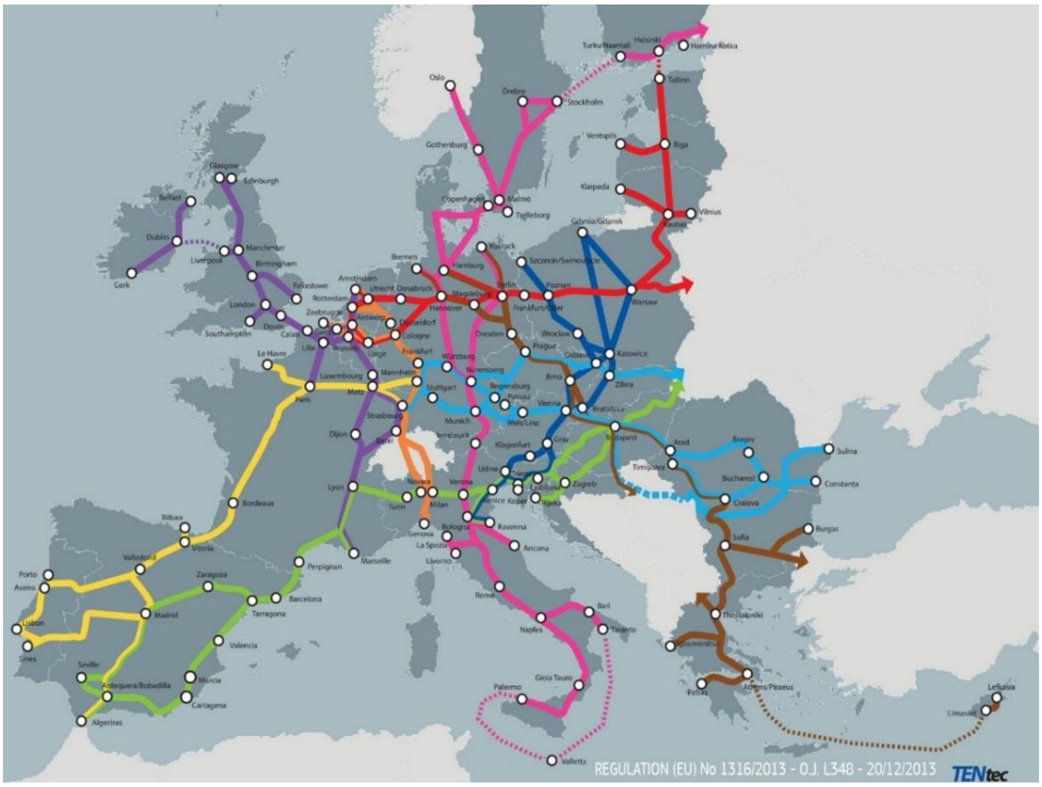

Figure 13 - TEN-T Corridors [133]

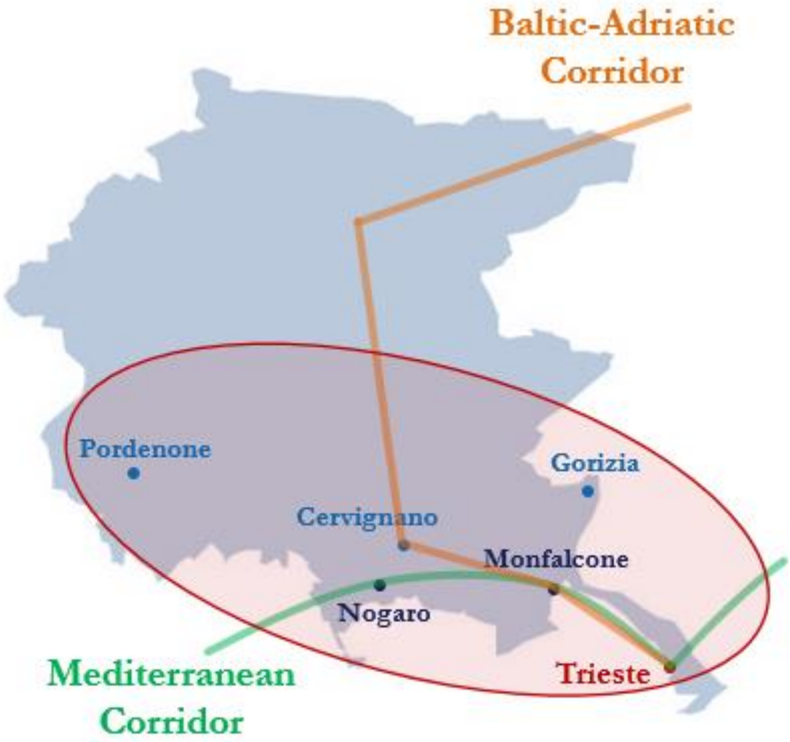

Figure 14 - TEN-T Corridors present in the Friuli Venezia Giulia region

The Port of Trieste is managed by a public entity called Port Network Authority of the Eastern Adriatic Sea (PNAEAS – *Autorità di Sistema Portuale del Mare Adriatico Orientale*), which gives in concession some of the areas and structures of the port to various terminal operators. These private subjects handle the movement of goods belonging to different product categories, which encompass containerized freights, fruit and vegetable products, coffee, cereals, metal, engines, steel and chemical products, wood, solid and liquid bulk, crude oil, and its derivative products [134]. Rail services performed by the principal economic entities in the Port of Trieste consist of freight intermodal transport solutions destined mainly to Austria, Germany, Luxembourg, Hungary, Czech Republic, and Slovakia. Only a limited number of those services is directed towards Italy.

As illustrated in Figure 15, the Port of Trieste is composed by two main parts, which distinguish themselves for the type of activity they are dedicated to: on one side, the commercial port, including the area called Punto Franco Nuovo, and on the other side, Scalo Legnami, Ferriera, Punto Franco Oli Minerali, and the industrial port, which is located in the area of the Canale Navigabile.

Figure 15 - The Port of Trieste

More specifically, Figure 16 depicts the current configuration of the railway infrastructure in the Port of Trieste, which includes the following stations, linked with the external national network and among them:

- Trieste Campo Marzio, located in the Punto Franco Nuovo and directly connected both to the national network, by means of the junction called "Galleria di Cintura" and the line Trieste Centrale-Bivio di Aurisina, and to the Villa Opicina, station through a single-track line ("*linea Transalpina*");
- Trieste Servola, in the proximity of the industrial establishment called Ferriera;
- Trieste San Sabba, situated between the areas of Servola and Punto Franco Oli Minerali;
- Trieste Aquilinia, located in the area of the Canale Navigabile.

The main infrastructure component of the railway network in the Trieste node is constituted by a circular double-track line under a tunnel, which links the Trieste Centrale station, used only for passenger services, with the one of Trieste Campo Marzio. At present, this latter represents the merging station not only of traffic flows generated in the area of the Punto Franco Nuovo, but also of those originated by Scalo Legnami, Ferriera and Punto Franco Oli Minerali. Indeed, the composition and decomposition operations of all freight trains are carried out in the Trieste

Campo Marzio station. This train management approach will be modified in the near future, thanks to the reopening of the junction connecting the Southern part of the port directly with the Galleria di Cintura, without passing through the Trieste Campo Marzio station.

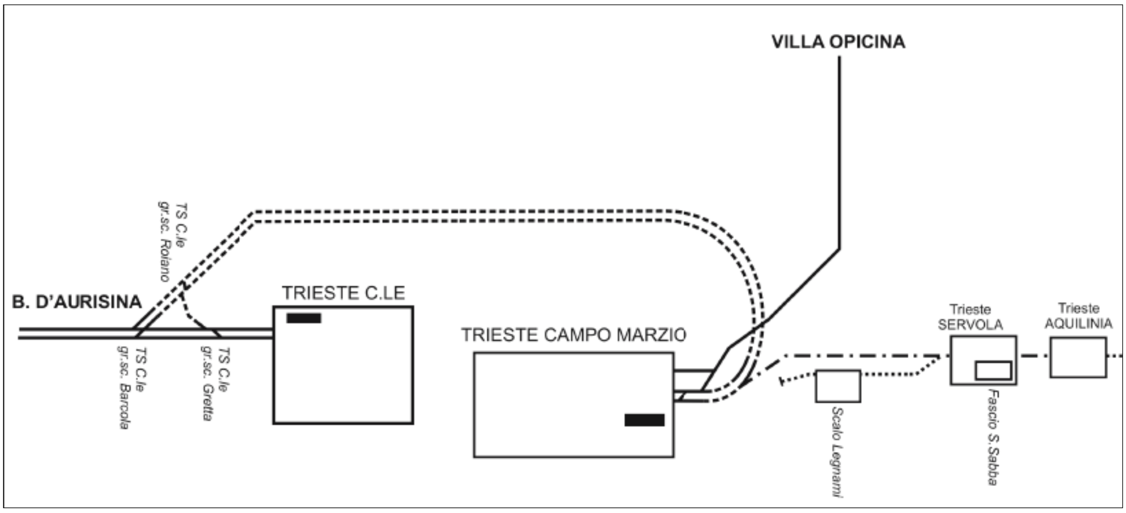

Figure 16 - Current configuration of the railway node of the Port of Trieste [135]

On behalf of railway companies, shunting operations for trains arriving and departing in the Trieste Campo Marzio station are carried out by the company Adriafer S.r.l., constituted and owned by the PNAEAS, which is the only operation manager for the Punto Franco Nuovo since 2016. Furthermore, Adriafer S.r.l. performs shunting operations at one of the terminals managing oil products and at the Interporto di Trieste, which is an inland terminal located in Fernetti and connected to the Villa Opicina station.

Analysing the railway context according to a wider perspective, Figure 17 shows that the Port of Trieste also has a good connection with the stations located in the proximity of the state borders skirting the Friuli Venezia Giulia region, namely the Austrian and the Slovenian ones. Concerning railway network usage, the residual capacity on the line sections connecting the port with state border stations has been estimated by the national infrastructure manager, called Rete Ferroviaria Italiana (RFI) S.p.A., as the difference between their maximum capacity and their actual use, based on the official planned timetable in reference to a weekday. A critical condition in terms of residual capacity is present on a specific section along the itinerary between Trieste and Tarvisio (Austrian cross border), where railway flows coming from North-South and East-West traffic routes converge. This limitation could hinder the increase in traffic volumes which is expected in the future for the Port of Trieste, but it is intended to be mitigated even thanks to the enhancement initiatives planned for the Baltic-Adriatic and the Mediterranean Corridors.

Figure 17 - The main railway network of the Friuli Venezia Giulia region [135]

As regard technological facilities, PNAEAS has lately introduced an IT platform, named Sinfomar and developed by Info.era S.r.l. [136], which constitutes the PCS of the Port of Trieste. It supports the computerization of the running process of port system operations and publicly provides detailed and real-time information on the vessels which are moored at the various port terminals. Besides, thanks to the creation of a reserved access section dedicated specifically to trains, a twofold objective has been achieved. Indeed, on one hand, Sinfomar has enabled the management of incoming and outcoming railway traffic flows by recording both the expecting and the actual time of train movements. On the other hand, it has permitted the dematerialization of the document called CH30, facilitating the interoperability with the information platforms of railway and logistics third parties. CH30 is a customs document containing precise information concerning both freights and the mean of transport, in term of the physical composition of trains. As such, it attests the arrival and departure of goods to and from the Port of Trieste. As illustrated in [137], this digital documentation evolves through different statuses along the arrival and departure processes of trains, tracking the development of the administrative activities performed on vehicles. For sure, the smoothness in freight data exchanges provided by the implementation of Sinfomar has beneficially impacted on railway port operations and it is meant to support intermodality even more through the integration with terminal operation systems and the information platform for the management of the railway national network.

In confirmation of this, ports are deemed to represent the leading area for shipping-related information technology, especially with reference to terminal operating systems and intra-port communications. As a matter of fact, together with the ability of such tools in handling a variety of data, their power and speed of information processing are considered the key features which contribute to reshape the shipping and port industry [7].

On a broader scale, the pronounced development of railway intermodal transport expected for the Port of Trieste can be motivated by evidence coming from future macroeconomic tendencies of the reference context. Indeed, bearing in mind the uncertainty underlying long-term forecasts, the main consideration on which future scenarios are based consists in a tendency for a shift of the principal centres of global economy towards the East, along with advancements in emerging and less developed countries. Such change is likely to define a new structure of trade relationships, in which the ever-growing share of container transfers will represent the driving force of global maritime traffic. In that economic framework, the Mediterranean Sea will continue to play an important role, due to the rise in traffic flows along trans-oceanic routes and to the intensification of trade exchanges between Europe and Africa. At international level, three major factors, namely technological development, containerisation, and naval gigantism, are considered to be the elements influencing maritime transport in the future. The first one, other than enhancing the efficiency, security and reliability of port operations, is likely to shorten logistics chains, modifying the asset of trade exchanges. Since its emergence in the 1960s, the diffusion of containerisation has induced companies to adapt their productive systems in order to suit them to intermodal transport: such transformation will probably continue to happen, in line with the possible marginal growth of container flows. Further pressure on ports will be exerted by naval gigantism and sectorial composition, affecting the spatial structure of maritime routes and drawing more and more attention on inland connections. Indeed, according to the concept of global logistics chains, these latter constitute the fundamental parameter determining the high level of competitiveness among ports, due to the great relevance of intermodal transport costs within the overall transport cost.

As mentioned, the Port of Trieste has recently undergone a remarkable intermodal development, that has led to an increase in its annual railway traffic volumes almost up to 10000 trains. In view of the future shift of its intermodal connections towards Central-Eastern European countries, it seems reasonable to assume that the Port of Trieste will acquire a share of the traffic flows which currently concern the Northern Range ports. The addition of this potential traffic demand would certainly contribute to further boost the use of the railway mode, even along the connections serving extra-continental marketplaces.

With reference to the contents of Chapters 3 and 4, the following sections report the application of the implementation phases of the proposed integrated methodology and of the adopted evaluation procedure to the case study of the Port of Trieste.

5.2 Application of the integrated methodology

In the light of the expected increase in traffic volumes, the proposed integrated optimization methodology has been applied to the Port of Trieste, with the aim of estimating the optimal port railway capacity at strategic level. In summary, as depicted in Figure 5, the analysed railway processes have been initially represented using BPMN and, then, the modelled elements have been parametrized through the BPSim standard. Subsequently, benefitting from the possibility of interchanging process analysis data provided by this latter, the simulation engine L-Sim has been adopted to animate processes. Finally, an optimization procedure has been carried out by means of the software modeFRONTIER, according to specific embedded genetic algorithms.

5.2.1 Railway process modelling

Railway processes in the Port of Trieste have been modelled through BMPN considering different aspects, namely both transport operations and administrative procedures. As a matter of fact, the developed models not only display the physical movements of trains and shunting locomotives during arrival and departure processes, but they also take into account the information flow needed to manage freight and train transfers in the port. More in detail, the sequential order of railway activities has been combined with the production or modification of the required technical documents, i.e. the CH30 in its various evolutionary statuses and shunting instructions. Modelling has been made even more articulated by distinguishing the responsible actor for each represented task: like saying, such complexity is partially due to the presence of the Free Port regime, which entails the involvement of larger number of stakeholders in the performing of intermodal services. The inclusion of documentary aspects in the created models has certainly contributed to shed light on possible and less evident procedural bottlenecks. Other than that, it has fostered the analysis of potential barriers in the transport processes, which are usually related to the availability of infrastructural and vehicles resources.

The information necessary to build process models have been gathered, on one hand, by consulting the official documentation provided by the PNAEAS, e.g. [137], and on the other hand, during frequent technical meetings with the Railway Infrastructure Department (RID – *Direzione Infrastrutture Ferroviarie*) of the PNAEAS. Especially the constant dialogue with the RID staff has facilitated the creation of process models, permitting the gradual refinement of such workflows and, thus, an in-depth comprehension of the investigated railway operations.

Sections 5.2.1.1 and 5.2.1.2 describe the preliminary version of the models concerning train arrival and departure processes in the Port of Trieste, which have been developed according to a more aggregated perspective of activities. Their correspondent graphical representation obtained using the editor Cardanit is reported in the Annexes A and B. Referring to BPMN notation, in both processes a single pool has been used to define in broad terms the context of the Port of Trieste and it has been divided into different lanes based on the various stakeholders involved in the examined processes. Each lane includes all the elements, in terms of events, tasks, gateways, and data objects, which the identified stakeholder is responsible for. More in detail, the following actors have been considered: Customs (*Dogana*), the Multimodal Transport Operator (MTO – *Agente treno*), the terminal operator (*Terminalista*), the railway company (*Impresa ferroviaria*), the shunting operations manager (*Gestore unico*), the Financial Police (*Guardia di Finanza*), and the national railway infrastructure manager RFI. Customs is in charge of verifying the correctness of the CH30 throughout the train arrival and departure processes and, thus, it is authorized to change its statutes according to the established evolution procedure. The MTO is responsible of making commercial decisions regarding freights to be transferred, along the whole logistics chain. In the framework of railway processes in the Port of Trieste, the MTO is engaged in the dematerialization procedure of the CH30, on which it makes modifications based on Customs instructions. Therefore, in this circumstance, the role of the terminal operator is limited to the execution of practical operations related to goods movement within the terminals. The tasks performed by the railway company concern train arrival and departure activities only at the main port railway station, i.e. the Trieste Campo Marzio station, which represents the interface between the port and the national railway network. Indeed, all shunting operations within the railway node of the Port of Trieste are carried out exclusively by the shunting operations manager. The Financial Police is in charge of checking the correspondence between the elaborated CH30 to the freight present on trains and, thus, of potentially indicating and requesting changes in such document in case of non-compliance. Finally, RFI is responsible for the authorization of the actual departure of trains from the port to the national railway network. Furthermore, it is important to underline that process models reported in the Annexes A and B have been intentionally developed to describe train arrival and departure processes in the Port of Trieste only in general terms. No precise reference to destination terminals and to the physical occupancy of railway infrastructural resources has been made, because the goal consisted in better understanding the integration between documentary procedures and railway operations. As a matter of fact, these latter have been represented in terms of macro-activities, whose detailed specification has been reported in the models created for simulation purposes.

5.2.1.1 Train arrival process model

The arrival process starts with Customs receiving the CH30 in its "definitive" version by part of the MTO, in order to check the correctness of its content. In case no variations of such document are needed, Customs proceed to change its status into "confirmed" and the railway company requests the shunting operations manager to enter the train into the port, prior to its actual arrival. Once the train coming from the national network has stopped at the main port railway station, the railway company detaches the electric locomotive and makes the train available to the shunting operations manager. This latter is now able to attach the diesel shunting locomotive, which firstly leads the train until the gateway limiting the Free Port zone from the remaining areas of the port. While passing through the gateway, the train is checked by the Financial Police, which notifies the MTO about the presence of possible irregularities. If inconsistency in train documents is observed, the MTO is required to control such anomalies and asks Customs for the permission to modify the CH30. After the adjustments to the CH30 are made, the status of the document is converted into "confirmed" by Customs and, again, the Financial Police validates the correspondence of the CH30 content with the cargo units actually loaded on the train. A further modification of the status of the CH30 attests the entrance of the train into the Free Port zone, which is recorded on a specific register by Customs. Subsequently, the terminal operator accepts the arrival of the train to its relative pier, which can be performed by the shunting operations manager through a single or double operation, according to the current occupancy of terminal tracks. Once the train has reached the destination terminal, the diesel locomotive is detached by the shunting operations manager, which officially makes the train available to the terminal operator for unloading activities.

5.2.1.2 Train departure process model

The departure process starts with Customs receiving a "provisional" version of the CH30, whose status is then changed into "authorized" in case of approval. Otherwise, if any mistake is observed in the document, Customs require the MTO to make the necessary modifications. After the CH30 authorization, the Financial Police verifies cargo units loaded on trains and orders the variation of the CH30 status from "authorized" to "verified", other than indicating the eventual cargo units that it is willing to check. Subsequently, if an empty train is already located at its corresponding terminal, loading activities are performed by the terminal operators. On the contrary, this latter asks the shunting operations manager to enter a train from the main port railway station. Once the train is loaded, the competent railway company execute a pre-check on cargo units, that, in case of irregularities, are potentially removed or added. Therefore, such control on cargo units entails the possible variation of the CH30 by part of the MTO. If the pre-check on cargo units provides a positive result, the MTO is permitted to generate a "definitive" version of the CH30, which is then recorded on a specific register and confirmed by Customs. Later on, the railway company is in charge of validating the departure of the train, which, in particular operational circumstance, is re-planned with a certain time shift due to the either physical or temporal suppression of the train. Whenever the train departure is confirmed, the terminal operator requests the shunting operations manager the permission of exiting the train from the terminal, which can be performed through a single or double shunting operation. In this latter case, the train is positioned on some buffer tracks located within the port for a certain period, after which the railway company can approve or not the train departure. When leaving the terminal, the train transits through the gateway that separates the Free Port zone from the surrounding port areas: exactly in correspondence to this passage, the Financial Police verifies the compliance of both the train wagons and the loading units. If any irregularity is encountered, additional shunting operations and the appropriate modifications in the CH30 content and status need to be performed. Otherwise, an affirmative result of such control entails the validation of the final version of the CH30 by the Financial Police, which allows the train to leave the port. Thereafter, the shunting operations manager detaches the diesel locomotive used to exit the train from the terminal at the main port railway station, making the train available to the railway company. If the train departure is confirmed, in line with the train traction system adopted on the national network, the electric locomotive is attached. Conversely, the train is cancelled and kept waiting for its rescheduling in the abovementioned station or on some trucks nearby, in the event that this latter infrastructural node is congested. Prior to the actual train departure, the railway company executes a brake test on the train. A non-regular outcome of such control implies the manual intervention of an operator and, eventually, the isolation or the discard of malfunctioning wagons, with the consequent variation of train documents. Finally, once the national railway infrastructure manager receives by the railway company the notification that the train is ready to leave, the departure signal is opened.

5.2.2 Railway process simulation

Starting from the BPMN models created in the initial phase of the proposed integrated methodology, further developments have been accomplished to effectively and realistically mimic the railway processes described above. Notably, a refinement of the models has been made contextually to the definition of some assumptions with respect to both the simulation functioning and to the parametrization of modelled elements. As a consequence, proper adaptations in the execution code have been performed, together with the model validation.

5.2.2.1 Adjustments to the BPMN models

As anticipated, in order to simulate railway processes taking place in the Port of Trieste, a few minor modifications of the developed BPMN models were first necessary. On one hand, variations have consisted in reducing the number of tasks by grouping the consecutive activities that require the same resources, intended in terms of tracks and shunting locomotives. On the other hand, further changes were made to the BPMN models to represent the occurrence of the same portion of processes in different locations of the port railway network. More particularly, the performing of identical activities at the three considered terminals has required to triple some tasks.

According to a more detailed perspective as compared to the one adopted for the initial models, the physical railway operations performed during train arrival and departure processes have been specified at graphical level. To this end, railway operations have been modelled using tasks, each of them defining the distances covered by trains on the various parts of the port network infrastructure. The visualization of such activities has implicated the elaboration of other secondary models to display the transfers travelled by single shunting locomotives to reach different parts of the network. The need of integrating these processes with the main ones related to the arrival and departure process of composed trains has entailed the use of peculiar BPMN elements, i.e. signals, allowing the communication among the two. In this way, the actual railway traffic in the Port of Trieste has been modelled, taking into account the mutual interaction not only among trains, but also between trains and single shunting locomotives, which is generated by the sharing of common infrastructural resources.

The amended version of models concerning train arrival and departure processes is reported, respectively, in Annexes C and D, while models representing the release and recall processes of shunting locomotives are included in Annexes E and F.

5.2.2.2 Schematization of the port railway network

The labelling of the elements displayed in the revised BPMN models, and concerning specifically railway operations, has been based on a schematization of the port railway network, that is reported in Annex G. Such representation has been developed according to the current layout of the railway infrastructure in the Punto Franco Nuovo and has also served the parametrization phase of the models, suggesting clear reference to the various parts of the port railway node. Other than the national railway network, as indicated in the legend, the schematization considers the following main components of the port railway network: the Trieste Campo Marzio station, the set of tracks denominated "Parenzane", the two gateways separating the Free Port zone from the external areas, the track called "Asta Lunga", the collection of tracks named "Fascio dei Moli", and the three terminals present in the Punto Franco Nuovo. In addition, some side but yet fundamental infrastructural resources have been taken into account and consist of the switches connecting with each other the abovementioned components, permitting the occurrence of train traffic. The developed overview of the port railway network has enabled also the identification of the itineraries that can be travelled by trains and, more in particular, the necessary shunting operations to enter/exit them in/from the port. This task has highlighted the existence of conflicting points due to the availability of some limited infrastructural resources (i.e. single tracks), anticipating the presence of potential bottlenecks that has been effectively proved by simulation runs at a later time.

Referring to the schematization of the port railway network configuration, trains heading to Piers V and VI leave the Trieste Campo Marzio station and passes back and forth over the switches connecting this latter infrastructural component and the Parenzane to reach the gateway crossroad. At that point, they transit through Gateway 3 and travel towards the Asta Lunga, from which their itinerary changes, also based on the occupancy of the respective terminal. Indeed, in the event that no available tracks are present at their relative terminal, trains directed both towards Pier V and Pier VI are transferred to Fascio dei Moli, where they stay for the necessary waiting time. On the contrary, trains are led to their destination terminal directly from the Asta Lunga, which still requires the passage through Fascio dei Moli only for trains heading to Pier V. Besides, due to the limited length of tracks present at both the mentioned piers, the entrance and the exit of trains to/from those terminals necessitate some additional shunting operations to, respectively, decompose and compose trains, so that their size can suit the one of the terminal tracks. Such supplementary operations implicate the transit over the switches used to access the terminals, restricting the performing of arrival and departure processes of further trains. In case of trains destined to Pier VII, they travel along the same itinerary of those heading to Piers V and VI just until the gateway crossroad, where they are led towards Gateway 4 and then straight to the terminal. Although with a rare frequency, if irregularities during the check at the gateway are observed, before carrying out freight loading and unloading activities trains are positioned onto the Fascio dei Moli by transiting over a specific junction and wait for document rectification. For all the analysed piers, the same shunting operations are performed also to exit trains from the corresponding destination terminal, in order to reach again the Trieste Campo Marzio station.

In line with the need of transferring trains between the principal port railway station and the terminals, shunting locomotives can be released and recalled in/to different parts of the port network, i.e. in correspondence to the Trieste Campo Marzio station, the Fascio dei Moli and the piers. When they are not required to serve train arrival and departure processes, single locomotives travel along the whole port infrastructure in order to reach depot locations, which lie at the Trieste Campo Marzio station, the Parezane and the Fascio dei Moli.

5.2.2.3 Definition of resources

The simulation of the examined railway processes has required the definition of different categories of resources, in order to consider the use of both the infrastructure and of shunting vehicles. Indeed, single resources have been set to model tracks and locomotives. More specifically, based on the schematization of the port railway network described above, the following classes of tracks have been established:

- the tracks of the Campo Marzio station;
- the tracks of the Parenzane switches;
- the tracks at Parenzane;
- the tracks of the switches preceding the gateway crossroad;
- the tracks of the gateway crossroad switches;
- the tracks of Gate 3;
- the tracks of Gate 4;
- the tracks of Asta Lunga;
- the tracks composing Fascio dei Moli;
- the tracks of the switch on the junction connecting Pier VII and Fascio dei Moli;
- the tracks of the junction connecting Pier VII and Fascio dei Moli;
- the tracks of the switches at the entrance to Pier V;
- the tracks of Pier V;
- the tracks of the switches at the entrance to Pier VI;
- the tracks of Pier VI;
- the tracks of the switches at the entrance to Pier VII;
- the tracks of Pier VII.

For each modelled task, both the type and the number of resources necessary to carry out the activity have been set. Besides, every resource has been associated to a certain quantity, which denotes the number of units that the resource has available. A more detailed indication of the entity of resources is provided in Section 5.2.2.5: the reported figures constitute some of the input values implemented in the modeFRONTIER workflow.

5.2.2.4 Definition of operational requirements and functional model arrangements

With the aim of reflecting the actual performing of the considered railway processes, a few conceptual requirements for the simulation model have been defined, specifically in reference to the use and management of both infrastructural and vehicle resources. Notably, the simulation model has been properly developed so as to capture the following operating principles:

- Waiting for shunting locomotives: once administrative formalities are completed, trains arriving from the national railway line are supposed to wait for the availability of the shunting locomotive on the set of tracks dedicated to train arrivals and departures at the Trieste Campo Marzio station;
- Continuous occupation and subsequent release of the locomotive resource: once a shunting locomotive is connected to a certain train, these vehicles constitute a single entity until the train reaches the terminal to which it is intended. After the shunting locomotive is detached by the train and it is officially made available, it can be requested by other trains;
- Exclusive occupation of tracks: while travelling along the port railway infrastructure, trains and single shunting locomotives occupy different parts of the network that are currently characterized for the most by single tracks and, thus, at times they constrain some infrastructure interlocks which consist of different portions of the considered itinerary;
- Two-way railway flows: to ensure the possibility for trains and locomotives to proceed in both directions, those parts of the railway infrastructure with multiple tracks are not intended to be completely occupied by vehicles heading in the same direction. In this manner, by reserving a certain number of tracks to travel in the opposite direction, the passage of vehicles in both ways is guaranteed and, thus, deadlocks are avoided.

Further arrangements to the BPSim standard have been made to realistically animate the analysed railway processes, in particular with respect to the use of resources and the management of queues and gateways.

As regard the consequential use of infrastructural resources, in the event that a certain track is required for multiple consecutive tasks, it remains associated with the corresponding train from the first activity requiring its use until the last one. Only once the final task is completed, the resource is made available to other trains. Besides, the insertion of additional intermediate tasks has been needed to correctly simulate the functional occupancy of infrastructural resources. Such tasks, labelled as "Resource exchange" ("*Scambio risorse*"), have been introduced whenever the tasks entailing the release of a certain resource and the acquisition of a new one corresponded to contiguous activities in the models. By using these intermediate tasks, the release of the previous resource is permitted only when the following needed resource is available; this means that those actions occur simultaneously. Representing fictitious activities, "Resource exchange" tasks have been associated to a null duration, just to prevent an infrastructural resource from being released before trains can occupy the next resource of the same type.

Concerning the use of vehicle resources, once locomotives are released, they cannot be considered straight available, since their readiness to perform shunting operations depends on whether and where the successive railway process is meant to take place. Indeed, as described in Section 5.2.2.2, based on the actual traffic situation, shunting locomotives can be required in different parts of the port railway network to enter/exit trains or, otherwise, they are stopped at a few depot locations. In any case, while travelling to reach destination, locomotives engage the necessary infrastructural resources for a certain time period, eventually impeding other contemporary train movements. Such dynamics have been displayed in a series of minor process models, which are triggered by specific signals visualized in the main process models along the train path. These signals activate the relocation process of shunting locomotives, enabling them to assume the correct position on the port railway network. If a locomotive is already present where it is requested, the recall process ends instantly.

With respect to queue management, the logic for ordering trains assumed in the simulation model considers that, just like in reality, priority is given to trains that respect the scheduled timetable. Therefore, in case of queues, these latter are prioritized over the others in the deployment of resources. This means that, whenever the execution of a certain task requires the use of any unavailable resource, trains waiting to access the same resource will be processed in an order dictated by their priority.

Finally, the management of gateways regulating flow splits has been modelled according to the specific cases for which these elements have been used to. Indeed, some gateways operate on a probabilistic basis, which entails that the sorting of tokens passing through such decision points is governed by a probability. On the contrary, the functioning of other gateways depends on information, called "attribute", that is assigned to tokens a priori, as in the case of train destination terminals. Indeed, before entering the simulation, i.e. before their actual creation, tokens already own that information and, thus, once they reach this kind of gateways, their path is defined according to the predetermined attribute. Lastly, further gateways have been set so as to operate on a logical basis, which relates to the availability of specific resources or to the presence of waiting queues for certain resources. The logical condition underlying these gateways is read internally during the simulation and automatically regulates the flow of tokens.

5.2.3 Parametrization of the model

The parametrization of the simulation model has concerned various aspects of the represented system, namely the scenario, the tokens, resources, tasks, and gateways. An explanation of the different settings for those model features is reported in the following sections.

5.2.3.1 Simulation scenario

First of all, the parameters defining the duration of the simulation scenario have been set, choosing minutes as measurement unit and establishing a two-day duration for simulation runs, of which the first day has been considered the time necessary to warm up the model. Therefore, since in that time period the system is not fully operational, railway processes performed during such part of the simulation run have not been considered for the estimation of railway capacity. The definition of a warm-up time proves to be essential to reflect the context in which the examined processes unfold because, as a concept of general validity, neglecting contextual factors may limit the predictive value of simulation models [75]. According to [138], the notion of "context" can be declined into four different levels, namely instance, process, social, and external context, of which especially the first two ones have proved to be significant for the correct simulation of the analysed transport phenomenon. The instance context considers that the execution of process instances might be influenced by some of their properties; while the process context relates to the fact that process instances should not be accounted in isolation, but based on a more comprehensive perspective, to capture interactions among them. Indeed, looking at single process instances does not enable the proper understanding of their real behaviour, which could be delayed because of the competition for common resources and the actual work-in-progress. Therefore, in line with a holistic approach suggested in [138], the setting of a fixed time to populate the developed simulation model has permitted to replicate the realistic functioning of the system, considering also the characteristics of the process context, intended in terms of workload and resource availability.

5.2.3.2 Tokens

Tokens have been actively generated in the simulation model only in the train arrival process, whose start event is triggered based on a random distribution. Besides, a table containing the number of train arrivals for each time slot has been implemented in order to regulate not only the amount of tokens entering the system, but also their arrival distribution throughout a simulated day. More in detail, the following four time slots have been defined, with reference to the potential capacity of the national railway network in an average-traffic weekday:

- an off-peak time slot, in which passenger railway flows are modest and, thus, a few freight rail services can be carried out;
- a peak time slot, in which passenger railway traffic almost saturates the available capacity of the national network, so a very limited number of freight rail services can be performed;
- a time slot in which no passenger railway flows are present, allowing freight rail services to fully exploit the capacity of the national railway network;
- a time slot during which the circulation of any component of train traffic is not permitted, in order to execute maintenance works on the national railway line; such works are performed at night, during the time slots when the presence of railway traffic volumes is usually at the lowest.

Of course, not all the trains generated considering the potential capacity of the national railway network can enter the system, due to the infrastructural and organizational limitations characterizing the railway capacity at the Punto Franco Nuovo. The avoidance of such tokens has been modelled with a specific BPMN event, i.e. an error event, which interrupts their processing along the workflow. However, a counting of the number of eliminated trains has been implemented in the execution code since, in view of future port development plans, it represents a useful information to quantitatively estimate the residual capacity for the railway stations of the industrial port.

Analogously, also train departure processes are limited by capacity availability on the national railway network and, thus, the exit of tokens from the simulation model has been properly hindered in the diverse time slots of the day.

As mentioned in Section 5.2.2.4, prior to their generation, tokens are attached to some attributes that determine how they are processed along the modelled workflow, particularly with respect to their priority and their destination. Regarding this latter information, trains have been assigned to destination terminals according to a stochastic basis, which considers the following split of train traffic: 50% of the total amount of railway flows is supposed to head towards Piers V and VI (of which 85% to Pier V and 15% to Pier VI), and the remaining 50% is destined to Pier VII. Such distribution approximately reflects the actual distribution of railway traffic volumes in the Port of Trieste, which can be deduced by the official statistics provided by PNAEAS.

5.2.3.3 Resources

Modelled resources fall into two categories: locomotives and tracks. On one hand, the former correspond to the shunting locomotives used to transfer trains between the Trieste Campo Marzio station and the terminals, and vice versa. They are represented in the model by a single resource. On the other hand, tracks represent the infrastructural resources of the port railway network, which have been quantified according to the current physical and/or operational layout of the Punto Franco Nuovo. Notably, the following values has been assigned to the infrastructural components listed in Section 5.2.2.3, each of them corresponding to a single resource:

- 8 tracks to the Campo Marzio station;
- 1 track to the Parenzane switches;
- 1 track to Parenzane;
- 1 track to the switches preceding the gateway crossroad;
- 1 track to the gateway crossroad switches;
- 1 track to Gate 3;
- 1 track to Gate 4;
- 1 track to Asta Lunga;
- 11 tracks to Fascio dei Moli;
- 1 track to the switch on the junction connecting Pier VII and Fascio dei Moli;
- 1 track to the junction connecting Pier VII and Fascio dei Moli;
- 1 track to the switches at the entrance to Pier V;
- 2 tracks to Pier V;
- 1 track to the switches at the entrance to Pier VI;
- 2 tracks to Pier VI;
- 1 track to the switches at the entrance to Pier VII;
- 4 tracks to Pier VII.

Besides, for a few specific resources with multiple tracks, i.e. the Campo Marzio station and Fascio dei Moli, some tracks have been reserved for the transfer of trains heading from terminals to the national railway network, so as to guarantee the bi-directional flowing of tokens. In addition, consistently with the future port development plans, the doubling of the tracks at Parenzane has been considered.

5.2.3.4 Tasks

A few parameters have been set up to regulate the processing of each task of the model, particularly with reference to its duration and use of resources. As far as duration is concerned, the processing time of activities has been established not only through estimations based on the length and transfer speed of vehicles (i.e. trains and single shunting locomotives), but also according to evidence gathered during some on-field data collection sessions on an elevated port location. Although collected data captures a time series which is neither sufficiently long nor statistically significant, the use of such information in parametrization has enabled the accomplishment of a twofold objective. On one hand, data has been used to verify the correctness of the order of magnitude characterising the times of the analysed tasks, thanks to the comparison with other available values. On the other hand, the gathered information has permitted to detect possible anomalies that can occur in the examined railway processes. In the event of poor visibility circumstances, further time estimations have been carried out resorting to real-time shooting of railway processes, which is recorded by various monitoring cameras owned by the RID.

Two different sets of tasks duration have been implemented in the simulation model, one considering the current layout of the port railway network and the other one assuming the demolition of the wall that physically separates the Free Port zone from the surrounding port areas. Indeed, according to port development plans, such wall is meant to be removed in the future, entailing a possible decrease in the duration of some of the tasks included in the model.

5.2.3.5 Gateways

Gateways concerning decisional points for administrative procedure have been regulated using a statistical distribution of flows, whose percentage values have been determined based on notifications reported in the CH30 and on evidences observed by the RID during the performing of railway processes. On the contrary, as mentioned in 5.2.2.4, in other situations the split of process flows exiting from gateways has been managed according to a logic functioning, in relation to the availability of resources or on the priority of tokens. In the former case, such approach has been adopted to govern the access of trains into certain infrastructural parts of the port railway network, i.e. based on the occupancy of terminals and of the Trieste Campo Marzio station. In the second case, priority rules have been used in release and recall processes of shunting locomotives, in order to assign that resource to trains intended to enter or exit the port.

Initially, attention has been focused on simulating only the train arrival process because, since it is characterized by a lower complexity with respect to the train departure one, the verification of the correct functioning of the model resulted to be easier, permitting to detect possible anomalies straightforwardly. Then, bearing in mind the need of considering interactions among tokens to reflect the effective behaviour of the system, the same arrangements have been implemented to the other modelled processes, obtaining the animation of the actual railway traffic in the Port of Trieste. Finally, simulation results have been used to validate the developed model, so as to ensure that its calibration had been performed adherent to reality. To this end, attention has been focused mainly on considering the lifelike duration of the entire train arrival and departure process and, more in detail, of the travelling time covered by trains and shunting locomotives on specific infrastructural components or along significant partial itineraries. The accuracy of the timings arising from simulation runs has been tested through the comparison with data gathered on-field. Besides, given the presence of many single-track elements in the port railway network, the admissibility of possible contemporary operations has been checked by the confrontation with real-life ones, in order to ascertain the avoidance of conflicting circumstances. This latter condition has been verified based on random tests of simulation results.

5.2.4 Process optimization procedure

The simulation of the analysed railway processes has been followed by the performing of an optimization procedure, with the aim of estimating the maximum number of train flows that can be potentially carried out in the Port of Trieste. To this end, as mentioned in Section 3.4, the multi-disciplinary software modeFRONTIER has been used. In line with the approach adopted throughout the whole methodology illustrated in this thesis, the scope of the optimization procedure has been referred to a strategic perspective of the increase in port railway capacity. This means that such procedure has been performed not to strictly optimize shunting operations, but rather to define the optimal arrangement of various aspects that contribute to the execution of train transfers within the Port of Trieste. Nevertheless, the amount of shunting locomotives, and their related work crews, have of course been taken into account in the determination of the maximum railway capacity, incorporating them as essential resources to move trains.

More specifically, a multi-layer optimization procedure with two nested layers has been performed in order to capture different levels of detail of the problem at hand. As a matter of fact, an internal layer has been defined to carry out the actual optimization procedure, while an external layer has been elaborated to test all the possible combinations of infrastructural and operational configurations by applying DOE algorithms. A graphical visualization of the developed mF workflow for the diverse layers is reported, respectively, in Figures 18 and 19. Despite the different purpose of the two layers, it can be noticed the mF framework presents a similar structure in both cases. Proceeding from the top to the bottom, the Data Flow can be observed: input variables (displayed as green squared icons) are placed in the upper side and are connected with the elements positioned in the lower side of the mF framework, which consist of output variables (visualized as blue squared icons), the objective (marked as a single blue arrow) and constrains (depicted as multiple blue arrows pointing in diverse directions).

Regarding the internal layer (Figure 18), the following input variables have been set:

- the duration of the simulation scenario ("*Durata*"), which is a constant scalar data;
- the possible presence of the wall separating the Free Port zone from the surrounding port areas ("*Presenza_muro*"), which is also a scalar data;
- the quantity of modelled resources ("*Quantità_risorse*"), which is a vector containing the number of available resources for each modelled resource;
- the number of trains entering the simulation model each hour of the day ("*Numero_Treni_Ore*"), which is a vector whose entity has been determined according to the defined time slots;
- the number of tracks dedicated to the train departure process ("*Binari_Riservati*"), which is a scalar data that has been set for the infrastructural resources of the Trieste Campo Marzio station.

In the internal layer, a constrain has been set only on this latter input parameter, imposing that the number of tracks dedicated to train departures is always lower than the total number of available tracks in the mentioned multiple infrastructural resource.

With reference to the external layer, other than the scenario duration and the possible presence of the wall delimiting the Free Port zone, the following input variables have been set: the number of tracks at Parezane ("*N_Parenzane*"), at the Trieste Campo Marzio station

(“*N_CampoMarzio*”), at Fascio dei Moli (“*N_FascioDeiMoli*”), and the number of locomotives (“*N_Locomotive*”). They correspond to the modelled resources considered in the input variable called “*Quantità_Risorse”* of the internal layer. Each of these latter variables is constituted by a vector of scalar data, whose entity depends on the values that have been individually defined for such resources, according to future port development plans. Indeed, infrastructural advancement works are intended to be executed in a series of stages hindering the use of resources to a different extent and, thus, corresponding to various evolving port layout scenarios. The gradual and partially concurrent implementation of infrastructural works has been meant not to severely affect railway port operations, ensuring also the deployment of a proper number of shunting locomotives.
The possible range of input variables concerning the presence of the wall and infrastructural resources have been defined only in the external layer, but they are automatically inherited by the internal one, where they are considered constant. The same implementation principle has been used to set the value for the duration of the simulation scenario, even if its entity proves to be fixed during both the optimization and combinatory procedure.

The middle part of the mF framework corresponds to the Process Flow and it encompasses different elements according to the examined layer. The Scheduling Start node indicates the algorithms employed in the initialization and optimization procedure, which has been made using MOGA-II for the internal layer. Concerning this latter, the Black Box is constituted by the node called “LSimEasyDriver”, which has enabled the integration between mF and L-Sim. At the end of the procedure, the mF workflow related to the internal layer provides a file containing the results generated by L-Sim. In this way, the mF workflow permits to study the response of the simulations obtained via L-Sim when the parametrization for selected parameters changes.
On the contrary, the Process Flow for the external layer is started applying a DOE sequence and considers the implementation of a specific Black Box, called “SchedulingPrj”, which enables the integration of the two layers. Prior to the completion of the overall optimization procedure, the “DesignSpaceNode” provides two outcomes, i.e. the design space (“DesignSpace” node) and the Pareto front (“ParetoFront” node), allowing to exchange results based on the internal layer. Notably, the former node stores input and output variables, objectives and constraints obtained in the internal workflow, while the latter records only the values of optimal solutions. All the results are provided in the form of tables.
Finally, in both layers, the Process Flow ends with an exit node, denominated “Exit”.

The two developed optimization layers share the same output variables, objective and constrain. With respect to the first parameters, the following output variables have been set:

- the number of completed processes ("*Processi_Completati*"), which is a vector containing the number of trains that flow throughout the whole modelled transport process (namely, both the arrival and the departure process), within the scenario duration;
- the number of shunting locomotives ("*Numero_Locomotive*"), which is a scalar data representing the number of vehicles used to perform train transfers in the considered process scenario;
- the number of excluded trains ("*Numero_Treni_Esclusi*"), which is a scalar data expressing the amount of potential trains that do not enter the simulation model, due to the absence of available tracks at the Trieste Campo Marzio Station;
- the number of departed trains ("*Numero_Treni_Partiti*"), which is a vector containing the number of trains leaving the Trieste Campo Marzio station every hour of the considered process scenario.

The entire optimization procedure has been constrained in the number of departing trains ("*Vincolo_Treni_Partiti*"), imposing that trains can leave the Trieste Campo Marzio station according to the limitations that characterize the capacity on the national railway network in the various time slots.

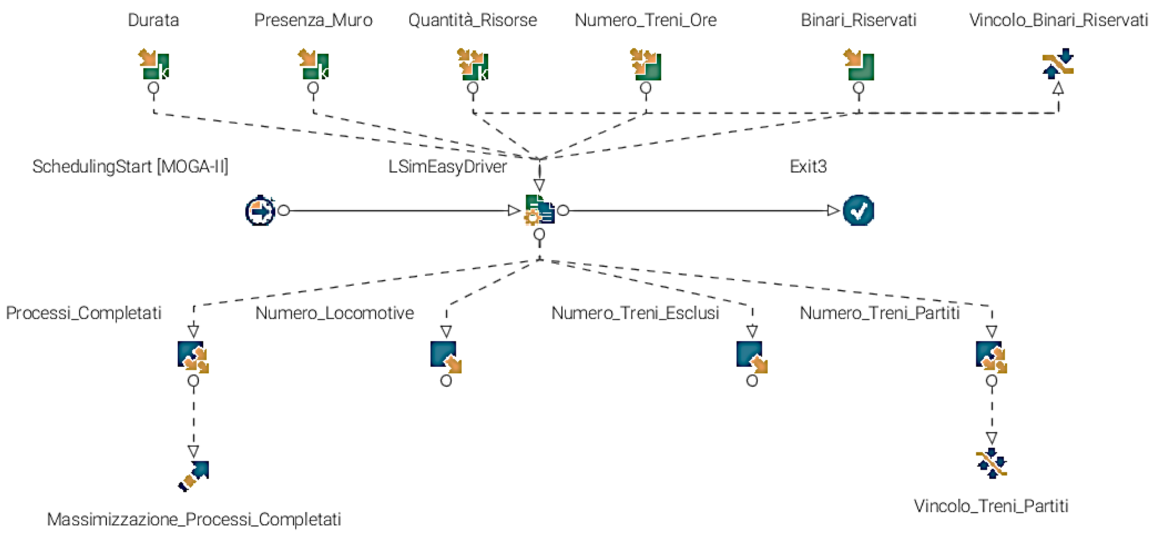

Figure 18 - Internal layer of the developed mF workflow

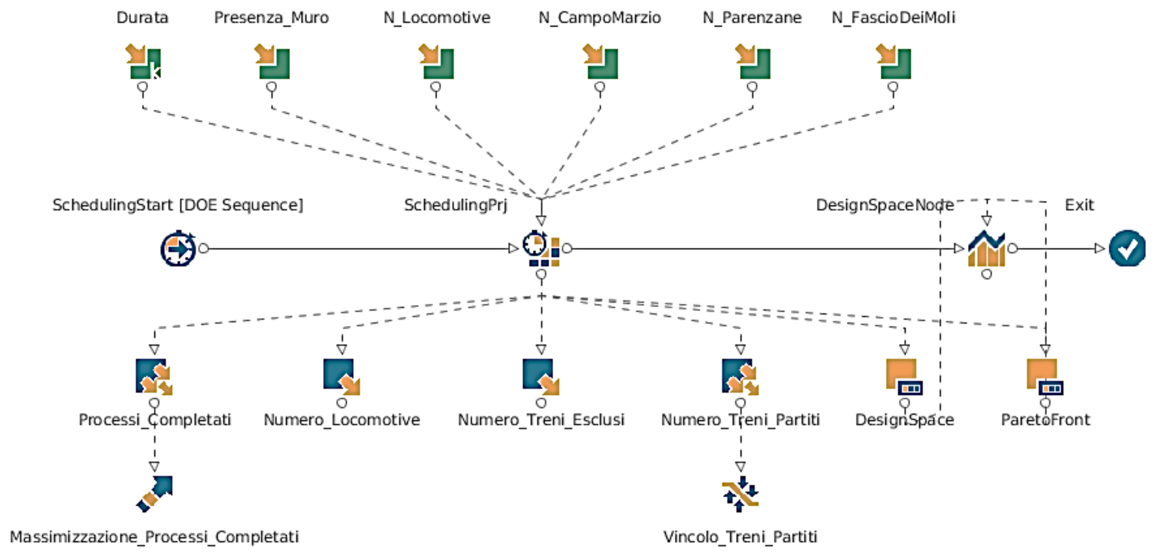

Figure 19 - External layer of the developed mF workflow

5.3 Conclusions

In the face of future macroeconomic tendencies, the potential increase in trains flows expected to occur in the Port of Trieste brings to light even more the residual railway capacity that currently characterizes such intermodal hub. Given this context, the proposed methodology has been applied to estimate the maximum number of trains that can be handled in the Port of Trieste, thanks to a strategic optimization procedure for the arrangement of infrastructural and operational aspects. More in detail, the BPMN standard has been used to efficiently represent and analyse train arrival and departure processes, including also the transfers of individual shunting locomotives. To this end, not only port railway operations, but also the necessary documentary procedures have been displayed, highlighting the complexity of the investigated transport phenomenon. For parametrization purposes, BPMN models provided by the Cardanit editor has been integrated with the BPSim standard. Indeed, the entity of the simulation scenario, tokens, resources, tasks, and gateways has been defined in order to actually animate the created models. Simulation has been performed using L-Sim with the aim of both identifying process bottlenecks and estimating railway traffic volumes, based on some operational parameters. Finally, a multi-layer optimization procedure has been carried out via modeFRONTIER, by means of a black box that allows its integration with L-Sim. Results offered by the optimization tool consist of a set of compromise solutions to maximize capacity and consider both infrastructural and operational requirements, with reference to the various work phases of port advancements.

6. Case study – The evaluation procedure

Referring to Figure 5, the AHP method, in its form of a multi-criteria multi-actor evaluation procedure, has been adopted for the case study of the Port of Trieste in two applications. Even though in reference to the same main objective, i.e. the increase in port railway capacity, the examined decision problems are characterized by a different level of detail:

- in the first one, according to a narrower and yet crucial perspective, the appraisal has concerned the determination of priorities for some key port railway operational features;
- in the second one, based on a more strategic and holistic viewpoint, the assessment has been performed to rank a series of selected scenarios of intervention.

Insights coming from the first application have been functional also to thoroughly analyse punctual optimization results, while the outcomes of the second application have served to formulate a recommendation supporting port decision makers in the development of the most effective line of action to grow railway capacity.

6.1 Application of the AHP method

Following the principles of the AHP technique, in both the mentioned applications, the initial step of the evaluation procedure has consisted in the creation of the assessment framework for the decision problem at hand. Therefore, the number and the structure of the hierarchical levels have been defined, using nodes and clusters to arrange the elements to be evaluated. Like mentioned in Section 4, just as the final result of the overall assessment procedure, even building the appraisal framework implies making choices that can influence the recommendation. Nevertheless, they pertain to a different decisional level if compared to the one in which the actual resolution of the problem is reached. Tracing and motivating such choices are fundamental tasks that analysts should perform, in order to engage decision makers in an open and transparent evaluation process. Other than in the determination of the main goal, of the actors to be involved and of the alternatives to be assessed, the impact of the decisions taken to create the evaluation framework proves to be quite evident in the identification of the criteria against which the performances of the initiatives are appraised. The review carried out in [139] regarding the approaches adopted to define AHP criteria reveals that, in most of the examined research studies, criteria are selected from literature or based on the significance that a specific organisation assigns them. As a matter of fact, it turns out that only in a limited share of the analysed scientific contributions criteria are identified thanks to the support of external experts.

Besides, according to the observations proposed in [140] concerning the definition of performance indicators for business processes, starting from scratch to determine criteria definitely shows to be a more promising method rather than selecting them from a generic available list. In doing so, the adequate level of detail of criteria and their adaptation to the investigated case study can be arbitrarily set. Anyway, the reference to the main goal of the decision problem constitutes the essential requirement for the individuation of appropriate criteria. In this respect, in both the applications illustrated in the present thesis, criteria have been established by a group of experts according to the involved stakeholders' objectives and they have been partially derived from the analysis of the BPMN representation of railway processes. Such analysis has highlighted various process features related to managerial, technical and financial aspects, whose conversion into performance parameters has suggested some of the elements considered in the appraisal procedure [141]. Thus, consistently with the context-sensitive approach adopted to develop the BPMN models of the examined railway processes (cfr Section 3.1.2), the resorting to an analogous method for the definition of criteria has enabled the creation of a case-specific evaluation framework.

Subsequently, the priority of the elements composing the elaborated appraisal frameworks has been determined according to two distinct techniques. In the assessment of port railway operational features, the relative importance of such elements has been estimated through pair-wise comparisons between elements during some structured interviews, which have been administered in person to the engaged stakeholders. In that occasion, interviewees have been provided with a survey questionnaire and, prior to the attribution of judgements, they have been assisted in the comprehension of the AHP method, especially for the use of the Saaty's 1-9 rating scale. Judgements expressed by each individual stakeholder during interviews have been then aggregated, in order to obtain comprehensive assessment results. On the contrary, the preferences with respect to the elements concerning the evaluation of scenarios of intervention have been suggested by a group of experts during a technical meeting. In this case, direct normalized judgements have been assigned to the relative significance of the considered elements, taking into account the various perspectives of the involved actors. Due to the impossibility of asking stakeholders to express their preferences through pair-wise comparisons, experts have put much effort in the attribution of realistic values, so as to capture the actual priority of the assessed elements [141].

Finally, judgements have been implemented into the decision making software called Super Decisions [142], developed by the team collaborating with Saaty, which is based on the AHP and the ANP techniques. By embedding these two synthesis methodologies, it permits to set

priorities through the combination of judgements and data, with the aim of effectively ranking options and of carrying out sensitivity analysis. The use of such supporting software is widely spread in different practical and research fields, like manufacturing, agriculture, environmental management and transport.
A similar evaluation approach considering a multiplicity of criteria and of stakeholders has been adopted also in [143].

6.1.1 Evaluation of key port railway operational features

The evaluation framework developed for the evaluation of key port railway operational features is reported in Annex H. As it can be noticed, at the top of the hierarchy there is the main goal of the decision problem, which consists in the increase in railway capacity at the Punto Franco Nuovo, i.e. the commercial part of the Port of Trieste where the majority of railway traffic is currently generated and attracted.
The second level of the hierarchical framework contains the actors engaged in the evaluation procedure, namely the PNAEAS – RID, the terminal operator of the Piers V and VI, the terminal operator of Pier VII, and the shunting operations manager Adriafer. RID has been engaged in the assessment since it represents the department of the PNAEAS that is specifically in charge of managing railway traffic in the Port of Trieste. The terminal operators of the piers located at the Punto Franco Nuovo have been considered because they are the subjects who actually handle freight and provide intermodal services. Finally, Adriafer has been included in the appraisal process because it is currently the only company responsible for the performing of shunting operations in the port, whose execution directly impacts on railway capacity.
In order to evaluate the priority of the major features affecting railway capacity, in the third level of the hierarchy the following criteria have been inserted:

- the infrastructural occupancy time to carry out train arrival/departure processes;
- the waiting time for terminal availability;
- the time needed to perform administrative procedures;
- the number of shunting locomotives and working crews; and
- the number of infrastructural resources.

The first two time-related criteria have been selected for their primary importance in the determination of the possible annual number of trains with respect to the physical movement of vehicles. On the contrary, although concerning non-material aspects of railway processes, the duration of administrative activities has been considered for its eventual repercussion on the infrastructure occupancy, especially during the train passage through the gateway separating the Free Port zone from the remaining port areas. Lastly, the two final criteria correspond to the different types of resources that are essential to perform train transfers.

The survey questionnaire used to interview the involved actors is reported in Annex I, while the numerical judgements expressed by each actor against pair-wise comparisons are illustrated below, together with a qualitative explanation.

6.1.1.1 PNAEAS – RID

According to the preferences indicated in Table 1, RID considers to cover a greater role with respect to both the terminal operators because, referring to the aim of enhancing the railway capacity at the Punto Franco Nuovo, it attributes a quite remarkable importance to its responsibility in managing and arranging railway port infrastructure. However, it recognizes that also the quality of operations performed at terminals to load and unload goods significantly affects the amount of train flows that can be generated in the port. Indeed, in line with this reasoning, judgements expressed by the RID suggest that the influence of terminal operators for the attainment of the main goal is not negligible at all, even if with the different extent between the two involved operators. Notably, RID deems itself to be much more relevant than the terminal operator of Piers V and VI, while just slightly more important than the terminal operator of Pier VII. This difference is motivated by the fact that, comparing the two operators, the latter one proves to be more independent by the RID in managing its own railway traffic and because, in the future, its activities could potentially concern a wider area of the port. On the contrary, the RID assigned equal importance to its role in the confrontation with Adriafer, since it considers that organizational aspects regulating the use of infrastructural resources are as meaningful as the performing of efficient shunting operations for the achievement of capacity increases. In comparing the engaged terminal operators, a slightly higher relevance has been attributed by the RID to the one operating at Piers V and VI, since potential advancements in the management of train flows related to its relative terminals would entail greater beneficial effects to the traffic of the whole Punto Franco Nuovo. Proof to this, it must be noted that train arrival and departure processes concerning the Pier VII currently results to be more seamless, thanks to its more pronounced independence in the occupation of the infrastructural elements composing the port railway network. Lastly, the RID prioritizes the influential role of both the considered terminal operators with respect to the one of Adriafer, giving thus more significance to terminal activities rather than to shunting operations in the accomplishing a growth in port railway capacity.

Table 1 - Comparisons between actors according to PNAEAS - RID

COMPARISON BETWEEN ACTORS		
Actor i	**Comparison**	**Actor j**
PNAEAS - RID	5>	Terminal Operator – Piers V and VI
PNAEAS - RID	3>	Terminal Operator – Pier VII
PNAEAS - RID	1	Adriafer
Terminal Operator – Piers V and VI	3>	Terminal Operator – Pier VII
Terminal Operator – Piers V and VI	5>	Adriafer
Terminal Operator – Pier VII	3>	Adriafer

Regarding the preferences expressed by the RID when confronting criteria, as indicated in Table 2, the infrastructural occupancy time for train arrival and departure processes has been assigned to a greater relevance in all the identified pair-wise comparisons, except for the one with the time for administrative procedures. Indeed, evidences observed on field prove that those documentary activities can severely impact on the performing of railway operations, especially at the gateway delimiting the Free Port zone, substantially hindering the railway capacity. According to the RID, a quite significant role is covered also by the waiting time for the terminal availability because, as mentioned in the discussion of the judgement concerning stakeholders' level of influence, loading and unloading activities definitely affect the possible entity of the train traffic volume. Conversely, the infrastructural occupancy time has been deemed to prevail by far not only the number of shunting locomotives and of work crews, but also the number of infrastructural resources. As a matter of fact, a great amount of both kinds of resources does not ensure a shorter duration in the railway network occupancy, stressing that even organizational aspects in carrying out operations are a key feature to enable a potential increase in capacity. The waiting time for the terminal availability has been considered by the DIF slightly less important just in the confrontation with the time needed for administrative procedures, while it has been preferred over the criteria related to human, vehicle and infrastructural resources, due to the influence of terminal operations in processing trains. In light of the relevance of the time for administrative procedures stressed previously, the DIF has attributed an outstanding significance to this criterion, with respect to the ones regarding all the different types of considered resources. Finally, in relation to these latter, the number of infrastructural resources has been considered by the RID to have a very limited higher priority as against the ones strictly necessary to perform shunting operations, because network availability represents an essential requirement to transfer trains to/from the terminals.

Table 2 - Comparisons between criteria according to PNAEAS - RID

COMPARISON BETWEEN CRITERIA		
Criterion i	**Comparison**	**Criterion j**
Infrastructural occupancy time for A/D processes	3>	Waiting time for terminal availability
Infrastructural occupancy time for A/D processes	1	Time for administrative procedures
Infrastructural occupancy time for A/D processes	8>	N° of shunting locomotives and work crews
Infrastructural occupancy time for A/D processes	7>	N° of infrastructural resources
Waiting time for terminal availability	<3	Time for administrative procedures
Waiting time for terminal availability	5>	N° of shunting locomotives and work crews
Waiting time for terminal availability	4>	N° of infrastructural resources
Time for administrative procedures	7>	N° of shunting locomotives and work crews
Time for administrative procedures	6>	N° of infrastructural resources
N° of shunting locomotives and work crews	<2	N° of infrastructural resources

6.1.1.2 Terminal operator – Piers V and VI

As reported in Table 3, the terminal operator of Piers V and VI considers all the terminal operators to be of the same importance of the RID because, although according to a different perspective, both parts are fundamental to attain the goal of increasing railway capacity at the Punto Franco Nuovo. Indeed, the former contribute in the achievement of such objective playing a commercial role, while the latter acts as the managerial responsible for port railway improvements. Also Adriafer is considered to be of equal importance with respect to the RID, since it is currently the only company performing shunting operations at the Punto Franco Nuovo. Between the two terminal operators, the one carrying out freight movements at Piers V and VI recognises a quite moderate greater relevance of the terminal operator of Pier VII, in terms of a higher number of processed trains. Taking into account the present operational conditions at the Punto Franco Nuovo, a mutual influence between the activities of the two terminal operators is evident due to the common use of resources, intended as railway infrastructure and shunting locomotives. This reciprocal interaction has been recently limited by differentiating the use of Pier V and Pier VI based on the available handling equipment: the former is employed for loading and unloading operations, whereas the latter is meant to be a buffer for waiting trains, in order to decongest the Trieste Campo Marzio station. Regarding the comparison between terminal operators and Adriafer, the terminal operator of Piers V and VI suggests to attribute them the same importance, because the scheduling of train arrival/departure to/from all the terminals is agreed with Adriafer, without creating disproportional arrangements between the involved terminals. Finally, the inclusion also of the Italian infrastructure manager RFI among the engaged actors has been proposed by the terminal operator of Piers V and VI, given its role in scheduling freight train traffic on the national railway network.

Table 3 - Comparisons between actors according to the terminal operator of Piers V and VI

COMPARISON BETWEEN ACTORS		
Actor i	**Comparison**	**Actor j**
PNAEAS - RID	1	Terminal Operator – Piers V and VI
PNAEAS - RID	1	Terminal Operator – Pier VII
PNAEAS - RID	1	Adriafer
Terminal Operator – Piers V and VI	<5	Terminal Operator – Pier VII
Terminal Operator – Piers V and VI	1	Adriafer
Terminal Operator – Pier VII	1	Adriafer

Referring to the first comparison between criteria indicated in Table 4, during the interview the terminal operator of Piers V and VI provided discordant judgments based on the different availability of infrastructural resources in the two terminals under his management. Indeed, more tracks are present on Pier V, allowing to simultaneously perform loading and unloading activities on two trains. On the contrary, Pier VI has available a lower number of tracks, which permits to execute terminal operations exclusively on one train at time. Given this situation, taking into account Pier V, the infrastructural occupancy time for arrival and departure processes represents by far a much more significant criterion as compared to the waiting time for terminal availability, because of the ability of such pier to process more trains in parallel. Indeed, as principle of general value, eventual delays on the remaining port railway network leading to the main train station severely hinder the productivity of terminals. Conversely, this barrier is deemed to be less pronounced for Pier VI, due to the inherent limit of possessing just few tracks. Proof to this is shown in the preference expressed by the terminal operator concerning such pier, for which the waiting time for terminal availability covers a definitely much more meaningful role as against to the infrastructural occupancy time. Despite these controversial circumstances, in the evaluation procedure only the judgement concerning Pier V has been considered, because of its greater contribution in attaining a possible increase in port railway capacity at the Punto Franco Nuovo. Besides, the infrastructural occupancy time for train arrival and departure processes has been considered, respectively, by far and absolutely much more important than the time for administrative procedures and the number of shunting locomotives and work crews. In the first case, the duration of administrative procedures is not intended as a barrier, because the activities for the preparation of the documents accompanying trains are usually carried out in advance by the shipping agency. In the second case, the terminal operator of Piers V and VII suggests giving more attention on the management of work crews performing shunting operations, rather than on the entity of their composition. On the contrary, the infrastructural occupancy time has been considered only almost much more significant than the number of infrastructural resources, due to the great importance of the potential availability of these latter, for example for buffer purposes. Furthermore, based on the interviewee's opinion, the waiting time for terminal availability definitely represents a more important parameter with respect to both the time for administrative procedures and the number of shunting locomotives and work crews, but it covers a less meaningful role if compared to the number of infrastructural resources. With regard to the vehicle and human resources, a slightly greater significance has been attributed to the time for administrative procedures, since such activities are performed when trains are still on the terminals and, thus, their smooth execution is key for operators willing to enhance railway capacity. Given the need of disposing of more tracks to increase train flows, the number of infrastructural resources proves to be much more important than the time for administrative procedures, while it has the same relevance as against the number of shunting locomotives and work crews. Indeed, both these last two criteria are equally essential to manage and grow port train traffic.

Table 4 - Comparisons between criteria according to the terminal operator of Piers V and VI

COMPARISON BETWEEN CRITERIA		
Criterion i	**Comparison**	**Criterion j**
Infrastructural occupancy time for A/D processes	7>	Waiting time for terminal availability
Infrastructural occupancy time for A/D processes	8>	Time for administrative procedures
Infrastructural occupancy time for A/D processes	9>	N° of shunting locomotives and work crews
Infrastructural occupancy time for A/D processes	4>	N° of infrastructural resources
Waiting time for terminal availability	9>	Time for administrative procedures
Waiting time for terminal availability	9>	N° of shunting locomotives and work crews
Waiting time for terminal availability	4>	N° of infrastructural resources
Time for administrative procedures	2>	N° of shunting locomotives and work crews

Time for administrative procedures	<5	N° of infrastructural resources
N° of shunting locomotives and work crews	1	N° of infrastructural resources

6.1.1.3 Terminal operator – Pier VII

According to judgements included in Table 5, the terminal operator of Pier VII considers that terminal operators are of equal importance with respect to the RID, since this latter is in charge of supporting the commercial interests of operators in terms of both managerial and infrastructural aspects. Conversely, the RID is deemed to cover a much more significant role as compared to Adriafer. Regarding the assessment of the influence of the considered terminal operators, the same relevance is attributed to both of them, suggesting that there is no competition between the two since they refer to different logistics marketplaces. On the contrary, in the confrontation with Adriafer, terminals operators turn out to be by far much more important, even though efficient shunting operations are considered a meaningful contribution for the functioning of the terminals.

Table 5 - Comparisons between actors according to the terminal operator of Pier VII

COMPARISON BETWEEN ACTORS		
Actor i	**Comparison**	**Actor j**
PNAEAS - RID	1	Terminal Operator – Piers V and VI
PNAEAS - RID	1	Terminal Operator – Pier VII
PNAEAS - RID	5>	Adriafer
Terminal Operator – Piers V and VI	1	Terminal Operator – Pier VII
Terminal Operator – Piers V and VI	7>	Adriafer
Terminal Operator – Pier VII	7>	Adriafer

Regarding operational features, based on the perspective of the terminal operator of Pier VII illustrated in Table 6, the waiting time for terminal availability proves to be by far much more important than the occupancy time of the remaining port railway infrastructure, because it directly impacts on the number of transfers that the operator can potentially perform. As opposed to the previous comparison, the infrastructure occupancy time assumes a more relevant role in the confrontation with the time needed for administrative procedures, since these latter are usually finalised in advance and, thus, they limitedly hinder train arrival/departure processes. The strict correlation between the infrastructural time occupancy and the number of shunting locomotives and work crews is reflected in the entity of the judgement expressed by the terminal operator of Pier VII, for which the same importance is attributed to the two criteria

under examination. With respect to infrastructural resources, they are considered to be much more relevant than infrastructural occupancy time, since the availability of tracks enables to compensate possible criticalities, like train delays. Indeed, the presence of buffer tracks external to the terminals proves to be very useful, allowing to dedicate internal terminal tracks only for train loading and unloading activities and, consequently, to increase the potential number of served trains. This opportunity would be particularly advantageous for the terminal operator of Pier VII because, at present, train loading and unloading operations at his terminal are carried out based on the train time scheduling of the national railway network, rather than on the traditional management approach considering time slots. Generally speaking, the possibility provided by buffer tracks of permitting a rapid turnover of trains at terminals represents a concern of utmost importance shared by all operators, similarly to the management of traffic flows related to the other transport modes converging at ports.
In line with previous reasonings, the waiting time for terminal availability is deemed to be by far much more important than the time for administrative procedures, while it assumes equal relevance with respect to the number of human, vehicle and infrastructural resources, due to their connection. Both these latter elements cover a quite greater role if compared to the time for administrative procedures, whereas they have been attributed to the same level of significance in the confrontation between them.

Table 6 - Comparisons between criteria according to the terminal operator of Pier VII

COMPARISON BETWEEN CRITERIA		
Criterion i	**Comparison**	**Criterion j**
Infrastructural occupancy time for A/D processes	<7	Waiting time for terminal availability
Infrastructural occupancy time for A/D processes	7>	Time for administrative procedures
Infrastructural occupancy time for A/D processes	1	N° of shunting locomotives and work crews
Infrastructural occupancy time for A/D processes	<5	N° of infrastructural resources
Waiting time for terminal availability	7>	Time for administrative procedures
Waiting time for terminal availability	1	N° of shunting locomotives and work crews
Waiting time for terminal availability	1	N° of infrastructural resources
Time for administrative procedures	<7	N° of shunting locomotives and work crews
Time for administrative procedures	<7	N° of infrastructural resources
N° of shunting locomotives and work crews	1	N° of infrastructural resources

6.1.1.4 Adriafer

Judgements included in Table 7 report the standpoint of Adriafer with regard to the level of influence of the engaged stakeholders, for which both the terminal operators are considered slightly more important than the RID. The relevance of this latter is acknowledged especially in terms of its role in managing the infrastructural investments that have been planned for the near future in the Port of Trieste. On the contrary, in the confrontation between itself and the RID, Adriafer has been deemed to have an equal importance for the attainment of the main goal. According to Adriafer, the involved terminal operators are meant to exert the same influence in achieving an increase in railway capacity. This assumption is expected to be confirmed also in the next years, when the implementation of the planned infrastructural interventions will permit the independence between the train flows generated/attracted by the two terminals. Indeed, due to the current port railway network configuration, a certain mutual interaction between such traffic volumes is present. Nevertheless, in this regard Adriafer claims to ensure neutrality in performing shunting operations, so as to accomplish the optimal functioning of the port system, without favouring any individual terminal. Such explanation motivates the preferences expressed by Adriafer in relation to the comparison as against terminal operators, for which Adriafer suggests covering a much more important role for attaining a growth in railway capacity. Indeed, Adriafer argues to sustain the commercial interests of terminal operators by serving their demand for shunting operations, in the view of enhancing the capacity of the whole port.

Table 7 - Comparisons between actors according to Adriafer

COMPARISON BETWEEN ACTORS		
Actor i	**Comparison**	**Actor j**
PNAEAS - RID	<2	Terminal Operator – Piers V and VI
PNAEAS - RID	<2	Terminal Operator – Pier VII
PNAEAS - RID	1	Adriafer
Terminal Operator – Piers V and VI	1	Terminal Operator – Pier VII
Terminal Operator – Piers V and VI	<6	Adriafer
Terminal Operator – Pier VII	<6	Adriafer

Referring to Table 8, based on the preferences stated by Adriafer, the infrastructural occupancy time for arrival/departure processes proves to be almost slightly more important than the waiting time for terminal availability due to their strict interrelation. In contrast, even though to a limited extent, it covers a less significant role when compared to the time needed for administrative procedures. Indeed, as for example, the duration of the train check at the gateway separating the Free Port zone from the surrounding port areas definitely influences the performing of shunting operations, regardless the distance to be travelled and the speed adopted along the infrastructure while carrying out arrival/departure processes. Besides, infrastructural time occupancy reveals to be much more relevant in the confrontation with the number of shunting locomotives and work crews, since performing shunting operations more quickly is considered to have greater relevance rather than introducing additional vehicles or staff. Instead, with regard to infrastructural resources, the disposal of a good amount of tracks is preferred over the network time occupancy, as it permits the seamless conducting of railway operations. Concerning the waiting time for terminal availability, while it is slightly less meaningful than the time for administrative procedures, it assumes the same importance of the number of shunting locomotive and work crews due to their functional link. In line with previous judgements, the number of infrastructural resources has been deemed to be nearly much more important also than the waiting time for terminal availability. The almost equal relevance attributed to the time for administrative procedures when compared to the number of both shunting-related and infrastructural resources reflects the scarce correlation captured by Adriafer between the two analysed criteria. Finally, the availability of an adequate number of infrastructural resources is considered much more significant than the one of shunting locomotives and work crews, since it represents an essential requirement to efficiently carry out shunting operations, avoiding peak work periods. To this end, the necessity of disposing of buffer tracks has been marked as a crucial factor.

Table 8 - Comparisons between criteria according to Adriafer

COMPARISON BETWEEN CRITERIA		
Criterion i	**Comparison**	**Criterion j**
Infrastructural occupancy time for A/D processes	2>	Waiting time for terminal availability
Infrastructural occupancy time for A/D processes	<2	Time for administrative procedures
Infrastructural occupancy time for A/D processes	5>	N° of shunting locomotives and work crews
Infrastructural occupancy time for A/D processes	<5	N° of infrastructural resources
Waiting time for terminal availability	<3	Time for administrative procedures
Waiting time for terminal availability	1	N° of shunting locomotives and work crews
Waiting time for terminal availability	<4	N° of infrastructural resources

Time for administrative procedures	1	N° of shunting locomotives and work crews
Time for administrative procedures	<2	N° of infrastructural resources
N° of shunting locomotives and work crews	<5	N° of infrastructural resources

Judgements expressed by the engaged actors on the relative importance of criteria have turned out to be quite consistent, apart from the ones stated by the terminal operator of Piers V and VI, whose inconsistency ratio slightly exceeds the threshold value of 0,1 established by Saaty. However, the preferences of such stakeholder have not been reviewed due to the very modest entity of the inconsistency and also because, as mentioned in Section 4.1.1, forcing the improvement of judgements may alter the actual perspective of actors.

6.1.2 Evaluation of scenarios of intervention

The decision framework developed for the evaluation of the scenarios of intervention is reported in Annex J. As it can be noticed, the top level of the hierarchy contains the main goal of the decision problem, which consists in the increase in railway capacity in the Port of Trieste. It must be noted that, as explained in Section 6.1.1, at the moment the area of interest of the Port of Trieste for railway traffic almost corresponds exclusively to the Punto Franco Nuovo, since railway operations are largely performed there. However, strategic plans for the future reopening of existing railway stations located in other port areas have been already developed and, thus, according to a long-term perspective, the scope of the objective of this application has been broadened to the whole port zone.

The second level of the framework includes the actors engaged in the evaluation process, namely the Port Authority, the terminal operators, the railway companies, and the shunting operations manager. Apart from railway companies, the remaining actors have been involved for the same reasons underlying the selection of actors in the evaluation of operational features, which are illustrated in Section 6.1.1. Railway companies are responsible for the transfer of trains right until the main railway station of the Port of Trieste, in which the shunting operations manager takes charge of trains heading to terminals on their behalf. In line with the wider extent of the principal goal differentiating this application from the one regarding the evaluation of port railway operational features, the denomination of some of the engaged actors, namely the terminal operators and the railway companies, have been intentionally left generic, in order to consider the entire category and not individual subjects related to specific piers of the Port of Trieste. Similarly, even the Port Authority has been taken into account in general terms, rather than referring to its dedicated railway department, because potential increases in railway capacity in the port can depend also on managerial choices made by the representatives of that entity, according to macroeconomic tendencies and/or in compliance with international sustainable policies. Indeed, PNAEAS is asked to face challenges to address strategic issues, that are placed on a higher level if compared to those concerning the more practical railway operations managed by the RID. No misunderstandings are possible for the stakeholder representing the shunting operations manager since, as indicated in Section 6.1.1, reference is made univocally to the company Adriafer.

In the third level of the hierarchy the macro-criteria selected to describe the various aspects characterizing the alternatives have been included; each macro-criterion has been further specified by some criteria, making the evaluation even more articulated. For the macro-criterion related to costs, intended as the financial expenditures needed to carry out port rail transfers, two criteria have been distinguished, i.e. operational costs and investment costs. The former encompasses the costs necessary to practically perform freight railway services, by means of human and vehicle resources, whereas the latter concerns the expenses required to implement infrastructural, technological and/or organizational interventions. Referring to the aspects that determine the quality of the railway operations execution, the macro-criterion defining process efficiency has been categorized through three diverse criteria, namely the administrative procedure smoothness, the technological innovation level and the operations management. The first one expresses how seamlessly the exchange of documents needed to manage train flows occurs in the Port of Trieste; the second facet measures the adoption of IT solutions to verify the compliance of train document indications to both the transferred cargo units and the rolling stock and, finally, the third feature indicates the efficiency in using resources, in terms of tracks and shunting locomotives, so as to avoid idle times. Also the macro-criterion regarding the transport improvement has been declined into a few aspects, in order to better capture the advancements obtainable in the port in relation to the transport sector. More in detail, the following three criteria have been defined: port competitiveness, which is connected to the ability of the Port of Trieste to meet customers' demand; the increase in interoperability, meant as the growth of cooperation among the involved stakeholders; and the impact on modal shift, intended as the effect of the assessed initiatives on the rail modal share. Finally, the aspects of the macro-criterion concerning the environmental and social impacts of alternatives have been distinguished into the reduction of emissions, noise reduction and the level of employment. The effect of interventions considered in the first criterion contributes to enhance the environmental sustainability of railway services and, thus, of air quality; the one of the second criterion facilitates the acceptance of port operations by part of citizens living in the nearby;

and in the third criterion, the consequences on the port employment rate have been taken into account, since they are expected to possibly change according to the realised alternative.
The fourth and last level of the hierarchy contains the various scenarios of intervention to be evaluated, which are the status quo, the realization of organizational and technological interventions, and the actualization of infrastructural interventions. The status quo represents the current situation of railway processes in the Port of Trieste, while organizational and technological initiatives encompass the introduction of IT interventions, like for example the installation of optical reading portals to automatically read the identification code of cargo units. Finally, infrastructural interventions consider not only the implementation of technological and organizational arrangements, but also of infrastructural measures aimed at adding further tracks to the existing port railway network and at upgrading the traffic control system used to manage the occupancy infrastructural elements [141].

In the following, the numerical judgements expressed by the group of experts with respect to each element of the evaluation framework are reported, accompanied by a qualitative explanation. More in detail, normalized judgements have been assigned to define the priorities of all the elements, except for the alternatives, whose performances on criteria have been expressed using a 1-10 rating scale or, just in a few cases, by a quantitative value. In this appraisal application, no inconsistency check has been needed, since judgements have been attributed directly by the experts, i.e. without resorting to pair-wise comparisons.

Table 9 illustrates the level of influence attributed to the involved actors with reference to the attainment of the main goal. In this regard, the greatest importance has been assigned to Port Authority, while railway companies have considered to play the least significant role among all stakeholders. On the contrary, the shunting operations manager and the terminal operators have been ascribed to a quite similar influential level, due to their responsibility in operationally provide intermodal transport services.

Table 9 - Actors' level of influence

ACTORS' LEVEL OF INFLUENCE	
Actor	**Priority**
Port Authority	0,45
Railway companies	0,05
Shunting operations manager	0,3
Terminal operators	0,2

For the sake of clarity, as in the previous real application of the AHP method, the priorities assigned by the group of experts to evaluation elements are described in the following in separate sections, one for each engaged stakeholder.

6.1.2.1 Port Authority

As reported in Table 10, when expressing judgements according to the Port Authority's perspective, experts have considered that for such entity the macro-criteria related to costs, process efficiency and transport improvement are equally important, whereas the one concerning the environmental and social impact has a quite modest relevance. The attribution of such weight values reflects the greater concern of the Port Authority for more practical aspects of railway processes in the view of attaining an increase in capacity.

Table 10 - Macro-criteria priorities according to the Port Authority's perspective

Macro-criterion	Priority
Costs	0,3
Environmental and social impact	0,1
Process efficiency	0,3
Transport improvement	0,3

Referring to Table 11 for explanations on the significance of criteria within every macro-criterion, investment and operational costs have been deemed by experts to have the same priority, since they both represent fundamental items of expenses. Even the reduction of emissions and noise are meant to cover an equal role in the comparison between environmental impacts. However, within its relative macro-criterion, the importance of these latter is outclassed by the one attributed to social aspects, expressed in terms of level of employment. Indeed, despite the ever-more pressing concern for environmental sustainability, experts considered that, as a public entity, the Porth Authority is primarily committed in ensuring job placement, for its contribution to the enhancement of port competitiveness. With respect to process efficiency, the administrative procedure smoothness has been attributed by experts to an overriding relevance as against the operations management and the technological innovation level, since it constitutes a critical feature related to intangible bureaucratic superstructures whose rigidity can severely hinder the performing of railway processes. Finally, in line with the global perspective of the port adopted by the Port Authority, port competitiveness has been assigned to the highest priority in the confrontation with the other criteria regarding improvements in the transport sector.

Table 11 - Criteria priorities according to Port Authority perspective

Macro-criterion	Criterion	Priority
COSTS	Investment costs	0,5
	Operational costs	0,5
ENVIRONMENTAL AND SOCIAL IMPACT	Level of employment	0,7
	Noise reduction	0,15
	Reduction of emissions	0,15
PROCESS EFFICIENCY	Administrative procedure smoothness	0,6
	Operations management	0,2
	Technological innovation level	0,2
TRANSPORT IMPROVEMENT	Impact on modal shift	0,3
	Increase in interoperability	0,1
	Port competitiveness	0,6

6.1.2.2 Railway companies

Table 12 contains the priorities of macro-criteria which have been attributed by experts reflecting the standpoint of railway companies. Such values suggest that costs and process efficiency cover the same meaningful role, in face of a more limited significance of both the environmental and social impact, and the port-related transport improvement. As a matter of fact, those companies are external figures with respect to port management dynamics, since their interaction with that intermodal hub relates almost exclusively to transport aspects.

Table 12 - Macro-criteria priorities according to railway companies' perspective

Macro-criterion	Priority
Costs	0,35
Environmental and social impact	0,1
Process efficiency	0,35
Transport improvement	0,2

Based on Table 13, experts have deemed that, with respect to their corresponding macro-criterion, railway companies put great attention to operational costs and operations management when providing services derived by port demand. Even noise reduction and the technological innovation level have considered to play a remarkable role within their relative macro-criterion, because they both represent influential factors for railway companies in carrying out transport services. Indeed, on one hand, the former contributes to enhance the acceptance of port operations by part of citizens living in the nearby, since it enables an improvement of their life quality. On the other hand, technological advancements are essential components that facilitate the performing of intermodal services, especially in terms transport data exchange, which allow a better cooperation among the actors involved in the logistics chain. Finally, concerning the macro-criterion related to improvements in the transport field, particular importance has been attributed by experts to the impact on modal shift, since railway companies can certainly take advantage from an increase in the traffic share of their respective mode.

Table 13 - Criteria priorities according to railway companies' perspective

Macro-criterion	Criterion	Priority
COSTS	Investment costs	0,2
	Operational costs	0,8
ENVIRONMENTAL AND SOCIAL IMPACT	Level of employment	0,2
	Noise reduction	0,6
	Reduction of emissions	0,2
PROCESS EFFICIENCY	Administrative procedure smoothness	0,25
	Operations management	0,4
	Technological innovation level	0,35
TRANSPORT IMPROVEMENT	Impact on modal shift	0,6
	Increase in interoperability	0,3
	Port competitiveness	0,1

6.1.2.3 Shunting operations manager

As reported in Table 14, assuming the viewpoint of the shunting operations manager, experts have indicated that the macro-criterion related to process efficiency possesses the highest priority, followed by the one concerning costs. The attribution of such weight values is motivated by the fact that these two parameters directly affect the daily execution of shunting operations. In this respect, the macro-criterion regarding the transport improvement has been deemed by experts to have a lower but yet significance, because, although it relates to a sector of interest for the shunting operations manager, the attainment of possible advancements can moderately influence activities on trains. The least priority has been attributed by experts to the environmental and social impact, since, adopting the perspective of the shunting operations manager, it has been considered not particularly significant for the performing of train transfers.

Table 14 - Macro-criteria priorities according to the shunting operations manager's perspective

Macro-criterion	Priority
Costs	0,3
Environmental and social impact	0,05
Process efficiency	0,4
Transport improvement	0,25

With reference to the relative importance of criteria for the identified macro-criteria, Table 15 points out that, in terms of the financial expenses which the shunting operations manager incurs, operational costs have been considered by far more significant than investments costs. Indeed, encompassing both human and vehicle resources, those expenditures are the cost items that affect operability the most, due to the fact that large investments are required more rarely. Concerning environmental and social consequences, the same priority has been attributed to the reduction of noise and emissions, which result to be a little less significant than the level of employment. As a business company, this latter criterion has been supposed to have a greater impact on the performing of activities. In line with such reasoning, within the macro-criterion related to process efficiency, the administrative procedure smoothness and the operations management have been attributed to an equal importance and they have been prioritized over the technological innovation level. As a matter of fact, the technological component of processes has been deemed not to have a remarkable influence when carrying out shunting operations, which in turn can be highly constrained by poor quality in the other two analysed criteria. Lastly, regarding possible improvements in the transport field, experts considered that the impact on modal shift and port competitiveness likewise cover a meaningful role, since their growth would directly reflect on shunting operations. A lower priority has been given to the increase in interoperability because, referring to cooperation among terminal operators, by serving piers giving no preferential treatment to any of them the shunting operations manager plays a very marginal role in arranging train flows in the port.

Table 15 - Criteria priorities according to the shunting operations manager's perspective

Macro-criterion	Criterion	Priority
COSTS	Investment costs	0,2
	Operational costs	0,8
ENVIRONMENTAL AND SOCIAL IMPACT	Level of employment	0,4
	Noise reduction	0,3
	Reduction of emissions	0,3

PROCESS EFFICIENCY	Administrative procedure smoothness	0,4
	Operations management	0,4
	Technological innovation level	0,2
TRANSPORT IMPROVEMENT	Impact on modal shift	0,4
	Increase in interoperability	0,2
	Port competitiveness	0,4

6.1.2.4 Terminal operators

As indicated in Table 16, experts considered that based on the terminal operators' point of view, the macro-criteria related to costs and process efficiency are characterized by the highest priority, as they primarily affect the activities carried out by those actors. On the contrary, lower significance has been attributed to the aspects concerning the environmental and social impact, and the transport improvement, because they have been deemed to be less influential for terminal operators when handling trains.

Table 16 - Macro-criteria priorities according to the terminal operators' perspective

Macro-criterion	Priority
Costs	0,35
Environmental and social impact	0,1
Process efficiency	0,35
Transport improvement	0,2

With respect to the relative importance of criteria, Table 17 illustrates that experts have attributed the same level of significance to investment costs and to operational costs, since terminal operators incur in financial expenses regarding both strategic and operational purposes. Indeed, in the first case, capital is allocated, for example, to implement on berths the adequate equipment to enable the seamless transfer of freight through the terminals and, thus, to meet customers' demand. As already stressed in Section 2.2, this commitment by part of terminal operators has become increasingly relevant due to the rapid and substantial development of the maritime sector that occurred worldwide in the recent past and that has put much pressure on ports as intermodal systems. Along with advancements in facilities, efficiency in operations is essential to ensure quality in freight transfers, and eventually a traffic increase, so that large financial expenditures are required also in the more practical aspects of terminal activities. No particular predominance has been assigned by experts to any criteria related to the environmental and social impact, since they have been supposed to equally affect decision-making processes of terminal operators when planning the execution of activities. Referring to process efficiency, the administrative procedure smoothness and operations management have been considered slightly more relevant than the technological innovation level, because, to a limited extent, railway operations prescind from this latter parameter. On the contrary, according to the experts' judgements, a remarkable gap in the priority of criteria related to the transport improvement can be noticed. As a matter of fact, port competitiveness has been deemed to be of utmost importance if compared with the other two criteria, between which the impact on modal shift covers the least meaningful role. The motivation for this attribution of weights lies in the prevalence of such criterion at conceptual level, which means that, in the view of a rise in port railway capacity, both modal shift and interoperability can be considered secondary features with respect to the position of the port itself within the reference logistics context.

Table 17 - Criteria priorities according to the terminal operators' perspective

Macro-criterion	**Criterion**	**Priority**
COSTS	Investment costs	0,5
	Operational costs	0,5
ENVIRONMENTAL AND SOCIAL IMPACT	Level of employment	0,33
	Noise reduction	0,33
	Reduction of emissions	0,33
PROCESS EFFICIENCY	Administrative procedure smoothness	0,35
	Operations management	0,35
	Technological innovation level	0,3
TRANSPORT IMPROVEMENT	Impact on modal shift	0,1
	Increase in interoperability	0,2
	Port competitiveness	0,7

Concerning the evaluation of the effectiveness of alternatives, Tables 18, 19 and 20 contain the judgements stated by the group of experts for the three scenarios under examination, with respect to each identified criterion. In this regard, the following two peculiarities must be highlighted: on one hand, the performances of investment costs have been expressed in terms of the actual financial expenditures necessary to implement the considered initiatives and, on the other hand, the scale of values used to assess the impact of operational costs has been inverted, suggesting that the need of lower expenses corresponds to a more favourable condition.

Giving a global overview of the effectiveness of the analysed alternatives, it is evident that experts have deemed that the status quo poorly performs in every criterion, entailing also the highest operational costs. On the contrary, confronting the remaining two scenarios of intervention, more similar performance judgements have been assigned, even though with some remarkable differences. First of all, a quite significant discrepancy can be observed with respect to costs. Indeed, despite the larger capital investments, the scenario considering the realization of infrastructural interventions, in combination with technological and organizational ones, proves to necessitate less operational costs, thanks to the benefits provided by the realized measures. Conversely, the incurrence of more modest initial expenditures in the scenario proposing just the implementation of technological and organizational interventions implicates a greater amount of operational costs. Apart from the performances in the criteria related to the environmental and social impact, quite significant differences can be noted with reference to the further two selected macro-criteria. With the only exception of the administrative procedure smoothness, the scenario considering the realization of infrastructural interventions stands out in all the other aspects, particularly in the operations management, in the impact on modal shift and in port competitiveness.

Table 18 - Performance judgements for the alternative considering the status quo

Alternative: STATUS QUO		
Macro-criterion	**Criterion**	**Performance judgement**
COSTS	Investment costs	0
	Operational costs	10
ENVIRONMENTAL AND SOCIAL IMPACT	Level of employment	1
	Noise reduction	2
	Reduction of emissions	1
PROCESS EFFICIENCY	Administrative procedure smoothness	1
	Operations management	1
	Technological innovation level	1
TRANSPORT IMPROVEMENT	Impact on modal shift	1
	Increase in interoperability	1
	Port competitiveness	2

Table 19 - Performance judgements for the alternative considering organizational and technological interventions

Alternative: ORGANIZATIONAL AND TECHNOLOGICAL INTERVENTIONS		
Macro-criterion	**Criterion**	**Performance judgement**
COSTS	Investment costs	2000000
	Operational costs	5
	Level of employment	2

ENVIRONMENTAL AND SOCIAL IMPACT	Noise reduction	1,5
	Reduction of emissions	1,5
PROCESS EFFICIENCY	Administrative procedure smoothness	3
	Operations management	5
	Technological innovation level	4
TRANSPORT IMPROVEMENT	Impact on modal shift	4
	Increase in interoperability	2
	Port competitiveness	4

Table 20 - Performance judgements for the alternative considering infrastructural interventions

Alternative: INFRASTRUCTURAL INTERVENTIONS		
Macro-criterion	**Criterion**	**Performance judgement**
COSTS	Investment costs	150000000
	Operational costs	0
ENVIRONMENTAL AND SOCIAL IMPACT	Level of employment	5
	Noise reduction	1
	Reduction of emissions	2
PROCESS EFFICIENCY	Administrative procedure smoothness	3
	Operations management	9
	Technological innovation level	7
TRANSPORT IMPROVEMENT	Impact on modal shift	8
	Increase in interoperability	8
	Port competitiveness	6

6.2 Conclusions

In support of the optimization procedure, two diverse applications of the AHP method have been performed, considering quantitative and qualitative appraisal criteria. One has served the prioritization of the key operational features of port railway processes, while the other one has enabled the definition of the ranking of some selected design alternatives. Both evaluation applications have addressed the aim of increasing railway capacity in the Port of Trieste and they have engaged different actors, based on the respective level of analysis. In the former application, the main involved stakeholders have actively participated to the assessment process, as they have been administered to a survey questionnaire to determine the priorities of the decision elements. In that circumstance, they have complemented their numerical preferences with some discursive judgements, which provided useful insights to better capture their diverse perspective. On the contrary, in the latter application, the more complex articulation of the decision problem has challenged a group of experts in the assignment of adequate judgements reflecting the standpoint of the various actors. Nevertheless, the aggregated outcome obtained from such evaluation process consists of a shared and robust recommendation, that can effectively sustain decision makers in elaborating development strategies for the Port of Trieste.

7. Results and discussion

The present section illustrates the results achieved from both the optimization procedure and the AHP-aided evaluation, which have been performed in order to investigate on a possible railway capacity increase in the Port of Trieste. Furthermore, a discussion of the relationship among the outcomes of the two adopted techniques is provided, highlighting how their combination has been functional to formulate a comprehensive decision recommendation.

7.1 Optimization procedure

The outcomes obtained directly from the optimization procedure have been processed with the aim of offering port decision makers an agile approach to query the entire set of generated data, enabling them to rapidly estimate port railway capacity. Indeed, further optimization results have been derived applying the Response Surface Methodology (RSM), that is a collection of mathematical and statistical techniques used to model and analyse the outcomes of complex applications in which the response is a function of multiple variables. Such methodology entails the development of an approximated model of the objective function, that permits to significantly reduce the computation time spend to attain the optimal configuration. The creation of a Response Surface (RS) requires an initial training set of exact values and it can be accomplished using different techniques, which distinguish for the level of difficulty in defining parameters, computation time and accuracy of results. One of them is called the Gaussian Process (GP), that is a stochastic method based on the notion of the Gaussian distribution, for which every finite linear combination of random variables is normally distributed. It enables to detect and approximate outliers, and to estimate an uncertainty measure in the form of a standard deviation for predicted function values. In the case of the examined application, such measure corresponds to a variation in the entity of the optimal value of port railway capacity, i.e. it is expressed in terms of a range for the maximum number of potential trains.

In line with the adopted approach, optimization results constitute stochastic variables indicating the maximum number of trains that can be potentially handled at the Punto Franco Nuovo, when modifying some infrastructural and/or operational features. According to the probability theory, a stochastic process consists of the representation of a variable that randomly changes in time, expressing the probabilistic nature of a parameter in a dynamic system. Such representation properly reflects the actual behaviour of transport networks because, as argued in [144], those systems do not remain in the same state over successive periods due to the occurrence of several actions of cause. This characteristic entails that, in later times, a certain system passes through a diverse sequence of states, even in face of similar boundary conditions.

For instance, a typical source of variation is the temporal fluctuation of the level and composition of traffic demand. This example is just the motivation for the stochastic behaviour of the transport phenomenon analysed in the present dissertation, since a random approach has been used to manage the distribution of trains generated or attracted by the Trieste campo Marzio station. Therefore, under equal circumstances of the process scenario, simulation is meant to produce different outcomes at each run. However, the entity of such difference in the value of results is quite limited because, based on the parametrization of tokens, the range in which the potential number of trains coming from or heading towards the national railway network proves to be not so wide in any defined time slot of the simulated day.

The following assumptions have been made for the estimation of the optimal number of trains at the Punto Franco Nuovo:

- the values obtained for port railway capacity are related to the growth of traffic demand which is expected to concern the Port of Trieste, according to the future macroeconomic tendencies;
- results provided by the optimization procedure in terms of the split of train flows among the three considered terminals may not reflect the actual distribution of traffic volumes, due to the implementation of a specific mechanism to exclude further potential trains based on tracks availability at the Trieste Campo Marzio station;
- an ideal situation with no possible additional delay at the gateway check has been considered, because the happening of this phenomenon was not observed during on-field data collection sessions. However, although with imprecise frequency and duration, the occurrence of such delay depending on verification activities by the Financial Police has been noted by port operators.

Although the last two assumptions may seem to limit the simulation model, and thus the final optimization outcomes, they can actually offer useful insights for future developments. In regard to the first one, the approach adopted to split railway traffic flows among terminals has revealed to provide an indication to improve the definition of the train schedule on the national railway network. Indeed, the obtained results can suggest the railway companies serving the three examined terminals some helpful considerations to more efficiently evaluate the purchase of train time slots on the national railway network, based on tracks availability at the Trieste Campo Marzio station. Concerning the second assumption, a more accurate estimation of the entity and the real probability of occurrence of delays at the gateway check could be accomplished in the future thanks to the enrichment of the information content reported in the PCS of the Port of Trieste. As a matter of fact, statistical analyses could be performed on data recorded in Sinformar in relation to the evolution of the statuses of the CH30 document, enabling a more detailed representation of railway processes and, consequently, a refinement of the current optimal port capacity. In the context of this thesis, such particular situation at the gateway check has been intentionally overlooked, because it is of minor importance with respect to the other events unfolding in the considered railway processes.

The set of exact optimization values obtained by mF has been trained using the GP, providing a series of approximated data regarding the optimal port railway capacity that reflect different combinations of the considered infrastructural and operational parameters. The consultation of the values derived from the created RS has been facilitated by the development of an intuitive Microsoft Excel interface, which automatically queries the RS data and, thus, offers port decision makers a smart approach to elaborate a variety of what-if scenarios. Those outcomes have been also visualized using the graphical outputs provided by mF, in order to allow a more effective understanding of compromise solutions lying on the Pareto front. Considering all the possible combinations of levels of input variables computed by the Full Factorial DOE algorithm, each displayed solution has been obtained by means of 500 runs of MOGA-II.
According to an operational perspective, the optimal port railway capacity has been evaluated in terms of the maximum number of completed processes during simulation runs (cfr. the output variable "*Processi_Completati*" in Section 5.2.4) to varying of input parameters.
Figure 20 represents a 3D-scatter chart which illustrates the variation of the maximum number of completed processes ("*MaxProcessiCompletati*" – Z Axis), in function of the number of shunting locomotives ("Numero_Locomotive" – Y Axis) and of the tracks at the Trieste Campo Marzio station ("*Numero_CM*" – X Axis). It can be noted that a tendency for a growth of the optimal port railway capacity is related to the increase in the availability of both kinds of resources. A clearer examination of the individual contribution of those factors can be carried out referring to the 2D-scatter charts reported in Figures 21 and 22, which depict, respectively, the influence of shunting locomotives and of the tracks at the main port railway station on the maximum number of train flows. In both figures, the various points represented along the y axis correspond to the different trade-off solutions generated performing the multi-dimensional optimization procedure. Taking into account the maximum values, in Figure 21 it can be observed that a significant rise in the entity of completed processes is attainable until the number of shunting locomotives employed for train transfers equals to 5. On the contrary, with

the increasing of those operational resources, the marginal growth of the maximum amount of train flows decreases. Analogously, Figure 22 captures an increase in the number of completed processes when increasing the quantity of tracks at the Trieste Campo Marzio station.

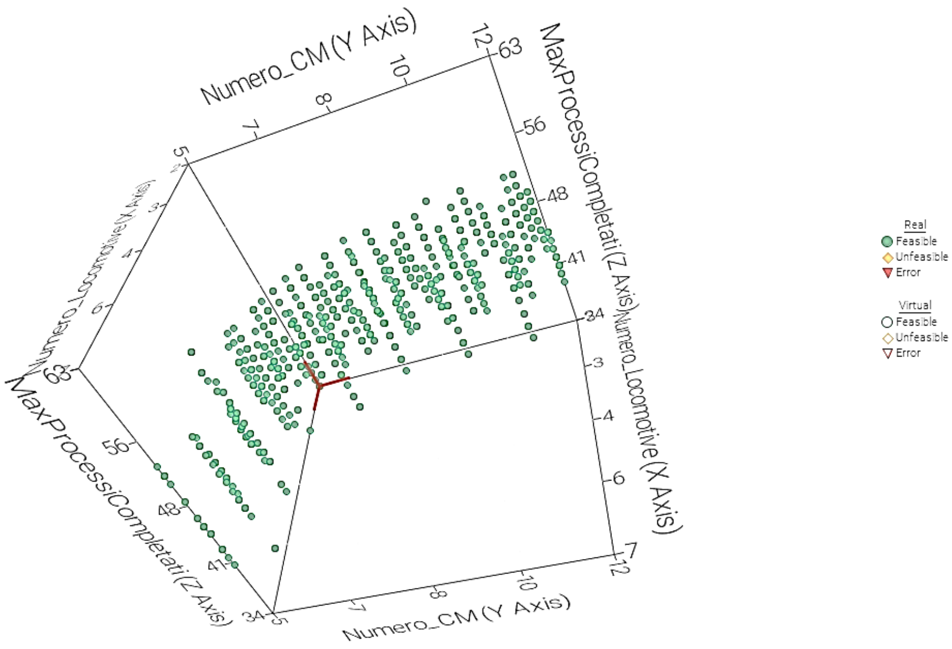

Figure 20 - Maximum number of completed processes to vary of the number of shunting locomotives and of the tracks at the Trieste Campo Marzio station

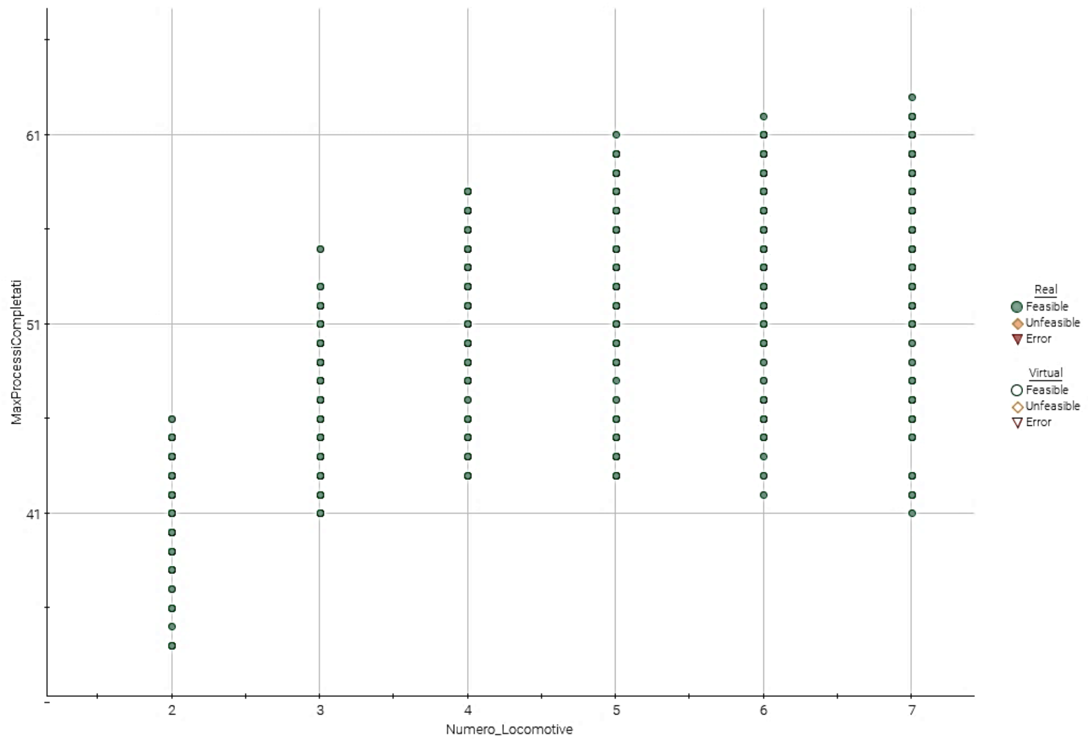

Figure 21 - Maximum number of completed processes in function of the number of shunting locomotives

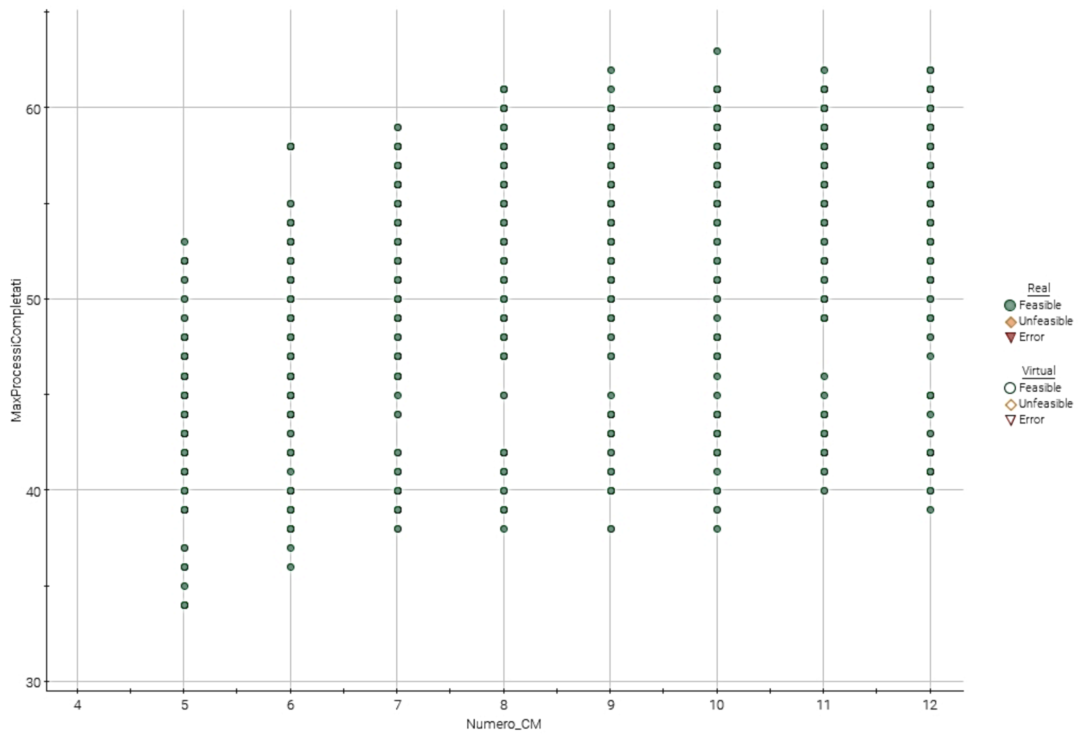

Figure 22 - Maximum number of completed processes in function of the number of tracks at the Trieste Campo Marzio station

Conversely, as depicted in Figure 23, no relevant increases in the maximum number of completed processes is attainable to varying of the amount of tracks at Fascio dei Moli.

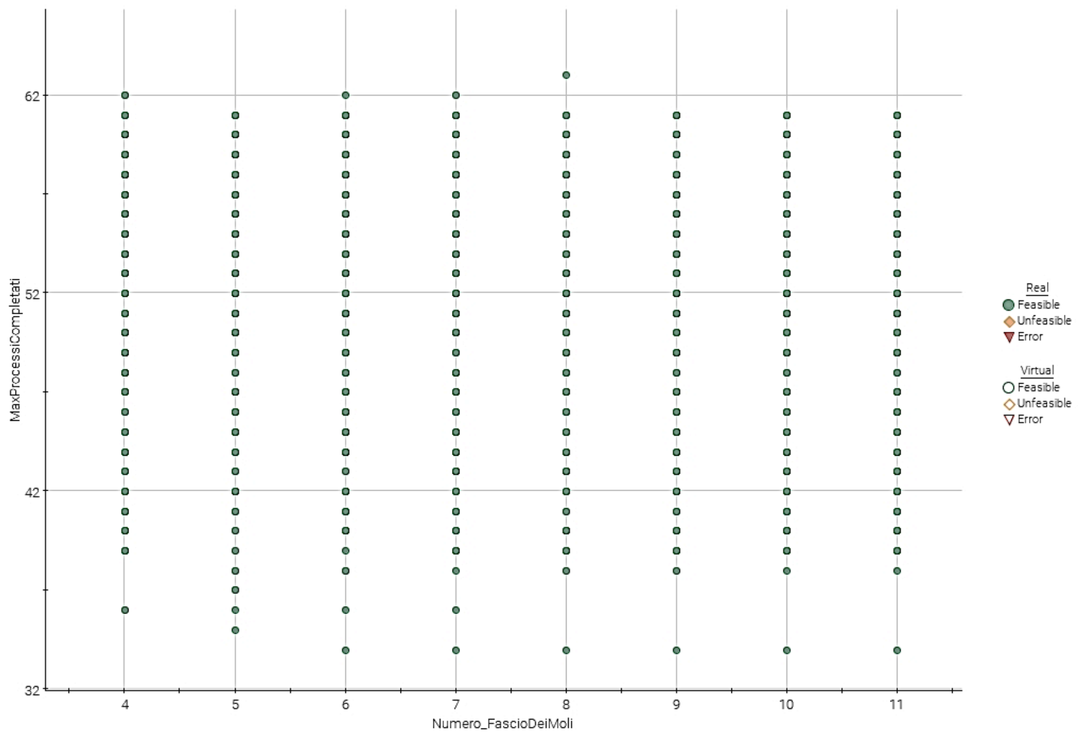

Figure 23 - Maximum number of completed processes in function of the number of tracks at Fascio dei Moli

Considering only influential input variables on the number of completed processes, the bubble chart reported in Figure 24 offers a graphical representation which combines all of them. Indeed, using a colour scale to express changes in the number of tracks at the Trieste Campo Marzio station, Figure 24 illustrates the same tendency depicted separately in Figures 21 and 22. The absence of blue-filled dots in the maximum values of this three-dimension chart suggests that no compensation is possible between operational and infrastructural resources. This means that, even in face of the availability of great amount of shunting locomotives, the lack of a high number of tracks at the Trieste Campo Marzio station definitely compromises the increase in the maximum number of trains flows.

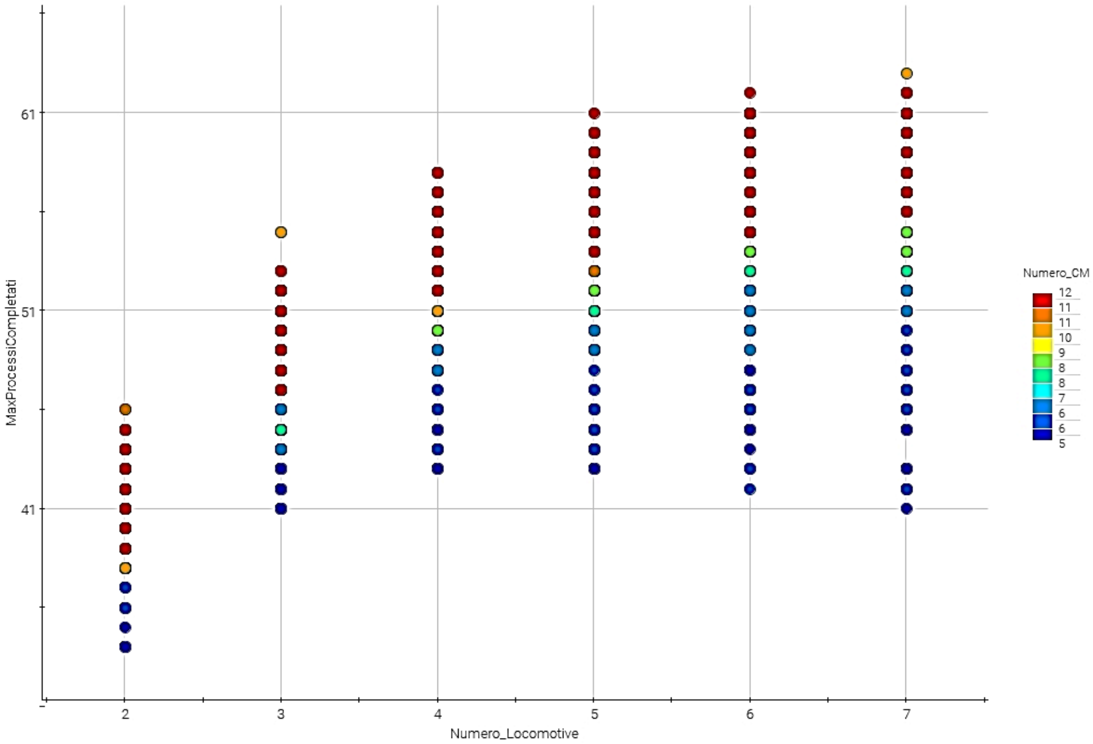

Figure 24 - Maximum number of completed processes in function of influential input variables

The four-dimension bubble chart reported in Figure 25 allows to analyse the growth of the maximum number of completed processes encompassing also the possible variations in the amount of the tracks at Fascio dei Moli, whose entity is expressed by the diameter size of bubbles. The minor influence of the availability of those infrastructural resources is confirmed by the fact that, in correspondence to high values of the optimal amount of train flows, also bubbles with a quite small circumference are present and they are mainly coloured red, which characterizes a large quantity of tracks at the Trieste Campo Marzio station.

Therefore, in general terms, it can be concluded that the increase in the maximum number of

completed processes at the Punto Franco Nuovo mostly depends on the number of tracks at the Trieste Campo Marzio station and, to a lesser extent, on those at Fascio dei Moli, while it proves to be almost constant beyond a certain amount of shunting locomotives. With regard to this latter parameter, the lower marginal rise of port railway capacity provides an indication of the number of locomotives which is actually necessary to perform shunting operations and, thus, it preliminarily suggests decision makers a line of action for the choice of investments.
No figures illustrating the influence of the demolition of the wall delimiting the Free Port zone and of the doubling of tracks at Parezane have been included in the discussion of optimization results, because they did not provide any useful insights. Indeed, when elaborating charts, more attention has been focused on input variables with a wider range, rather on those two binary parameters, in order to elaborate a greater variety of potential port configuration scenarios. Besides, the exclusion of investigations about the impact of the mentioned variables is in line with the aim of assessing the optimal port railway capacity at strategic level, since the future layout of the Port of Trieste will for sure encompass the absence of the separating wall and the availability of two tracks at Parenzane.

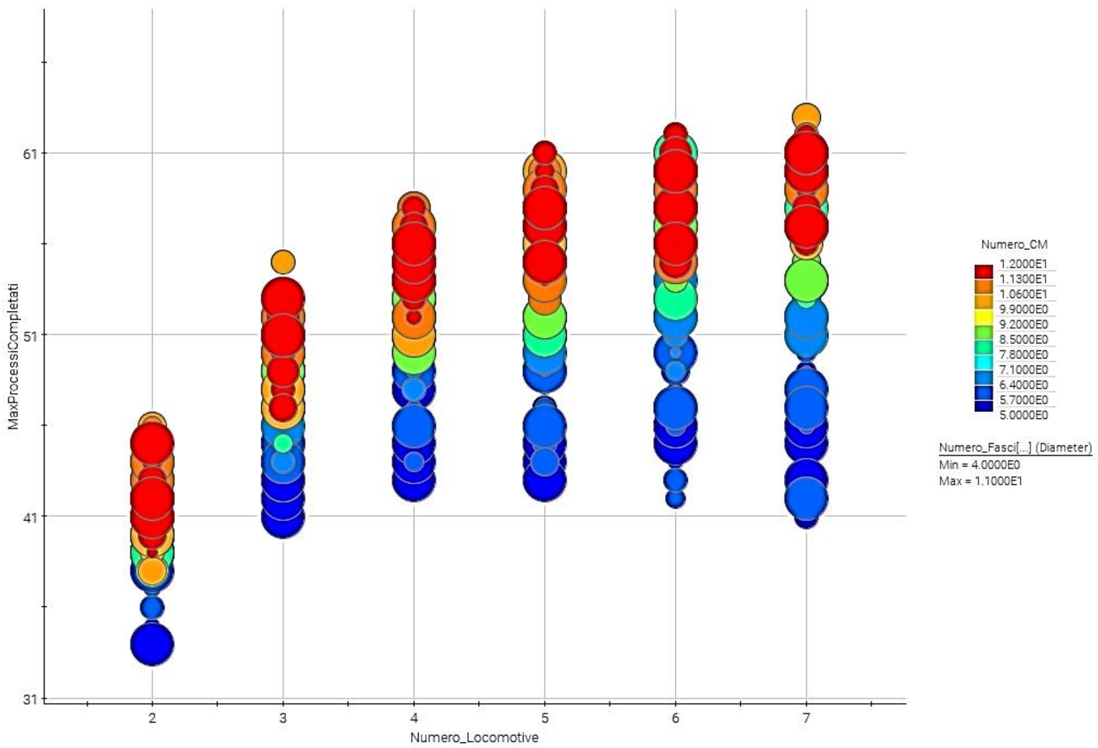

Figure 25 - Maximum number of completed processes in function of the number of shunting locomotives and of the tracks at the Trieste Campo Marzio station and at Fascio dei Moli

Further insights can be drawn evaluating possible increases in the optimal port railway capacity adopting a temporal perspective, which involves considering the implementation phases of works that have been planned to enhance such port feature. Like saying in Section 5.2.4, the necessary works are not intended to be realized contemporarily, so as to not overly restrict railway operations in the whole Port of Trieste. Indeed, infrastructural arrangements are meant to be performed first at the Trieste Campo Marzio station and, at a later time, at Fascio dei Moli. Based on the diverse asset that could be assumed by those components of the port railway network, two scenarios with a different time horizon have been taken into account. On one hand, a mid-term scenario has been determined to appraise the potential rise in the optimal railway capacity in the time span between 2022 and 2028 and, on the other hand, a long-term scenario ending in 2030 has been defined to capture possible increases in railway traffic volumes after the completion of all work phases. In line with this high-level approach to assess the expected growth of port railway capacity, optimization results have been displayed in some additional figures with respect to the optimal number of trains in a year. These values have been derived multiplying the maximum number of completed processes by the annual amount of actual working days, which corresponds to 288. Referring to the official statistics offered by PNAEAS, more than 9700 train movements have been carried out in the Port of Trieste in 2019: this information has been considered as the reference value for the appraisal of potential increases in port railway capacity in the developed scenarios of intervention.
To this end, parallel charts provided by mF have been used to visualize both approximated and exact optimal values to changes in the level of input parameters. In this kind of charts, insights on the resulting amount of possible optimal solutions can be derived by the numerosity of depicted coloured lines for a specific solution, since the greater it is, the larger is the quantity of potential combinations of input variables. On the contrary, grey lines reported in the background indicate all the possible solutions that can be obtained considering further combinations, for which the value of input parameters is not included in the selected range.
Bearing in mind evidence coming from previous charts, especially the one reported in Figure 21, the range of the number of locomotives has been supposed to vary only between 2 and 4, because a higher quantity of such resources has proved not to entail any remarkable beneficial effects on port railway capacity.
Figure 26 indicates the maximum amount of train flows attainable during infrastructural works at the Trieste Campo Marzio station assuming a reduction in its current track availability, while maintain all the ones at Fascio dei Moli fully operational. It can be noticed that limiting the number of tracks at the main port railway station between 5 and 7 would severely affect the

value of the optimal port railway capacity, which would not be larger than approximately 15500 trains per year.

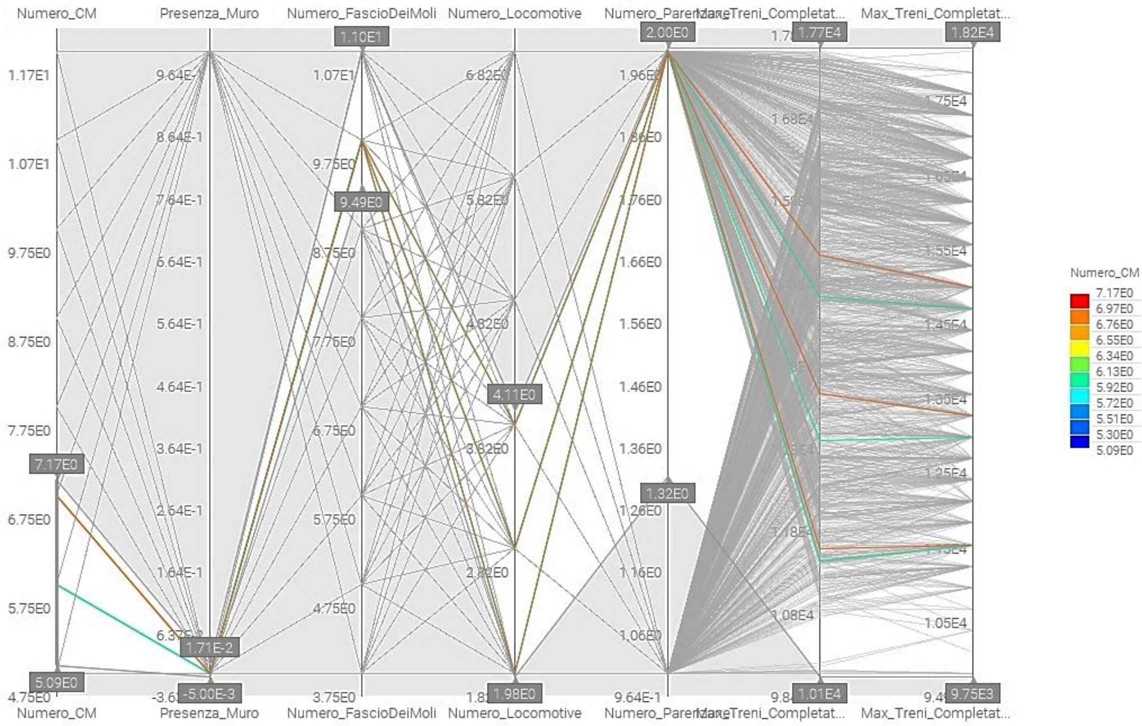

Figure 26 - Optimal port railway capacity during infrastructural works at the Trieste Campo Marzio station

The important role covered by the Trieste Campo Marzio station with respect to the whole port railway capacity is even more evident in Figure 27, in which a lower number of available tracks at that infrastructural component have been considered. As a matter of fact, the reduction of possible optimal solutions resulting from this scenario suggests the need of preserving the operability of as many tracks as possible during work phases in such part of the port railway network. To that end, the most detrimental work activities should be realized in the lowest traffic days at the Trieste Campo Marzio station.

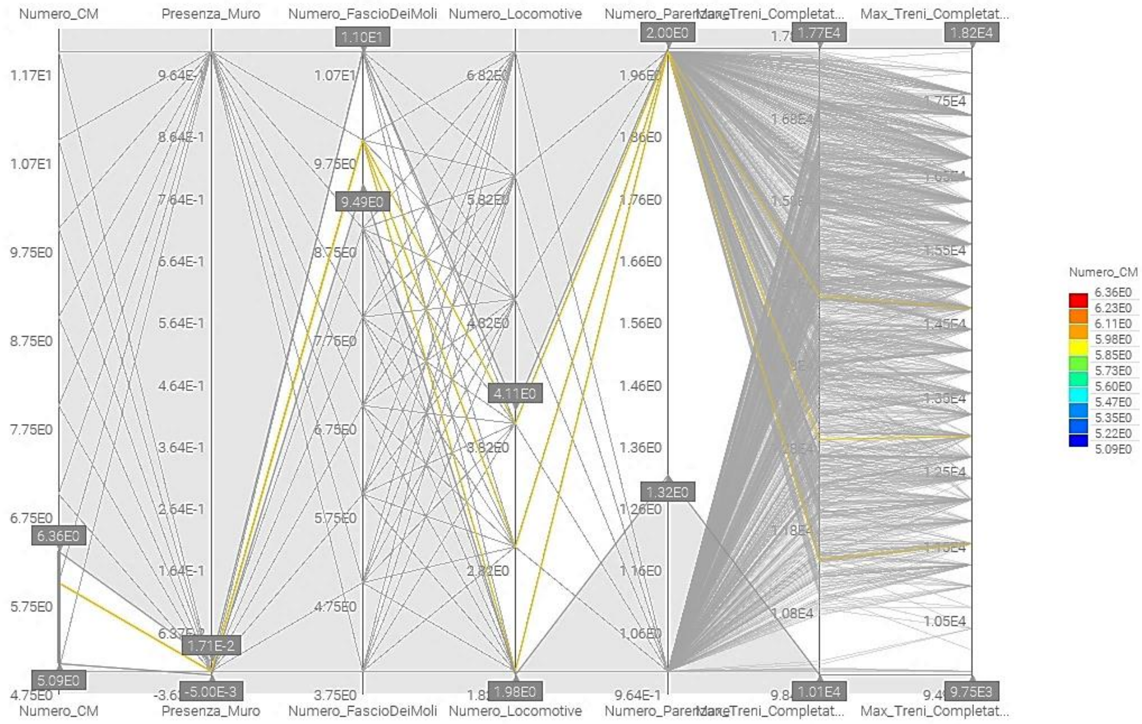

Figure 27 - Optimal port railway capacity during infrastructural works at the Trieste Campo Marzio station

Reversely, Figure 28 illustrates the values of the optimal port railway capacity considering the implementation of infrastructural works at Fascio dei Moli, for which the number of available tracks has been restricted in a range between 4 and 6. Since work activities at the Trieste Campo Marzio station are supposed to be completed by that time, the number of its available tracks has been assumed equal to 12. In those operational circumstances, the maximum annual amount of railway volumes in the Port of Trieste would potentially exceed 16500 trains per year.

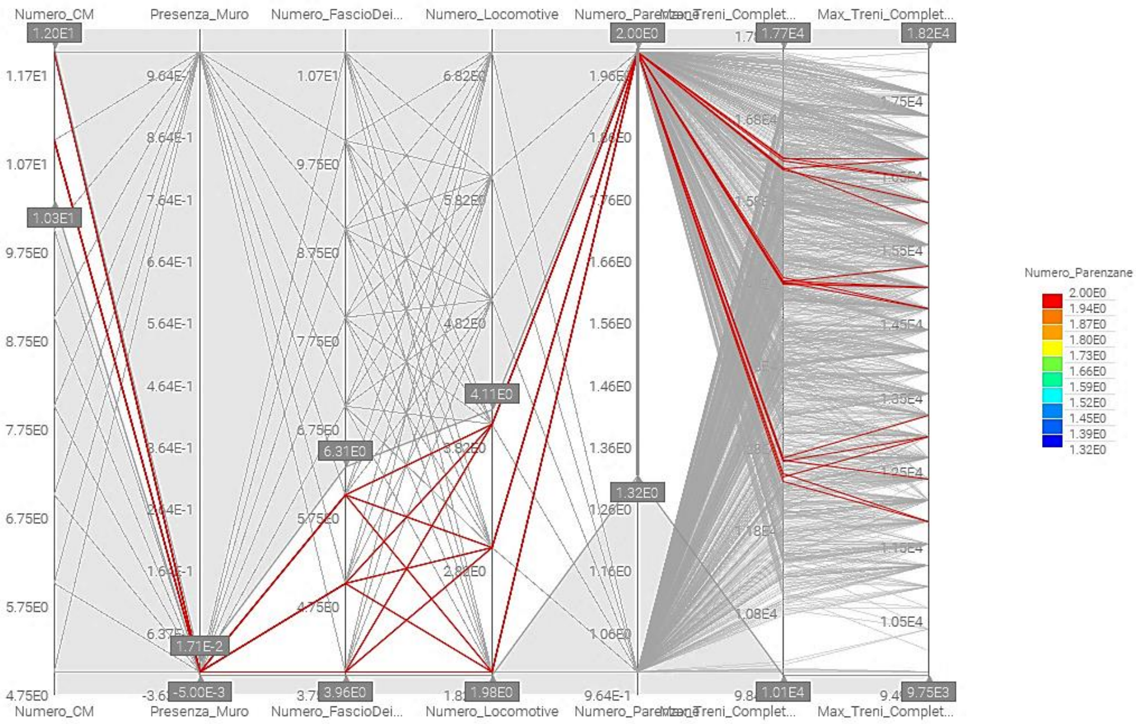

Figure 28 - Optimal port railway capacity during infrastructural works at Fascio dei Moli

Figure 29 depicts possible solutions for the optimal port railway capacity considering the completion of all infrastructural works, revealing similar values for the potential maximum amount of train flows if compared to results reported in Figure 28. This fact confirms the minor relevance covered by the availability of a large number of tracks at Fascio dei Moli, suggesting that the realization of advancement activities on those resources mainly addresses the aim of having more buffer tracks at the Punto Franco Nuovo.

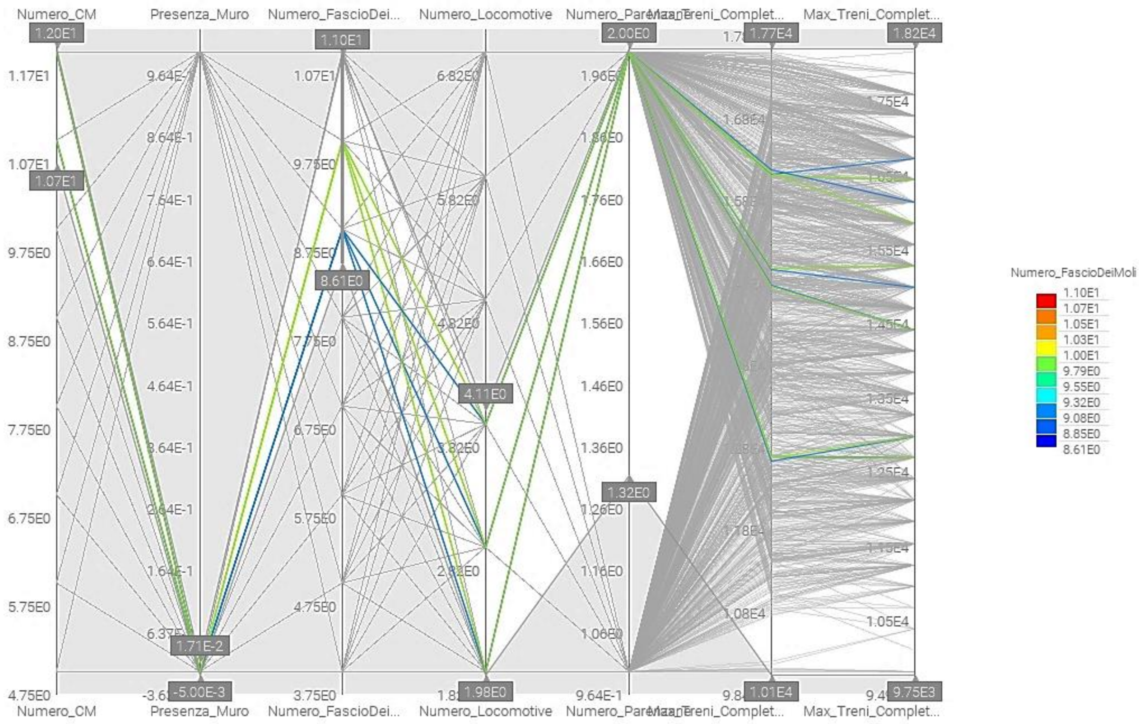

Figure 29 - Optimal port railway capacity after the completion of all infrastructural works

The mentioned infrastructural works are planned to be combined with some technological and organizational interventions, which consider mainly the implementation of a centralized traffic control system aimed at more efficiently managing railway traffic in the node of the Port of Trieste.

7.2 Multi-actor multi-criteria evaluation

As mentioned in Section 6.1, in both the applications, final evaluation results have been obtained by implementing the judgements passed on the various elements of the evaluation frameworks into a decision support software, providing suggestions on their overall importance. Furthermore, according to the level of detail of each application, some sensitivity analyses have been performed to assess possible modifications in the outcomes, to varying of the relevance of certain elements.

7.2.1 Priorities of elements and ranking of the alternatives

The diverse degree of complexity inherent to the elaborated evaluation frameworks is reflected in the articulation of their corresponding results and, thus, in the scope of the recommendations descending from the two applications. Indeed, in the assessment of port railway operational features, only the actors' level of influence and the global priority values for the considered parameters have been determined; while in the appraisal of possible scenarios of intervention, a ranking of the alternatives has been also defined. Aggregated results for the estimation of the stakeholders' influential contribution in reaching the main goal have been obtained synthesising judgements through the geometric mean [145].

7.2.1.1 Evaluation of key port railway operational features

Regarding actors' level of influence in the appraisal of port railway operational features, Figure 30 shows that the PNEAS – RID has revealed to be the most influential stakeholder for the attainment of an increase in railway capacity at the Punto Franco Nuovo. Even terminal operators have turned out to cover a remarkable role in achieving the main goal, while Adriafer has proved to be attributed to a less impacting role. This aggregated outcome demonstrates homogeneity among the interviewed actors in attributing preferences to stakeholders' influence, agreeing on the greater importance of the tasks performed by the RID to manage both port railway infrastructure and operations.

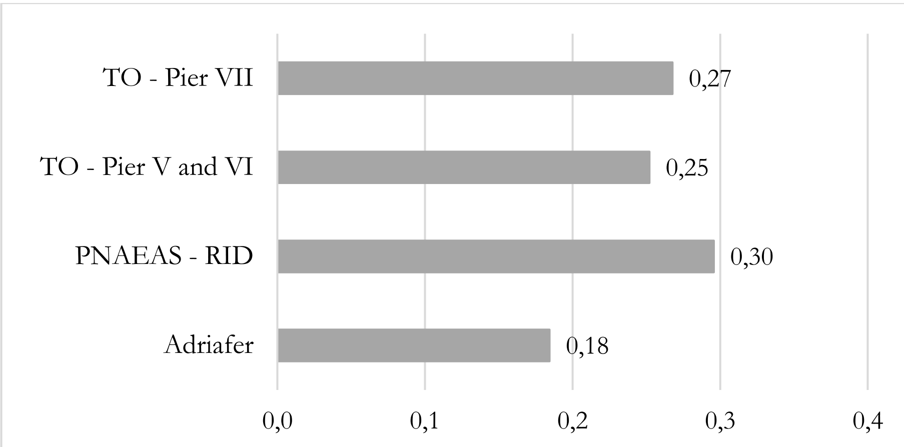

Figure 30 - Actors' level of influence in the evaluation of port railway operational features

With respect to the relative significance of criteria, Figure 31 illustrates that, aggregating judgements coming from the different engaged actors, the infrastructural occupancy time represents the most important criterion, followed by the waiting time for terminal availability and, immediately after, by the number of infrastructural resources. Besides, a remarkable importance has been attributed to the time needed to accomplish administrative procedures, while the least meaningful priority has been associated to the number of shunting locomotives and work crews. The quite distinct gap between the weight value of the criterion related to the infrastructural occupancy time and those of the remaining factors stresses that enabling seamless train transfers along the port railway network is deemed to be the crucial feature to attain an increase in railway capacity.

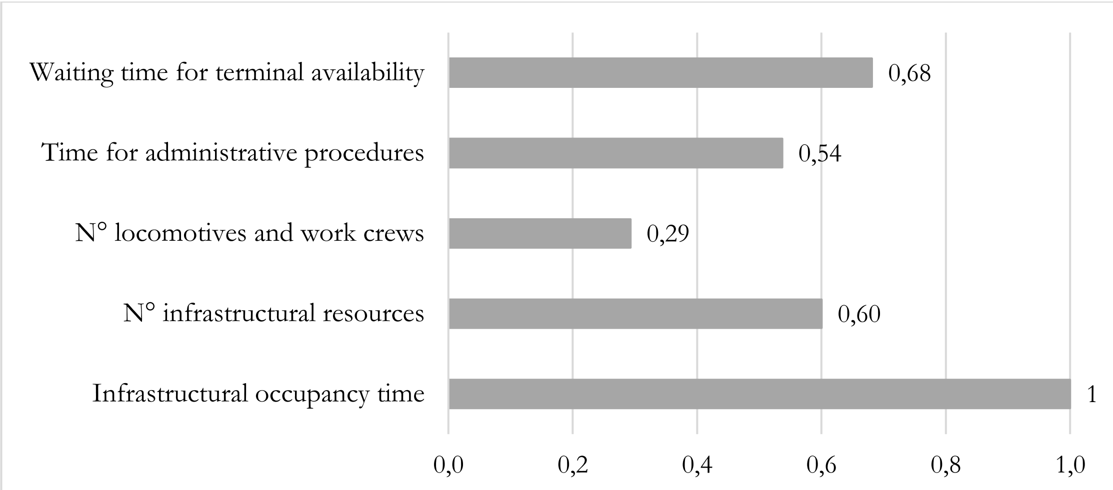

Figure 31 - Prioritization of criteria

Insights coming from the evaluation of port railway operational features prove to strongly sustain the results obtained by the optimization procedure, highlighting the usefulness of combining the two approaches. As a matter of fact, referring to Figure 31, the aggregated value estimated for criteria priorities confirm the importance of the infrastructural availability, in terms of both the entity of resources and their occupancy time. Such consideration can be observed especially in relation to port railway network, but also to terminals. Even the minor relevance of operational resource is line with optimization outcomes, since the increase in the optimal port railway capacity has turned out not to be influenced beyond a certain value of the number of shunting locomotives.

7.2.1.2 Evaluation of scenarios of intervention

As regard actors' influence in the evaluation of possible scenarios of intervention, in accordance to Figure 32, the Port Authority covers the most meaningful role for the attainment of increases in port railway capacity. Even the shunting operations manager has revealed to be quite influential with respect to the accomplishment of the main goal, followed by terminal operators. On the contrary, the influence of railway companies in potentially achieving a growth of port train flows has turned out to be almost negligible. Such outcomes highlight the importance of the managerial activities carried out by the Port Authority and, also, the relevance of shunting operations, confirming that efficiency in these two aspects is fundamental to succeed in rising railway traffic volumes in the Port of Trieste.

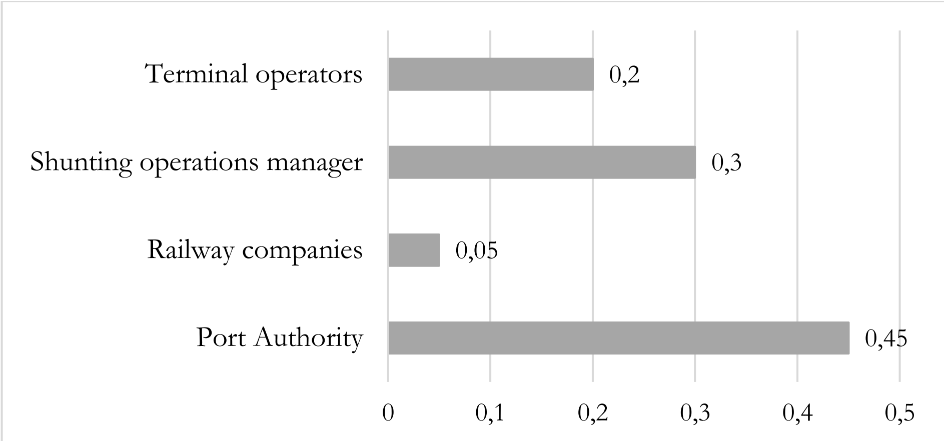

Figure 32 - Actors' level of influence in the evaluation of scenarios of intervention

Concerning macro-criteria, based on Figure 33, process efficiency has proved to be the macro-criterion with the highest priority, immediately followed by the one related to costs. The attainment of possible improvements in the transport field have been also attributed to a remarkable priority, whereas the relative weight of environmental and social impacts has turned out to be barely inconsiderable. In the context of the present assessment application, this latter result suggests a weak dependence between environmental and social impacts, and the increase in port railway capacity, even if the achievement of such goal would certainly contribute to enhance those aspects. The assignment of such great value to process efficiency points out the preference with respect to beneficial operational effects, even in face of financial expenses.

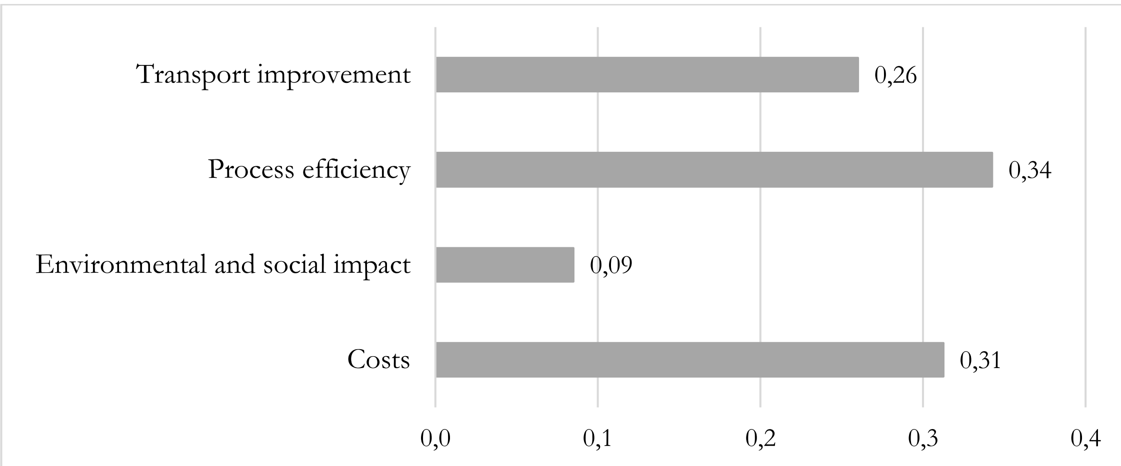

Figure 33 - Macro-criteria priorities

Figure 34 reports the relative priority of the criteria considered in the macro-criterion regarding costs: it can be noticed that operational costs have been attributed to a greater relevance as against investment ones. Such prioritization underlines the importance associated to aspects directly related to practical operational activities, in line with the more high-level weight pattern resulting from the comparisons among macro-criteria.

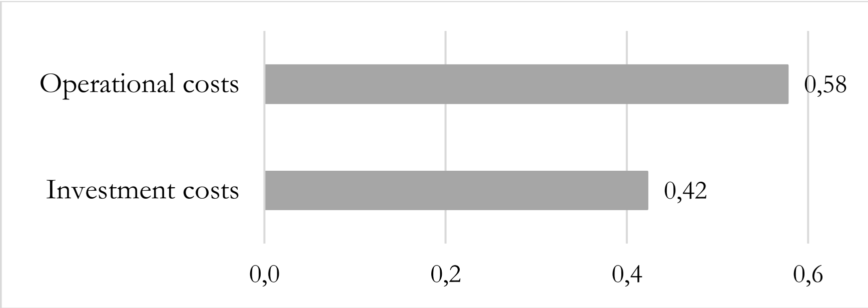

Figure 34 - Priorities of criteria related to costs

Priority values illustrated in Figure 35 indicate that, within the macro-criterion regarding process efficiency, the administrative procedure smoothness is deemed to be the most significant factor, preferred over both the technological level and the operations management. This result stresses once again the remarkable impact of documentary activities affecting the performing of railway processes, suggesting that it represents a barrier which, in a certain extent, neither technology nor operational efficiency can overcome.

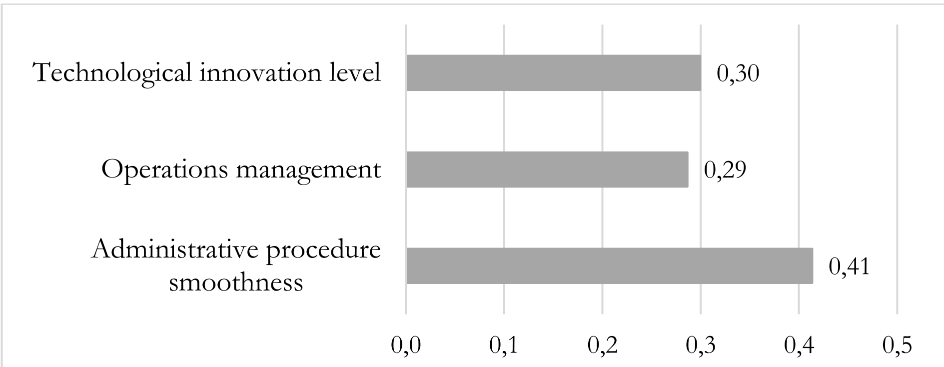

Figure 35 - Priorities of criteria related to process efficiency

In Figure 36, it can be observed that port competitiveness has definitely resulted to be the criterion with the highest weight for the macro-criterion related to transport improvement, marking a quite noticeable priority difference compared to the increase in interoperability and modal shift. Shedding light to the leading role of the position of the port within the reference marketplace, such priority gap underlines the importance of adopting a comprehensive transport perspective when planning strategies for a potential railway capacity increase.

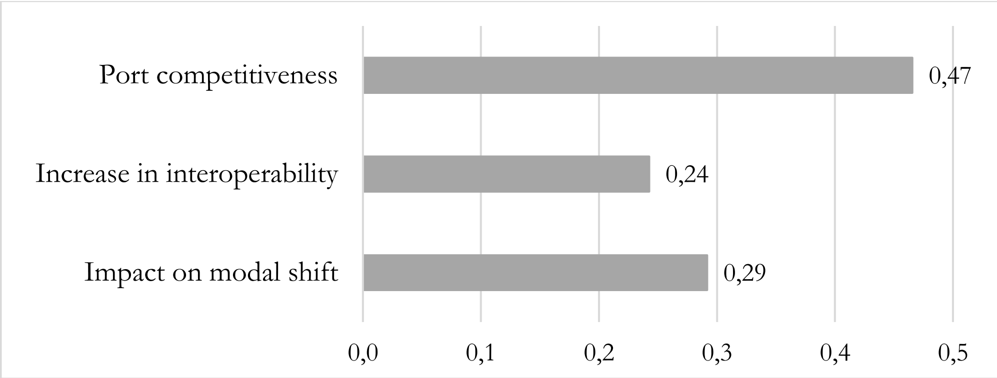

Figure 36 - Priorities of criteria related to transport improvement

Aggregated results included in Figure 37 reveal that social impacts are associated to a greater significance with respect to the environmental ones: as a matter of fact, the level of employment has been by far prioritized over the reduction of both emissions and noise.

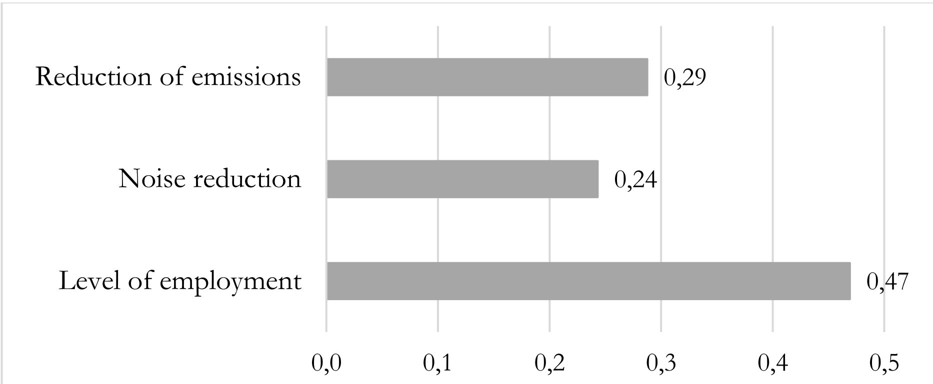

Figure 37 - Priorities of criteria related to environmental and social impact

Finally, based on the actors' level of influence and the priorities of macro-criteria and criteria, the overall ranking of the alternatives has been defined, so as to propose decision makers the most valuable scenario of intervention. In this regard, Figure 38 shows that the alternative considering infrastructural interventions has clearly resulted to be the best one, since it outperforms more twice the other two scenarios. The reason for this outcome is that the expected effects of the combined implementation of arrangements on the railway network and of organizational and technological measures is likely to exceed the impacts deriving by the actualization only of these latter. Nevertheless, the realization of the second-best alternative would undoubtedly ensure a growth in the annual port railway traffic as against the status quo, even if in a more limited extent in comparison with the one generated by the preferred solution.

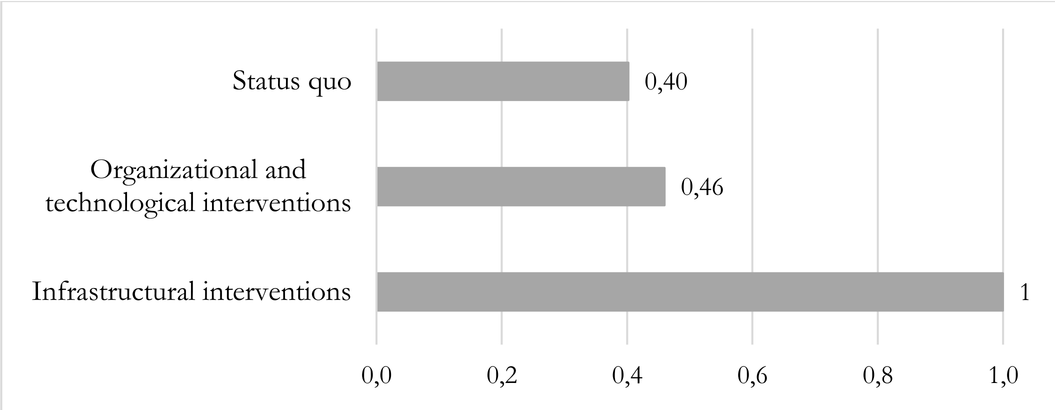

Figure 38 - Ranking of the alternatives

Similarly to the assessment of port railway operational features, a relationship between evaluation and optimization outcomes can be captured also referring to the resulting ranking of the alternatives illustrated in Figure 38, in which the importance of realizing infrastructural works in the Port of Trieste definitely stands out. Indeed, as revealed by the optimization procedure, the availability of an adequate amount of tracks, especially in the critical components of the port railway network, severely influences the optimal value of railway capacity, which can be for sure enhanced even by the implementation of some side technological and organizational interventions.

7.2.2 Sensitivity analysis

Sensitivity analyses have been performed in order to capture changes in the preferences attributed to certain elements of the evaluation frameworks, to varying of the importance of related factors. More specifically, modifications in the priorities of criteria have been examined in the assessment of key port railway operational features, whereas alterations in the ranking of alternatives have been investigated in the appraisal of the selected scenarios of intervention.
Such analyses prove to offer decision makers a useful support to better understand how changes in the significance of different aspects can possibly influence the final recommendation.

7.2.2.1 Evaluation of key port railway operational features

As mentioned, in the evaluation of port railway operational features, sensitivity analyses have been carried out to study changes in the relative importance of the considered criteria, with respect to variations in the actors' level of influence. Table 21 reports the diverse colours attributed by the Super Decisions software to identify the various criteria in the graphical representation of their significance trends.

Table 21 - Legend for criteria

LEGEND FOR CRITERIA	
Infrastructural occupancy time	
N° infrastructural resources	
N° locomotives and work crews	
Time for administrative procedures	
Waiting time for terminal availability	

Concerning the PNAEAS – RID, Figure 39 highlights that a quite remarkable inversion in the priorities of criteria occurs when the level of influence of the port technical department is close to 0.4. Indeed, it implicates a meaningful increase in the relevance of the time for port administrative procedures, accompanied by a more modest growth in the significance of the infrastructural occupancy time. Along with the rise in the weight value of such criteria, a decrease in the importance of the remaining parameters can be observed, especially for the one related to the number of infrastructural resources. Although no reversals in the overall priority classification of criteria has been recorded, the slope of the line marking the relevance of the time for administrative procedures suggests a pronounced increase in its importance in face of small changes in the RID's level of influence. Therefore, in the view of a railway capacity increase, these tendencies in criteria priorities confirm the significance attributed also to organizational aspects, and not only to resource availability.

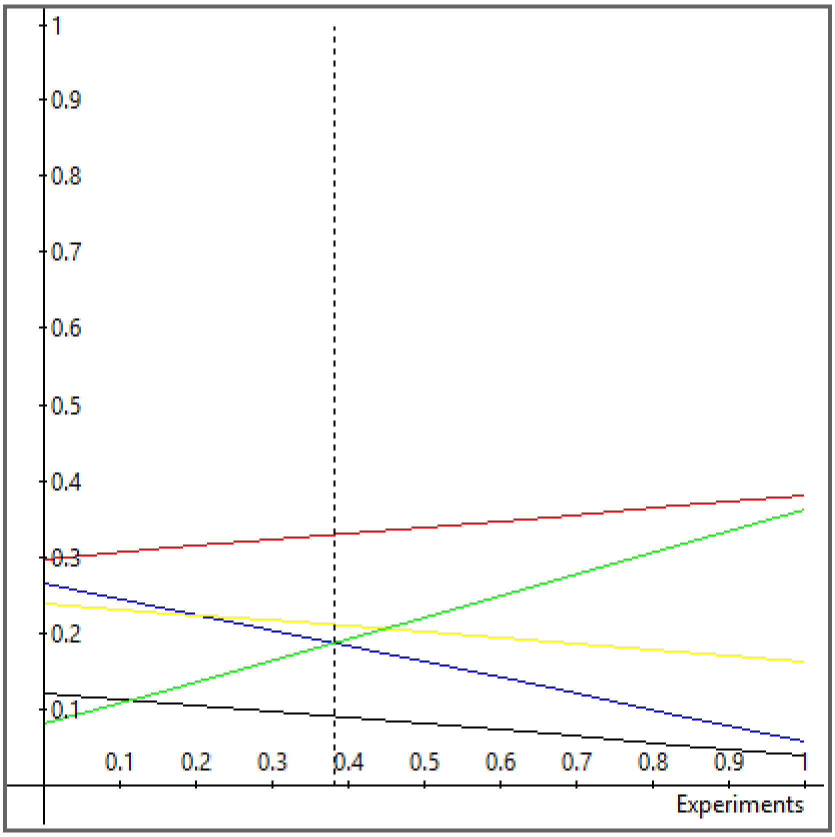

Figure 39 - Sensitivity analysis for the level of influence of PNAEAS - RID

No significant inversions in the criteria classification have resulted from variations in the level of influence of the Terminal Operator managing Piers V and VI, so any graphical visualization of the tendencies in criteria priorities has not been reported.

As illustrated in Figure 40, the increase in the level of influence of the Terminal Operator handling Pier VII implicates a noticeable rise in the weight value of criteria related to the waiting time for terminal availability and the number of both the considered types of resources. Such growth occurs concurrently to a remarkable reduction in the priority concerning the infrastructural occupancy time and the duration of administrative procedures. Indeed, clear inversions in the prioritization of criteria can be observed in correspondence to an influence value equalling approximately to 0.55 and 0.8 for the examined actor. This trend underlines that, with the aim of growing railway capacity, a rise in the level of influence of the Terminal Operator of Pier VII throws light on the importance of the smoothness in performing terminal and shunting operations, given a larger availability of resources.

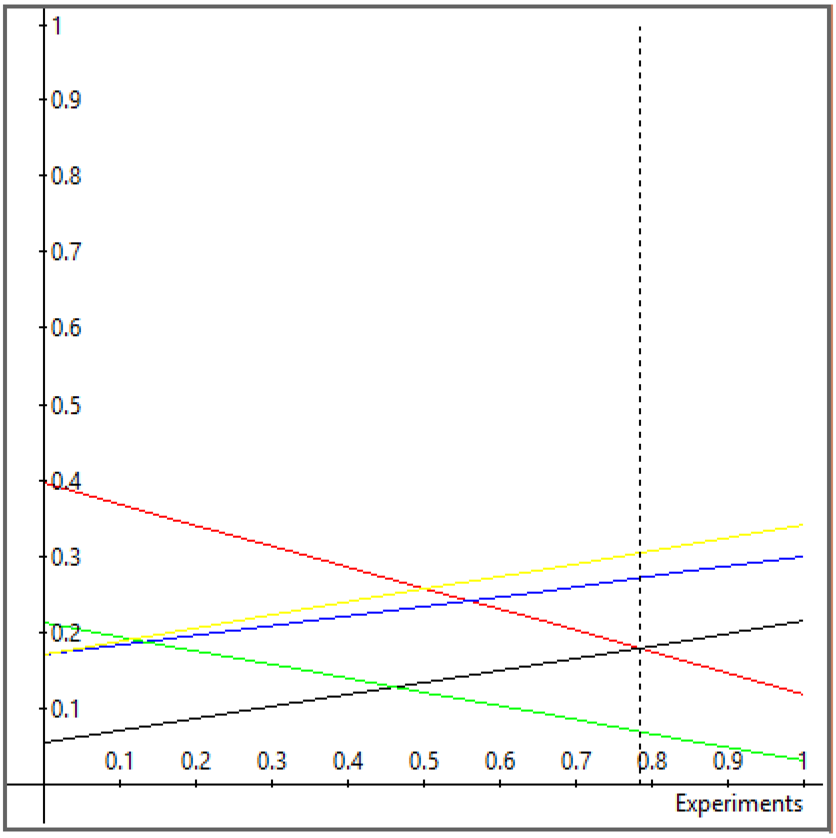

Figure 40 - Sensitivity analysis for the level of influence of the Terminal Operator of Pier VII

Regarding the shunting operations company, Figure 41 shows a distinct reversal in the priority of criteria in the range between 0.4 and 0.5 of Adriafer level of influence. As a matter of fact, for an almost equal importance attributed to the number of locomotives and work crews, greater relevance is definitely assumed by the criterion related to number of infrastructural resources and, to a more modest extent, also by the one concerning the time for administrative procedures. As such, the resulting variation in the criteria classification points out that, based on a more influential role of Adriafer, the attainment of an increase in port railway capacity mainly depends on the availability of infrastructural resources, paired with an efficient preparation of the documents necessary for train transfers.

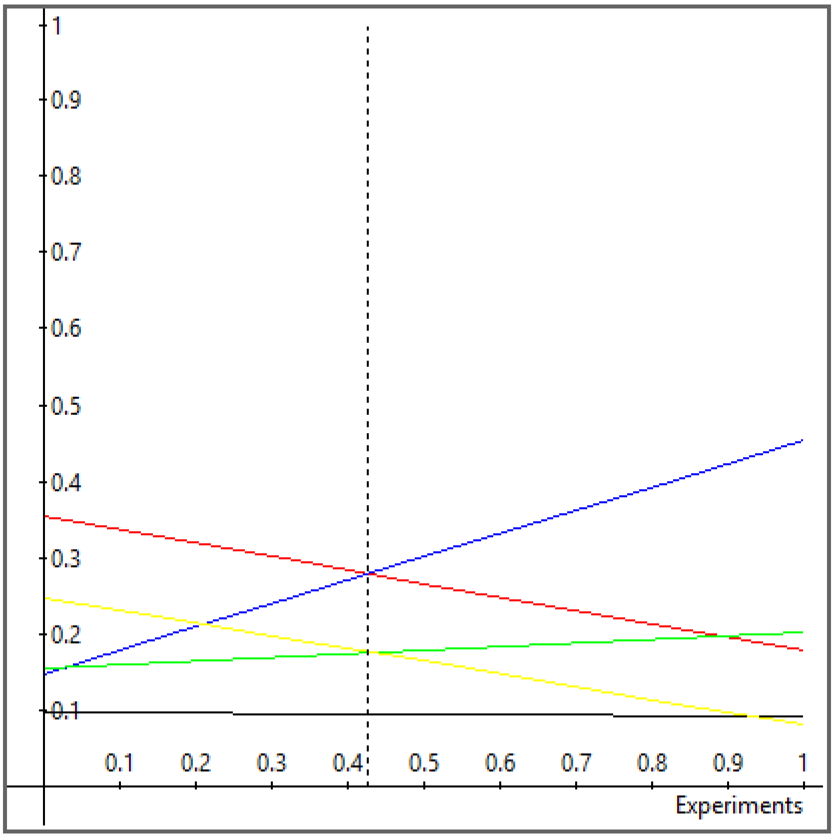

Figure 41 - Sensitivity analysis for the level of influence of Adriafer

7.2.2.2 Evaluation of scenarios of intervention

As anticipated, in the evaluation of scenarios of intervention, sensitivity analyses have been performed to examine changes in the ranking of the considered alternatives, in face of variations in the criteria priority. Table 22 indicates the diverse colours assigned by the Super Decisions software to the selected alternatives to visualize possible modifications in their ordering.

Table 22 - Legend for scenarios of intervention

LEGEND FOR SCENARIOS OF INTERVENTION	
Infrastructural interventions	
Organizational and technological interventions	
Status quo	

Modest changes in the ranking of the analysed scenarios of intervention have been observed only in relation to the criteria which refer to operational costs and the administrative procedure smoothness and an inversion in the alternatives trend has been recorded just in this latter case.

Indeed, in Figure 42 it can be noticed that the divergence in the performances between the scenario considering infrastructural interventions and the remaining two alternatives intensifies with the increasing of the relative importance of operational costs, suggesting that the combined effect given by infrastructural and organizational initiatives enables a higher daily financial sustainability, even in face of greater initial investments.

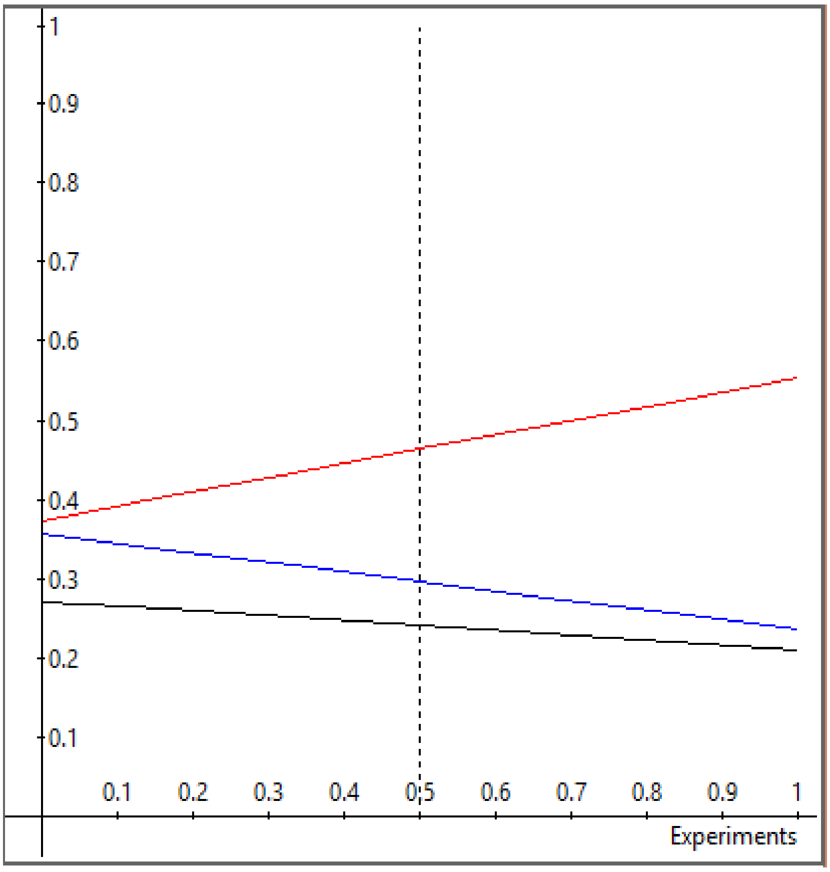

Figure 42 - Sensitivity analysis for the criterion related to operational costs

Figure 43 reports a minor inversion in the arrangement of alternatives to varying of the significance of the criterion related to the administrative procedure smoothness, in the weight value interval between 0.8 and 0.9. As a matter of fact, it results that the status quo slightly outperforms the scenario considering the implementation of organizational and technological interventions, which is motivated by the attribution to both alternatives of a similar effectiveness in various aspects.

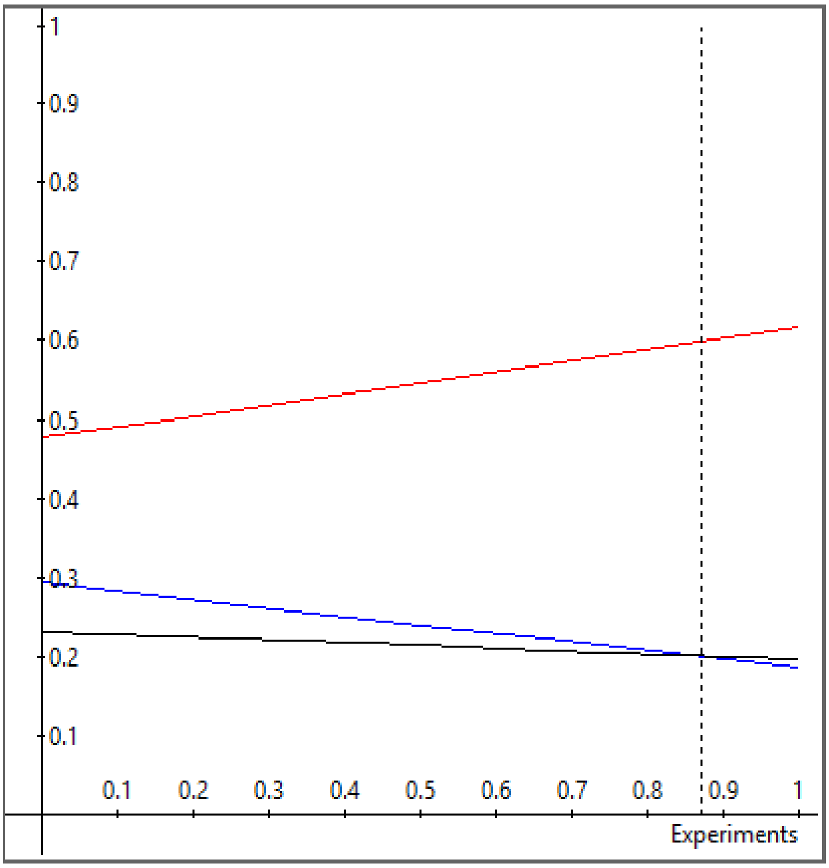

Figure 43 - Sensitivity analysis for the criterion related to the administrative procedure smoothness

7.3 Conclusions

The proposed integrated methodology has been applied to the case study of the Port of Trieste, with the aim of estimating the optimal port railway capacity under the occurrence various infrastructural and operational circumstances in such node. To that end, optimization outcomes have been processed using the RSM, in order to obtain an approximated model of the objective function. More specifically, this task has been accomplished building a RS by means of the stochastic process GP, in line with the nature of transport-related data to be elaborated. A few assumptions have been made in the simulation model, which directly feeds the developed multi-layer mF framework: they concern traffic demand data, the split of train flows towards the terminals and the timing for the gateway check. The creation of diverse graphical outputs offered by mF has served the examination of many combinatory optimization results at different levels of detail and considering a mid-term and a long-term scenario for the implementation of infrastructural works for port advancements. Such analysis has revealed that, in general terms, increases in the optimal port railway capacity largely depend on the availability of tracks at the Trieste Campo Marzio station and, to a lesser extent, of those at Fascio dei Moli. Indeed, a limited amount of tracks at that network component has shown to severely hinder a growth of the optimal port railway capacity, which would not exceed 15500 trains per year when operating only on up to 7 tracks. Anyway, the execution of infrastructural works at Fascio dei Moli is motivated by the need of having buffer tracks to enhance the rise of port railway capacity. On the contrary, referring to operational resources, the influence of the number of shunting locomotives on the potential optimal number of train flows has turned out to be almost constant beyond a value equal to 4.

Evidence deriving from the two applications of the multi-actor multi-criteria AHP-aided evaluation procedure have proved to sustain the observations regarding optimization outcomes, with respect to both the criteria priorities and the ranking of the alternatives. As a matter of fact, those appraisals have confirmed the importance of the availability infrastructural resources and, thus, the possibility of achieving greater port railway capacity performances thanks to the implementation of strategic infrastructural works.

8. Conclusions and future developments

In this thesis, the estimation of the optimal railway capacity in the Port of Trieste has been faced developing a methodology that integrates modelling, simulation and optimization techniques, with the aim of formulating suggestions that can help port decision makers in selecting the best strategy. More in detail, the first stage of the proposed methodology has consisted in the representation of railway processes through the BPMN modelling standard, considering both railway operations and documentary activities. This task has facilitated the comprehension of processes and it has enabled a preliminary analysis of potential bottlenecks. Prior to the actual simulation of processes, operational requirements have been defined and the parametrization of modelled elements has been performed via the BPSim standard, especially with reference to tasks, gateways and resources. Then, railway processes have been animated using L-Sim according to a discrete-event approach, which has permitted to identify the main factors hindering the execution of train transfers within the Port of Trieste. Finally, in the view of future port development works, an optimization procedure has been carried out by means of a multi-layer modeFRONTIER workflow, determining the maximum annual number of train flows under different possible combinations of infrastructural and operational resources. Results proved that the optimal value of port railway capacity largely depends on the amount of available tracks at the Trieste Campo Marzio station, while it becomes almost stationary beyond a limited quantity of deployed shunting locomotives.

At last, the integrated optimization procedure has been combined with the application of a multi-actor multi-criteria evaluation process at two different levels of detail. On one hand, the assessment has served the prioritization of the main port railway operational features while, on the other hand, the appraisal has addressed the goal of selecting the best scenario of intervention to increase port railway capacity. In both cases, evidence derived by process optimization have been confirmed by evaluation outcomes, highlighting the significance of infrastructural resources and the benefits of implementing new ones to enhance port railway capacity performances. This kind of evaluation approach proves to suit particularly well the transport intermodal sector, since it permits to capture the inherent complexity characterizing those systems and it allows to create a participatory decision-making process engaging various stakeholders.

Future developments of the suggested methodology can regard both the optimization and the evaluation procedure. The former could be enhanced by implementing an alternative to the First-In-First-Out logic functioning used for the management of tasks, so as to simulate token processing at gateways in a more accurate way. Besides, the elaborated BPMN models could be advanced by adopting the Decision Model and Notation (DMN), which is a standard provided by the OMG to specify business decisions and rules [146]. Indeed, it has been designed to complement BPMN in order to model decision-making aspects in business processes, supporting stakeholders in the understanding of complex decision domains. Allowing to define business rules in the form of decision tables, DMN could contribute to simplify the BPMN models of railway processes at hand and, thus, it could give the opportunity to easily analyse even more articulated and/or unconventional operational conditions.

Concerning evaluation, the methodological integration embraced for the optimization procedure could be further extended to include also assessment results and, therefore, to effectively take into account insights generated by the dynamics of group decision making. As a matter of fact, the implementation of these latter into the optimization workflow could suggest useful feedbacks and provide port decision makers a comprehensive tool to investigate on development lines of action.

Finally, at application level, the proposed methodology could be adopted for case studies on a larger scale and even with respect to additional transport-related aspects.

Annex A

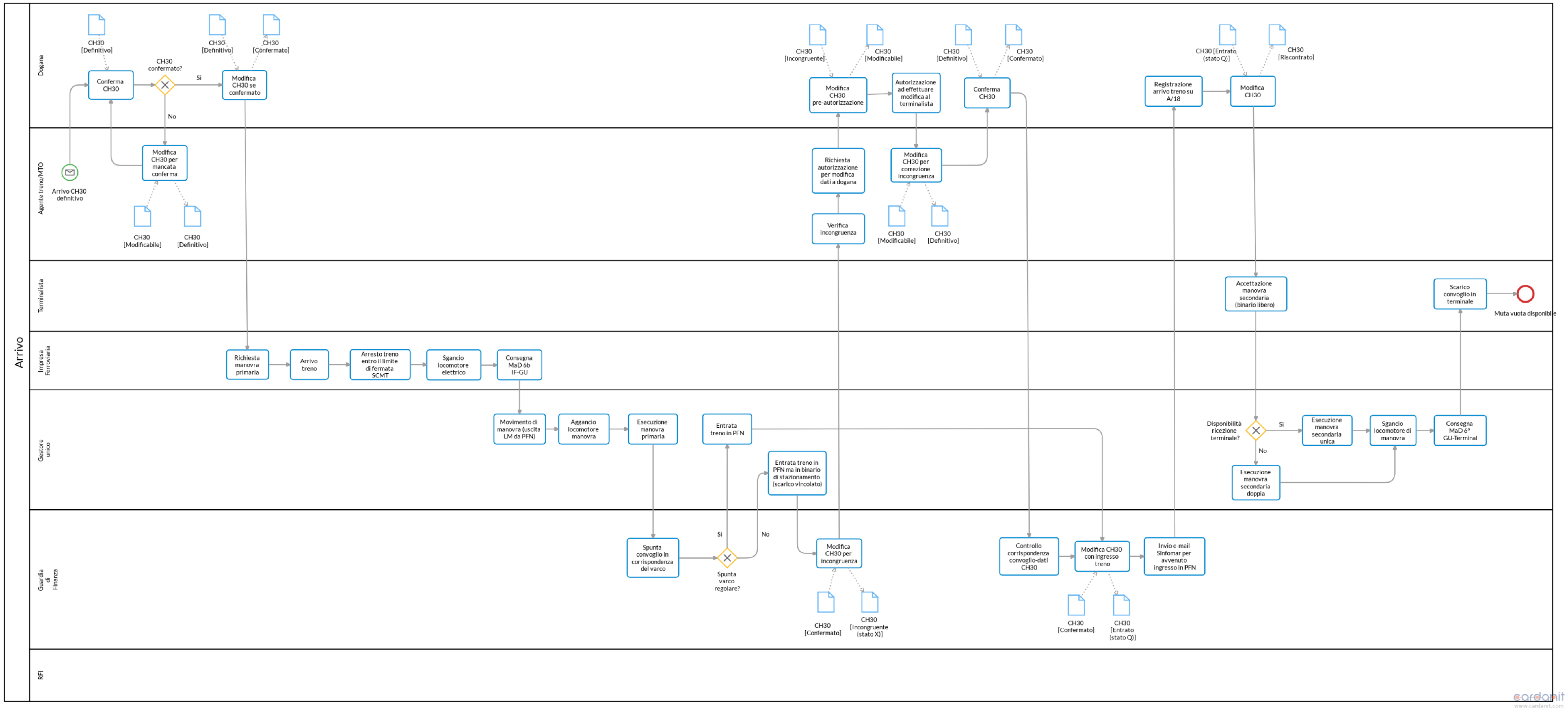

Figure 44 - BPMN descriptive model of the train arrival process

Annex B

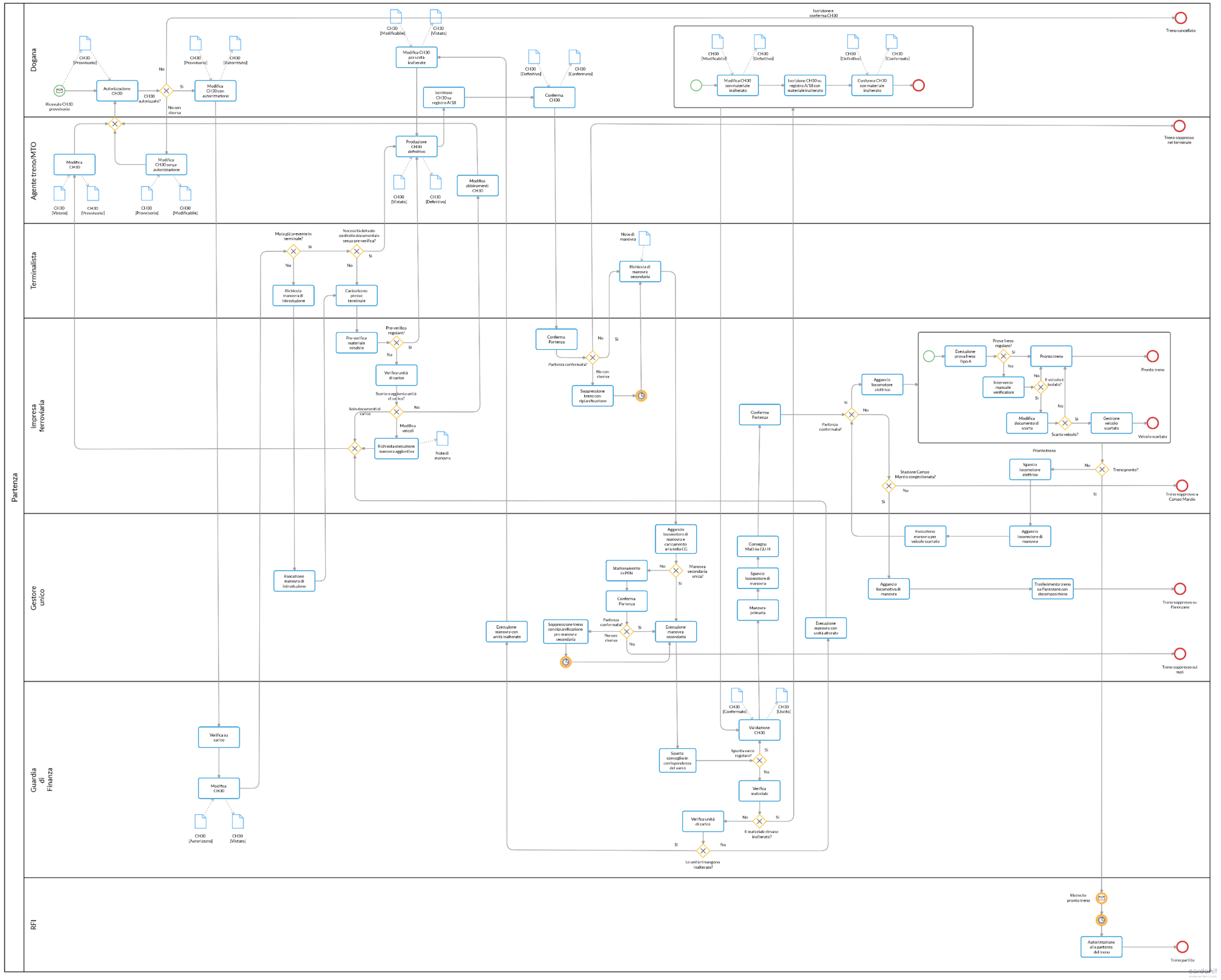

Figure 45 - BPMN descriptive model of the train departure process

Annex C

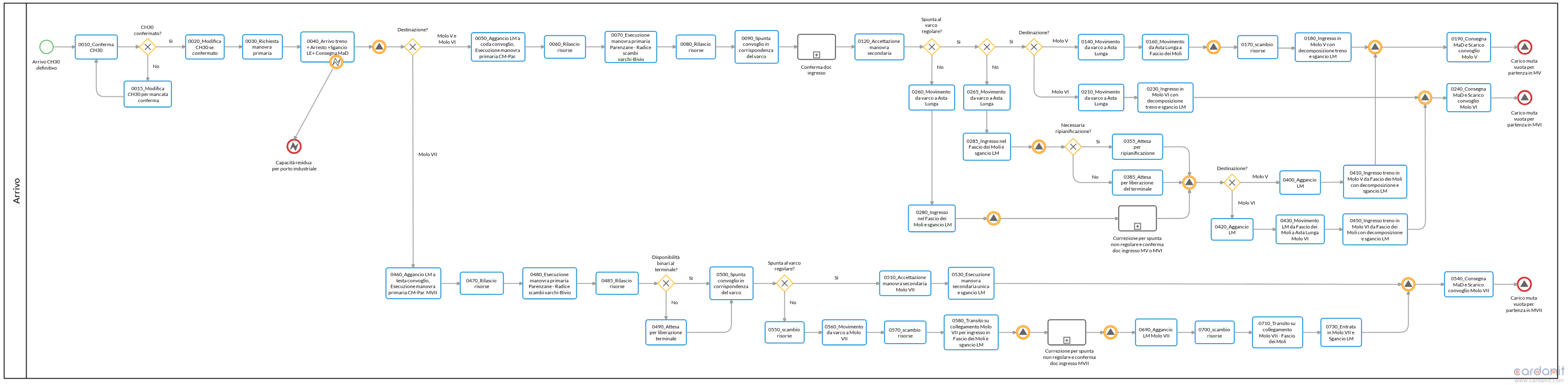

Figure 46 - BPMN simulation model of the train arrival process

Annex D

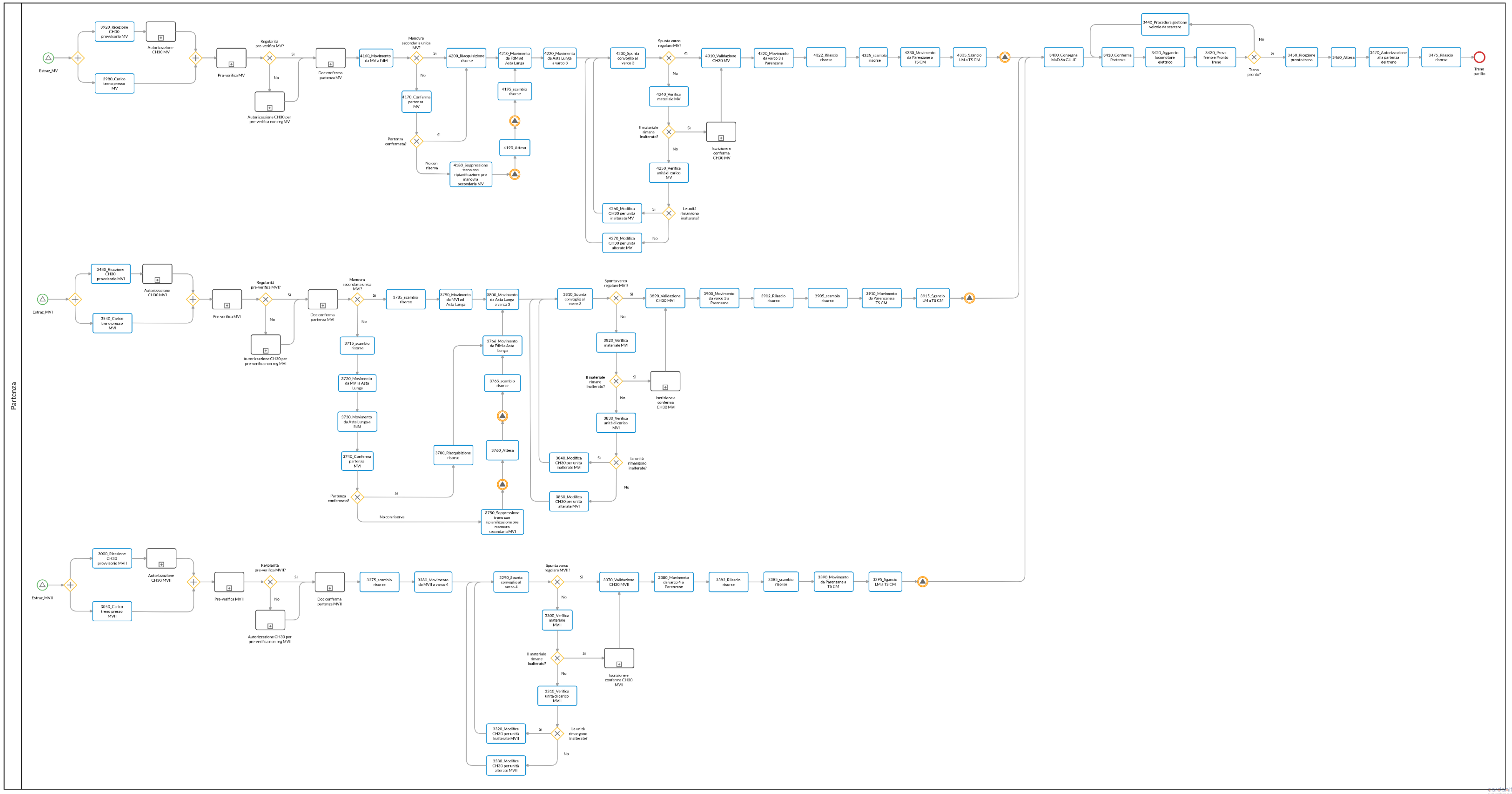

Figure 47 - BPMN simulation model of the train departure process

Annex E

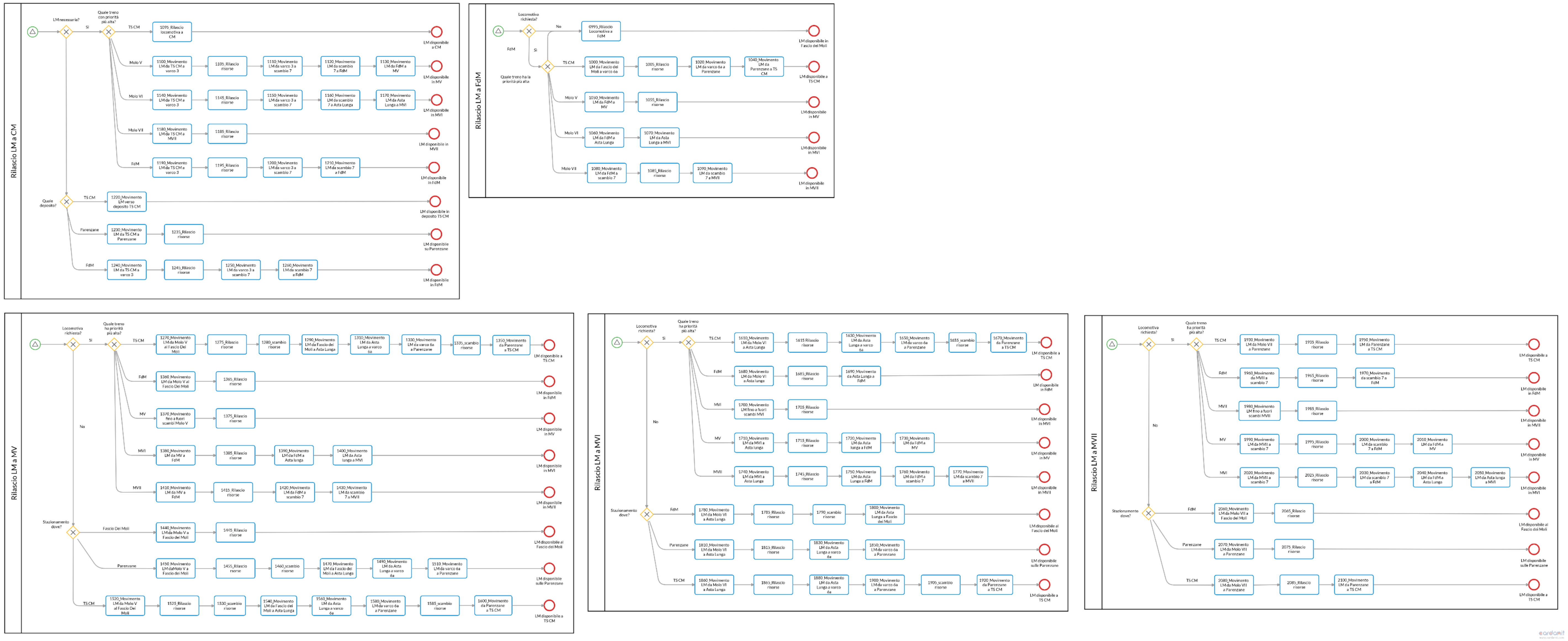

Figure 48 - BPMN simulation model of the shunting locomotive release processes

Annex F

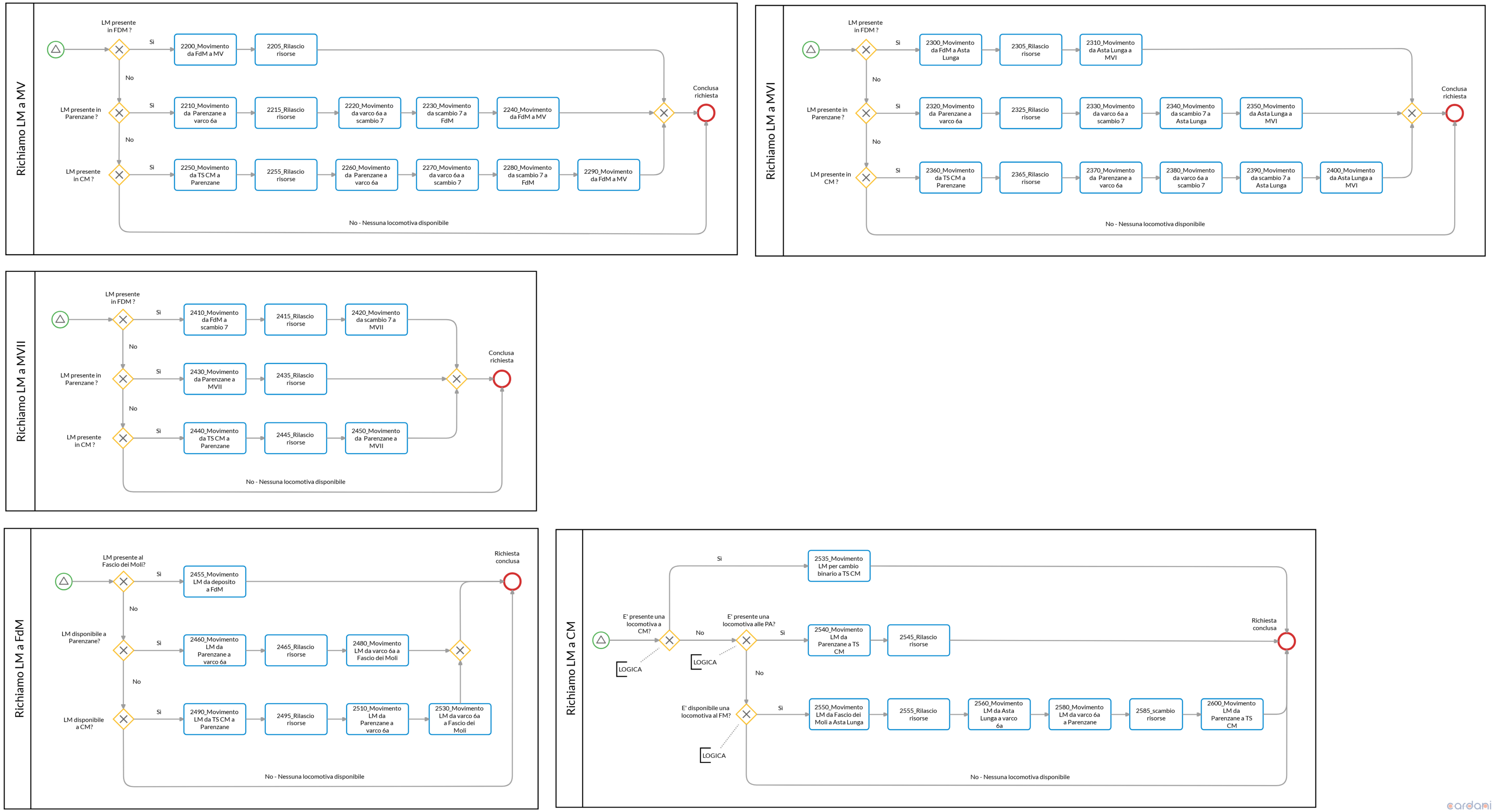

Figure 49 - BPMN simulation model of the shunting locomotive recall processes

Annex G

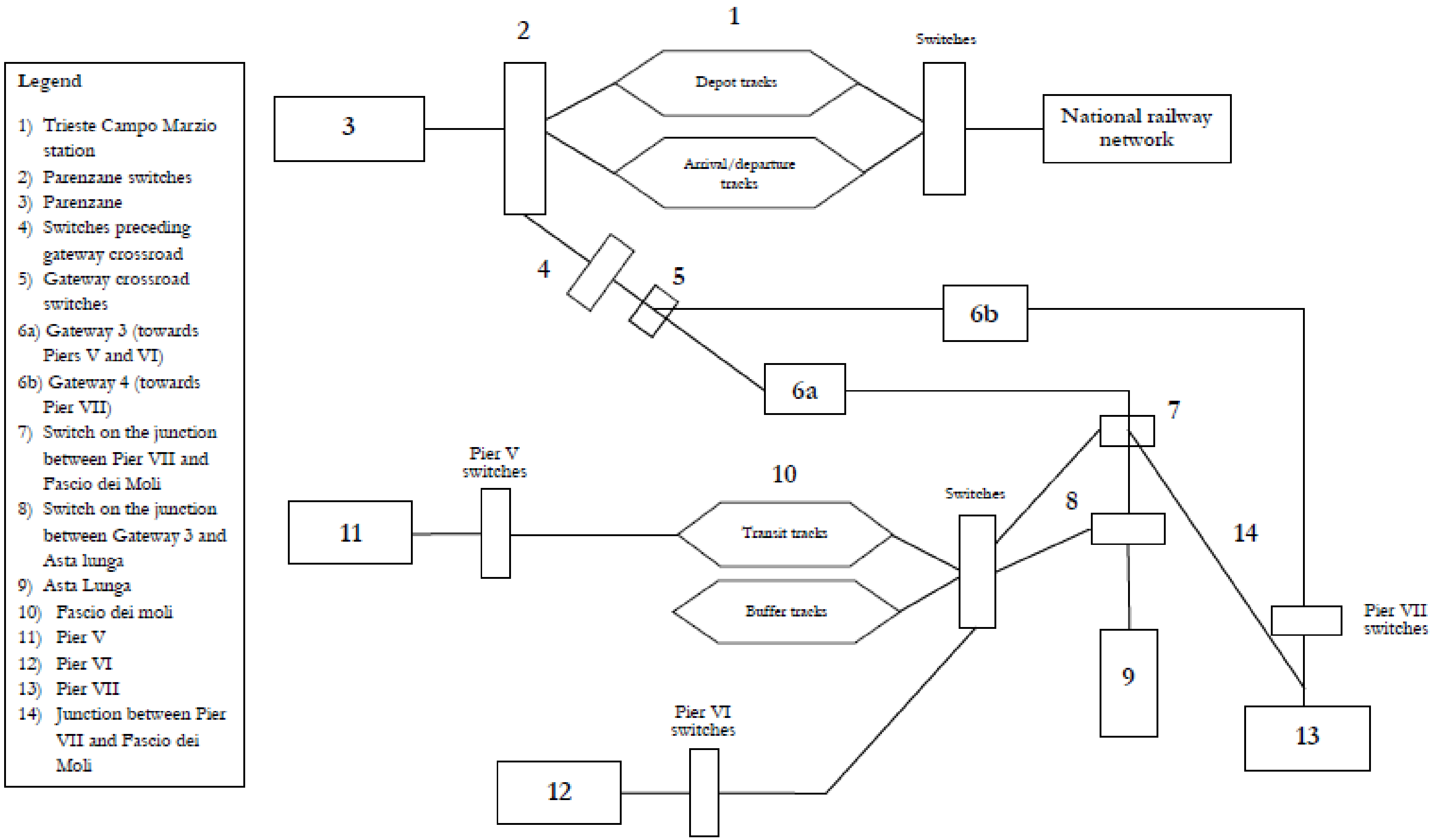

Figure 50 - Schematization of the port railway network

Annex H

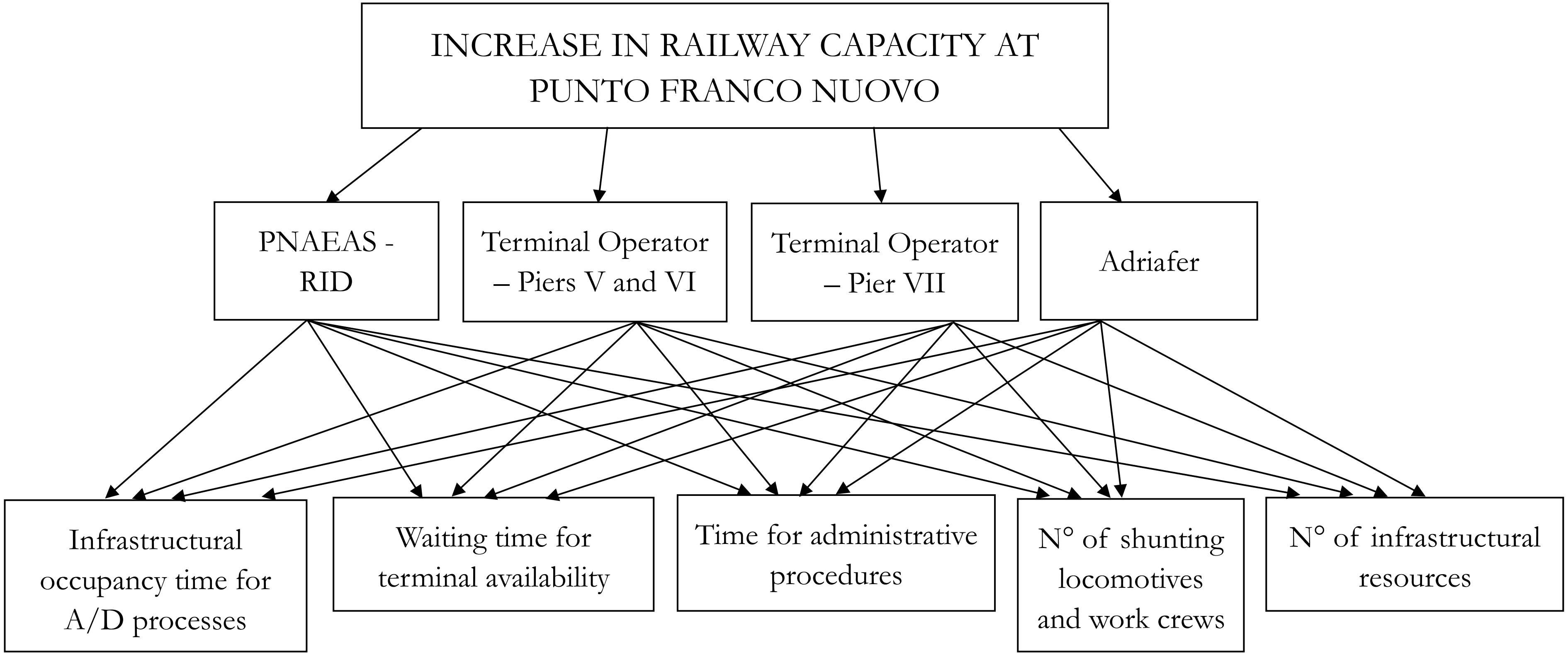

Figure 51 - Evaluation framework related to port railway operational features

Annex I

Rating scale:

- 1 if the two compared elements are of equal importance;
- 3 if an element is slightly more important than the other;
- 5 if an element is much more important than the other;
- 7 if an element is by far much more important than the other;
- 9 if an element is definitely much more important than the other;
- 2, 4, 6, 8 for intermediate values between two adjacent judgements.

COMPARISON BETWEEN ACTORS																		
Actor i	**Comparison**																	**Actor j**
PNAEAS - RID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Terminal Operator – Piers V and VI
PNAEAS - RID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Terminal Operator – Pier VII
PNAEAS - RID	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Adriafer
Terminal Operator – Piers V and VI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Terminal Operator – Pier VII
Terminal Operator – Pier V and VI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Adriafer
Terminal Operator – Pier VII	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Adriafer

COMPARISON BETWEEN CRITERIA																		
Criterion i	**Comparison**																	**Criterion j**
Infrastructural occupancy time for A/D processes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Waiting time for terminal availability
Infrastructural occupancy time for A/D processes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time for administrative procedures
Infrastructural occupancy time for A/D processes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	N° of shunting locomotives and work crews
Infrastructural occupancy time for A/D processes	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	N° of infrastructural resources
Waiting time for terminal availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time for administrative procedures

Waiting time for terminal availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	N° of shunting locomotives and work crews
Waiting time for terminal availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	N° of infrastructural resources
Time for administrative procedures	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	N° of shunting locomotives and work crews
Time for administrative procedures	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	N° of infrastructural resources
N° of shunting locomotives and work crews	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	N° of infrastructural resources

Annex J

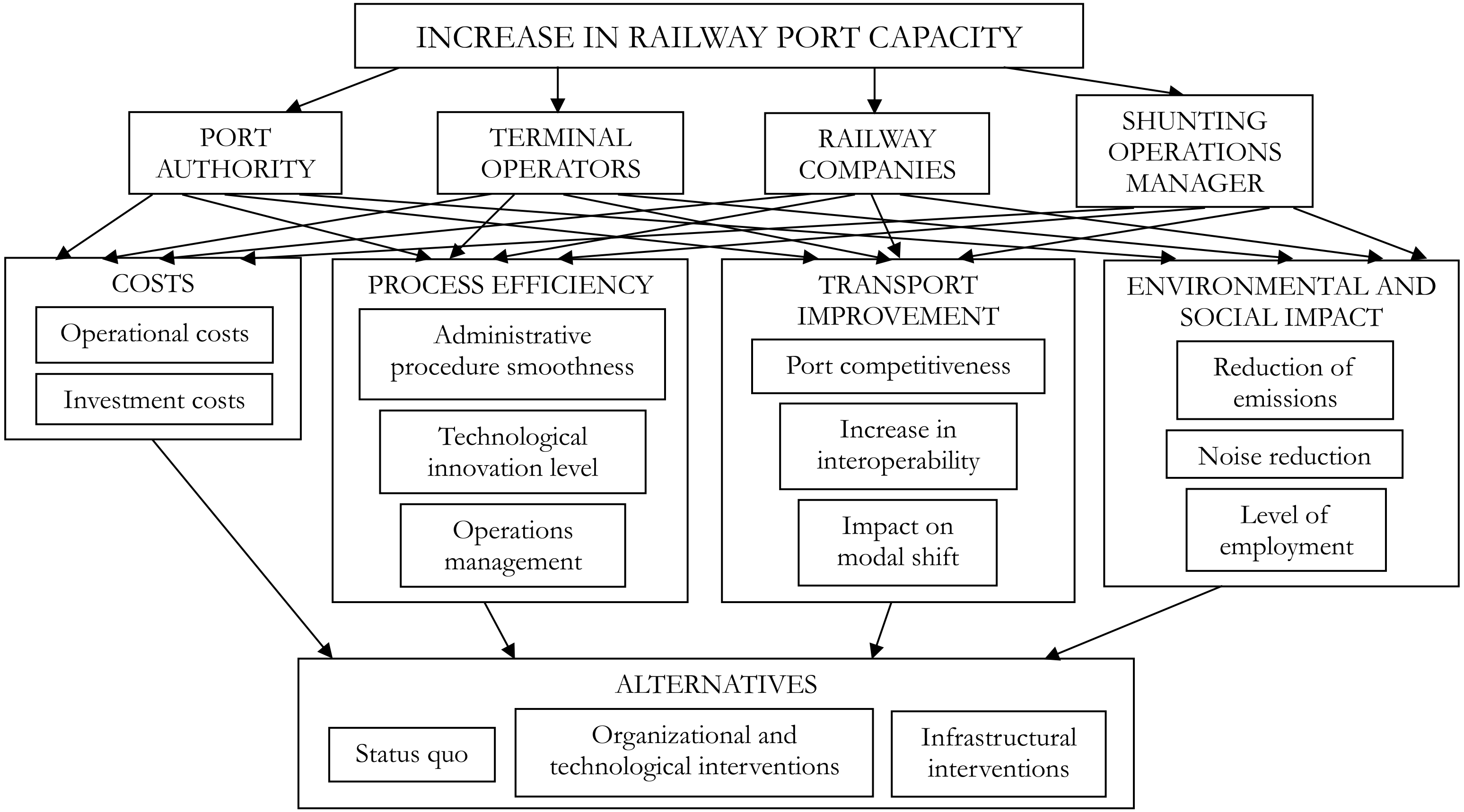

Figure 52 - Evaluation framework for the ranking of port scenarios of intervention

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