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DIGITAL DECISION-MAKING SUPPORT FOR RAILWAY NODE CAPACITY OPTIMIZATION: AN APPLICATION TO THE PORT OF TRIESTE

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Abstract

In a context of private operators competing for the same infrastructure, digitalisation is essential to support public entities in decision-making processes to ensure both fairness and efficiency when managing transport systems. This contribution presents the methods and instruments which have been integrated to face such task in the Port of Trieste, which is the first Italian port for throughput and rail movements. According to the proposed approach, railway transport processes have been first modelled through a standardized modelling language to facilitate the analysis of the operational model and the identification of possible bottlenecks. Then, graphical models have been parametrized to serve process simulation, which has been carried out by means of a discrete-event simulation engine. This latter has represented the black box of a multi-disciplinary optimization framework implementing genetic algorithms, which enabled to compute the optimal port railway capacity on varying of the destination sequence of arriving trains. Further optimization runs have been performed maximising also the capacity of the most potentially critical terminal in terms of traffic volumes, in order to evaluate the consequences on the productivity of the remaining terminals. Finally, obtained outcomes have been gathered into a database and visualized using a parallel coordinates plot, which displays the capacity of the entire port railway system and of every individual terminal as the numerical variables under investigation. Thanks to this resulting chart, authorities in the Port of Trieste now dispose of an effective digital tool to estimate changes in railway capacity at terminal and port level, and to assess the system responsiveness by comparing optimized values with expected trends. The successful application of the adopted methodology to a real-word case study demonstrates its validity and suggests its transferability to other freight transport and logistics issues and environments, fostering the use of digitalisation to make more informed decisions.

Keywords: intermodality, port railway capacity, digitalisation, multi-objective optimization, decision making

1 Introduction

As initially conceptualized by the United Nations Conference on Trade and Development [1], ports have evolved over time marking the definition of successive port generations which differ among each other in operational, spatial and societal aspects. Similarly, modifications in the role of port-related stakeholders have occurred during the decades, increasing the complexity of their inter-relations and, thus, of the whole transport system. Notably, at the internal firm level, the role of Port Authorities (PAs) has changed under the pressure of various actors, like market players (e.g., haulers, terminal and logistics operators), govern-

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ments and societal interest groups [2]. In general terms, PAs are the entities in charge of port governance and organization, and they are characterized by a hybrid nature mixing a public-oriented and a private-oriented logic. Although PAs have substantially moved away from operational activities and port service provision, they still hold a prominent position in guiding port developments [3].
This overview exactly reflects the situation which generated in Italy following the emanation of Law no. 84/1994, which prevented PAs from performing the operator function and let them assume only the landlord function [4]. Further regulations and amendments, including the Port reform of 2016, have then assigned PAs even more strategic competences in order to increase port competitiveness and sustainability [5]. As a consequence, such administrative framework constantly calls for PAs to find a balance between the political and the technocratic management approach, i.e., between distributional equity and efficiency at system level [6].
Nowadays, challenges connected to decision making in contexts with conflicting interests and goals can be faced using digital decision support systems. These latter are computerized solutions able to solve specific problems through the implementation of techniques which range from analytical methods to operations research algorithms, simulation models and multi-criteria evaluation methods. In practice, they represent technological platforms with the potential to assist port stakeholders in making informed decisions, especially for strategic planning [7].
With reference to the case study of the Port of Trieste, Italy, this paper deals with the development of an integrated methodology to optimize port railway capacity according to a holistic perspective. The ultimate goal of such methodology is to sustain the PA to efficiently manage future traffic flows and, at the same time, to guarantee fair operational conditions among competing private terminal operators. The modelling, simulation and optimization of transport processes have been performed thanks to the combination of different methods and instruments, which enabled, on one side, an in-depth analysis of possible bottlenecks and, on the other side, an estimation of the optimal port railway capacity for various scenarios. Lastly, the graphical visualization of results has allowed the PA to effectively gain insights on the implications of scenarios at both terminal and node level.
The article is structured as follows. The second section contains a literature review of previous scientific papers concerning port railway capacity optimization, whereas the third section explains the methodology developed in this paper. Then, the fourth section describes the application of the proposed methodology to the case study, and the fifth section discusses the obtained results. Finally, in the sixth section conclusions are drawn and future developments of the study are suggested.

2 Literature review

As anticipated, in this study the contribution provided by digital solutions to port stakeholders has been related to the digitalization of decision-making processes for strategic planning, rather than to the digitization of single port operations for their seamless execution. Although both digitalization and digitization share the common objective of increasing port efficiency and sustainability, they typically refer to different levels of detail. This premise serves the definition of the scope of the literature review reported in the followings, which has been performed concentrating the attention on applications aimed at optimizing port railway capacity. Previous investigations have focused on various aspects of sea-rail intermodality which can be grouped into two main categories:
- On one hand, the management of port-related train traffic on the railway network outside the port, i.e., on the national railway network;
- On the other hand, terminal operations involving the railway mode.

More specifically, as regard the first category, existing articles have addressed scheduling problems caused by the competing use of shared railway corridors considering, for example, the interaction of freight traffic with traditional passenger services in light of the high-speed railway expansion [8]. Analogously, the authors of [9] have examined the use of dispatching delays so as to prevent the generation of disturbances on regular train paths due to the shuttle train services for dry ports.
On the contrary, with respect to the second category, further research studies deal with optimization approaches to efficiently integrate sea-rail terminal operations, such as loading and unloading activities. For instance, this task has been faced at analytical level in [10], where the authors accomplished to maximize the train traffic volume while reducing the involved costs. A similar investigation on the optimization of port railway transportation has been performed at a qualitative level in [11], which provides an analysis of the problems characterizing the port-railway collection and distribution system, along with recommendations on possible solutions.
Bearing in mind the scope of the methodology suggested in this study, which means the railway network within the port boundaries, the authors of [12] propose an approach to evaluate the capacity of port rail networks by optimally sizing infrastructural resources and planning shunting operations. Rail transport in a port system has been examined also in [13] to assess potential growths of container flows based on different scenarios of intervention. Nevertheless, the evaluation of traffic volumes in [13] has been performed only using a what-if simulation approach, without encompassing any optimization procedure. Moreover, the modelling of railway operations has been limited mostly to train loading and unloading activities at the terminal.
At methodological level, the articles mentioned above mainly adopt operations research models and optimization algorithms, e.g., genetic algorithms, in order to solve tactical or operational problems.
Given the scarcity of available papers specifically dedicated to optimize railway capacity in port networks, the study presented in this article is meant to expand the knowledge about that topic suggesting an integrated methodology to sustain strategic planning. Indeed, unlike previous contributions which focus mainly on scheduling or network sizing problems, the proposed study examines capacity allocation at terminal and node level by varying the destination of arriving trains, so as to appraise the efficiency of the operations model on a certain infrastructural layout.

3 Methodology

The methodology presented in this paper consists in an evolution of the methodology illustrated in [14], and although the improvements were mainly motivated by the different scope of the considered case study, they turned out to be beneficial even on a more conceptual level. Anyway, as anticipated, the proposed methodology considers the combination of methods and instruments to model, simulate and optimize railway processes, with the aim of estimating the optimal port railway capacity under varying operational conditions. Indeed, in this study the optimization procedure aims at analysis the efficiency of the operations model given a certain infrastructural layout, rather than sizing the railway network for the optimal capacity.
Regarding the modelling of processes, unlike the previous contribution, only transport processes have been graphically modelled in this study, while the related administrative processes have been overlooked since they proved not to be so influential for the identification of bottlenecks. To this end, the Business Process Modelling and Notation (BPMN) standard [15] has been used to display processes related to both trains and shunting locomotives. The readability of process models has been enhanced assigning a different color to the various

kinds of activities (tasks) represented in the model, which permitted to intuitively recognize activity patterns and, thus, to better understand the examined transport phenomena. These tasks have been defined according to the infrastructural resources involved by the actual port railway operations model, with reference to a specific configuration of the network. The BPMN standard had been already adopted in [16] to model port operations as a starting point to evaluate potential rail port capacity increases.
The BPMN graphical elements have been then converted into the corresponding XML elements, which served the successive phases of process parametrization and simulation. Indeed, parametrization has been carried out quantifying some of the main aspects characterizing the developed model, like the duration of tasks and of the simulation scenario, the entity of infrastructural resources, and the potential residual capacity of the national railway network, although without suggesting any timetable. Other than that, the logic underlying process decision points (gateways), such as the probability of occurrence of specific events, have been set based on the process flows they were referred to. With respect to process simulation, a discrete-event simulation approach has been adopted and a 2-day warm-up time has been imposed to analyze more stable results as related to a fully operational system. The generation of trains in the model has been managed by combining possible variations in the residual capacity on the national network and in the destination of arriving trains among the port terminals. In its turn, this latter has been obtained integrating the distribution of trains among the terminals with the actual availability of infrastructural resources at a certain simulation instant. Stochasticity has been introduced in the model by performing multiple replications of each simulation run.
Successively, process optimization has been carried out by means of a multi-disciplinary optimization framework which computes output variables according to input variables using the “black box” concept for the integration with external tools, like, for example, the simulation engine. Both the single-optimization and the multi-objective optimization procedures have been carried out using a genetic algorithm, namely the MOGA-II algorithm [17], with the goal of exclusively or jointly maximizing railway capacity at node and terminal level on varying of the destination sequence of arriving trains. As a matter of fact, the optimization framework has served also the definition of the probability percentages of train destinations which fed the simulation runs. Besides, a constrain of minimum operability of each terminal has been optionally imposed to evaluate various scenarios.
Finally, all optimization results have been collected into a single database and they have been visualized through a parallel coordinates plot using an intuitive interface, which provides the optimal node capacity by filtering the capacity of each terminal.

4 Case study

The methodology suggested in this paper has been applied to the case study of the Port of Trieste, which is the first Italian port for both throughput and rail traffic. More in detail, as compared to [14], the application has covered a wider area of the port including not only the main railway station, but also a further station which will be involved by future increasing traffic flows. Therefore, a total of nine terminals have been taken into account to define train destinations, based on the specific operations model and the resource availability indicated by the PA. Regarding the infrastructural resources, some shunting trucks between the terminals and the railway station are present, but just one line connects the whole node to the national railway network. Hence, there is, and there will be, a quite high competition among private terminal operators in the use of shared resources, which the PA, in light of its hybrid nature, needs to manage guaranteeing both equity and system efficiency.

As mentioned in Section 3, according to the developed BPMN model, train movements have been simulated without imposing any timetable, but respecting the scheduled traffic interruptions and the potential residual capacity of each hourly interval throughout the day. Furthermore, the transfers of released shunting locomotives have been explicitly modelled in order to consider the actual occupation of infrastructural resources. The single-optimization and the multi-objective optimization procedures have been carried out maximizing the following variables: on one hand, the port railway capacity and, on the other hand, the railway capacity of the most critical terminal in terms of traffic volumes, in order to evaluate the consequences on the productivity of the remaining terminals. Due to the several replications of every simulation run during the optimization algorithm evolution, 18000 designs have been evaluated, which required a computational time equal to 225 hours.

5 Results and discussion

Results obtained from the different optimization procedures have been analyzed through parallel coordinate plots with respect not only to the railway capacity at node and terminal level, but also to the numerosity of feasible solutions. Referring to Fig. 1 and Fig. 2, each axis of the parallel coordinate plots indicates the railway capacity of the entire node of the Port of Trieste and of the nine considered terminals, whose values can be filtered by varying the size of the gray bar reported on top of them. According to the analyzed scenario, the highlighted green lines display the feasible solutions among all the obtained optimal solutions, which lie in the background. For instance, Fig. 1 shows that considering the highest capacity values for the most critical terminal implies a limitation in the node capacity in a range between 18000 and 20000 trains per year, with just few corresponding feasible solutions. On the contrary, Fig. 2 shows that a reduction in the capacity of the most critical terminal is beneficial to an increase in both node capacity, which ranges between 20000 and 22000 trains per year, and in the number of possible optimal solutions. These two examples clearly underline the influence of terminal capacity on the performance of the whole port system due to the common use of infrastructural resources, supporting the PA in decision-making processes concerning the operations model. Indeed, the strategic and holistic perspective which led the development of the proposed methodology definitely enables to sustain the PA in balancing the competing interests of private terminal operators and its responsibility to ensure equity in resource management and port competitiveness. Of course, using such interface, further traffic configurations at terminal level can be examined in a very intuitive way, gaining insights about the respective in implications on node capacity.

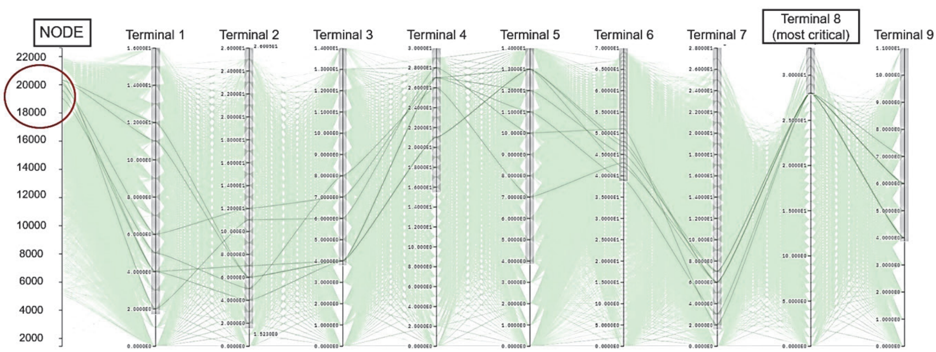

Figure 1 Solutions for greater capacity values related to the most critical terminal

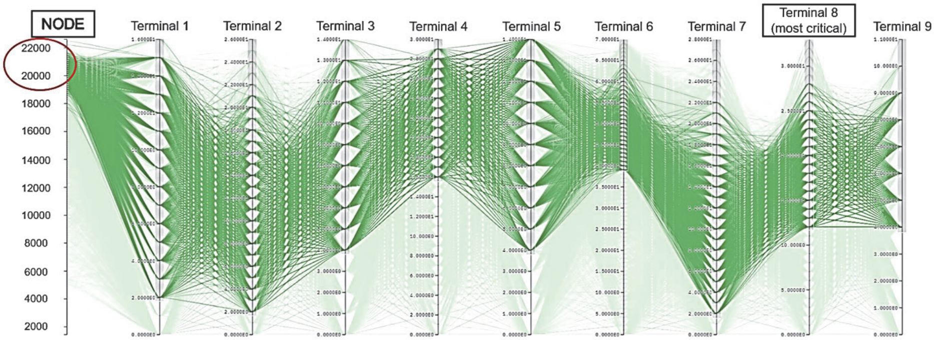

Figure 2 Solutions for lower capacity values related to the most critical terminal

6 Conclusions

In conclusion, the study reported in this paper illustrates the great support provided by digitalization in assisting PAs in decision-making processes concerning port railway capacity management, in light of limited shared infrastructural resources and, at the same time, of competing interests among private terminal operators. Indeed, given a certain port network configuration, the developed methodology integrating process modelling, simulation and optimization has enabled to investigate the implications of the considered operations model on node capacity according to a strategic perspective. The validity of the methodology has been tested through its application to the case study of the Port of Trieste, revealing the significant influence of the distribution and destination sequence of arriving trains on port capacity. Furthermore, the adoption of a graphic interface has enabled to intuitively analyse results, especially in terms of the effects of variations in the capacity of the most critical terminal on the capacity of the whole system.
The outcomes of this study can be also used to compare optimal capacity values with future traffic trends and, thus, to evaluate the compliance of results with economic projections. Other than that, each obtained solution can represent the proposal for a potential train timetable.
Finally, future developments of the study consist in using digitalisation to perform real measurements of task duration and distribution, since at the moment only average values have been considered, and in transferring the methodology to other case studies.

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