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A planning approach for sizing the capacity of a port rail system: scenario analysis applied to La Spezia port network

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Abstract: This paper presents an optimization approach for sizing the capacity of port rail networks, in terms of maximum number of trains that can be managed over a certain time horizon. The proposed optimization method is based on a discrete-time model of the overall system in order to represent the shunting operations in the port rail network. The resulting MILP optimization problem has been applied to a real case study referred to the port rail network of La Spezia Container Terminal, in Northern Italy. What-if analyses have been carried out to test the system potentiality by varying some parameters, i.e. the terminal equipment productivity, the number of locomotives and the time to perform some technical operations.

1. INTRODUCTION

Rail freight transport is recognized to be a sustainable mode, both for pollution and for congestion [1]. However, this transport mode is characterized by a higher number of constraints compared to road transport, so requiring a very efficient planning to be competitive. In particular, it is quite important to develop rail transport in seaport container terminals, which represent crucial nodes in worldwide logistic networks [2, 3].

The present paper provides an optimization approach for properly sizing the capacity of a port rail network, in terms of maximum number of trains that can be managed over a certain time horizon. In the literature, different approaches have been developed for sizing railway networks, some of which are based on optimization techniques, such as [4]. Simulation approaches have also been used for studying railway networks, as for instance in [5] adopting a mesoscopic model, and in [6] using the framework of Petri Nets.

In order to model the import and export flows in a port rail network, in this paper a dynamic model is adopted to represent the movement of rail cars in the system; the system dynamics is given by discrete-time conservation equations. Such model takes inspiration from [7], where a simpler approach was proposed for optimizing the timing of only import trains. Similar aggregate queue-based discrete-time models for container terminals have been used in [8] and [9], where different systems are planned with different objectives. In the literature, other aggregate models for container terminals have been proposed, based on discrete-event simulation or Petri Nets, as for example in [10, 11, 12].

The planning approach described in this paper is a tool to take decisions on rail operations, in terms of sequence and timing of all the shunting operations that have to be performed for satisfying arrivals and departures of import and export flows. At the same time, the proposed planning procedure allows to evaluate the capacity of a port rail system (in terms of maximum number of trains that can be correctly managed over a specific time horizon) and to carry out what-if analyses, where different scenarios can be tested. This latter purpose is specifically pursued in the present work, where some what-if analyses are done in order to evaluate the capacity of the overall system by varying specific system parameters, i.e. the productivity of the terminal equipment, the number of locomotives serving the different areas of the system and the time needed to perform some technical operations inside the network. The same port rail network is studied also in [13], where the main focus is on planning shunting operations and evaluating the system capacity.

The paper is organized as follows. In Section 2 the considered problem is described; in Section 3 the discrete-time dynamic model of the port rail network is provided, together with the formulation of the planning problem. The results of some scenario analyses based on a real case study of an important Italian port are discussed in Section 4. Finally, in Section 5 some conclusions are presented.

2. PROBLEM DESCRIPTION

The model presented in this work takes into consideration both the import and export flows in a port rail network, which is sketched in Fig. 1. The import flow is modeled starting from the movement of containers, by means of the terminal equipment, from the yard area to the rail tracks in the internal rail park, located inside the port terminal. Here, once containers are loaded on rail cars, shunting operations by diesel locomotives are performed to move trains to one of the railway stations located outside the terminal. We refer to "internal" stations if they are not directly connected with the electrified rail lines and to "external" stations in the opposite case. If the scheduled departure is not close in time or there is a high level of occupation of rail tracks inside the stations, trains can be

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moved by diesel locomotives to storage parks where they wait until their departure. The export flow is opposite to the import one and represents the movement of freight trains from the hinterland to the seaport terminal.

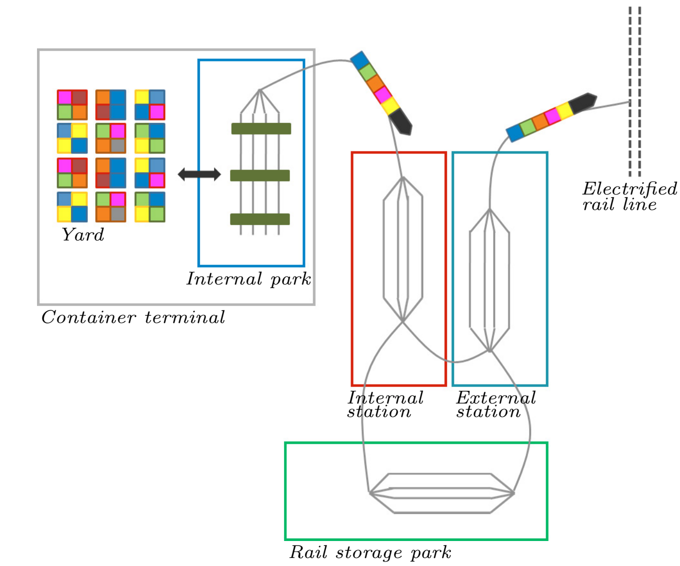

Fig. 1. The port rail network.

Some delays affect the import and export cycles, regarding both physical and documentary aspects. Delays associated with shunting operations and technical checks (i.e. to test the correct weight patterns of rail cars and the train braking system) are considered, as well as the time needed for the emission of legal documents to allow trains departures. Moreover, the model adopted in this paper considers the dynamic evolution of rail cars, distinguished in different typologies, and the operations of composition/decompostion of trains (note that these operations are required in case the length of a full train is greater than the length of tracks in a rail park). The number of available tracks in rail parks, the number of connecting tracks, the allowable length of each track, the limited number of diesel locomotives and the maximum productivity of the handling equipment represent the main constraints that have been taken into account in this problem, as described in detail in Section 3.

3. MATHEMATICAL FORMULATION

In the proposed model, the dynamic evolution of buffers, representing the positions of rail cars inside the port rail network, is described by discrete-time equations with sample time equal to Δt. In the paper, if a given variable z refers to the import flow, the corresponding variable associated with the export flow is denoted with $\bar{z}$.

Let us start from the network structure and the problem parameters. The port rail network is described through a graph, in which the nodes can be gathered in set $\mathcal{N} \cup \{0\}$, where $\mathcal{N}$ is the set of railway parks or stations, whereas 0 is a source node, representing the yard area where both import and export containers are stored (containers are properly converted into rail cars since the model dynamics is referred to flows of rail cars in the network). The set $\mathcal{N}$ can be subdivided into four disjoint sets, i.e. $\mathcal{N} = \mathcal{N}^{\mathrm{T}} \cup \mathcal{N}^{\mathrm{S}} \cup \mathcal{N}^{\mathrm{IS}} \cup \mathcal{N}^{\mathrm{ES}}$. $\mathcal{N}^{\mathrm{T}}$ is the set of internal railway parks devoted to rail cars loading/unloading; $\mathcal{N}^{\mathrm{S}}$ represents the storage parks where trains or groups of rail cars wait before being moved to other nodes; $\mathcal{N}^{\mathrm{IS}}$ is the set of internal stations; $\mathcal{N}^{\mathrm{ES}}$ is the set of external stations where trains arrive/leave by electrified line.

Let $\mathcal{S}_n^{\mathrm{I}}$ and $\mathcal{S}_n^{\mathrm{E}}$ indicate the set of successor nodes of node n, in import and in export respectively; analogously, $\mathcal{P}_n^{\mathrm{I}}$ and $\mathcal{P}_n^{\mathrm{E}}$ indicate the set of import and export predecessor nodes of node n. It holds that $\mathcal{S}_n^{\mathrm{I}} = \mathcal{P}_n^{\mathrm{E}}$, $\mathcal{P}_n^{\mathrm{I}} = \mathcal{S}_n^{\mathrm{E}}$, $\forall n \in \mathcal{N}$. Each node $n \in \mathcal{N}$ is modelled as a physical resource composed of a certain number of rail tracks: $\mathcal{R}_n$ indicates the set of tracks in node n and $R_{n,m}$ is the number of tracks connecting node n with node m in the network. These connecting tracks are shared by import and export flows, so $R_{n,m} = R_{m,n}$, $\forall n, m \in \mathcal{N}$. $L_{n,i}$ indicates the length of track $i \in \mathcal{R}_n$ of node n, whereas $\mathcal{R}_n^{\mathrm{L}} \subseteq \mathcal{R}_n$ and $\mathcal{R}_n^{\mathrm{S}} \subseteq \mathcal{R}_n$ indicate the set of long and short tracks of node $n \in \mathcal{N}$, that can host a whole train or a group of rail cars respectively. Q' and Q'' represent the number of rail cars composing an entire train or a group of rail cars, respectively $(Q'' < Q')$.

The rail cars in the network can be of different types and can belong to different railway companies. C indicates the number of railway companies and $\mathcal{W}$ is the set of rail car types. The set $\mathcal{W}$ is partitioned into subsets according to the railway company, i.e. $\mathcal{W} = \mathcal{W}_1 \cup \mathcal{W}_2 \ldots \cup \mathcal{W}_C$. l^w denotes the length of car type w. Diesel locomotives are shared in a certain number of areas H, i.e. in sets of nodes of the considered network. Λ_h is the number of locomotives available in area h, whilst $\mathcal{N}_h \subseteq \mathcal{N}$, $h = 1, \ldots, H$, indicates the set of nodes of area h served by the Λ_h locomotives. The productivity of the handling means moving the rail cars from the yard area to the internal park and vice versa is denoted with Γ_n, $n \in \mathcal{N}^{\mathrm{T}}$. Delays are supposed to be multiple of the sample time Δt and can be of three types: $\tau_{n,m}$, $n, m \in \mathcal{N}$, is the time required to cross the tracks between node n and node m, δ represents the time required to realize shunting operations in storage parks, γ^w is the time required for technical checks and documentary practices on rail cars of type w, $w \in \mathcal{W}$.

In node 0 import rail cars arrive and export rail cars leave: quantities $a_0^w(t)$ and $\bar{d}_0^w(t)$, $w \in \mathcal{W}$, $t = 0, \ldots, T-1$, indicate the number of rail cars of type w arrived and left at time t, respectively. Analogously, in the external stations, arrivals of export containers and departures of import containers occur, i.e. $d_{n,i}^w(t)$ and $\bar{a}_{n,i}^w(t)$, $w \in \mathcal{W}$, $n \in \mathcal{N}^{\mathrm{ES}}$, $i \in \mathcal{R}_n$, $t = 0, \ldots, T-1$.

The problem variables are given by the state variables and the decision variables, listed in the following. The state variables are the number of rail cars, in import and in export respectively, of type w present in track i of node n at time t, denoted with $q_{n,i}^w(t)$ and $\bar{q}_{n,i}^w(t)$, $w \in \mathcal{W}$, $n \in \mathcal{N}$, $i \in \mathcal{R}_n$, $t = 0, \ldots, T$. Analogously, referring to the source node, $q_0^w(t)$ and $\bar{q}_0^w(t)$, $w \in \mathcal{W}$, $t = 0, \ldots, T$ indicate respectively the number of import and export rail cars of type w present at time t.

Inside the network, the movements of trains (composed of Q' rail cars) from a node to another one, in the import flow, are represented with a set of binary decision variables, i.e. $y_{n,i,m,j}^c(t)$, $n \in \mathcal{N}$, $i \in \mathcal{R}_n^{\mathrm{L}}$, $m \in \mathcal{S}_n^{\mathrm{I}}$, $j \in \mathcal{R}_m$, $c = 1, \ldots, C$,

$t = 0, \ldots, T-1$. Specifically, $y^c_{n,i,m,j}(t) = 1$ means that, at time t, an import train belonging to railway company c leaves track i of node n, being directed to track j of node m. In the same way, the binary variable $\bar{y}^c_{n,i,m,j}(t)$, $n \in \mathcal{N}$, $i \in \mathcal{R}^{\mathrm{L}}_n$, $m \in \mathcal{S}^{\mathrm{E}}_n$, $j \in \mathcal{R}_m$, $c = 1, \ldots, C$, $t = 0, \ldots, T-1$, models the shift of trains in the export cycle. Analogously, binary decision variables $x^c_{n,i,m,j}(t) = 1$, $n \in \mathcal{N}$, $i \in \mathcal{R}_n$, $m \in \mathcal{S}^{\mathrm{I}}_n$, $j \in \mathcal{R}_m$, $c = 1, \ldots, C$, $t = 0, \ldots, T-1$, indicate that, at time t, a group of rail cars of railway company c is moved from track i of node n to track j of node m. For the export flow binary variables $\bar{x}^c_{n,i,m,j}(t)$, $n \in \mathcal{N}$, $i \in \mathcal{R}_n$, $m \in \mathcal{S}^{\mathrm{E}}_n$, $j \in \mathcal{R}_m$, $c = 1, \ldots, C$, $t = 0, \ldots, T-1$, are defined.

Other decision variables associate each movement of trains or groups of rail cars with the corresponding number of rail cars actually moved. So, two sets of continuous decision variables are defined, for the import and export flow respectively: $r^w_{n,i,m,j}(t)$, $w \in \mathcal{W}$, $n \in \mathcal{N}$, $i \in \mathcal{R}_n$, $m \in \mathcal{S}^{\mathrm{I}}_n$, $i \in \mathcal{R}_m$, $t = 0, \ldots, T-1$, represent the number of rail cars of type w that, at time t, leaves track i of node n, being directed to track j of node m. Analogously, $\bar{r}^w_{n,i,m,j}(t)$, $w \in \mathcal{W}$, $n \in \mathcal{N}$, $i \in \mathcal{R}_n$, $m \in \mathcal{S}^{\mathrm{E}}_n$, $i \in \mathcal{R}_m$, $t = 0, \ldots, T-1$, is defined for the export flow. Similar variables are introduced for the connection with node 0, i.e. $r^w_{0,m,j}(t)$, $w \in \mathcal{W}$, $m \in \mathcal{S}^{\mathrm{I}}_0$, $j \in \mathcal{R}_m$, $t = 0, \ldots, T-1$, representing the number of rail cars of type w that, at time t, leave the yard stacking area to go to track j of node m. Similarly, $\bar{r}^w_{n,i,0}(t)$, $w \in \mathcal{W}$, $n \in \mathcal{P}^{\mathrm{E}}_0$, $i \in \mathcal{R}_n$, $t = 0, \ldots, T-1$, have the same meaning for the export flow.

The proposed planning problem allows to find the optimal sequence and timing of the shunting operations in the considered port rail network and can be stated with the following mixed-integer linear programming (MILP) formulation:

$$\sum_{t=1}^{T} \sum_{w \in \mathcal{W}} \Big[\sum_{n \in \mathcal{N}} \sum_{i \in \mathcal{R}_n} \alpha^w_{n,i} q^w_{n,i}(t) + \bar{\alpha}^w_{n,i} \bar{q}^w_{n,i}(t) + \alpha^w_0 q^w_0(t) + \bar{\alpha}^w_0 \bar{q}^w_0(t) \Big] + \sum_{c=1}^{C} \sum_{t=0}^{T-1} \sum_{n \in \mathcal{N}} \sum_{i \in \mathcal{R}_n} \Big[\sum_{m \in \mathcal{S}^{\mathrm{I}}_n} \sum_{j \in \mathcal{R}_m} \beta^c_{n,i,m,j} y^c_{n,i,m,j}(t) + \zeta^c_{n,i,m,j} x^c_{n,i,m,j}(t) + \sum_{m \in \mathcal{S}^{\mathrm{E}}_n} \sum_{j \in \mathcal{R}_m} \bar{\beta}^c_{n,i,m,j} \bar{y}^c_{n,i,m,j}(t) + \bar{\zeta}^c_{n,i,m,j} \bar{x}^c_{n,i,m,j}(t) \Big] \quad (1)$$

subject to

$$q^w_0(t+1) = q^w_0(t) + a^w_0(t) - \sum_{m \in \mathcal{S}^{\mathrm{I}}_0} \sum_{j \in \mathcal{R}_m} r^w_{0,m,j}(t) \qquad w \in \mathcal{W},\ t = 0, \ldots, T-1 \quad (2)$$

$$\bar{q}^w_0(t+1) = \bar{q}^w_0(t) + \sum_{n \in \mathcal{P}^{\mathrm{E}}_0} \sum_{i \in \mathcal{R}_m} \bar{r}^w_{n,i,0}(t) - \bar{d}^w_0(t) \qquad w \in \mathcal{W},\ t = 0, \ldots, T-1 \quad (3)$$

$$q^w_{n,i}(t+1) = q^w_{n,i}(t) + r^w_{0,n,i}(t) - \sum_{m \in \mathcal{S}^{\mathrm{I}}_n} \sum_{j \in \mathcal{R}_m} r^w_{n,i,m,j}(t) \qquad n \in \mathcal{N}^{\mathrm{T}},\ i \in \mathcal{R}_n,\ w \in \mathcal{W},\ t = 0, \ldots, T-1 \quad (4)$$

$$\bar{q}^w_{n,i}(t+1) = \bar{q}^w_{n,i}(t) + \sum_{m \in \mathcal{P}^{\mathrm{E}}_n : \tau_{m,n} \le t} \sum_{j \in \mathcal{R}_m} \bar{r}^w_{m,j,n,i}(t - \tau_{m,n}) - \bar{r}^w_{n,i,0}(t) \qquad n \in \mathcal{N}^{\mathrm{T}},\ i \in \mathcal{R}_n,\ w \in \mathcal{W},\ t = 0, \ldots, T-1 \quad (5)$$

$$q^w_{n,i}(t+1) = q^w_{n,i}(t) + \sum_{m \in \mathcal{P}^{\mathrm{I}}_n : \tau_{m,n} \le t} \sum_{j \in \mathcal{R}_m} r^w_{m,j,n,i}(t - \tau_{m,n}) - \sum_{m \in \mathcal{S}^{\mathrm{I}}_n} \sum_{j \in \mathcal{R}_m} r^w_{n,i,m,j}(t) \qquad n \in \mathcal{N}^{\mathrm{S}},\ i \in \mathcal{R}_n,\ w \in \mathcal{W},\ t = 0, \ldots, T-1 \quad (6)$$

$$\bar{q}^w_{n,i}(t+1) = \bar{q}^w_{n,i}(t) + \sum_{m \in \mathcal{P}^{\mathrm{E}}_n : \tau_{m,n} \le t} \sum_{j \in \mathcal{R}_m} \bar{r}^w_{m,j,n,i}(t - \tau_{m,n}) - \sum_{m \in \mathcal{S}^{\mathrm{E}}_n} \sum_{j \in \mathcal{R}_m} \bar{r}^w_{n,i,m,j}(t) \qquad n \in \mathcal{N}^{\mathrm{S}},\ i \in \mathcal{R}_n,\ w \in \mathcal{W},\ t = 0, \ldots, T-1 \quad (7)$$

$$q^w_{n,i}(t+1) = q^w_{n,i}(t) + \sum_{m \in \mathcal{P}^{\mathrm{I}}_n \cap \mathcal{N}^{\mathrm{S}} : \tau_{m,n} \le (t-\delta)} \sum_{j \in \mathcal{R}_m} r^w_{m,j,n,i}(t - \tau_{m,n} - \delta) + \sum_{m \in \mathcal{P}^{\mathrm{I}}_n \setminus \mathcal{N}^{\mathrm{S}} : \tau_{m,n} \le t} \sum_{j \in \mathcal{R}_m} r^w_{m,j,n,i}(t - \tau_{m,n}) - \sum_{m \in \mathcal{S}^{\mathrm{I}}_n} \sum_{j \in \mathcal{R}_m} r^w_{n,i,m,j}(t) \qquad n \in \mathcal{N}^{\mathrm{IS}},\ i \in \mathcal{R}_n,\ w \in \mathcal{W},\ t = 0, \ldots, T-1 \quad (8)$$

$$\bar{q}^w_{n,i}(t+1) = \bar{q}^w_{n,i}(t) + \sum_{m \in \mathcal{P}^{\mathrm{E}}_n \cap \mathcal{N}^{\mathrm{S}} : \tau_{m,n} \le (t-\delta)} \sum_{j \in \mathcal{R}_m} \bar{r}^w_{m,j,n,i}(t - \tau_{m,n} - \delta) + \sum_{m \in \mathcal{P}^{\mathrm{E}}_n \setminus \mathcal{N}^{\mathrm{S}} : \tau_{m,n} \le t} \sum_{j \in \mathcal{R}_m} \bar{r}^w_{m,j,n,i}(t - \tau_{m,n}) - \sum_{m \in \mathcal{S}^{\mathrm{E}}_n} \sum_{j \in \mathcal{R}_m} \bar{r}^w_{n,i,m,j}(t) \qquad n \in \mathcal{N}^{\mathrm{IS}},\ w \in \mathcal{W},\ i \in \mathcal{R}_n,\ t = 0, \ldots, T-1 \quad (9)$$

$$q^w_{n,i}(t+1) = q^w_{n,i}(t) + \sum_{m \in \mathcal{P}^{\mathrm{I}}_n \cap \mathcal{N}^{\mathrm{S}} : \tau_{m,n} \le (t-\delta)} \sum_{j \in \mathcal{R}_m} r^w_{m,j,n,i}(t - \tau_{m,n} - \delta) + \sum_{m \in \mathcal{P}^{\mathrm{I}}_n \setminus \mathcal{N}^{\mathrm{S}} : \tau_{m,n} \le t} \sum_{j \in \mathcal{R}_m} r^w_{m,j,n,i}(t - \tau_{m,n}) - \sum_{m \in \mathcal{S}^{\mathrm{I}}_n} \sum_{j \in \mathcal{R}_m} r^w_{n,i,m,j}(t) - d^w_{n,i}(t + \gamma^w) \qquad n \in \mathcal{N}^{\mathrm{ES}},\ i \in \mathcal{R}_n,\ w \in \mathcal{W},\ t = 0, \ldots, T-1 \quad (10)$$

$$\bar{q}^w_{n,i}(t+1) = \bar{q}^w_{n,i}(t) + \bar{a}^w_{n,i}(t) - \sum_{m \in \mathcal{S}^{\mathrm{E}}_n} \sum_{j \in \mathcal{R}_m} \bar{r}^w_{n,i,m,j}(t) \qquad n \in \mathcal{N}^{\mathrm{ES}},\ w \in \mathcal{W},\ i \in \mathcal{R}_n,\ t = 0, \ldots, T-1 \quad (11)$$

$$\sum_{w \in \mathcal{W}} l^w \left[q^w_{n,i}(t) + \bar{q}^w_{n,i}(t) \right] \le L_{n,i} \qquad n \in \mathcal{N},\ i \in \mathcal{R}_n,\ t = 0, \ldots, T-1 \quad (12)$$

$$\sum_{w \in \mathcal{W}} \sum_{i \in \mathcal{R}_n} r^w_{0,n,i}(t) + \bar{r}^w_{n,i,0}(t) \le \Gamma_n \qquad n \in \mathcal{N}^{\mathrm{T}},\ t = 0, \ldots, T-1 \quad (13)$$

$$\sum_{c=1}^{C}\sum_{i\in\mathcal{R}_n}\sum_{j\in\mathcal{R}_m} y^c_{n,i,m,j}(t)+x^c_{n,i,m,j}(t) + \sum_{c=1}^{C}\sum_{i\in\mathcal{R}_m}\sum_{j\in\mathcal{R}_n} \bar{y}^c_{m,i,n,j}(t)+\bar{x}^c_{m,i,n,j}(t)\le R_{n,m} \quad n\in\mathcal{N},\, m\in\mathcal{S}^{\mathrm{I}}_n,\, t=0,\dots,T-1 \tag{14}$$

$$\sum_{c=1}^{C}\sum_{m\in\mathcal{S}^{\mathrm{I}}_n}\sum_{j\in\mathcal{R}_m} y^c_{n,i,m,j}(t)+x^c_{n,i,m,j}(t) + \sum_{c=1}^{C}\sum_{m\in\mathcal{S}^{\mathrm{E}}_n}\sum_{j\in\mathcal{R}_m} \bar{y}^c_{n,i,m,j}(t)+\bar{x}^c_{n,i,m,j}(t)\le 1 \quad n\in\mathcal{N},\, i\in\mathcal{R}^{\mathrm{L}}_n,\, t=0,\dots,T-1 \tag{15}$$

$$\sum_{w\in\mathcal{W}_c} r^w_{n,i,m,j}(t)=Q'\cdot y^c_{n,i,m,j}(t)+Q''\cdot x^c_{n,i,m,j}(t) \quad c=1,\dots,C,\ n\in\mathcal{N},\ i\in\mathcal{R}^{\mathrm{L}}_n,\ m\in\mathcal{S}^{\mathrm{I}}_n,\ j\in\mathcal{R}_m,\ t=0,\dots,T-1 \tag{16}$$

$$\sum_{w\in\mathcal{W}_c} \bar{r}^w_{n,i,m,j}(t)=Q'\cdot \bar{y}^c_{n,i,m,j}(t)+Q''\cdot \bar{x}^c_{n,i,m,j}(t) \quad c=1,\dots,C,\ n\in\mathcal{N},\ i\in\mathcal{R}^{\mathrm{L}}_n,\ m\in\mathcal{S}^{\mathrm{E}}_n,\ j\in\mathcal{R}_m,\ t=0,\dots,T-1 \tag{17}$$

$$\sum_{c=1}^{C}\sum_{m\in\mathcal{S}^{\mathrm{I}}_n}\sum_{j\in\mathcal{R}_m} x^c_{n,i,m,j}(t)+\sum_{c=1}^{C}\sum_{m\in\mathcal{S}^{\mathrm{E}}_n}\sum_{j\in\mathcal{R}_m} \bar{x}^c_{n,i,m,j}(t)\le 1 \quad n\in\mathcal{N},\, i\in\mathcal{R}^{\mathrm{S}}_n,\, t=0,\dots,T-1 \tag{18}$$

$$\sum_{w\in\mathcal{W}_c} r^w_{n,i,m,j}(t)=Q''\cdot x^c_{n,i,m,j}(t) \quad c=1,\dots,C,\ n\in\mathcal{N},\ i\in\mathcal{R}^{\mathrm{S}}_n,\ m\in\mathcal{S}^{\mathrm{I}}_n,\ j\in\mathcal{R}_m,\ t=0,\dots,T-1 \tag{19}$$

$$\sum_{w\in\mathcal{W}_c} \bar{r}^w_{n,i,m,j}(t)=Q''\cdot \bar{x}^c_{n,i,m,j}(t) \quad c=1,\dots,C,\ n\in\mathcal{N},\ i\in\mathcal{R}^{\mathrm{S}}_n,\ m\in\mathcal{S}^{\mathrm{E}}_n,\ j\in\mathcal{R}_m,\ t=0,\dots,T-1 \tag{20}$$

$$\sum_{m\in\mathcal{S}^{\mathrm{I}}_n}\sum_{j\in\mathcal{R}_m} r^w_{n,i,m,j}(t)\le q^w_{n,i}(t) \quad w\in\mathcal{W},\, n\in\mathcal{N},\, i\in\mathcal{R}_n,\, t=0,\dots,T-1 \tag{21}$$

$$\sum_{m\in\mathcal{S}^{\mathrm{E}}_n}\sum_{j\in\mathcal{R}_m} \bar{r}^w_{n,i,m,j}(t)\le \bar{q}^w_{n,i}(t) \quad w\in\mathcal{W},\, n\in\mathcal{N},\, i\in\mathcal{R}_n,\, t=0,\dots,T-1 \tag{22}$$

$$\sum_{c=1}^{C}\sum_{n\in\mathcal{N}_h}\sum_{i\in\mathcal{R}_n}\sum_{m\in\mathcal{N}_h}\sum_{j\in\mathcal{R}_m} y^c_{n,i,m,j}(t)+\bar{y}^c_{n,i,m,j}(t) + x^c_{n,i,m,j}(t)+\bar{x}^c_{n,i,m,j}(t)\le\Lambda_h \quad h=1,\dots,H,\, t=0,\dots,T-1 \tag{23}$$

The objective function (1) is a weighted sum of the number of rail cars present in the nodes, as well as of the movements of trains and groups of rail cars in the linking tracks between nodes. In particular, α^w_0 and $\bar{\alpha}^w_0$, $w\in\mathcal{W}$, $\alpha^w_{n,i}$ and $\bar{\alpha}^w_{n,i}$, $w\in\mathcal{W}$, $n\in\mathcal{N}$, $i\in\mathcal{R}_n$, are the weights associated with the presence of rail cars in the different areas of the network. By suitably tuning these weights, it is possible to privilege the presence of rail cars in specific areas of the network or reducing them in other zones. Moreover, $\beta^w_{n,i,m,j}$ and $\zeta^w_{n,i,m,j}$, $w\in\mathcal{W}$, $n\in\mathcal{N}$, $i\in\mathcal{R}_n$, $m\in\mathcal{S}^{\mathrm{I}}_n$, $j\in\mathcal{R}_m$, $\bar{\beta}^w_{n,i,m,j}$ and $\bar{\zeta}^w_{n,i,m,j}$, $w\in\mathcal{W}$, $n\in\mathcal{N}$, $i\in\mathcal{R}_n$, $m\in\mathcal{S}^{\mathrm{E}}_n$, $j\in\mathcal{R}_m$ are the weights for the movements of trains and groups of rail cars, which represent fixed transportation costs paid for each movement.

Constraints (2)-(11) are conservation equations, for import and export flows, in node 0, in internal rail parks, in rail storage parks, in internal and external stations, respectively. Constraints (12) are related to the track length, constraints (13) take into account the maximum productivity of the handling means between node 0 and the internal rail parks, while constraints (14) account for the number of linking tracks. Constraints (15) impose that, at each time step, at most one train or group of rail cars can leave each long track. Constraints (16), together with (15), ensure that, at each time step, the number of import rail cars of a given railway company leaving each long track is equal to 0, or equal to Q' (whole train), or equal to Q'' (group of rail cars). Similarly, constraints (17) refer to the export flow. Constraints (18)-(20) are analogous to (15)-(17), but referred to short tracks. Constraints (21) and (22) guarantee that the quantity of rail cars of a given type leaving each track, in import and in export respectively, is not greater than the quantity of rail cars present in that track. Finally, constraints (23) take into account the number of locomotives in the different areas.

4. SCENARIO ANALYSIS: APPLICATION TO LA SPEZIA PORT RAIL SYSTEM

The proposed planning procedure has been applied to the rail network of the Italian port of La Spezia and, more specifically, to the rail system of La Spezia Container Terminal (LSCT), whose rail activity is provided by La Spezia Shunting Railways (LSSR) company. LSCT is run by Contship Italia Group, a leading logistic company in Italy. Fig. 2 shows La Spezia port rail system, which is composed of 10 nodes: three internal rail parks, two internal rail stations, three external rail stations and two rail storage parks.

A planning horizon of $T = 32$ time steps has been considered (corresponding to 8 hours, with sample time Δt of 15 minutes). The values of the main model parameters are the following:

- $|\mathcal{W}| = 4$ types of rail cars belonging to two different railway companies;
- number of tracks for each node $|\mathcal{R}_1| = |\mathcal{R}_5| = |\mathcal{R}_6| = 4$, $|\mathcal{R}_2| = |\mathcal{R}_3| = 2$, $|\mathcal{R}_4| = |\mathcal{R}_8| = |\mathcal{R}_9| = 11$, $|\mathcal{R}_7| = 9$, $|\mathcal{R}_{10}| = 18$;
- lengths of tracks varying between 100 and 700 metres;
- number of connecting tracks equal to 1 except for $R_{4,9} = R_{4,6} = R_{7,10} = 2$;
- number of rail cars $Q' = 16$ and $Q'' = 8$;
- delays $\tau_{n,m}$, $n, m\in\mathcal{N}$, varying between 1 and 4 (i.e. between 15 minutes and 1 hour);

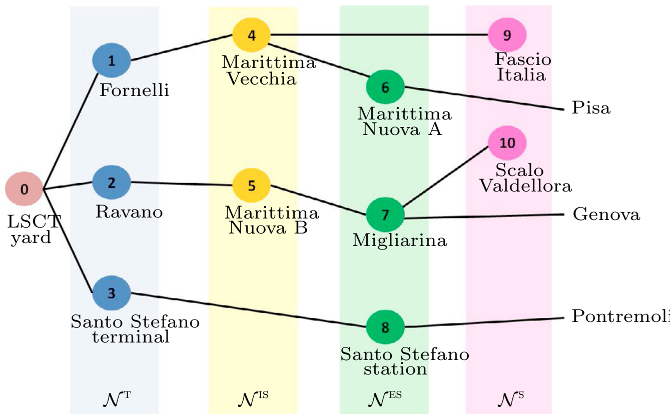

Fig. 2. The rail network of La Spezia port.

- other delays $\gamma^1 = 9$ and $\gamma^2 = 12$, corresponding respectively to more than 2 hours and 3 hours.

As previously described, the optimization problem proposed in Section 3 can be used both to plan the timing of shunting operations and to evaluate the system capacity. The objective of this section is to evaluate the system capacity (i.e. the maximum number of trains that the whole system can manage over a given time horizon) under different scenarios. In particular, in this analysis we focus on testing the impact of three main parameters on the system capacity. The considered parameters are the number of available locomotives, the productivity of the terminal equipment in the yard area and the time necessary for performing technical checks and documentary procedures.

The Scenario "as-is" is analysed and compared with 5 different scenarios which have been obtained from the "as-is" situation by varying the considered system parameters:

- *Scenario 1*: the number of locomotives Λ_h is increased of 1 unit for each area h;
- *Scenario 2*: the productivity of the terminal equipment in the yard area (Γ_n) is increased of 15%;
- *Scenario 3*: the productivity of the terminal equipment in the yard area (Γ_n) is decreased of 15%;
- *Scenario 4*: the time delays γ^w needed for performing the technical checks and documentary practices on rail cars of type w, and the time δ, needed for realizing shunting operations in the storage parks, are increased of 15 minutes;
- *Scenario 5*: the time delays γ^w and δ are decreased of 15 minutes.

For each scenario, 10 random instances have been generated and solved (with the MILP solver Cplex 12.5). The randomization is associated with the initial conditions, the number of train arrivals and departures, and the time instants in which such arrivals and departures occur. As for the initial conditions, they have been generated randomly, uniformly distributed between a lower and an upper value, considering realistic values for the La Spezia rail network.

For each scenario and for each instance it is evaluated whether the associated problem admits a solution or not. Indeed, if the problem is unfeasible, i.e. no admissible solution exists, it means that the port rail system is not able to meet the considered number and pattern of train arrivals and departures. Hence, for each scenario, considering cases

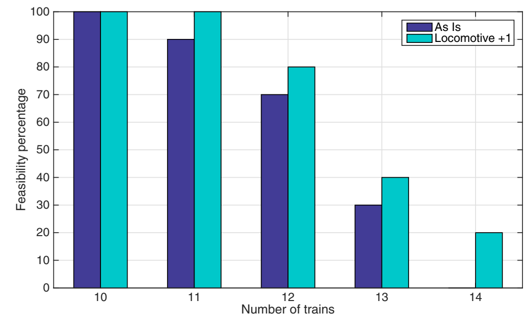

Fig. 3. Feasibility percentage in Scenario 1: variation of the number of locomotives.

of increasing number of trains, a *feasibility percentage* has been computed as the number of feasible instances over the total number. This index will be used to evaluate the capacity of the considered port rail network.

Figs. 3, 4 and 5 report the feasibility percentage values in the different scenarios, compared with the Scenario "as-is", with increasing number of trains. Note that the lack of bars in these figures denotes that no trains can be performed for the corresponding scenario, i.e. it is not a feasible scenario.

Starting from Fig. 3, the feasibility percentage values for Scenario 1 and the Scenario "as-is" is depicted, with number of trains from 10 to 14. First of all, comparing Scenario 1 with the "as-is" situation, it is evident that increasing the number of locomotives ensures a better performance of the system and a higher capacity, in terms of number of trains that can be managed. Moreover, in Scenario 1 the feasibility percentage is 100 % only in case of 10 and 11 trains to be managed. By increasing the number of trains, this percentage drops down to 80%, 60% and 20% in case of 12, 13 and 14 trains, respectively.

The results related to Scenarios 2 and 3 are provided in Fig. 4; it can be observed that, when decreasing the productivity of the terminal handling equipment of 15%, only 8 trains can be performed with a full feasibility percentage, and no more than 10 trains (whose feasibility percentage is only 20%) can be executed for this scenario. On the contrary, by increasing this productivity of the same value (i.e. 15%), up to 12 trains can be performed with a 100% feasibility percentage, which drops to 20% in case of 16 trains. It should be noted that Scenario 3 definitely performs better than the "as-is" case, which allows to execute maximum 13 trains (instead of 16 for Scenario 3) with a very low feasibility percentage (30%).

Fig. 5 reports the results obtained for Scenarios 4 and 5. It shows that a decrease of time delays of 15 minutes allows to execute up to 11 trains with a full feasibility percentage, which decreases to 20% when 15 trains are run (note that, in the "as-is" case, the maximum number of allowed trains is 13). On the opposite side, an increase of 15 minutes of these delays generates a situation in which only 9 trains can be performed with a full feasibility percentage; 11 and 12 trains are carried out only in the 40% and 20% of cases, respectively.

To conclude, by observing Figs. 3, 4 and 5, it is evident that, analyzing the impact of the three considered pa-

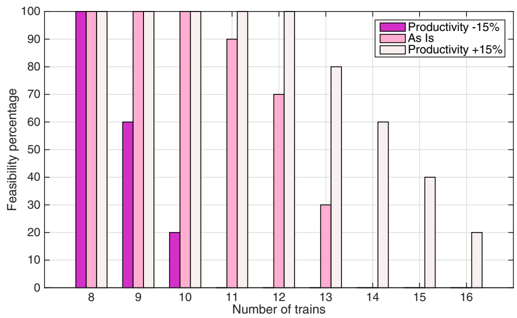

Fig. 4. Feasibility percentage in Scenarios 2 and 3: variation of the terminal equipment productivity.

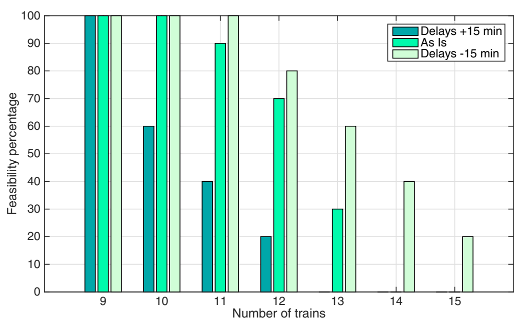

Fig. 5. Feasibility percentage in Scenarios 4 and 5: variation of time delays.

rameters (number of locomotives, productivity and time delays), the maximum benefit on the potentiality of La Spezia port rail system is obtained by increasing the productivity of the terminal handling equipment in the yard area (up to 16 trains can be performed), whilst the smallest benefit is provided by a unitary increase of the locomotives in each network area (up to 14 trains can be executed).

5. CONCLUSION

The optimization approach proposed in this paper can be used for properly evaluating the maximum number of trains that a port rail network can manage, considering both the import and the export cycle. The application of this planning procedure to an important port rail network of Northern Italy (the port of La Spezia) has shown the effectiveness of the proposed approach for determining the capacity of the system. The analysis of numerous scenarios related to the variation of the terminal equipment productivity, the number of locomotives and the time needed to perform technical operations has provided interesting insights on the potentiality of the system.

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