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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.

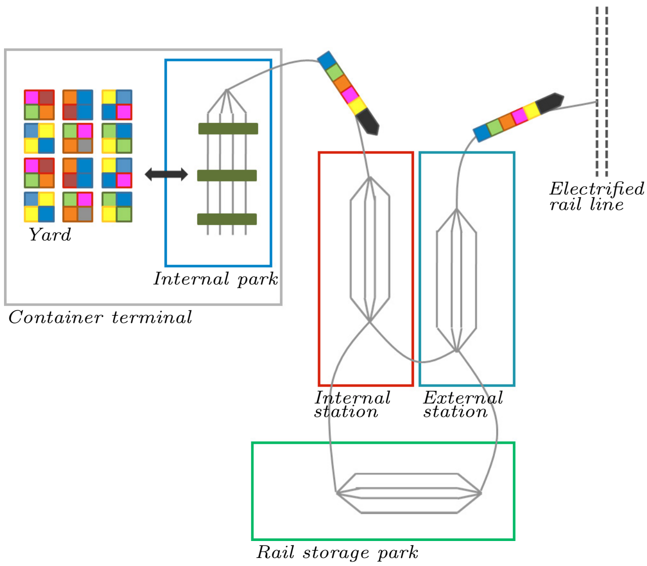

Fig. 1. The port rail network.

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. $y_{n,i,m,j}^c(t)$, $n \in \mathcal{N}$, $i \in \mathcal{R}_n^{\mathrm{L}}$, $m \in \mathcal{S}_n^{\mathrm{I}}$, $j \in \mathcal{R}_m$, $c = 1, \ldots, C$,