An event-triggered receding-horizon scheme for planning rail operations in maritime terminals

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Abstract—This paper proposes a planning approach to optimize railway operations in seaport terminals by adopting a queue-based discrete-time model of the considered system. Firstly, a mixed-integer linear mathematical programming problem is defined in order to optimize the timing of import trains and the use of the handling resources devoted to rail port operations. Secondly, in order to deal with unexpected situations or uncertainty in estimating some data necessary to the planning, an event-triggered receding-horizon planning approach is proposed in which the finite horizon optimization problem is solved whenever a critical event happens or the real values of some problem data significantly differ from the predicted ones. Both these planning approaches are tested on data referred to a real terminal and deeply discussed in the paper.

Index Terms—Seaport container terminals; rail operations; optimization; receding-horizon planning.

I. INTRODUCTION

CONTAINER terminals are very complex systems with highly dynamic interactions among the various handling, transportation, and storage units and are affected by incomplete knowledge about future events, both in terms of data accuracy and correctness and in terms of timing of information arrival [1]. Different simulation, optimization and control approaches have been developed by researchers for planning terminal operations, as shown for instance in [2], [3]. The planning techniques and the models adopted can be classified according to different decision levels, i.e. terminal design, operative planning, and real-time control [1] or they can be classified according to the specific process they address, as done in [4], [5]. In these two latter surveys, in particular, optimization methods can be distinguished among those referred to ship planning processes, those related to storage and stacking logistics, those devoted to transport optimization and simulation-based techniques.

This work is devoted to model the rail port cycle in a seaport terminal and to define a planning approach in order to optimize the timing of the different processes involved (preliminary versions can be found in [6] and [7]). The dynamic model adopted is quite aggregate and represents the movement of containers in the railway area of the terminal as a set of flows; the presence of containers in a specific zone of the terminal is modelled as a queue and the queue dynamics is given by conservation discrete-time equations. The movement of containers is represented as a transfer between queues. Such model takes inspiration from [8] in which the whole seaport container terminal is modeled by a system of queues and the proposed optimization problem aims at defining the optimal utilization of terminal resources in order to minimize the transfer delays of containers. More in detail, in [8] the queue model represents the entire terminal at a very aggregate level and the resulting planning problem is linear and characterized by continuous variables (indicating flows of containers). Instead, this work focuses specifically on the rail port cycle and models it more in detail; in fact, some “binary” decisions have to be taken and then the resulting planning problem has a mixed-integer linear structure. Moreover, in this paper we propose an event-triggered receding-horizon approach for planning the operations, whereas in [8] a standard receding-horizon scheme is adopted. A similar model, again on the entire terminal, can be found in [9] where two feedback control strategies for the allocation of terminal resources are proposed and compared through sensitivity and scenario analyses.

Whereas the models and optimization approaches present in the literature and devoted to specific terminal processes are manifold, few works address the planning of the terminal by adopting aggregate models. For instance, in [10] a mathematical model is developed to optimize import and export processes in a seaport terminal assuming that many aspects (such as loading/unloading plans, container locations, and so on) have been already planned. The overall view of the terminal is also considered in many works adopting discrete simulation, which can be considered as an effective and challenging alternative approach for container terminal analysis [11]. In [12] a microscopic simulation model is developed for evaluating four different automated container terminal concepts in terms of performance and costs. In [13] a discrete-event simulation model is adopted to study inland terminals for combined rail/road transport, whereas in [14] an object-oriented model to be used in a port decision support system is proposed. In [15] queuing network-based models are adopted to optimally manage the container discharge/loading at any given berthing point via discrete-event simulation. The modelling tool of Petri nets is used in [16] in order to evaluate the impact of Information and Communication Technologies in the connection between a port and a truck terminal.

As already mentioned, the queue-based discrete-time model considered in this paper addresses the processes associated with the import rail cycle, starting from the storage of containers, going through their loading on trains, till the shunting operations of trains and their exit from the terminal through the electric line. Some papers can be found in the literature referred to rail operations in container terminals, more often inland than maritime terminals, generally with a different focus.
with respect to the present work. Some results are devoted to the definition of the train loading plan, such as in [17] where some models and heuristic methods are developed for rail-rail terminals with rapid transfer yards. In [18] the authors propose several techniques for defining the assignment of containers to train slots in a terminal where containers are transferred to and from trucks on a platform adjacent to rail tracks provided with a short-term storage area. Other works, such as [19] and [20], are devoted to the definition of mathematical programming models for the train loading plan, considering specific weight constraints for the different types of wagons. Rail-rail transshipment yards are considered in [21] where a mathematical model is presented to solve the train location problem. In [22] a three-stage algorithm to manage the container exchange facility is presented and, at the strategic planning level, a discrete-time model is considered, similarly to the present work, even though the objective and the considered system are quite different.

The contribution of this paper regards planning rail operations in container terminals and the proposed optimization procedure can be adopted at different planning levels. The proposed scheme is first of all intended to be used for planning over a multiple-day or weekly period, and in particular it allows to take decisions on train departure timing, how much to use handling resources, and so on. Moreover, the proposed methodology can also help, considering a longer time horizon, to verify different terminal scenarios and to size terminal resources. For instance, it is possible to evaluate how many resources (in terms of handling systems and rail tracks) are necessary to satisfy a given set of import flows or, conversely, which is the maximum number of trains per day that a given terminal can serve with a defined number of resources. Finally, it is important to highlight that the proposed model is very general and, for this reason, it can be easily adapted to represent different real terminals.

This paper is organized as follows. Section II is devoted to introduce the main aspects of the rail port cycle and to describe the discrete-time model adopted to represent the system dynamics. In Section III the planning approach is formally described and explained through the detailed description of a real case study; a computational analysis dedicated to evaluate the computational time necessary to solve the proposed optimization problem is also reported. Then, Section IV proposes the event-triggered receding-horizon planning scheme, in order to be able to react to system disturbances or unexpected events. Finally, some conclusions are drawn in Section V.

II. THE DYNAMIC MODEL FOR THE RAIL PORT CYCLE
A. General description of the rail port cycle

In this work the rail port cycle is studied and, in particular, a planning approach is proposed for the import flow of containers, that is the flow from a seaport terminal to its hinterland. The considered system is shown in Fig. 1: the flow of containers is modeled starting from their wait in the yard stacking area until the moment in which they leave the terminal by rail. More specifically, containers stored in the yard are transported by terminal resources to the rail park inside the terminal where they are loaded onto trains, usually through Rail Mounted Gantry (RMG) cranes. Then, through a shunting operation executed by a diesel locomotive, trains are brought to an interchange park outside the terminal from which they will depart by using the electric traction. In the following, we will call domestic (or internal) rail park the internal tracks inside the terminal area, where containers are loaded on trains and where there is a diesel traction (it is worth noting that the diesel traction is necessary to allow vertical loading/unloading operations by cranes). On the other hand, we will call external rail park the area in which the change of traction occurs (from diesel to electric).

The entire process is affected by a certain number of delays, related to both physical and informative/documentary processes. In particular, we consider documentary checks that are carried out in the internal rail park, and technical checks realized in the external rail park (verification of the train braking system due to the change of traction and check of the correct load of containers on wagons).

![Fig. 1. The rail port cycle.](image-url)

Depending on the specific layout of the considered terminal, there can be more than one import yard and different handling means, hence corresponding to different operative cycles to be represented. For instance, import containers can be stored in the main yard areas or in specific zones where there are only containers to be loaded on trains. Moreover, the handling equipment can be different from a terminal to another. In some cases, containers stored in the stacking area are lifted up by yard cranes (for instance, Rubber Tyred Gantry cranes (RTG)), then loaded with reach stackers on trailers that bring them to the domestic rail park; in other cases containers located in the stacking area are directly loaded by reach stackers on trailers and transported close to the domestic rail park. Other transportation and stacking logics (rules) can be found in container terminals managed with straddle carriers, which are typically used in Northern European ports [4]. In any case, the proposed model is very general, it can represent different operative cycles with different handling systems and it can also be easily adapted to different possible configurations.

The objective of this paper is to define an optimization approach in order to determine the optimal system configuration in relation to the import rail port cycle in terms of productivity of terminal resources and timing of handling operations. Moreover, an optimization framework for this
system is proposed also in case of unexpected events, evolving situations or changing data.

B. The discrete-time model

In the proposed model the considered system is represented with a set of queues, modelling the presence of containers in specific areas of the terminal. The dynamics of the system is represented with discrete-time equations with sample time equal to $\Delta t$. In Fig. 2 the queue system is shown, as well as the main variables present in the model.

There are two types of stacking areas: the former corresponds to import stacking blocks that are not close to the railway park (we refer in this case to the main terminal yard composed by containers that will continue in the inland either by rail or truck), while the latter relates to some blocks close to the domestic rail park in which only containers devoted to be loaded on trains are stored. According to the specific stacking area, a different number of handling operations with different handling means is executed on containers to be loaded on trains. More specifically, in the first case two consecutive handling operations are considered to move containers from the main yard to the domestic railway park (for instance, RTGs pick containers up from the blocks in order to allow reach stackers to put them on trailers that carry them to the railway park to be loaded). Instead, in the second case only one type of operation is performed on containers (for instance reach stackers directly pick containers up from the yard blocks and put them on trailers).

Let us denote with $M$ the number of stacking areas of the first type, with $S$ the number of stacking areas of the second type, with $I$ the number of internal rail tracks and with $E$ the number of external ones.

![Fig. 2. Queue model of the import rail port cycle.](image)

At a generic time step $t$, the arrival rates of containers (that will be forwarded by rail) in the two types of import stacking areas of the terminal are given by the quantities $a_i^M(t)$, $i = 1, \ldots, M$, and $q_i^E(t)$, $i = 1, \ldots, S$, respectively (expressed in containers per hour). Analogously, $d(t)$ models the demand of containers in import, given by trains scheduled to leave the terminal towards the inland. Specifically, $d(t)$ represents the quantity of containers that exit the terminal at time step $t$; it is set equal to 0 if there are no train departures at time step $t$ and it is set equal to the train capacity if a train is scheduled to leave at $t$.

The queue lengths corresponding to containers stored in the $M$ stacking areas of the first type and in the $S$ stacking areas of the second type, at each time step $t$, are denoted as $q_i^M(t)$, $i = 1, \ldots, M$, and $q_i^S(t)$, $i = 1, \ldots, S$, respectively (the queue lengths are expressed in terms of number of containers). As already introduced, containers in the first type of stacking areas cannot reach the railway yard directly but they are firstly stored in an intermediate buffer (that represents the space under the RTG cranes where containers wait for reach stackers to pick them up); the length at time step $t$ of the corresponding queues is denoted as $q_i^E(t)$, $i = 1, \ldots, M$.

All the containers present in the different stacking areas are moved to the internal rail park where, no matter from which particular yard area they come from, they wait on trailers to be loaded on the rail wagons by the rail crane. The queue length corresponding to containers waiting under the rail crane, at time step $t$, is denoted as $q_i^R(t)$. The queue lengths of containers loaded on trains in the internal park at time step $t$ are denoted with $q_i^E(t)$, $i = 1, \ldots, I$.

As explained above, all the movements of containers from the stacking areas to the internal park are realized by the terminal handling resources. In particular, let us denote with $u_i(t)$, $i = 1, \ldots, M$, the productivity at time step $t$ of yard cranes for the $i$-th stacking area of the first type and with $u_i(t)$, $i = M + 1, \ldots, 2M$, the productivity at time step $t$ of the combination of reach stackers and trailers for the corresponding intermediate buffer. Moreover, let us denote with $u_i^E(t)$, $i = 1, \ldots, I$, the productivity at time step $t$ of the rail crane working on the $i$-th track in the internal park.

The external rail park is composed of $E$ tracks and $q_i^E(t)$, $i = 1, \ldots, E$, denote the queue lengths of containers on trains in these tracks that at time step $t$ are ready to leave the terminal. In the proposed model we suppose that a train can leave the internal park only if it is fully loaded (we denote with $C$ the train capacity expressed in number of containers), all the necessary checks have been realized and the siding track is free. As a matter of fact, the transit of containers from the internal to the external park is realized through a siding track connecting the two rail parks. In this model we suppose that the terminal is provided with two siding tracks, but it is worth noting that the extension of the model to a generic number of siding tracks is straightforward. The departures of trains from the internal park are represented with a set of binary variables; specifically, a variable $y_{i,j}(t) = 1$, $i = 1, \ldots, I$, $j = 1, \ldots, E$, represents that, at time step $t$, a train in queue $q_i^E$ leaves the internal park and is directed to the queue $q_j^E$ in the external park by using the first siding track. Analogously, $y_{i,j}(t) = 1$, $i = 1, \ldots, I$, $j = 1, \ldots, E$, represents that, at time step $t$, a train in queue $q_i^E$ in the internal yard leaves towards the queue $q_j^E$ in the external park by using the second siding track. The times required to cross the two siding tracks...
are supposed to be multiple of the sample time $\Delta t$ and denoted with $\tau_y$ and $\tau_w$, respectively. Of course, the departure of trains from the internal yard should be appropriately constrained, for instance in order to avoid the simultaneous use of a siding track. These aspects will be represented as constraints in the planning problem defined in Section III.

As already mentioned, in the external rail park technical checks are executed, in order to test the correct loading of containers on wagons and the functioning of the train braking system. The time required for these operations is modeled as a multiple $\delta^E$ of the sample time $\Delta t$. Therefore, a train in the external park is not considered for the time steps later than the time in which it departed from the internal park. If a train is scheduled to depart at time step $t$, then $d(t) = C$. Moreover, in order to correctly model the train departures from a specific external rail track, another set of binary variables is introduced. In particular, $z_{i}(t) = 1$, $i = 1, \ldots, E$, means that, at time step $t$, the train $q_{i}(t)$ is available to satisfy the demand. Of course, it is necessary to impose that, at each time step $t$, only one variable $z_{i}(t)$, $i = 1, \ldots, E$, is equal to 1. Hence, the departure of a train from the external rail track $q_{i}^{E}$, $i = 1, \ldots, E$, is verified when $d(t) = C$ and $z_{i}(t) = 1$.

The dynamics of the overall transfer activities in the terminal can be described with conservation equations that, at time step $t+1$, update the queue lengths according to their length at the previous time step $t$ and the number of entering and exiting containers in the time interval $[t, t+1]$, with length $\Delta t$. The discrete-time equations representing the system dynamics over an horizon of $T$ time steps are the following:

$$q_{i}^{M_{1}}(t+1) = q_{i}^{M_{1}}(t) + [a_{i}^{M_{1}}(t) - u_{i}(t)]\Delta t$$
$$i = 1, \ldots, M, \quad t = 0, \ldots, T - 1$$

$$q_{i}^{M_{2}}(t+1) = q_{i}^{M_{2}}(t) + [u_{i}(t) - u_{i+1}(t)]\Delta t$$
$$i = 1, \ldots, M, \quad t = 0, \ldots, T - 1$$

$$q_{i}^{S}(t+1) = q_{i}^{S}(t) + [u_{i}^{S}(t) - u_{2M+i}(t)]\Delta t$$
$$i = 1, \ldots, S, \quad t = 0, \ldots, T - 1$$

$$q_{i}^{R}(t+1) = q_{i}^{R}(t) + \left[\sum_{j=M+1}^{2M+S} u_{i}(t) - \sum_{j=1}^{I} u_{i}^{R}(t)\right]\Delta t$$
$$t = 0, \ldots, T - 1$$

$$q_{i}^{l}(t+1) = q_{i}^{l}(t) + u_{i}^{R}(t)\Delta t - C \sum_{j=1}^{I} \left(y_{i,j}(t) + w_{i,j}(t)\right)$$
$$i = 1, \ldots, I, \quad t = 0, \ldots, T - 1$$

$$q_{i}^{E}(t+1) = q_{i}^{E}(t) + \sum_{j=1}^{I} \left(y_{i,j}(t - \tau_{y} - \delta^{E})
+ w_{i,j}(t - \tau_{w} - \delta^{E})\right) - d(t)z_{i}(t)$$
$$i = 1, \ldots, E, \quad t = 0, \ldots, T - 1$$

### III. Planning of the Rail Port Cycle

#### A. The planning problem

In order to plan the rail port cycle for satisfying a given external demand (i.e. a given schedule of trains), a mathematical programming problem is defined. This problem must take into account the system dynamics represented by the discrete-time queue-based equations described in Section II-B and some other operative constraints, over a time horizon given by $T$ time steps.

The problem for planning the rail port cycle can be stated with the following mixed-integer programming formulation.

**Problem 1:** Given:

- the arrival rates $a_{i}^{M_{1}}(t), i = 1, \ldots, M$ and $a_{i}^{S}(t), i = 1, \ldots, E$,
- the initial conditions $q_{i}^{M_{1}}(0), q_{i}^{M_{2}}(0), q_{i}^{S}(0), q_{i}^{R}(0), q_{i}^{l}(0), q_{i}^{E}(0), i = 1, \ldots, I, \quad t = -\tau_{y} - \delta^{E}, \ldots, 1$; and $w_{i,j}(0), i = 1, \ldots, I, \quad j = 1, \ldots, E, \quad t = -\tau_{w} - \delta^{E}, \ldots, 1$;
- the maximum queue lengths $q_{i}^{M_{1}}, q_{i}^{M_{2}}, q_{i}^{S}, q_{i}^{R}, q_{i}^{l}, q_{i}^{E}, i = 1, \ldots, I, \quad E$;
- the sets of shared resources and the corresponding maximum handling rates, i.e. $O_{k}, \Omega_{k}, k = 1, \ldots, K, \quad K_{k}, \Omega_{k}^{R}, k = 1, \ldots, K$;
- the cost weighting parameters $\omega_{i}^{M_{1}}, i = 1, \ldots, M$, $\omega_{i}^{M_{2}}, i = 1, \ldots, M$, $\omega_{i}^{S}, i = 1, \ldots, S$, $\omega_{i}^{R}, \omega_{i}^{l}, i = 1, \ldots, I, \quad \omega_{i}^{E}, i = 1, \ldots, E, \omega_{w}^{y}$ and $\omega_{w}^{w}$;
- the parameters $C$, $\tau_{y}$, $\tau_{w}$, $\delta^{l}$ and $\delta^{E}$;

find:

- the state variables $q_{i}^{M_{1}}, i = 1, \ldots, M, \quad q_{i}^{M_{2}}, i = 1, \ldots, M, \quad q_{i}^{S}, i = 1, \ldots, I, \quad q_{i}^{R}(t), q_{i}^{l}(t), i = 1, \ldots, I, \quad t = 1, \ldots, T$; and the decision variables $u_{i}(t), i = 1, \ldots, 2M + S, \quad u_{i}^{l}(t), i = 1, \ldots, I, \quad z_{i}(t), i = 1, \ldots, E, \quad t = 0, \ldots, T - 1$;

that minimize

$$\sum_{t=1}^{T} \left[\sum_{i=1}^{M} \omega_{i}^{M_{1}} q_{i}^{M_{1}}(t) + \sum_{i=1}^{M} \omega_{i}^{M_{2}} q_{i}^{M_{2}}(t) + \sum_{i=1}^{S} \omega_{i}^{S} q_{i}^{S}(t)
+ \omega_{R} q_{i}^{R}(t) + \sum_{i=1}^{I} \omega_{i}^{l} q_{i}^{l}(t) + \sum_{i=1}^{E} \omega_{i}^{E} q_{i}^{E}(t)\right]
+ C \sum_{t=0}^{T-1} \sum_{i=1}^{I} \sum_{j=1}^{E} \left(\omega_{w}^{y} y_{i,j}(t) + \omega_{w}^{w} w_{i,j}(t)\right)$$

subject to the model dynamics given by (1)-(6), and

$$\sum_{i=1}^{I} \sum_{j=1}^{I} y_{i,j}(t+k) \leq 1 \quad t = 0, \ldots, T - \tau_{y} + \delta^{l}$$

$$\sum_{i=1}^{I} \sum_{j=1}^{I} w_{i,j}(t+k) \leq 1 \quad t = 0, \ldots, T - \tau_{w} + \delta^{l}$$
\[
\sum_{i=1}^{E} z_i(t) = 1 \quad t = 0, \ldots, T - 1 \tag{10}
\]
\[
\sum_{j=1}^{E} \left( y_{i,j}(t) + w_{i,j}(t) \right) \leq 1 \\
i = 1, \ldots, I, \quad t = 0, \ldots, T - 1 + \delta^f \tag{11}
\]
\[
\sum_{i=1}^{I} \left( y_{i,j}(t) + w_{i,j}(t) \right) \leq 1 \\
j = 1, \ldots, E, \quad t = 0, \ldots, T - 1 + \delta^f \tag{12}
\]
\[
q_i^f(t) - C + G \left[ 1 - \sum_{j=1}^{E} \left( y_{i,j}(t + \delta^f) + w_{i,j}(t + \delta^f) \right) \right] \geq 0 \\
i = 1, \ldots, I, \quad t = 0, \ldots, T - 1 \tag{13}
\]
\[
\sum_{i \in O_k} u_i(t) \leq \Omega_k \\
k = 1, \ldots, K, \quad t = 0, \ldots, T - 1 \tag{14}
\]
\[
\sum_{i \in O_k^R} u_i^R(t) \leq \Omega_k^R \\
k = 1, \ldots, K^R, \quad t = 0, \ldots, T - 1 \tag{15}
\]
\[
u_i(t) \Delta t \leq q_i^{M_i}(t) \\
i = 1, \ldots, M, \quad t = 0, \ldots, T - 1 \tag{16}
\]
\[
u_{M+i}(t) \Delta t \leq q_i^{M_i}(t) \\
i = 1, \ldots, M, \quad t = 0, \ldots, T - 1 \tag{17}
\]
\[
u_{2M+i}(t) \Delta t \leq q_i^{S_i}(t) \\
i = 1, \ldots, S, \quad t = 0, \ldots, T - 1 \tag{18}
\]
\[
\sum_{i=1}^{I} u_i^R(t) \Delta t \leq q^R(t) \\
t = 0, \ldots, T - 1 \tag{19}
\]
\[
0 \leq q_i^{M_i}(t) \leq q_i^M \\
i = 1, \ldots, M, \quad t = 1, \ldots, T \tag{20}
\]
\[
0 \leq q_i^{M_i}(t) \leq q_i^M \\
i = 1, \ldots, M, \quad t = 1, \ldots, T \tag{21}
\]
\[
0 \leq q_i^S(t) \leq q_i^S \\
i = 1, \ldots, S, \quad t = 1, \ldots, T \tag{22}
\]
\[
0 \leq q^R(t) \leq R^k \quad t = 1, \ldots, T \tag{23}
\]
\[
0 \leq q_i^f(t) \leq Q_i^f \\
i = 1, \ldots, I, \quad t = 1, \ldots, T \tag{24}
\]
\[
0 \leq q_i^f(t) \leq Q_i^f \\
i = 1, \ldots, I, \quad t = 1, \ldots, T \tag{25}
\]
\[
y_{i,j}(t) \in \{0, 1\}, \quad w_{i,j}(t) \in \{0, 1\} \\
i = 1, \ldots, I, \quad j = 1, \ldots, E, \quad t = 0, \ldots, T - 1 + \delta^f \tag{26}
\]
\[
z_i(t) \in \{0, 1\} \\
i = 1, \ldots, E, \quad t = 0, \ldots, T - 1 \tag{27}
\]

where $G$ is a large quantity arbitrarily chosen.

The objective function (7) is a weighted sum of the queues over the whole time horizon, in which each queue is appropriately weighted with the coefficients $\omega^{M_i}, i = 1, \ldots, M, \omega^{M_2}, i = 1, \ldots, M, \omega^{S_i}, i = 1, \ldots, S, \omega^R, \omega^I, i = 1, \ldots, I, \omega^E, i = 1, \ldots, E$. The last two terms in the sum model the presence of containers on trains in the two siding tracks, weighted respectively with coefficients $\omega^M$ and $\omega^W$. By adopting this weighted sum as cost function, the total transfer delay in the terminal is minimized. It is worth noting that, by suitably tuning the weights associated with the different queue lengths, it is possible to provide the defined cost function with different objectives, privileging the presence of containers in given areas of the terminal or limiting them in areas where there are space limitations to be taken into account. In this model, in order to plan correctly the departure of trains from the internal and external parks according to the scheduled demand, the highest weights will be associated with the queues of the external tracks and with the siding tracks connection, medium weights will be related to internal tracks queues, while the smallest weights will be assigned to the remaining queues.

Constraints (8)-(9) model the presence of the two siding tracks connecting the domestic with the external rail park and the fact that $\tau_y$ and $\tau_w$ time steps are needed to cross them, respectively. For this reason, in the time needed to cross each of them only one train can be transiting on each siding track, i.e. the sum of the $y_{i,j}(t)$ and the $w_{i,j}(t)$ must be lower or equal to 1.

Constraints (10) impose that, at each time step $t$, only one external track can be available to satisfy the external demand. Constraints (11) impose that no more than one train can leave at each time step from each internal track; analogously, constraints (12) impose that no more than one train can reach each external track at each time step.

Constraints (13) ensure that a train can leave the domestic rail park only $\delta^f$ time steps after the moment in which it has been loaded with $C$ containers. In fact, we denote with $\delta^f$ the time required for documentary checks in the internal rail park. More specifically, constraints (13) impose that, if $q_i(t) < C$, $i = 1, \ldots, I$, at a given time step $t$, then $\sum_{j=1}^{E} y_{i,j}(t + \delta^f) + w_{i,j}(t + \delta^f)$ must be equal to 0, i.e. no trains can leave from the $i$-th internal track at time step $t + \delta^f$.

Constraints (14)-(15) model the maximum handling rates considering that some handling resources (for instance cranes) are shared among different processes. More specifically, as regards the handling rates $u_i(t), i = 1, \ldots, 2M + S$, $K$ resource sets are considered representing the handling rates corresponding to the same handling resource. For the resource set $k = 1, \ldots, K$ a maximum handling rate $\Omega_k$ and the set $O_k$ are defined (this latter representing the set of indexes of decision variables $u_i$ related to the $k$-th resource set); then, $O_k \subset \{1, \ldots, 2M + S\}, k = 1, \ldots, K$, and $O_k \cap O_h = \emptyset, h, k = 1, \ldots, K, h \neq k$. For each resource set $k$ and for each time step $t$, constraints (14) ensure that the sum of handling rates using that resource set are limited by its maximum capacity.

Analogously, for the handling rates $u^R_i(t), i = 1, \ldots, I, K^R$ resource sets are considered; for each resource set $k = 1, \ldots, K^R$ a maximum handling rate $\Omega_k^R$ and the set $O_k^R$ are defined; then, $O_k^R \subset \{1, \ldots, I\}, k = 1, \ldots, K^R$ and $O_k^R \cap O_h^R = \emptyset, h, k = 1, \ldots, K^R, h \neq k$. Constraints (15) impose that, for each resource set $k$ and for each time step $t$, the sum of handling rates using that resource set are limited by its maximum capacity.

Constraints (16)-(19) guarantee that the quantity exiting each queue at time step $t$ is not greater than the queue length at the same time step. Constraints (20)-(25) impose that each queue at each time step is not larger than its maximum value.
Finally, constraints (26)-(27) impose that $y_{i,j}(t)$, $w_{i,j}(t)$ and $z_i(t)$ are binary variables.

It is worth noting that in some cases Problem 1 can be unfeasible, mainly because either the arrival rates can be too high (and then the queues can become higher than the maximum capacity) or the departure rates are too high (and then the queues representing containers in the external tracks can become negative). However, if the problem to solve is unfeasible, this means that the terminal under concern is not able to serve the required flows and, in this sense, the proposed planning procedure can be used also to verify a priori the capability of the terminal to accept given transportation demands.

Problem 1 is a mixed-integer linear programming problem. It is worth noting that the system considered in this paper can be seen as a mixed logical dynamical (MLD) system, as proposed in [23], i.e. a system described by linear dynamic equations and inequalities involving real and integer variables. In particular, in our model, the queue lengths represent the system state variables, whereas the decision (control) variables are given by the productivity of the handling resources, the binary variables indicating the departure of trains from internal tracks and the binary variables representing the availability of external tracks. Moreover, the arrival rates and the departure sequences are uncontrollable inputs, which can be regarded as disturbances. Finally, it is important to consider that the objective of this paper is to formalize a planning problem in order to minimize a given cost function and not to stabilize the system on desired equilibrium points, as done instead in [23].

Finally, it has to be highlighted that the proposed model considers the import flow of the rail port cycle but it would be straightforward to represent analogously the export flow, and the sizes of the resulting model (in terms of number of queues and decision variables) would be similar to those considered in this paper for the import flow. Moreover, considering the import and export flows jointly would be slightly more elaborate and would lead to a higher number of queues and decision variables but, again, the modelling and optimization approach would be exactly the same.

B. Application to a real case study

The planning problem described in Section III has been implemented in CPLEX by using Cplex 12.3 as MILP solver. In this section, the application of the proposed model to a real case study is presented. The container terminal under consideration is located in a Mediterranean port in Northern Italy and it represents a relevant terminal, both in terms of size and as regards its maritime and hinterland connections.

The model proposed in Section II-B with two types of import areas is suitable to represent the operative cycle of the considered terminal. This container terminal is characterized by $M = 4$ stacking areas of the main yard and $S = 2$ stacking areas of the secondary yard. Moreover, the number of internal rail tracks $I$ is equal to 8 while the number of external rail tracks $E$ is equal to 3. The planning horizon of the problem has been set equal to one week, which represents the typical planning interval for rail transportation in a container terminal. Since the sample time $\Delta t$ is set to 15 minutes, the number of time steps is consequently $T = 672$.

As already described, the weights in the cost function are assigned in order to limit the stop of containers in critical areas of the terminal, such as the railway parks and the two siding tracks and, on the contrary, to allow the presence of containers in the import stacking areas. More specifically, in the considered case study, the following weights have been fixed:

- $\omega^\text{M}_i = 13$, $i = 1, \ldots, 4$;
- $\omega^\text{M}_2 = \omega^\text{S}_i = 15$, $i = 1, \ldots, 4$, $j = 1, 2$;
- $\omega^\text{R}_i = \omega^\text{F}_i = 20$, $i = 1, \ldots, 8$;
- $\omega^\text{C}_i = 25$, $i = 1, \ldots, 3$;
- $\omega^\text{Y} = \omega^\text{W} = 50$.

It is worth specifying that only the relative values of these weights are meaningful. Other model parameters are the number of containers for composing a full train, i.e. $C = 40$ (which, in case of a TEU factor equal to 1.5, corresponds to 60 TEUs, that is a realistic value for the considered container terminal) and the number of time steps necessary to cross the siding tracks, i.e. $\tau_\text{y} = \tau_\text{w} = 2$, since about 30 minutes are required. According to the model, once the train is composed, a number of time steps $\delta^M$, which is set equal to 1, has to be waited in order to perform documentary operations, while a number of time steps $\delta^W$ fixed to 4 is needed for the change of traction and to carry out the technical check.

In order to show the possible application of the proposed planning approach, three scenarios have been considered. The first one represents the current configuration of the considered terminal (in terms of handling productivity and rail slots distribution), while in the second one a higher availability of handling equipments is considered. Finally, the third scenario considers a demand of train slots uniformly distributed along the day (unlike the other two scenarios in which rail slots are concentrated during the night and in the early morning, as it usually happens for freight trains).

All the three scenarios are characterized by the same values for the maximum capacity of queues, initial conditions and arrival rates. More specifically, the maximum queue lengths are set taking into account the physical space present in the terminal:

- $Q^\text{M}_i = 3500$ containers, $i = 1, \ldots, 4$;
- $Q^\text{M}_2 = 5$ containers, $i = 1, \ldots, 4$;
- $Q^\text{S}_i = 500$ containers, $i = 1, 2$;
- $Q^\text{R} = 10$ containers;
- $Q^\text{C}_i = 40$ containers, $i = 1, \ldots, 8$;
- $Q^\text{Y} = 40$ containers, $i = 1, \ldots, 3$.

The initial conditions of the queues are set in order to represent a generic initial state of the system. Specifically, 1100 containers are supposed to be initially in the main yard and 400 containers in the second yard, whereas only one container is stocked in the intermediate stacking area. As regards the initial state of internal rail park, one full train ready to leave the internal tracks is considered as well as two trains in the loading phase. Additional initial conditions are needed to represent the siding track occupancy state in
the instants before the starting of optimization; in this case study it is \( y_{i,j}(t) = w_{i,j}(t) = 0 \), \( i = 1, \ldots, 8 \), \( j = 1, \ldots, 3 \), \( t = -6, \ldots, -1 \).

The container arrival rates are determined considering the real container flows in the terminal, in which the daily import flow is equal to an average of 270 containers; 70% of this flow corresponds to containers for which it is not known in advance if they will exit the terminal by truck or train, while the remaining 30% refers to containers for which it is already known that they will be transported by rail. It is also supposed that this flow of containers is constant during the whole day (this is a realistic assumption for the case under study in which the number of ships unloaded in the terminal is numerous and rather uniformly distributed along the week). Then:

- \( a_{i}^{M}(t) = 2.0 \) containers/hour, \( i = 1, \ldots, 4 \), \( t = 0, \ldots, T - 1 \);
- \( a_{i}^{R}(t) = 1.7 \) containers/hour, \( i = 1, \ldots, 2 \), \( t = 0, \ldots, T - 1 \).

Other data regard the handling resources and their capacities:

- \( O_{1} = \{1, 2, 3, 4\} \), representing the set of indexes \( i \) of the decision variable \( u_{i} \) related to one RTG crane operating in the main yard, whose maximum handling rate is \( \Omega_{1} = 30 \) containers/hour;
- \( O_{2} = \{5, 6, 7, 8, 9, 10\} \), representing the set of indexes \( i \) of the decision variable \( u_{i} \) related to the reach stacker-trailer system;
- \( O_{3} = \{1, 2, 3, 4, 5, 7, 8\} \), representing the set of indexes \( i \) of the decision variable \( u_{i}^{R} \) related to one RMG crane adopted to load containers on trains, with a maximum productivity \( \Omega_{1}^{R} = 30 \) containers/hour.

The three scenarios differ for the values of \( \Omega_{2} \) (i.e. the productivity of the reach stacker-trailer system operating in the area close to the main yard and in the second yard) and the distribution of rail slots along the day, as better specified in Table I. In particular, in scenarios 1 and 3 the productivity of the reach stacker-trailer system is \( \Omega_{2} = 18 \) containers/hour, corresponding to one reach stacker combined with two trailers, whereas in scenario 2 such productivity is doubled, hence corresponding to two reach stackers and four trailers.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( \Omega_{2} ) (cont/hr)</th>
<th>Rail slot distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>concentrated</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>concentrated</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>equally distributed</td>
</tr>
</tbody>
</table>

As regards the demand, i.e. the departures of trains from the terminal, in scenarios 1 and 2 the current situation is considered, in which rail slots are concentrated during the first hours of the day and in the late evening and night. As a matter of fact, during the central day hours, the priority to circulate on the rail network is given to passenger trains. Since in the proposed model the demand \( d(t) \) is expressed as the number of containers that exit the terminal at time step \( t \), a full train departure in a given time step \( t \) is modelled by \( d(t) = 40 \). In the first two scenarios, 6 train departures are allowed every day for a total of 42 trains per week. The daily train schedule, which is repeated equally for the entire week, considers the following departures: at 2:00 a.m., at 6:00 a.m., at 8:00 a.m., at 10:00 a.m. and at 12:00 p.m.. In scenario 3, on the other hand, 7 train departures per day are considered with the following daily schedule: at 2:00 a.m., at 8:00 a.m., at 12:00 a.m., at 4:00 p.m., at 6:00 p.m., at 10:00 p.m. and at 12:00 p.m..

With these data, Problem 1 has been solved and the optimal values of the state and decision variables have been found. The resulting problem is characterized by 81591 decision variables (34221 are binary and the remaining 47370 are continuous), 15433 equality constraints and 11463 inequality constraints. The solution is found by Cplex in about 300 seconds, with an optimality gap equal to 0.08%. The results obtained for the three scenarios are provided in the following graphs (Figs. 3-8).

![Fig. 3. Total productivity of the reach stacker-trailer system, in scenario 1.](image1)

![Fig. 4. Total productivity of the reach stacker-trailer system, in scenario 2.](image2)

![Fig. 5. Total productivity of the RMG crane, in scenario 1.](image3)

More specifically, Fig. 3 and Fig. 4 show the optimal behaviour of the reach stacker-trailer system productivity in the first and second scenario, respectively. Such productivity at each time step \( t \) has been obtained as \( \sum_{i=1}^{8} u_{i}(t) \). In scenario 2, where the productivity of the reach stacker-trailer system has been doubled, the optimal value of the relative handling rates is almost doubled as well. Moreover, in Fig. 5 and Fig. 6 the total productivity of the RMG crane is shown, again in scenario 1 and scenario 2, computed as \( \sum_{i=1}^{8} u_{i}^{R}(t), \forall t \). It
can be easily realized that, by doubling the productivity of reach stacker-trailer system in the second scenario, also the RMG crane, operating in series, increases its handling rate.

![Graph of containers](image)

**Fig. 6.** Total productivity of the RMG crane, in scenario 2.

**Fig. 7.** The daily evolution of $q^1_I(t)$, in scenario 1.

**Fig. 8.** The daily evolution of $q^3_I(t)$, in scenario 3.

Fig. 7 and Fig. 8 represent, instead, the evolution of $q^1_I(t)$, i.e. the queues modeling the internal railway park, in the first and third scenario, i.e. respectively with concentrated and distributed rail slots. In both figures the increasing curve represents the loading phase of the train, while the vertical segment indicates the instantaneous emptying of the queue and the consequent departure of the train from the internal railway park.

C. **Computational analysis**

The objective of this section is to analyse, in different cases, the computational times required to solve Problem 1, since this is a crucial aspect especially for real applications of the proposed planning approach.

With some preliminary tests it has been shown that the computational complexity of the problem is surely affected by the length of the planning horizon and the sizes of the external demand, i.e. the number of trains exiting the terminal. For this reason, in order to perform an accurate computational analysis, we have created some groups of instances characterized by different planning horizons (specifically, 1 day, 2 days, 3 days, 7 days and 30 days) and different demands (i.e. 4 trains/day, 6 trains/day and 8 trains/day). For each group, we have solved 5 instances and, for each instance, both the arrival rates and the maximum capacity of handling resources have been randomly generated. In particular, the value of the arrival rates at each time step is generated from the uniform distribution between a minimum and a maximum value, so that arbitrary (not constant) arrival rates are considered for each instance.

**Table II. Computational analysis**

<table>
<thead>
<tr>
<th>Group</th>
<th>Horizon</th>
<th>Trains/day</th>
<th>Time [s]</th>
<th>Percentage gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>4</td>
<td>8.20</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>6</td>
<td>10.64</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>8</td>
<td>53.80</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>4</td>
<td>60.00</td>
<td>0.04</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>6</td>
<td>60.00</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>8</td>
<td>60.00</td>
<td>0.08</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>4</td>
<td>60.00</td>
<td>0.03</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>6</td>
<td>60.00</td>
<td>0.04</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>8</td>
<td>60.00</td>
<td>0.07</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>4</td>
<td>300.00</td>
<td>0.01</td>
</tr>
<tr>
<td>11</td>
<td>7</td>
<td>6</td>
<td>300.00</td>
<td>0.07</td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>8</td>
<td>300.00</td>
<td>0.15</td>
</tr>
<tr>
<td>13</td>
<td>30</td>
<td>4</td>
<td>1200.00</td>
<td>0.03</td>
</tr>
<tr>
<td>14</td>
<td>30</td>
<td>6</td>
<td>1200.00</td>
<td>0.13</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>8</td>
<td>1200.00</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table II reports, for each group of instances, the average value of the computational times (in seconds) and of the optimality gap (as a percentage) in case the time limit imposed to the solver has been reached. Specifically, due to the increasing “difficulty” of the problems to be solved, the time limit for the solver has been set equal to 60 seconds for the instances of groups 1-9, equal to 300 seconds for groups 10-12 and equal to 1200 seconds for groups 13-15. It is worth noting that the solver is stopped by the time limit in all the instances except the ones of groups 1-3. However, the optimality gaps obtained in all the other cases are very low and, from a practical point of view, the relative solutions can be considered as the optimal ones; as a matter of fact, in the worst case, the optimality gap is equal to 0.21%. Then, these results show that the proposed approach can be applied for planning the rail port cycle in real cases.

IV. AN EVENT-TRIGGERED RECEIVING-HORIZON PLANNING APPROACH

A. The proposed scheme

The optimization approach proposed in Section III is suitable for planning the rail port cycle over a given planning horizon whenever all the problem data are known and correctly estimated since the beginning, i.e. the time instant in which the problem is solved. However, in real cases it can happen that some problem data and parameters are initially estimated for the considered planning horizon but, then, their values result different from the predicted ones due to unforeseen events. In the case of a container terminal, there are many aspects that cannot be easily estimated, such as the arrival times of ships, the breakdowns of handling resources, and so on. In this section, an event-triggered receding-horizon planning
scheme is proposed in order to tackle these disturbances and unpredicted situations.

The planning scheme we propose for the rail port cycle is inspired from the classical Model Predictive Control (MPC) in which, at each time step, a finite horizon optimization problem is solved over a given prediction horizon. In this problem a suitable objective function is optimized, subject to constraints on control and state variables (among these constraints there are also the state equations, allowing to take into account the prediction of the system behaviour). A sequence of optimal control variables for the whole horizon is determined but only the first element of this sequence becomes the control action at the present time step. This procedure is then iterated in the following time steps.

In the event-triggered planning approach we propose for the rail port cycle, the idea is not to solve the finite horizon problem at each time step, as in classical MPC approaches, but only when it is useful or even necessary for the system. In particular, Problem 1 has to be solved again when some problem data have changed or when, for some reasons, the system has a behaviour significantly different from the expected one.

In the event-triggered receding-horizon scheme a new finite horizon problem is solved when some triggering conditions are verified periodically, i.e. at each time step in which the planning problem is solved for the n-th time. Moreover, let $C$ be the set of conditions that yield the necessity of re-planning; in particular, it is $C = C^c \cup C^r \cup C^s$, where

- $C^c$ regards the variations on exogenous data as the arrival rates and the departure sequences;
- $C^r$ includes the variations on the system resources, i.e. on handling rates and number of internal or external tracks;
- $C^s$ considers the variations on the system state, in particular the queue lengths referred to stacking areas.

The event-triggered scheme is applied as follows. The triggering conditions are verified periodically, i.e. at each time step $h$, and if they are not fulfilled, the finite horizon problem is solved again. Assume that in $h$ the triggering conditions are not fulfilled and that the finite horizon problem has already been solved $n$ times; then the index $h_{n+1} = h$ is defined. The finite horizon problem is solved by considering $h$ as the initial time instant (corresponding to $t = 0$ in Problem 1) and the system conditions in $h$ as the problem initial conditions.

Again, assuming that the present time step is $h$ and that the finite horizon problem has already been solved $n$ times (i.e., $h > h_n$), the triggering conditions are defined in the following. In such conditions, quantities $\bar{x}$ are intended as the real values of the corresponding quantities $x$ used in the finite horizon problem.

Conditions $C^c$ are defined as follows:

$$d(l) = \bar{d}(l) \quad l = h, \ldots, h_n + T - 1$$

Conditions $C^r$ are:

$$|\Omega_k - \bar{\Omega}_k| \leq \beta \quad k = 1, \ldots, K$$

$$|\Omega_k^R - \bar{\Omega}_k^R| \leq \beta \quad k = 1, \ldots, K^R$$

$$l = \bar{l} \quad E = \bar{E}$$

Conditions $C^s$ are:

$$|q^{M_i}_i(h) - \bar{q}^{M_i}_i(h)| \leq \gamma \quad i = 1, \ldots, M$$

$$|q^{S_i}_i(h) - \bar{q}^{S_i}_i(h)| \leq \gamma \quad i = 1, \ldots, S$$

In (28), (29), (31), (32), (35) and (36), $\alpha$, $\beta$ and $\gamma$ are appropriate threshold values.

### B. Application to a real case study

The event-triggered receding-horizon planning scheme explained above has been applied to the real case study provided in Section III-B, considering a planning horizon $T = 480$, a demand of 5 trains/day, and representing a case in which the productivity of the RMG decreases suddenly as a consequence of an unexpected event. More specifically, at the initial time step (i.e. $h = 0$) the rail crane productivity is set to 30 containers/h and Problem 1 is solved over the planning horizon $T$. The optimal handling rates of the RMG crane are shown in Fig. 9.

![Fig. 9. The total handling rates of the RMG crane (optimal values obtained as solution of Problem 1 solved at $h = 0$).](image-url)
Fig. 10 and Fig. 11 show, respectively, the RMG and the reach stacker-trailer system productivity as a result of the solution of Problem 1 at $h = 192$. The decrease and the following re-increase of the RMG productivity is quite evident and obvious; the analogous trend in the reach stacker-trailer system is due to the fact that the RMG productivity decrease introduces a system bottleneck in the whole system. This causes a consequent negative variation of the reach stacker-trailer performance, which is restored only when the RMG productivity is brought to its initial value of 30 containers/h.

V. CONCLUSION

In this paper, an event-triggered receding-horizon optimization approach has been proposed for planning rail port operations. Since seaport terminals are often affected by unexpected events or disturbances to the system behaviour, as well as it is often difficult to estimate all the required data, the idea is to re-plan rail operations whenever the last defined plan is no more valid. In this sense, the proposed receding-horizon planning scheme is event-triggered, since the recomputation is done at the occurrence of specific events. The effectiveness of the proposed approach has been shown in the paper through its application to a real case study and through a computational analysis, showing that each finite horizon problem can be solved in acceptable computational times.

The proposed event-triggered receding-horizon planning approach could be applied to any container terminal also thanks to the fact that it has been devised as a very general approach, suitable to represent different situations. The application to a relevant Italian container terminal has been shown in the paper to be effective and the application to other terminals could be easily realized. As a matter of fact, if the proposed model were applied to another terminal in the world, the model sizes in terms of number of queues (and then of number of decision variables) would not change so much, since the considered model is rather aggregate. From the point of view of implementation, the procedure proposed in the paper could be applied in real terminals by interfacing it with the already present Terminal Operating Systems, even though it has to be highlighted that sometimes this is not so easy to be realized due to the narrow sensitivity of some terminal operators and technical limitations of the Terminal Operating Systems.

REFERENCES


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