Management of intermodal container terminals using feedback control

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Abstract—The problem of modelling and controlling transportation operations inside intermodal terminals is the objective of the present paper. More specifically, maritime container terminals are here considered, involving three kinds of transportation modes, namely, maritime, rail and road transport.

A simple model for the considered kind of container terminals is proposed in the paper. In the model, the position of containers and their movements inside the terminal are modelled by means of buffers. The dynamic evolutions of such buffers are described by discrete-time equations, where the control variables take into account the utilization of terminal resources as load/unload capabilities and the available yard space. On the basis of the proposed model, an optimal control problem is stated that consists in minimizing the transfer delays of containers in the terminal. A receding–horizon control strategy is proposed for the solution of such a control problem.

I. INTRODUCTION

A major feature of intermodal transportation systems is the presence of large container terminals, where loading, stocking and unloading operations are split in different tasks that depend on carrier categories, cargo types and service requirements. The efficiency of a terminal is influenced by the ability to manage the various transfer tasks done by means of quay cranes, transfer cranes, trucks and so on. The productivity of a terminal and, then, of an overall intermodal network can be significantly improved by suitably modelling and, above all, optimizing the terminal resources and their utilizations.

The literature on modelling of intermodal operations is quite recent. Different types of models have been proposed: basic simulation models [1], [2], generic discrete-event systems [3], [4] and multi agents [5]. Clearly, the choice of a model has to be made depending on the required level of detail, as well as on the specific goals of performance evaluation and decision support [6]. As a matter of fact, every modelling paradigm is affected by both advantages and drawbacks. For example, event-driven models allow to obtain a precise description of overall terminal operations but are unsuitable to synthesize a control strategy, which, on the contrary, can be more easily addressed by means of aggregate models.

In this work, an “ad hoc” designed model is proposed which constitutes the basis for developing an optimal control strategy. Specifically, the model is based on a set of queues each representing a different container allocation stage in the terminal area. A deterministic version of the model was proposed in [7]. An extension of such a model presenting two major innovative aspects is here addressed. First of all, quantities relevant to arrival and departure flows of containers are defined as unknown (but bounded) quantities. Then, as regards the control strategy, a receding-horizon control scheme in which, at each time step, the control actions are taken so as to minimize the cost function over a sliding horizon in the next future is considered. The innovation here stands in the fact that some suitable assumptions regarding the existence of a feedback control strategy for the problem under concern and at each time interval are developed following some key ideas provided in [8] in the framework of inventory control.

II. A MODEL OF TERMINAL OPERATIONS

A general structure of maritime container terminals is depicted in Fig.1. Different areas can be identified in the proposed structure; first of all, a quay is a part of the terminal devoted to handling operations with container ships. Analogously, gates for trucks and railway yards for trains are present in the terminal. The transfer machines operating in the yard are quay cranes, transfer cranes, transtainers, reach stackers and yard trucks. In the considered kind of container terminal, the storage yard also includes a dedicated area where containers are opened and goods inside containers are processed before being stocked again.

As already mentioned, the overall container terminal is modelled by representing the different physical areas as buffers. Fig. 2 describes pictorially the proposed model. Arrivals of containers at the terminal by ship, road and rail are given by quantities $a_1$, $a_2$ and $a_3$, respectively. Analogously, $d_1$, $d_2$ and $d_3$ model departures of containers from the terminal by ship, road and rail. When a container ship reaches the terminal, the unloading process is modelled...
by a queue, which has a length at time $t$ denoted by $q_1(t)$ in TEUs. Containers in this queue are routed to the same transport mode (transhipment) or to the other ones. Similarly, containers arriving by road and rail and waiting to be unloaded are buffered in the queues $q_2$ and $q_3$: in this case, the direction of transfer is only for ship export, as we deal with a maritime terminal.

After being unloaded from a ship, containers wait either in the queue $q_4$ or in the queue $q_5$, depending on whether they are going to be transferred to another ship (in this case they remain in the quay) or to trucks or trains (in this case containers are moved to the yard). Moreover, when containers are unloaded from trains, they are supposed to be located in the ground in the railway yard, waiting in the queue $q_6$, before being handled to the yard.

The containers temporary storage in the yard is made by means of the queues $q_7$ up to $q_{15}$. In particular, $q_7$, $q_8$ and $q_9$ are queues for containers that are stored in the yard and will be loaded on ship, truck and train respectively, while queues $q_{10}$ up to $q_{15}$ are queues for containers that are going to be loaded on ship, truck and train respectively, but need to be opened and worked in the yard. As a matter of fact, in this latter case, containers have to go through two queues, the former representing the wait for being processed and the latter representing the wait in the storage area. The export buffering is represented by means of the queues $q_{16}$ up to $q_{20}$. In particular, $q_{16}$ and $q_{17}$ represent queues for loading operations to ship and train, respectively, whereas $q_{18}$, $q_{19}$ and $q_{20}$ represent the wait for the departures of ship, truck and train, when their storage levels equal the external demands.

In order to better clarify the meaning of each queue of the proposed model, some sketches are provided in Figs. 3 - 5, representing the queue sequences for ship-to-ship, ship-to-truck, ship-to-train, in the case they are simply handled and not processed (the queue sequences relevant to truck-to-ship and train-to-ship containers can be simply derived). Moreover, the case of containers that are opened and processed in the yard is analogous, involving queues $q_{10}$ and $q_{11}$ for containers destined to ship, $q_{12}$ and $q_{13}$ for containers leaving by truck, and $q_{14}$ and $q_{15}$ for containers destined to train.
A complete model of the transfer activities in the terminal is described by the following discrete-time equations:

\[
\begin{align*}
q_1(t+1) &= q_1(t) + \Delta T \left[ a_1(t) - \mu_1 u_1(t) \right] \\
q_2(t+1) &= q_2(t) + \Delta T \left[ a_2(t) - \mu_2 u_2(t) \right] \\
q_3(t+1) &= q_3(t) + \Delta T \left[ a_3(t) - \mu_3 u_3(t) \right] \\
q_4(t+1) &= q_4(t) + \Delta T \left[ a_{14} \mu_4 u_4(t) - \mu_4 u_4(t) \right] \\
q_5(t+1) &= q_5(t) + \Delta T \left[ a_{15} \mu_5 u_5(t) - \mu_5 u_5(t) \right] \\
q_6(t+1) &= q_6(t) + \Delta T \left[ \mu_3 u_3(t) - \mu_6 u_6(t) \right] \\
q_7(t+1) &= q_7(t) + \Delta T \left[ a_{27} \mu_{27} u_7(t) + a_{67} \mu_6 u_6(t) - \mu_7 u_7(t) \right] \\
q_8(t+1) &= q_8(t) + \Delta T \left[ a_{58} \mu_5 u_5(t) - \mu_8 u_8(t) \right] \\
q_9(t+1) &= q_9(t) + \Delta T \left[ a_{59} \mu_5 u_5(t) - \mu_9 u_9(t) \right] \\
q_{10}(t+1) &= q_{10}(t) + \Delta T \left[ a_{10} \mu_{10} u_2(t) + a_{610} \mu_6 u_6(t) - \mu_{10} u_{10}(t) \right] \\
q_{11}(t+1) &= q_{11}(t) + \Delta T \left[ \mu_{10} u_{10}(t) - \mu_{11} u_{11}(t) \right] \\
q_{12}(t+1) &= q_{12}(t) + \Delta T \left[ a_{312} \mu_5 u_5(t) - \mu_{12} u_{12}(t) \right] \\
q_{13}(t+1) &= q_{13}(t) + \Delta T \left[ \mu_{12} u_{12}(t) - \mu_{13} u_{13}(t) \right] \\
q_{14}(t+1) &= q_{14}(t) + \Delta T \left[ a_{14} \mu_{14} u_5(t) - \mu_{14} u_{14}(t) \right] \\
q_{15}(t+1) &= q_{15}(t) + \Delta T \left[ \mu_{14} u_{14}(t) - \mu_{15} u_{15}(t) \right] \\
q_{16}(t+1) &= q_{16}(t) + \Delta T \left[ \mu_{16} u_{16}(t) + \mu_{711} u_{11}(t) + \mu_{16} u_{16}(t) \right] \\
q_{17}(t+1) &= q_{17}(t) + \Delta T \left[ \mu_{17} u_{17}(t) + \mu_{17} u_{17}(t) - \mu_{16} u_{16}(t) \right] \\
q_{18}(t+1) &= q_{18}(t) + \Delta T \left[ \mu_{18} u_{18}(t) + \mu_{15} u_{15}(t) - \mu_{17} u_{17}(t) \right] \\
q_{19}(t+1) &= q_{19}(t) + \Delta T \left[ \mu_{19} u_{19}(t) + \mu_{13} u_{13}(t) - \mu_{2} u_{2}(t) \right] \\
q_{20}(t+1) &= q_{20}(t) + \Delta T \left[ \mu_{17} u_{17}(t) - \mu_{2} u_{2}(t) \right]
\end{align*}
\]

where

- $\Delta T$ is the sampling time;
- $q_i(t) \geq 0$ is a queue length (in TEU) of containers waiting to be processed, $i = 1, \ldots, 20 \ \forall t$;
- $\alpha_{t,i,j} \geq 0$ is a sharing percentage from the queue $i$ to the queue $j$; recall that $\sum_j \alpha_{t,i,j} = 1 \ \forall i$;
- $a_i(t) \geq 0$ (i.e., $a_i(t) \geq 0$) (in TEU/h) is an arrival (departure) rate of containers, $i = 1, 2, 3 \ \forall t$;
- $\mu_i \geq 0$ (in TEU/h) is a container handling capacity, $i = 1, \ldots, 17$;
- $u_i(t) \geq 0$ is a control variable, $i = 1, \ldots, 17 \ \forall t$.

Parameters $\mu_i, i = 1, \ldots, 17$ denote the handling capacities in the different allocation stages of containers inside the terminal. A simple sketch of the meaning of such parameters is depicted in Fig. 6.

To sum up, in the proposed model $q_i(t), i = 1, \ldots, 20$ and $u_i(t), i = 1, \ldots, 17$ represent the state and the control variables, respectively. The constraints on the positivity of both state variables and control inputs are obvious but some additional requirements are necessary, i.e.,

\[
\begin{align}
&u_i(t) \leq 1 \quad i = 1, \ldots, 17 \quad \forall t \quad (2) \\
&q_i(t) \leq q_{i max} \quad i = 1, \ldots, 20 \quad \forall t \quad (3) \\
&\mu_i u_i(t) \leq q_i(t) \quad i = 1, \ldots, 17 \quad \forall t \quad (4) \\
&a_i^{M11} \leq a_i(t) \leq a_i^{M14} \quad i = 1, \ldots, 3 \quad \forall t \quad (5) \\
&d_i^{M11} \leq d_i(t) \leq a_i^{M14} \quad i = 1, \ldots, 3 \quad \forall t \quad (6)
\end{align}
\]

The meaning of constraints (2), (3), and (4) is straightforward. Constraints (5) and (6) represent the fact that arrival and departure rates of containers are unknown but bounded quantities, taking values over predefined intervals. It is to be noted that $a_2, a_3, a_2, a_3$ (i.e., trucks and trains arrival/departure rates) are effectively bounded by constant quantities which can remain unchanged in the different time instances. Rates $a_1$ and $d_1$, instead, would be more effectively bounded by time-varying values, depending on the fact that ships arrivals and departures actually occur in specific and “sparse” time instances, whereas in the remaining time instances the lower and upper bounds for $a_1$ and $d_1$ could be posed equal to zero. For the sake of simplicity, this fact is not actually taken into account, even if it can be easily introduced in the control approach that will be discussed later on. Further constraints taking into account not only the limited space in the yard but also the separation, in the yard, between containers to be opened and worked and containers to be handled only, follow.

\[
\begin{align}
&\sum_{i=7}^{9} q_i(t) \leq Y_{max}, \ t = 0, 1, \ldots \quad (7) \\
&\sum_{i=10}^{15} q_i(t) \leq W_{max}, \ t = 0, 1, \ldots \quad (8)
\end{align}
\]

### III. DESIGN OF A FEEDBACK CONTROL STRATEGY

In this section, an optimal control scheme for the considered class of systems is discussed. For the sake of brevity, the focus is on the following system description

\[
x(t+1) = x(t) + Bu(t) + Ed(t), \quad \forall t = 0, 1, \ldots
\]

where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$, and $d(t) \in \mathbb{R}^p$ are the state vector, control vector, and disturbance vector, respectively. Note that (1) can be more generally represented as (9), where $x(t) \triangleq \text{col} \left(q_i(t), i = 1, \ldots, 20 \right)$ is the set of the state variables, $u(t) \triangleq \text{col} \left(u_i(t), i = 1, \ldots, 17 \right)$ is the control vector, and $d(t) \triangleq \text{col} \left(a_1(t), a_2(t), a_3(t), d_1(t), d_2(t), d_3(t) \right)$ is the vector that...
includes all the uncontrollable inputs, which can be regarded as disturbances.

The following constraints are assigned to the model:

$$\bar{x}(t) \in X, \ u(t) \in U, \ d(t) \in D$$ \hspace{1cm} (10)

where $X \subseteq \mathbb{R}^n$, $U \subseteq \mathbb{R}^m$, and $D \subseteq \mathbb{R}^p$ are compact sets. The constraint sets (10) enable to account for the positivity of the variables as well as for (2)-(6). As to matrices $B$ and $E$, they can be easily derived from the model equations.

Among the possible control strategies, feedback control is generally preferable and will be specifically addressed. In this respect, some preliminary definitions and notations necessary to define a general control scheme are now reported for the sake of clarity.

**Definition.** Given system (9) subject to constraints (10), the function $\Phi : X \rightarrow U$ is an admissible control strategy and $X_0 \subseteq X$ is an admissible initial condition set, if, for all $\bar{x}(0) \in X_0$ and for all $d(t) \in D$, $t = 0, 1, \ldots$, the sequences $\bar{x}(t)$ and $u(t) = \Phi(\bar{x}(t))$ are feasible (i.e., $\bar{x}(t) \in X$ and $u(t) \in U$).

Some further notations still need to be introduced. Given two sets $X \subseteq \mathbb{R}^n$ and $S \subseteq \mathbb{R}^n$, the erosion of $X$ with respect to $S$ is defined as

$$X_S = \{ x \in \mathbb{R}^n : x + s \in X, \forall s \in S \}$$ \hspace{1cm} (11)

A general result on the existence of feedback control for systems given by (9) is available from the literature.

**Theorem 1.** (see [8]) There exist an admissible control strategy and an admissible initial condition set if and only if the following conditions are verified

$$X_{ED} \neq \emptyset$$ \hspace{1cm} (12)

$$ED \subset -BU.$$ \hspace{1cm} (13)

Moreover, the largest initial condition set is

$$X_0 = (X_{ED} - BU) \bigcap X$$ \hspace{1cm} (14)

and any function $\Phi(x) \in U$ such that

$$\bar{x} + B\Phi(\bar{x}) \in X_{ED}, \ \forall \bar{x} \in X_0, t = 0, 1, \ldots$$ \hspace{1cm} (15)

is an admissible control.

A fundamental aspect regarding the proposed control scheme is the possibility of managing terminal operations in some optimal sense. To this end, a discrete-time receding-horizon (RH) control scheme is proposed. More specifically, consider the finite-horizon (FH) cost function as

$$J^{FH}(\bar{x}(t), u(t, t + N - 1)) = \sum_{k=t+1}^{t+N} c^T(k) x(k), \ t = 0, 1, \ldots$$ \hspace{1cm} (16)

where $u(t, \tau) \triangleq \operatorname{col}(u(t), \ldots, u(\tau))$, $c_i \in \mathbb{R}^n$, $c_i > 0$, $i = 1, 2, \ldots, n$, and $N$ is a positive integer corresponding to the length of the control horizon. Cost function (16) is very simple with respect to other performance indices (see, as instance [9], [10]). In particular, here the objective is the minimization of the sum of queue lengths and, then, of the total transfer delay in the terminal.

Then we can state the following problem.

**Problem 1.** At a generic time instant $t$ and with reference to the state $\bar{x}(t)$, find the FH optimal feedback control sequence $\{u(t)^{FH}, \ldots, u(t + N - 1)^{FH}, t = 0, 1, \ldots\}$ that minimizes cost (16) subject to (9), (10).

Problem 1 has the structure of a linear mathematical programming problem that can be optimally solved by the Simplex algorithm (and, thus, by standard mathematical programming software tools). Then, thanks to the RH mechanism, once the solution of Problem 1 has been achieved, only the first optimal FH control function (i.e., the one corresponding to $j = t$) is actually applied to the system. This means that

$$u(t)^{RH} \triangleq u(t)^{FH}, \ \forall t = 0, 1, \ldots$$ \hspace{1cm} (17)

and, more clearly, the RH control mechanism corresponds to the solution of the following problem:

**Problem 2.** At every time instant $t = 0, 1, \ldots$, find the RH optimal control law $u(t)^{RH}$ as the first vector of the control sequence $u(t)^{FH}, \ldots, u(t + N - 1)^{FH}$, solution of Problem 1 for the state $\bar{x}(t)$.

Note that the general result of Theorem 1 holds true for the RH optimal control law $u(t)^{RH}$, which is feedback. However, it is important to ensure that the control law can perform over an arbitrarily large period, which requires the following assumption.

**Assumption 1.** Given system (9) subject to constraints (10), the solution of Problem 2 at time $t = 0$ is feasible.

**Lemma 1.** Assume that Assumption 1 hold. Then Problem 2 is feasible $\forall t = 1, 2, \ldots$

**Proof.** Assumption 1 guarantees that there exists a solution to Problem 1 at time $t = 0$ and let us denote such a solution with $u(0, N - 1|t = 0)^{FH}$. Consider Problem 2 at time $t = 1$ and note that the corresponding Problem 1 at time $t = 1$ admits $u(1, N|t = 1)^{FH} = \operatorname{col}[u(1, N - 1|t = 0)^{FH}, 0]$ as a feasible solution. This can be repeated in turn from a generic time step $t$ to the next $t + 1$, which allows to conclude.

**IV. APPLICATION OF THE MODEL TO A CASE STUDY**

The effectiveness of the proposed control scheme has been tested using real data relevant to a container terminal of an Italian port. To this end, a simulative tool implementing the control scheme has been realized by interfacing Matlab 6.5.1 framework with Lindo 6.1 mathematical programming software. More specifically, the RH mechanism working in Matlab uses the Lindo optimization kernel to solve, at
every time instant, the current instance of Problem 1. The interface between the two software frameworks is developed by means of the high level interface tools Lindo API 2.0.

The container terminal here considered is supposed to have a throughput of 720 TEUs per day, that corresponds to 21600 TEUs a year, if it is assumed that the terminal works continuously, 24 hours a day and 365 days a year. The traffic flows are splitted up as follows:

- from ship to ship (transhipment flows): 72 TEUs a day (10%);
- from ship to truck: 252 TEUs a day (35%);
- from ship to train: 72 TEUs a day (10%);
- from truck to ship: 216 TEUs a day (30%);
- from train to ship: 108 TEUs a day (15%).

For the sake of simplicity, arrival and departure flows of containers are here considered as exogenous random variables. The ship arrival rate is equal to 396 TEUs a day; since it is assumed that 200 TEUs are unloaded from a ship on average, it is possible to state that 2 ships a day arrive in this container terminal, in other words a ship arrives every 12 hours. Therefore, the ship arrival rate 

\[ \alpha_{1} \]

in TEU/h is often posed equal to zero, because in some time intervals no ships arrive; on the contrary, \( \alpha_{1} \) will be different from zero in some time instants, that are fitted by a Normal probability distribution, with mean \( \mu = 12 \) and mean square deviation \( \sigma = 2 \). As regards the value of \( \alpha_{1} \), it is assumed to be an integer random number between 190 and 210.

The ship departure rate is equal to 396 TEUs a day, that is the same quantity as the ship arrival rate. Moreover, the ship departure rate \( \alpha_{2} \) is dependent on the ship arrival rate \( \alpha_{1} \), since it is assumed that it is not possible that a ship leaves the port without being loaded. Another assumption considers that the number of containers unloaded from a ship is exactly equal to the number of containers loaded on the same ship. All these hypotheses imply that \( \alpha_{2} \) is exactly equal to \( \alpha_{1} \), but translated of 20 hours (average time for unloading and then loading a ship).

The truck arrival rate is equal to 216 TEUs a day; since each truck is supposed to carry 1 TEU, this means that 9 trucks arrive every hour at the terminal, on average. In particular, the pattern of truck arrivals \( \alpha_{3} \) is assumed as an integer random variable, that can vary between 7 and 11 TEU/h. The truck departure rate is equal to 252 TEUs a day; this means that 10.5 trucks leave every hour the terminal, on average. In particular, the pattern of truck departure rate \( \alpha_{4} \), as the truck arrival rate \( \alpha_{3} \), is assumed to be an integer random variable, that can vary between 9 and 12 TEU/h.

The train arrival rate is equal to 108 TEUs a day; since each train is supposed to carry 18 TEUs, this means that 6 trains arrive every day at the terminal. Therefore, a train arrives every 4 hours, on average; in particular, the intervals at which a train arrives are assumed as following a Normal probability distribution, with mean \( \mu = 4 \) and mean square deviation \( \sigma = 1 \). The value of \( \alpha_{5} \), when it is not equal to zero, is considered an integer random number between 16 and 20. The train departure rate is equal to 72 TEUs a day; since each train is supposed to carry 18 TEUs, this means that 4 trains leave every day the terminal. Therefore, a train leaves every 6 hours, on average; in particular, the intervals at which a train leaves, as for trains arrivals, are assumed as following a Normal probability distribution; in particular, as regards train departures, this distribution has mean \( \mu = 6 \) and mean square deviation \( \sigma = 1 \). Analogously to \( \alpha_{3} \), the value of \( \alpha_{6} \), when it is not equal to zero, is considered an integer random number between 16 and 20.

In the case study here discussed, all container handling capacities \( \mu_{i} \) have been posed equal to 50 TEU/h. Moreover, an important assumption is made: among containers stored in the yard, half are handled only, while the other half are opened and processed. This hypothesis, together with the previously described division of traffic flows, permits to calculate the values of \( \alpha_{i,j} \), as follows:

- \( \alpha_{1,4} = 0.18 \);
- \( \alpha_{1,5} = 0.82 \);
- \( \alpha_{2,7} = \alpha_{3,10} = 0.5 \);
- \( \alpha_{6,7} = \alpha_{6,10} = 0.5 \);
- \( \alpha_{5,8} = \alpha_{5,12} = 0.39 \);
- \( \alpha_{5,9} = \alpha_{5,14} = 0.11 \).

The cost coefficients \( c_{i} \), \( i = 1, \ldots, 20 \) in the objective function have been fixed as follows:

- \( c_{1} = c_{2} = c_{3} = c_{18} = c_{19} = c_{20} = 2.0 \);
- \( c_{4} = c_{5} = c_{6} = c_{16} = c_{17} = 1.8 \);
- \( c_{i} = 1.0, i = 8, \ldots, 15 \).

The above chosen coefficients take into account the following aspects: first of all loading and unloading operations must be realized as soon as possible. Moreover, containers must be stored in the quay and in the railway yard only when it is necessary. Finally, the RH time horizon is equal to 50 time intervals (hours), while the FH time horizon is supposed equal to 10 time intervals (hours).

Figs. 7 report some simulation results regarding this case study. In particular, Fig. 7 shows containers in the queue \( q_{1} \), that is containers waiting to be unloaded from the ship. Looking at this graph, it is quite clear that when a ship arrives, it is unloaded as soon as possible. In this particular case, since a ship carries about 200 TEUs and the unloading capacity is assumed to be equal to 50 TEUs/h, the unloading operations take about 4 hours to be accomplished. The same
meaning can be associated with Fig. 8, in which the control variable $u_1$ associated with queue $q_1$ is equal to 1 when the ship arrives, until it is completely unloaded, and then it is posed equal to 0.

Figs. 9 and 10 show containers stored in the quay (sum of $q_4$, $q_5$, and $q_{16}$) and in the yard (sum of $q_7$, $q_8$, $q_9$, $q_{10}$, $q_{11}$, $q_{12}$, $q_{13}$, $q_{14}$, and $q_{15}$), respectively. As it happens in a real maritime terminal, containers stored in the quay are fewer than those stored in the yard. Finally, Fig. 11 shows the control variable of queue $q_8$, which never exceeds the value 0.3. This means that the corresponding handling capacity $\mu_8$, posed equal to 50 TEU/h, is overestimated.

REFERENCES


Fig. 8. Control variable $u_1$.

Fig. 9. Containers in the quay.

Fig. 10. Containers in the yard.

Fig. 11. Control variable $u_8$. 