Technical report

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Delft University of Technology, Delft, The Netherlands

# A Novel Predictive Control Based Framework for Optimizing Intermodal Container Terminal Operations

João Lemos Nabais[1], Rudy R. Negenborn[2], and Miguel Ayala Botto[3]

[1] IDMEC, Department of Informatics and Systems Engineering
Setúbal School of Technology, Polytechnical Institute of Setúbal
Setúbal, Portugal
joao.nabais@estsetubal.ips.pt
[2] Delft University of Technology, Marine and Transport Technology
Transport Engineering and Logistics,
Delft, The Netherlands
r.r.negenborn@tudelft.nl
[3] IDMEC, Instituto Superior Técnico, Technical University of Lisbon
Department of Mechanical Engineering
Lisboa, Portugal
ayalabotto@ist.utl.pt

**Abstract.** Due to the increase in world-wide containerized cargo transport port authorities are facing considerable pressure to increase efficiency of existing facilities. Container vessels with $18,000$ TEUs (twenty-foot equivalent units) are expected soon to create high flow peaks at container terminals. In this paper we propose a new framework for managing intermodal container terminals, based on the model predictive control methodology. A model based on queues and container categorization is used by a model predictive controller to solve the handling resource allocation problem in a container terminal in an optimal way, while respecting constraints on resource availability. The optimization of the operations is performed in an integrated way for the whole terminal rather than only for an individual subprocess. Containers are categorized into empty and full containers, and divided in classes according to their final destination. With more detailed information available, like container final destination, it is possible to establish priorities for the container flows inside the terminal. The order in which the container classes should be loaded into a carrier can now be addressed taking into account the carrier future route. The model ability to track the number of containers per class makes this framework suitable for describing terminals integrated in an intermodal transport network and a valuable tool for coordinating the transport modal shift towards a more sustainable and reliable transport. The potential of the proposed framework is illustrated with a simulation study based on a high-peak flow scenario.

**Keywords:** intermodal transport, container terminals, flow networks, model predictive control

## 1 Introduction

Despite the current economic situation, on the mid to long-term the transportation of goods over water and tracks will keep increasing [3]. Sea port Rotterdam in the Netherlands (the tenth largest container port in the world and the largest container port of Europe in TEU transhipped in $2011$) expects in $2030$ a doubling of the number of full and empty containers, and in addition aims at an increase of the modal split in favor of inland shipping from $25\%$ to $45\%$ in $2030$. Already now major deep sea terminals (also outside The Netherlands) are reaching their maximum capacity. The expected increase in transported container volume will cause more terminals to reach their limits. In addition, the capacity of deep sea vessels has grown from $1,500$ TEU in $1980$ to about $14,500$ TEU in $2006$ [4]. This increase in vessel sizes leads to an increase in peak call sizes at terminals. Handling these larger volumes of instantaneously arriving load takes a significant amount of time and moreover delays other terminal operations. As a consequence, transit times of containers become more delayed. This on its turn affects the connecting transportation means (truck, barge and train), which therefore have to face long waiting times at terminals: in Rotterdam trucks may have to wait up to $6$ hours and barges have been reported to wait between $24$ and up to $72$ hours [11].

The container transportation network is composed by nodes (describing terminals, depots or warehouses) and links (describing available connections). According to [12] inland transportation accounts for a considerable part of the total cost for container shipping between $40\%$ to $80\%$. A container terminal is a complex system where solutions to different problems have to be integrated, like berth scheduling and resource allocation. Different scientific communities, such as operations research and more recently control systems, have devoted attention to the optimization of operations inside the container terminal, in particular those container terminals located at the sea [$1, 13, 16$]. One of the main approach for optimizing container terminal operations is based on finding an optimal handling resource allocation that can increase the freight flow through the terminal [5]. However, in some works only part of the terminal operations are considered: serving vessels, transfer between the quay and the yard [14]. All these approaches are common in the sense that they consider containers as undistinguished units and therefore they lack a basis to support strategic planning in a transportation network. Distinguishing containers can be extremely useful for developing measures at a strategic level to increase network performance.

The model and control strategy proposed in this paper is able to solve the handling resource allocation problem while at the same time tracking the containers final destination inside the network. The contribution of the model is the ability to deal with different container types, in particular it distinguishes empty and full containers and this last type is further categorized based on final destination. This feature allows further insight into the operations management of an intermodal terminal. More information regarding the container's final destination has to be shared in the transport network, while for trust reasons the privacy of the final customer should be respected. The information exchange required is likely to happen if benefits are shown to all actors in the transport network. With this framework it is possible to use a forecast of scheduled requests for unloading/loading of containers for each carrier. The container flow will be measured by the volume of TEUs in a time period. The container flows inside the intermodal terminal are determined in an optimal way by a so-called model predictive controller according to a defined performance index over a prediction horizon. Through the performance index it is possible to assign time varying priorities to container flows.

In this paper a new framework for intermodal container terminal operations management is proposed. In Section 2 the model used for describing the flows existing inside the intermodal container terminal is given. The resource allocation problem is formulated in Section 3 and addressed using a model predictive control strategy that solves an optimization problem at each discrete sample time. The performance of the proposed framework is tested through numerical simulations in Section 4 for a hinterland intermodal terminal taking into account the terminal layout and the available transport network connections. In Section 5 final conclusions are drawn and future research topics are addressed.

## 2 Modeling Intermodal Container Terminals

The intermodal container terminal is a key element in the transport network. A transport network can be represented by a graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ where the nodes $\mathcal{V}$ represent terminals or hubs and the links $\mathcal{E}$ represent the available transport mode connections. The challenge when looking at the container transport problem from a network perspective is to assure the cooperation between the different transport network actors (merchants, forwarders, terminal managers, shippers, infrastructure owners...) towards a more sustainable and reliable transport system. A terminal model should capture the necessary information to support the transport network analysis that is aimed at a more sustainable transport system.

The basic goal of a transport network is to deliver the cargo at the agreed time and at the agreed location (customer request) while minimizing the cost of transport (service provider request). The transport network actors have a challenge of satisfying the customer request while reducing the transport costs to remain competitive in a competitive sector. Reducing transport costs is related to an optimal route choice inside the transport network. For example, the shortest route in time may be the best option when time comes as a priority for respecting the agreed due time or if there is sufficient time left the option may be using a longer route but with less transport costs. For this objective it is required to distinguish containers inside the transport network according to their final destination. In this work the final destination of a container means the last terminal the container should visit before being transported by truck to the final customer. In this way the privacy of a client is still assured.

### 2.1 Proposed Model

A transport network is composed of a group of terminals or depots where cargo is redirected to the final destination and may undergo a transport mode switch. The proposed intermodal terminal model for describing the terminal dynamics is based on a flow perspective. The terminal model is basically a network of stowage areas described as queues that are connected by container handling capacity represented by links. The model describing the terminal dynamics is based on two main features:

– queues, to model the stowage capacity related to well-defined areas inside the terminal. From a network perspective these terminal areas are also referred to as nodes of the terminal-related network.

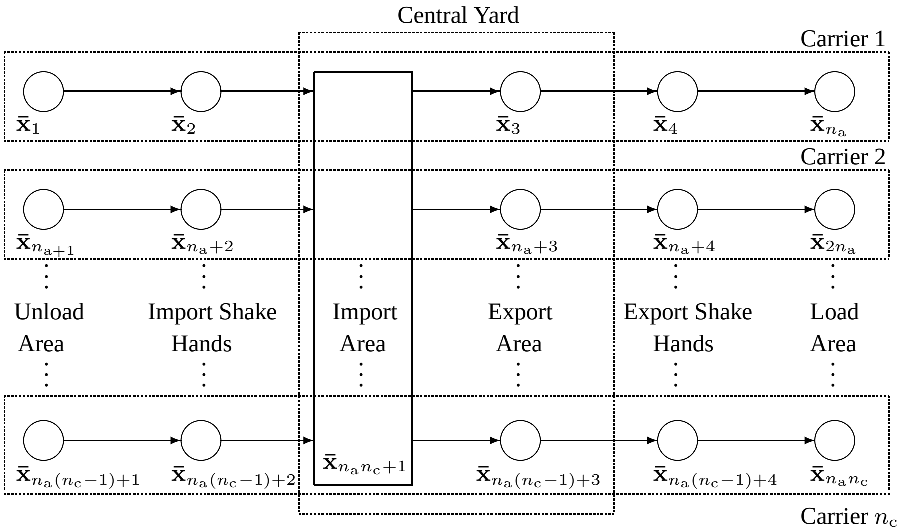



**Fig. 1.** Terminal-related network where the flow corresponding to a single carrier crosses 5 terminal areas plus a common area. The state-space vector $\bar{\mathbf{x}}_i$ description is given in equation (1).

– categorization of containers: if a container is empty or a full container, and for a full container a division is made according to its destination.

Combining the information of stowage volume and container category the intermodal terminal model can track the flow of containers of a particular class inside the terminal. The assumptions made in this work are intended to produce a general framework able to describe different terminal layouts.

The complexity of the terminal model is determined by the following parameters:

– $n_t$: number of container types considered in the transport network. A distinction is made between empty and full containers; full containers are further divided according to their final destination;
– $n_c$: number of different carriers served at the same time at the terminal. It is possible that a transport mode (deep sea, barge and trains) serves several carriers at the same time; for example more than one feeder or barge may be at the quay;
– $n_a$: number of terminal areas related specifically to one single carrier.

The terminal is considered divided in two main areas, see Fig. 1:

**Import Operations:** when a carrier arrives it brings containers that should be unloaded (unload demand – pushes containers to the terminal). The import flow starts at the *Unload Area* and goes until the *Import Area* at the *Central Yard* in Fig. 1;

**Export Operations:** when a load request for containers is assigned to a carrier (load demand – pulls containers from the terminal). In Fig. 1 starts from the *Export Area* and finishes at *Load Area*.

These two operations are the requested service the terminal should provide and are referred as a carrier service or demand. For each individual carrier a standard container flow is established consisting of the following operations:

1. unload the containers from the carrier according to the demand;
2. transport the containers from the *Unload Area* into the terminal *Import Area*;
3. rehandle the containers in the *Central Yard* from the *Import Area* to the *Export Area* according to the load demand;
4. take the containers from the *Export Area* to the *Load Area*;
5. load the containers into a carrier.

For the sake of simplicity and without loss of generality, according to this flow pattern the number of exclusive terminal areas per carrier $n_\mathrm{a} = 5$ is assumed to be a fixed parameter in the model. This parameter can be made varying for each carrier to model different terminal layouts. The control action is the number of containers per container type to move between different terminal areas per unit time; that is the container flow. The unloading/loading of a container from/to a ship is done with the same resource (quay crane) while the transfer to/from the *Central Yard* is made by another resource (automated guided vehicle or other); this transport mode switch is realized at the *Import/Export Shake Hands* areas. The *Import Area* located at the *Central Yard* is a special area inside the terminal as it is the only area common to all carriers where containers are stacked and wait to be picked up by some shipper.

For each node in the terminal-related network a state-space vector $\bar{\mathbf{x}}_i(k)$ is defined, and these are merged to form the state-space vector $\mathbf{x}(k)$ of the complete terminal,

$$\bar{\mathbf{x}}_i(k) = \begin{bmatrix} x_i^1(k) \\ x_i^2(k) \\ \vdots \\ x_i^{n_\mathrm{t}}(k) \end{bmatrix}, i = 1, \ldots, n_\mathrm{a}n_\mathrm{c} + 1, \quad \mathbf{x}(k) = \begin{bmatrix} \bar{\mathbf{x}}_1(k) \\ \bar{\mathbf{x}}_2(k) \\ \vdots \\ \bar{\mathbf{x}}_{n_\mathrm{a}n_\mathrm{c}+1}(k) \end{bmatrix}, \tag{1}$$

where $x_i^j(k)$ is the volume of containers of type $j$ at node $i$ at time instant $k$. The total number of nodes within a terminal network is associated with the number of carriers served and is given by $n_\mathrm{a}n_\mathrm{c}+1$. The state-space $\mathbf{x}(k)$ dimension is given by $n_\mathrm{t}(n_\mathrm{a}n_\mathrm{c}+1)$ corresponding to the number of available destinations from the terminal and carriers served simultaneously. The model for the terminal dynamics can now be represented in a compact form as,

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}_\mathrm{u}\mathbf{u}(k) + \mathbf{B}_\mathrm{w}\mathbf{w}(k) \tag{2}$$
$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) \tag{3}$$
$$\mathbf{x}(k) \geq \mathbf{0}, \tag{4}$$
$$\mathbf{u}(k) \geq \mathbf{0}, \tag{5}$$
$$\mathbf{y}(k) \leq \mathbf{y}_\mathrm{max}, \tag{6}$$
$$\mathbf{P}_\mathrm{uu}\mathbf{u}(k) \leq \mathbf{u}_\mathrm{max}, \tag{7}$$
$$\mathbf{x}(k) \geq \mathbf{P}_\mathrm{xu}\mathbf{u}(k) \tag{8}$$
$$\mathbf{x}(k) \in \mathcal{X} \tag{9}$$
$$\mathbf{u}(k) \in \mathcal{U} \tag{10}$$

where $\mathbf{u}(k)$ is the control action vector with length $n_\mathrm{u} \times 1$ with $n_\mathrm{u} = n_\mathrm{t}n_\mathrm{a}n_\mathrm{c}$, $\mathbf{w}(k)$ is a disturbance vector related to the arrival/departure schedule over time with dimension

$2n_\mathrm{t}n_\mathrm{c}$, $\mathbf{y}(k)$ is the current container volume at all nodes with dimension $n_\mathrm{y} = n_\mathrm{a}n_\mathrm{c}+1$, $\mathbf{y}_{\max}$ are the maximum storage capacities of the terminal areas, $\mathbf{u}_{\max}$ the maximum handling capacities according to the terminal design, $\mathbf{A}$, $\mathbf{B}_\mathrm{u}$, $\mathbf{B}_\mathrm{w}$ and $\mathbf{C}$ are the state-space matrices, $\mathbf{P}_\mathrm{xu}$ is the projection from the control action set $\mathcal{U}$ into the state-space set $\mathcal{X}$ and $\mathbf{P}_\mathrm{uu}$ is the projection matrix from the control action set $\mathcal{U}$ into the maximum handling capacity set $\mathcal{U}_{\max}$.

The terminal state of $\mathbf{x}$ at the next time step, $k+1$, is determined using (2) as a function of the current terminal state $\mathbf{x}(k)$ plus the contribution due to the control action $\mathbf{u}(k)$ decided upon by the terminal manager and the corresponding disturbances $\mathbf{w}(k)$ capturing the arrival and departure of carriers. The model output $\mathbf{y}(k)$ can be chosen as a combination of the terminal areas state $\bar{\mathbf{x}}_i(k)$ through the use of matrix $\mathbf{C}$. The control action $\mathbf{u}(k)$ is the flow of containers between nodes and is imposed through a corresponding resource allocation. Disturbances are impulses happening in time instants related to the arrival and departure of carriers and with an intensity corresponding to the load/unload request for that carrier. Inequalities (4)–(8) are necessary in this framework for imposing the terminal structural layout and assumptions made:

**Nonnegativity of States and Control Actions:** negative storage is not physically possible, imposed by (4), and all decision variables are assumed to be nonnegative, this is guaranteed by (5);

**Storage Capacity:** each terminal area has to respect its own stowage capacity and this is represented by (6). Considering the terminal-related network in Fig. 1 it is important to note that different nodes may be associated to the same physical location. For example, the different state-space variables concerning *Import/Export Shake Hands* areas should be considered together as they are describing the same physical location, and naturally share the same constraints;

**Maximum Handling Decisions:** the terminal structural layout in terms of handling capacity and handling resource type used for the different container transfer inside the yard is represented by (7). Different terminal layouts can be easily translated into the model. For example, if the same handling resource is used for all terminal transfer operations [16] this will affect the projection matrix $\mathbf{P}_\mathrm{uu}$;

**Consistent Handling Decisions:** not all handling decisions that satisfy (4) and (5) are allowed. The control action has to respect the existence of container type in the related terminal area and therefore equation (8) imposes this relation.

## 3 Model Predictive Control

Over the last decades Model Predictive Control (MPC) [9] has become an important strategy for finding control policies for complex, dynamic systems. MPC has shown successful applications in the process industry [9], and is now gaining increasing attention in fields like container terminals [2], power networks [6], water distribution networks [10] and road traffic networks [7].

MPC is an online optimization-based control approach that minimizes an objective function subject to constraints. The motivation for using such an approach arises from the following. In transport systems, costs can be associated to actions and states. Models can be constructed that describe how particular transport systems behave. By making

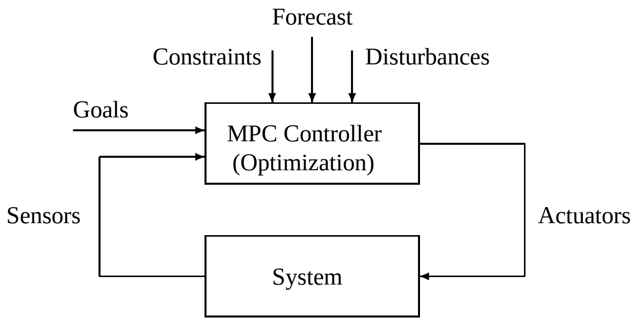



**Fig. 2.** Model predictive control structure.

predictions over a certain prediction horizon using these models, an MPC controller can determine which actions have to be chosen in order to obtain the best performance. An MPC controller determines which action to take at discrete control steps. At each control step the controller first obtains the current state of the system it controls using sensors, Fig. 2. It then formulates an optimization problem, using the desired goals existing constraints, disturbances and forecast information if available. The solution to the optimization problem determines the actions over the prediction horizon that give the best predicted performance. The controller implements these actions, using the existing actuators, until the beginning of the next control step, at which time the MPC controller repeats these steps in a receding horizon fashion, i.e., by obtaining new information about the current state and by reformulating the optimization problem starting from the next control step.

**Cost Function:** Terminal performance can be evaluated in different ways depending on the chosen perspective; the throughput of the terminal [1] or the customer satisfaction in terms of cost, time and service quality [15] are common choices. In this work we consider the throughput of the terminal as a performance index. With higher flows more competitive prices can be offered by the terminal managers in order to expand the market share and with that increase profit. The throughput can be increased by reducing the lay time of carriers, which increases the capacity available for receiving carriers. In our case, this performance index is translated into a mathematical representation using a weighted sum of the queues at the terminal areas while respecting the scheduled departure times. A weight $\mathbf{q}_i$ is associated at each sample time to the existing queues at each node,

$$\sum_{i=1}^{n_\mathrm{a}n_\mathrm{c}+1} \mathbf{q}_i^\mathrm{T}(k)\bar{\mathbf{x}}_i(k) = \left[\, \mathbf{q}_1^\mathrm{T}(k)\; \mathbf{q}_2^\mathrm{T}(k)\; \ldots\; \mathbf{q}_{n_\mathrm{a}n_\mathrm{c}+1}^\mathrm{T}(k) \,\right] \mathbf{x}(k) = \mathbf{q}_\mathrm{p}^\mathrm{T}(k)\mathbf{x}(k) \tag{11}$$

where $\mathbf{q}_\mathrm{p}$ can be time varying to allow changing the flow priorities according to the different terminal operation requests. Using this objective function it is possible to put different weights on different terminal areas, container types and carriers according to their role in the terminal dynamics and the desired strategic behavior. In this paper, we show that it is possible to act directly on the container flows inside the terminal. Flow priorities can be easily introduced in the optimization problem with a careful choice of weights, translating terminal operational requests into the optimization problem, namely:

– carriers can receive a higher priority according to the size of the requested operation;
– for the unloading and loading operations it is possible to define the desired order for handling each container type. This is particularly useful for letting the loading of empty containers be the last operation such that in case of a delay or anticipated departure the impact on transported cargo is bounded;
– any combination of priorities is possible. For example, in case of transshipment of one container type between two carriers simultaneously at the quay, maximum priority may be given for the pair container/carrier in the import area and minimum priority in the export area for the pair container/carrier such that the transhipment is fulfilled in the time window available.

The cost function is defined over the prediction horizon,

$$J(k) = \sum_{i=0}^{\mathrm{N}-1} \mathbf{q}_{\mathrm{p}}^{\mathrm{T}}(k+1+i)\mathbf{x}(k+1+i), \tag{12}$$

where N is the length of the prediction horizon.

**Constraints:** constraints are necessary to incorporate into the optimization problem the terminal system dynamics (2)–(10). The loading request imposed by clients is introduced in the optimization problem through,

$$\mathbf{P}_{\mathrm{dx}}\mathbf{x}(k) \leq \mathbf{w}_{\mathrm{d}}(k) \tag{13}$$

where the forecast load request vector $\mathbf{w}_{\mathrm{d}}(k+i)$ has to be updated at each sample time and $\mathbf{P}_{\mathrm{dx}}$ is the projection matrix from the state-space set into the load request set.

**MPC Problem Formulation:** the MPC optimization problem can be formulated as:

$$\min_{\mathbf{u}(k)} \sum_{i=0}^{\mathrm{N}-1} \mathbf{q}_{\mathrm{p}}^{\mathrm{T}}(k+1+i)\mathbf{x}(k+1+i) \tag{14}$$

$$\text{subject to } \mathbf{x}(k+1+i) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}_{\mathrm{u}}\mathbf{u}(k) + \mathbf{B}_{\mathrm{w}}\mathbf{w}(k), \tag{15}$$

$$\mathbf{y}(k+i) = \mathbf{C}\mathbf{x}(k), \quad i = 0, \ldots, \mathrm{N}-1, \tag{16}$$

$$\mathbf{x}(k+1+i) \geq \mathbf{0}, \tag{17}$$

$$\mathbf{u}(k+i) \geq \mathbf{0}, \tag{18}$$

$$\mathbf{y}(k+i) \leq \mathbf{y}_{\max}, \tag{19}$$

$$\mathbf{P}_{\mathrm{uu}}\mathbf{u}(k+i) \leq \mathbf{u}_{\max}, \tag{20}$$

$$\mathbf{x}(k+i) \geq \mathbf{P}_{\mathrm{xu}}\mathbf{u}(k+i), \tag{21}$$

$$\mathbf{P}_{\mathrm{dx}}\mathbf{x}(k+1+i) \leq \mathbf{w}_{\mathrm{d}}(k+1+i). \tag{22}$$

The problem is a constrained linear programming problem, due to the linear cost function and the existence of linear constraints.

## 4 Numerical Results

The presented framework is applied for a hinterland intermodal container terminal. Such a terminal is the basis of the hinterland transport network. Our focus is on considering the intermodal container transport problem as a network flow problem. We first define the throughput desired for the terminal in terms of import/export container flows, then the transport mode capacities available at the terminal and finally a fixed schedule for the hinterland transport mode connections is assumed to be imposed by shippers.

**Computational Scenario Design** Every intermodal container terminal faces two different types of flows:

**Import Flow:** all containers that are brought into the terminal by the available connections and that will be unloaded and stacked at the central yard waiting to be picked up by some other transport mode;

**Export Flow:** all containers that are waiting in the terminal and are redirected to an available connection proceeding towards the final destination.

It is assumed that the terminal will face an average week flow around $16,800$ TEUs, divided smoothly into import and export flows. On a yearly basis the hinterland terminal will face a flow of $890 \times 10^3$ TEUs. Consider this terminal layout to face the desired yearly throughput:

– a quay area able to berth simultaneously two barges at maximum. Containers will be unloaded/loaded from/to barges by quay cranes. The maximum terminal capacity is of $90$ TEUs/hour. In berth area A the maximum quay crane capacity of the terminal can be used while for berth area B only a handling capacity of $45$ TEUs/hour is available;
– there are two rail tracks in the area reserved for the train transport mode. Containers will be unloaded/loaded from/to wagons using straddle carriers and a maximum capacity of $40$ TEUs/hour is available;
– an area reserved for the truck transport mode is also included with a maximum capacity of serving $30$ TEUs/hour in single mode.

The transport transfer between the quay and the *Central Yard* is implemented by the same handling resource. The rehandling of containers at the *Central Yard* from the *Import Area* to the *Export Area* (or in other words reshuffling containers to prepare the loading operation) is performed by a different handling resource. Trucks and trains have their own handling resources for unload/load operations and for transfer to/from the *Central Yard*. The terminal handling resources are given in Table 1. The available handling resources inside the terminal are expressed as flows (TEUs/unit time) in accordance with the flow perspective used for modeling the terminal. Concerning the storage capacities the *Central Yard* total capacity is considered sufficiently large to never restrict terminal operations. The *Import/Export Shake Hands* storage capacities are limited to the respective unload/load maximum capacity for each carrier: $90$ TEUs for barge A, $45$ TEUs for barge B, $20$ TEUs for train A, $20$ TEUs for train B and $30$ TEUs in single

| Handling Resource | Maximum Flow | Handling Resource | Maximum Flow |
|---|---|---|---|
| Quay Cranes | 90 TEUs/h | Quay - Yard | 135 TEUs/h |
| Berth A | 90 TEUs/h | Rehandling | 190 TEUs/h |
| Berth B | 45 TEUs/h | Train Gates - Yard | 40 TEUs/h |
| Train Gate A | 40 TEUs/h | Truck Gates - Yard | 30 TEUs/h |
| Train Gate B | 40 TEUs/h | Truck Gate | 30 TEUs/h |

**Table 1.** Hinterland terminal handling resources.

| Transport Mode | TEUs / week | TEUs / year | share |
|---|---|---|---|
| Barge | $7,200$ | $382 \times 10^3$ | $42.9\%$ |
| Train | $3,840$ | $203 \times 10^3$ | $22.8\%$ |
| Truck | $5,760$ | $305 \times 10^3$ | $34.3\%$ |
| Total | $16,800$ | $890 \times 10^3$ | $100.0\%$ |

**Table 2.** Hinterland transport mode split.

mode for trucks. These terminal areas can not be used for stowage purpose but only for internal transport transfer.

In order to respond to the desired hinterland container flows a network of connections and weekly schedules is created. We assume that the schedule is a result of agreements between the terminal and other actors in the transport network, and therefore the terminal has no permission to change it without consent. The following assumptions are made per transport mode:

**Barges:** this transport mode is characterized with uncertainty in its schedule and therefore we assume that three connections per day will be available in a $6$ days week. An average handling of $280$ TEUs/demand and $120$ TEUs/demand for berth A and berth B, respectively, will be considered for numerical design;

**Trains:** two rail tracks are available that serve exclusively one train at the same time, the schedule for trains is assumed fixed and four canals for each rail track are available for a $6$ days week. The maximum capacity per train is $40$ TEUs;

**Trucks:** truck gates are only open for a $16$ hour period on a $6$ days week. The maximum served capacity during the day time is $500$ TEUs.

According to the available connections and schedule the hinterland transport modal split is shown in Table 2 assuming maximum transport capacity for each transport mode.

For this terminal we assume that all carriers have an equal number of terminal areas, $n_{\mathrm{a}} = 5$. Considering that the terminal is integrated in a transport network composed by $4$ terminals the number of container classes is $n_{\mathrm{t}} = 5$, including empty containers. Finally, the terminal is composed of $26$ terminal areas and the terminal state-space vector is described by $130$ states.

**Simulation Configuration** The MPC controller is set to use a prediction horizon of $3$ steps; the weights for the objective function are indicated in Table $3$. The weight related to the *Import Area* at the *Central Yard* is kept neutral as it acts as a warehouse

| Carrier | Unload Area | Import Shake Hands | Export Area | Export Shake Hands | Load Area |
|---|---|---|---|---|---|
| Barge A | [105 100 95 90 85] | $\mathbf{1}^{\mathrm{T}}5$ | $\mathbf{1}^{\mathrm{T}}2$ | $\mathbf{1}^{\mathrm{T}}2$ | -[80 75 70 65 60] |
| Barge B | [55 55 45 45 45] | $\mathbf{1}^{\mathrm{T}}5$ | $\mathbf{1}^{\mathrm{T}}2$ | $\mathbf{1}^{\mathrm{T}}2$ | -[40 35 35 35 20] |
| Train A | [50 30 30 30 30] | $\mathbf{1}^{\mathrm{T}}5$ | $\mathbf{1}^{\mathrm{T}}2$ | $\mathbf{1}^{\mathrm{T}}2$ | -[15 15 15 15 10] |
| Train B | [25 25 25 25 25] | $\mathbf{1}^{\mathrm{T}}5$ | $\mathbf{1}^{\mathrm{T}}2$ | $\mathbf{1}^{\mathrm{T}}2$ | -[15 15 15 15 5] |
| Trucks | [20 20 20 20 20] | $\mathbf{1}^{\mathrm{T}}5$ | $\mathbf{1}^{\mathrm{T}}2$ | $\mathbf{1}^{\mathrm{T}}2$ | -[10 10 10 10 5] |

**Table 3.** Weights used in the cost function ($\mathbf{1}$ stands for the column vector of length $n_{\mathrm{t}}$ with all entries with value 1).

for containers between deliver and pick up times. The weights in the *Load Area* are taken negative, such that containers are pulled from the *Central Yard*. The minimum allowable prediction horizon is $\mathrm{N} = 3$ as this is the number of time steps needed to move containers from the *Import Area* to the *Load Area*. To assure the containers will be attracted towards the *Load Area* fulfilling the load request it is important to assure the following relation for each carrier,

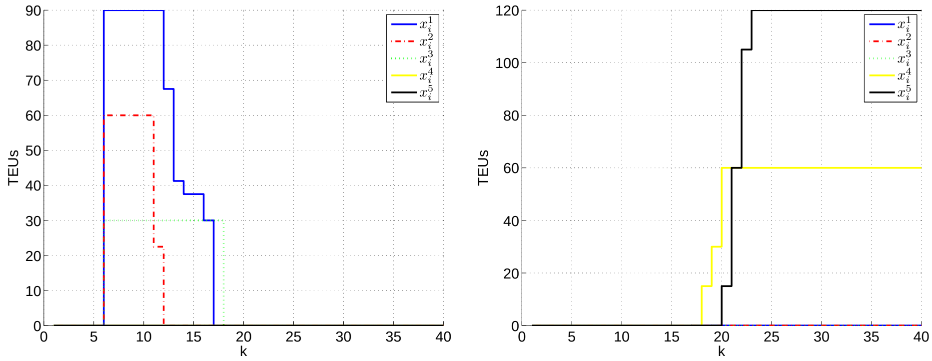
$$-\left(\mathbf{q}_{3+i} + \mathbf{q}_{4+i}\right) > \sum_{j=1}^{\mathrm{N}-2} \mathbf{q}_{5+i} \quad i = 0, \ldots, n_{\mathrm{c}} - 1. \tag{23}$$

This means that the benefit of staying at the *Load Area*, during the prediction horizon, has to be greater than the penalty the container faces while moving from the *Import Area* at the *Central Yard* to the *Load area*.

According to Section 3 the weights are assigned to the cost function in order to impose container flow priorities related to the terminal strategic goals. We assume for this terminal that the goal is to serve the bigger calls first. The carriers served at the terminal in a decreasing order are: Barge A, Barge B, Train A, Train B and Trucks. The unload operation is always the first operation to do for each carrier and only after the conclusion of this operation the loading operation will begin. After defining the hierarchical relation between carriers further priorities are included in respect to the container type. Only the weights related to the unload and load areas are considered element wise to impose the desired order in which the containers should be unloaded and loaded.

The MPC optimization problem is solved at each time step of the simulation using the MPT v2.6.3 toolbox [8] with the CDD Criss–Cross solver for linear programming problems. The simulations are performed using MatLab R2009b on a personal computer with a processor Intel(R) Core(TM) i7 at $1.60$GHz with $8$GB RAM memory in a $64$-bit Operating System.

**Test Scenario** In this scenario a challenging situation is created: all requests for one day start precisely at the same time. Although this is not a realistic scenario, it is appropriate for illustrating the framework ability to implement the desired priorities while respecting the constraints. The *Import Area* at the *Central Yard* is initialized with sufficient containers to fulfill all requests for loading containers. The departure of containers




(a) Unload operation ($i = 6$). (b) Load operation ($i = 10$).

**Fig. 3.** Evolution of container type unloaded/loaded to/into barge B.

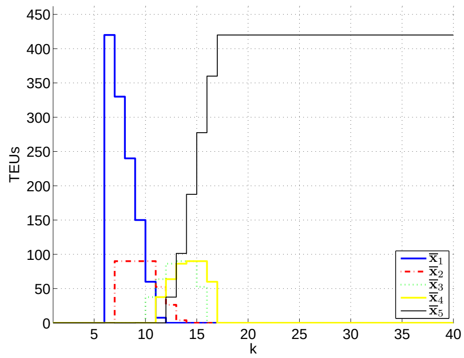
will not be executed to help visualize the terminal behavior. As a consequence the containers will be accumulated at the *Load Area*. In this congested situation the terminal operations management is put under severe pressure. All handling resources should be used to overcome this situation while respecting the carrier and container type priorities.

In Fig. 3 we see that the unloading and loading operation for barge B is done taking into account the container type priority. For the barge transport mode, depending on the size of the request, the time difference between unloading a given container type at the beginning or at the end of the scheduled time window may be important and have a significant impact on the *Central Yard* container flow management. The option to leave the empty containers as the last container type to load can reduce terminal costs in case of delays or anticipated departure.

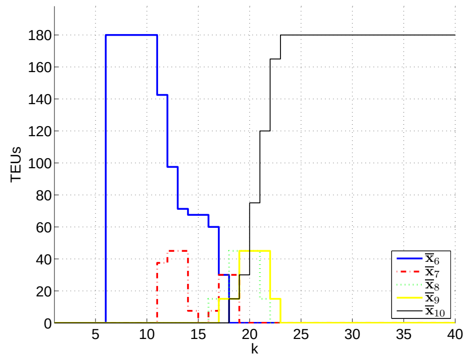
Fig. 4 shows that the order by which the carriers are served is in agreement with the size of the unload/load operation request (Table 3). The transport modes by land – trains and trucks – are not affected by the quay congestion because they use different handling resources at the terminal regarding the connection to the *Central Yard*. This terminal is decomposed in three main areas associated to flows: quay–yard flows, train gates–yard and truck gates–yard . This decomposition is due to the terminal structural layout concerning the handling resources used to connect the different terminal areas.

With Fig. 5 we can track the evolution of container types at the *Central Yard*. In this scenario the total amount stacked at the *Import Area* faces a maximum increase around $900$ TEUs. When looking in detail at the container type evolution only one container type – related to the location of the analyzed terminal – has a similar evolution. This is an improvement regarding the current situation that considers undistinguishable containers. In particular, it is possible for the strategic level to recognize the transport network routes that are facing more pressure and need a schedule enhancement.

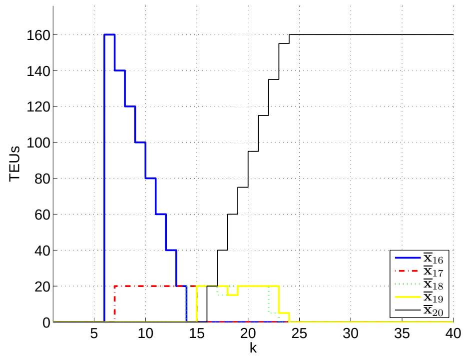
In Fig. 6 we observe that all crane resources are firstly allocated to barge A. The transfer handling capacity between the quay and the *Central Yard* is at maximum capacity. So in this configuration introducing more quay crane capacity will not be translated



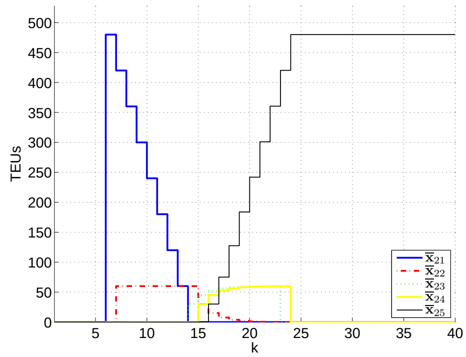

(a) Barge A.




(b) Barge B.

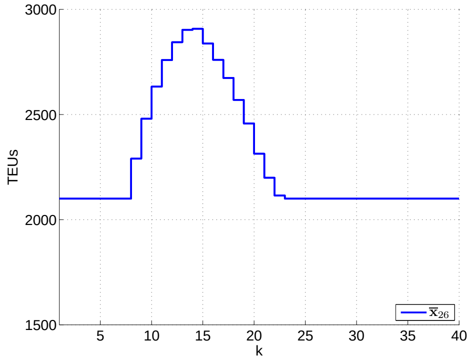



(c) Train B.

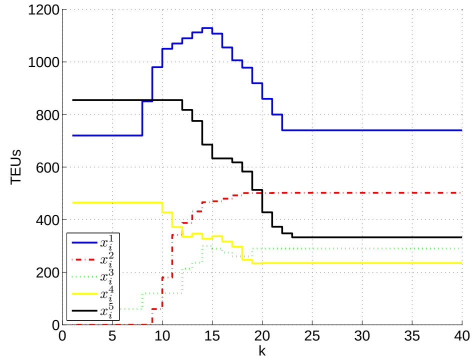



(d) Trucks.

**Fig. 4.** Evolution of the total storage for each carrier.

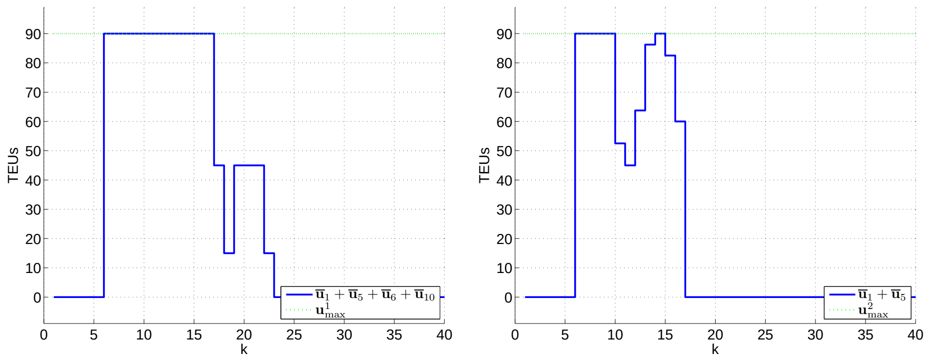



(a) Total volume.




(b) Total volume by container type ($i = 26$).

**Fig. 5.** Evolution of containers in the *Import Area* at the *Central Yard*.




(a) Quay crane capacity allocated.

(b) Quay crane capacity allocated for barge A.

**Fig. 6.** Handling resources allocated.

in any terminal performance increase if a similar investment is not made for the transfer capacity between quay and *Central Yard*.

In this scenario the average computation time was $64.0$ s with a standard deviation of $42.01$ s. The maximum computation time occurred for $k = 14$ and took $244.09$ s. This time step is close to the transition from unloading to loading operation for the majority of carriers at the terminal. The computation time is dependent on the problem complexity and also on the current terminal state.

## 5 Conclusions and Future Research

In this work we present a new perspective for looking at container terminal operations, based on a flow point of view. Containers are categorized according to criteria such as final destination, due time and type of cargo, depending on the terminal interest. The proposed framework for controlling container terminal operations is based on accessing more information than considering containers as undistinguishable. The required information about the container final destination is an improvement regarding the currently shared information. With more information available, without violating customer privacy, a different approach to the intermodal container terminal operations management is shown to be possible. More coordination is now possible regarding the goal of delivering the cargo at the agreed time and at the agreed location.

The model-based predictive control strategy is especially suitable for solving the resource allocation problem inside the container terminal. The possibility to include constraints in the optimization problem allows using all available handling resources at the terminal and the ability to consider different terminal layouts. By using forecasts related to client requests in terms of unloading/loading operations it is possible to accept updates in real-time and obtain the tactical decisions that respect the client request. The MPC approach through the resolution of an optimization problem in each sample time allows the translation of strategic goals into tactical decisions regarding resource allocation inside the terminal. This can be done in a real time configuration giving more flexibility to the terminal management as a node of the transport network. The translation of terminal strategic goals into cost function weights is still subject of research. Filling the gap between the operational decisions and the tactical goals is one of the future research directions. Natural extensions of the present work will focus on the transport modal shift for the hinterland flow, empty container reallocation problem and coordination of intermodal terminals in the hinterland transport network.

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