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Optimal Control of Container Terminal Operations

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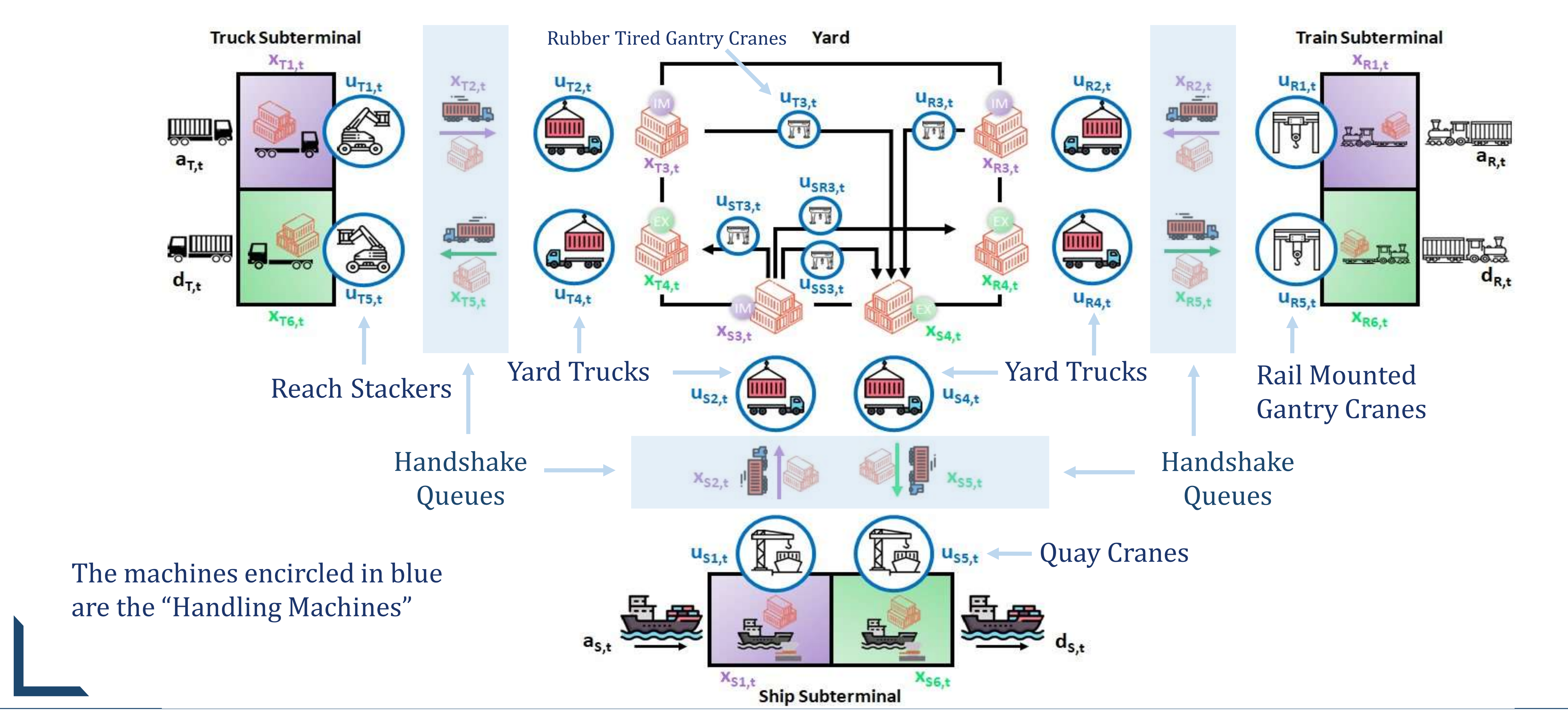
Introduction

We are investigating a maritime container terminal in which containers arrive and depart via ships, trucks, and trains. The terminal comprises three subterminals, each dedicated to a specific transportation mode (ship, truck, train), along with a vast storage yard. Containers are transported by various types of handling machines, each with its own maximum handling capacity, representing the maximum number of containers the machine can manage within a given period of time. The goal is to identify optimal percentages of the maximum handling capacities for the machines to minimize the duration of container remaining in the terminal.

Flow chart (maritime terminal)



The flow chart illustrates the overall layout of a maritime terminal, showcasing its various components and handling machines. The black, purple and green arrows indicate the directions of container movement. As the terminal is maritime, containers arriving by trucks or trains must depart via ships, whereas the departure does not matter if containers arrive via ship. Containers located at one specific part of the terminal (station) form a "Queue", the containers in movement between the yard and the subterminals form the so called "Handshake Queues".

Approach - Balance Equations

By using a discrete time grid, the movement and conservation of containers within the terminal are articulated through difference equations known as "Balance Equations". These equations establish a relationship between the queue lengths at two consecutive time points, the present handling capacities of the handling machines, and the containers arriving and departing the terminal.

Ship Subterminal

$$x_{S1,t+1} = x_{S1,t} + a_{S,t} - \Delta T \mu_{S1,t} u_{S1,t}$$
$$x_{S2,t+1} = x_{S2,t} + \Delta T(\mu_{S1,t} u_{S1,t} - \mu_{S2,t} u_{S2,t})$$
$$x_{S3,t+1} = x_{S3,t} + \Delta T(\mu_{S2,t} u_{S2,t} - \mu_{SS3,t} u_{SS3,t} - \mu_{ST3,t} u_{ST3,t} - \mu_{SR3,t} u_{SR3,t})$$
$$x_{S4,t+1} = x_{S4,t} + \Delta T(\mu_{SS3,t} u_{SS3,t} + \mu_{T3,t} u_{T3,t} + \mu_{R3,t} u_{R3,t} - \mu_{S4,t} u_{S4,t})$$
$$x_{S5,t+1} = x_{S5,t} + \Delta T(\mu_{S4,t} u_{S4,t} - \mu_{S5,t} u_{S5,t})$$
$$x_{S6,t+1} = x_{S6,t} - d_{S,t} + \Delta T \mu_{S5,t} u_{S5,t}$$

Truck Subterminal

$$x_{T1,t+1} = x_{T1,t} + a_{T,t} - \Delta T \mu_{T1,t} u_{T1,t}$$
$$x_{T2,t+1} = x_{T2,t} + \Delta T(\mu_{T1,t} u_{T1,t} - \mu_{T2,t} u_{T2,t})$$
$$x_{T3,t+1} = x_{T3,t} + \Delta T(\mu_{T2,t} u_{T2,t} - \mu_{T3,t} u_{T3,t})$$
$$x_{T4,t+1} = x_{T4,t} + \Delta T(\mu_{ST3,t} u_{ST3,t} - \mu_{T4,t} u_{T4,t})$$
$$x_{T5,t+1} = x_{T5,t} + \Delta T(\mu_{T4,t} u_{T4,t} - \mu_{T5,t} u_{T5,t})$$
$$x_{T6,t+1} = x_{T6,t} - d_{T,t} + \Delta T \mu_{T5,t} u_{T5,t}$$

Train Subterminal

$$x_{R1,t+1} = x_{R1,t} + a_{R,t} - \Delta T \mu_{R1,t} u_{R1,t}$$
$$x_{R2,t+1} = x_{R2,t} + \Delta T(\mu_{R1,t} u_{R1,t} - \mu_{R2,t} u_{R2,t})$$
$$x_{R3,t+1} = x_{R3,t} + \Delta T(\mu_{R2,t} u_{R2,t} - \mu_{R3,t} u_{R3,t})$$
$$x_{R4,t+1} = x_{R4,t} + \Delta T(\mu_{SR3,t} u_{SR3,t} - \mu_{R4,t} u_{R4,t})$$
$$x_{R5,t+1} = x_{R5,t} + \Delta T(\mu_{R4,t} u_{R4,t} - \mu_{R5,t} u_{R5,t})$$
$$x_{R6,t+1} = x_{R6,t} - d_{R,t} + \Delta T \mu_{R5,t} u_{R5,t}$$

where...

- $t \in \mathbb{N}_0$: point of time
- $T \in \mathbb{N}$: time horizon
- $\Delta T > 0$: Time step between consecutive points of time
- $x_{Si,t}, x_{Ti,t}, x_{Ri,t} \geq 0$: State variables, queue lengths at time t and station Si, Ti or Ri. S,T and R refer to the ship-, truck- and train- (rail-) subterminals, i referres to the concrete station in the subterminal.
- $\mu_{Ti,t}, \mu_{Ri,t}, \mu_{Si,t}, \mu_{SS3,t}, \mu_{ST3,t}, \mu_{SR3,t} > 0$: Maximum container handling capacities at time t and station Ti, Ri, Si, SS3, ST3 or SR3
- $u_{Ti,t}, u_{Ri,t}, u_{Si,t}, u_{SS3,t}, u_{ST3,t}, u_{SR3,t} \in [0,1]$: Corresponding control variables, percentage of maximum handling capacity
- $a_{S,t}, a_{T,t}, a_{R,t} \in \mathbb{N}_0$: Containers arriving the terminal at time t
- $d_{S,t}, d_{T,t}, d_{R,t} \in \mathbb{N}_0$: Containers departing the terminal at time t

Optimization Problem

Instead of directly minimizing the process time, we optimize the handling process to ensure swift transfer of containers from one machine to the next one using a targeted objective function, efficiently minimizing the time by preventing container delays on paths. To this end, the summands $J_{S,k}$, $J_{T,k}$ and $J_{R,k}$ in the objective function sum up the squared differences between the current handling capacities of two consecutive handling machines at point of time k, multiplied by suitably chosen weighting parameters, for the ship- truck and train-subterminal each. For example, the squared difference of the handling capacities of the quay cranes unloading and the yard trucks to the yard is given by $(\mu_{S1,t} u_{S1,t} - \mu_{S2,t} u_{S2,t})^2$.

Minimize the cost function

$$J = \sum_{k=t_0}^{t_0+T-1} [\, J_{S,k} + J_{T,k} + J_{R,k} \,]$$

Given:

Queue lengths at initial point in time t_0

With respect to:

The queue lengths (state variables) and the control variables

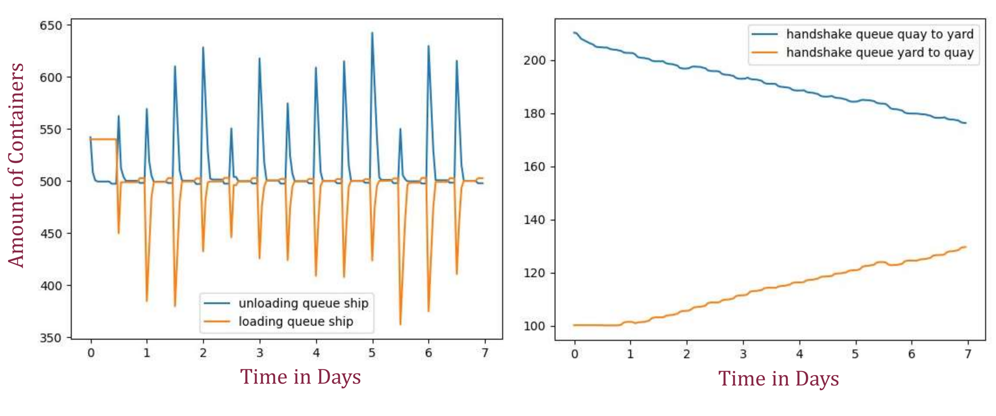
Subject to:

- The balance equations for all $k \in \{t_0, \ldots, t_0+T-1\}$
- Yard Limit: $x_{S3,k} + x_{S4,k} + x_{T3,k} + x_{T4,k} + x_{R3,k} + x_{R4,k} \leq b$ with $b > 0$ for all $k \in \{t_0+1, \ldots, t_0+T\}$
- Handshake queue limit: $x_{S2,k} + x_{S5,k} \leq b_S$, $x_{T2,k} + x_{T5,k} \leq b_T$, $x_{R2,k} + x_{R5,k} \leq b_R$ with $b_S, b_T, b_R > 0$ for all $k \in \{t_0+1, \ldots, t_0+T\}$

Results

The optimization problem was solved using the optimization software "WORHP", for the vizualization of the numerical results the programming language Python was used.

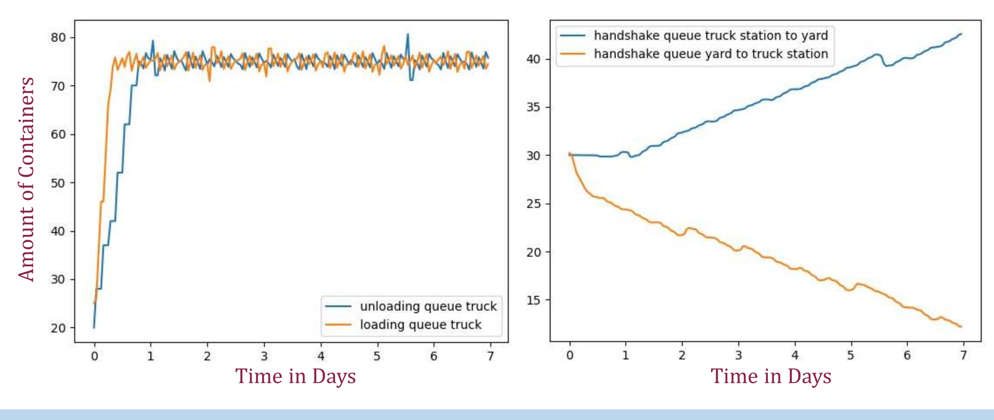
Ship Subterminal — (Un)loading and Handshake Queues



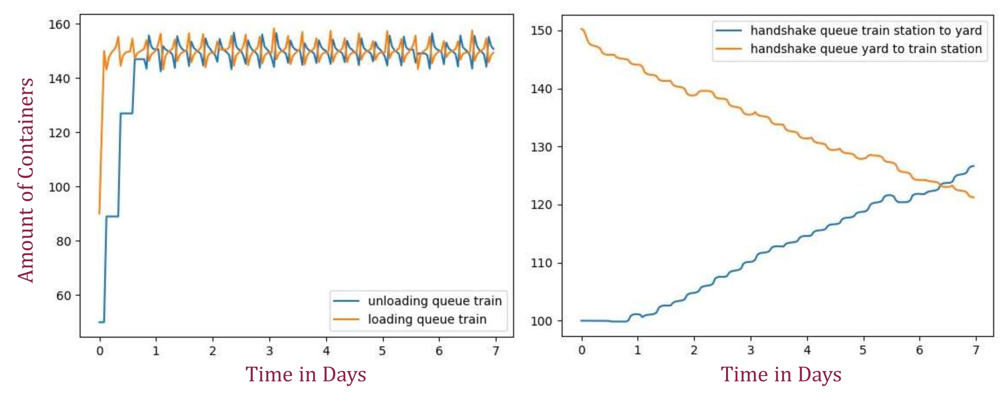
The loading and unloading queue graphs exhibit oscillations centered around an average of 500 containers. This is logical, given that arrivals and departures, as well as loading and unloading, occur in an alternating sequence. Looking at the handshake queues, one observes that most containers arriving via ship also depart via ship which explains the increasing and decreasing behavior in the queues.

Truck Subterminal — (Un)loading and Handshake Queues

Similar to the oscillations observed on the seaside part, the loading and unloading queue graphs demonstrate oscillations, centering around an average of 75 containers. Conversely, the handshake queue graphs exhibit a contrasting pattern compared to those in the seaside part. This is logical since, on one hand, there is an increased arrival and departure of containers through ships, while on the other hand, within the truck subterminal, there is a higher volume of containers arriving and departing via trucks than the capacity that can be managed by the Rubber Tired Gantry Cranes (RTGCs) in the yard.



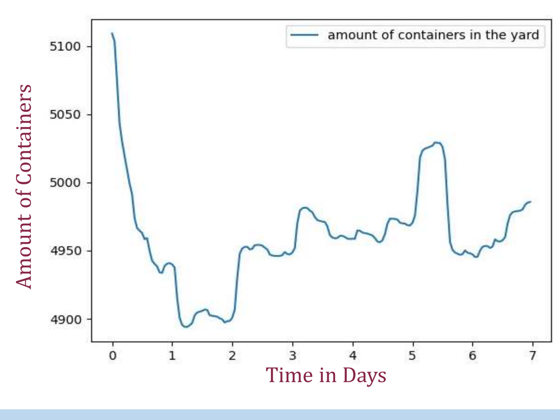
Train Subterminal — (Un)loading and Handshake Queues



Similar to the oscillations observed on the seaside part, the loading and unloading queue graphs demonstrate oscillations, centering around an average of 150 containers. Also here, the handshake queue graphs exhibit a contrasting pattern compared to those in the seaside Part. The reason for that is identical to the one observed for the truckside part.

Yard — Amount of Containers

It is evident that the number of containers in the yard varies, experiencing both increases and decreases. This observation indicates that there are no unusual occurrences in the terminal, and the situation appears to be balanced.



Conclusion/Outlook

In summary, the examination is focused on a maritime terminal where we enhance the efficiency of container flow under normal circumstances - ensuring a balance between incoming and outgoing containers without any irregularities. An extension of the model could involve incorporating considerations for unusual phenomena and determining an optimal container flow in such scenarios. One the one hand, these phenomena may encompass natural occurrences such as weather conditions, for instance strong winds. On the other hand, they also encompass human made disruptions, such as a lack of labor, failure of handling machines or accidents, for instance the Ever Given accident in the Suez Canal in March 2021.

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