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Survey of approaches for integrated control of intermodal container terminals

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***Abstract*— The volume of containers being transported all over the world is expected to increase, while requirements on quality of service are tightening, and transport infrastructure is reaching its capacity limits. This poses significant challenges for operational control, in particular as disturbances (e.g., due to bad weather conditions, congestion, breakdown of equipment) will have a larger impact. In order to still meet the service demands, transport has to be considered from a more integrated perspective, in which transport over different modalities (such as vessel, truck, and train) is considered simultaneously, as taking place in a large-scale intermodal transport network. This paper provides an overview of recent literature on integrated control of maritime container terminals, one of the key components of such intermodal transport networks. Time scales addressed, system components and control goals considered, and approaches taken are summarized, and based on this directions for future research are outlined.**

Keywords- Maritime container terminals, intermodal transport networks, integrated operational control.

I. INTRODUCTION

Over the last decades increasing economic growth and wealth are causing a significant increase in freight transportation across the world. Most of the overseas freight shipping of consumer goods is realized by shipping it in standardized containers [20] of 20, 40, and 45 feet, typically expressed in Twenty feet Equivalent Units (TEUs). Because of this standardization and the relative ease to handle these containers huge amounts of freight are transferred in containers. It is therefore worth to improve the performance of the container transportation as a small improvement can have a significant impact on economic benefits.

Usually the transport of containers takes place across multiple modes (such as truck, train, ship, plane, etc.), which means that the freight is involved in more than one modality of transportation. To improve the container transportation process one can look at each specific mode separately and try to improve the performance of that specific modality. Problems can emerge locally at one modality, e.g., congestion may arise or the event that freight cannot be transported due to restrictions caused by infrastructure can appear. Such local problems may however spread to other modalities. E.g., when containers cannot be transferred from truck to ship due to congestion on the roads ships may also be delayed. As such events are in the future more likely to happen due to the transport volume increase it becomes necessary to incorporate more modalities when modeling and controlling the transportation process. In order to get the most out of the transportation system as a whole, it has to be considered as a large intermodal transportation network, where the transport processes over the different modalities are considered simultaneously [6,8].

Maritime container terminals are critical elements in the total freight transportation chain as these terminals provide the interface between different modes of transportation [10]. Therefore, an improvement of the performance of these terminals is desired to decrease total transportation time and satisfy customer needs. Many studies have been performed to realize an improvement of the operation of these terminals, although initially these studies focused on improving smaller subproblems. In the last ten years, however, a trend towards more integrated approaches for modeling and controlling container terminals can be observed. These integrated approaches try to integrate the influences of the performances of different transport modes on one another, instead of considering the modes individually.

This paper provides an up-to-date and compact overview of properties of recently proposed methods for control of intermodal container terminal control. A systems and control point of view is adopted, in which explicitly a distinction is made between the system as being the physical infrastructure and equipment (i.e., the hardware) being considered and the control of this system as being the software/algorithms that determine how to best use the system. The papers considered here are therefore characterized based on the components of the system (the modes of transportation, terminal areas, and equipment), the level of operation, the control goals, and the control method, and the validation performed to verify the accuracy of models used. Making such a characterization facilitates pointing out directions for further research and improvement.

This paper is organized as follows. In Section II we introduce intermodal maritime container terminals. In Section III we provide a characterization of 16 recently published articles in the area of modeling and control of container terminals. Concluding remarks and directions for future research are given in Section IV.

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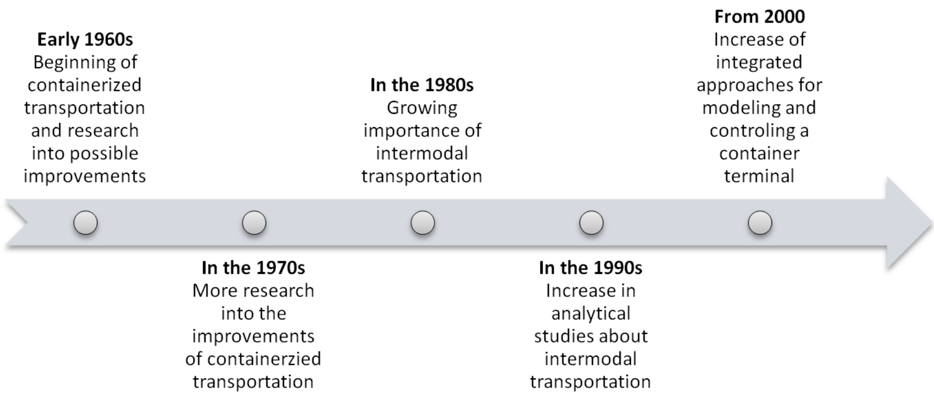

Figure 1:Timeline of developments regarding studies on containerized transportation.

II. INTERMODAL MARITIME CONTAINER TERMINALS

The research in containerized transportation steadily increased over the last 50 years [6]. Figure 1 summarizes the development of transportation research about containerized transportation and container terminal operations. Until the 1980s the research focus was primarily on the improvement of general transportation related issues, without giving attention to the intermodal aspect of transportation. Then in the 1980s a trend towards intermodal transportation research is observed. From the 1990s an increase in the number of analytical and more theoretical studies on intermodal transportation emerges. Finally, the last years have seen an increase in the number of research activities in the area of more integrated approaches for modeling and control of container terminals.

At maritime container terminals, containers are transshipped from one mode of transportation to another [25]. Within a terminal, different types of material handling equipment are used to transship containers from ships to barges, trucks, and trains, and vice versa. Basically, a container terminal can be divided into four areas: the quayside, the stack, the landside, and the transport area interconnecting the former three areas. In each of these areas different processes take place and different equipment is used to realize these processes. A particular configuration and layout of the quayside, stack, landside, transport area and used equipment constitute a maritime container terminal system.

At the quay side of a terminal, ships arrive. When a ship arrives it is assigned a berth and a number of quay cranes. These quay cranes transfer the containers from the ship to the shore or vice versa. Two types of quay cranes are commonly used: single-trolley and dual-trolley cranes. Single-trolley cranes are most often man-operated and move containers immediately from quay to shore or from shore to quay, whereas dual-trolley cranes first place a container on a platform, and then move it to shore or to quay [23]. Hereby, the movement from platform to ship can be automated. Quay cranes are typically capable of moving over a rail alongside the berth. This is practical when cranes serve ships of different sizes and more than one crane is assigned to a ship.

At the stack, or storage yard, storage operations take place, including container management and handling of containers [8]. The storage yard contains one or more lanes with several (most often seven) rows of containers. Different types of equipment are used to move containers into, within, and out from the storage yard, each with their own advantages and disadvantages. A chassis-based transporter is small and can simply move a container, but it cannot lift it. A reach stacker can move a container, including lifting; it does, however, need a significant amount of space next to a container to transport it. A straddle carrier requires less space, but still more space than that required by a so-called rubber tyred gantry crane; such a crane can move over seven rows of containers (one lane) and has the flexibility to move to other container lanes. Finally, a rail mounted gantry crane can be compared with a rubber tyred gantry crane, although the rail mounted gantry crane is attached to a track and therefore is not capable of moving containers from one lane to another.

At the landside the gates are located. Truck gates, train gates and other types of gates can be present. These gates provide the interconnection among different modes of transportation. Common types of equipment used at gates include truck gate cranes, which move containers to or from transport vehicles respectively onto or from external trucks and train gate cranes, which transfer containers to or from a train. For the loading and unloading of trucks straddle carriers used in the storage area can also be used.

The transport area forms the infrastructure that is the physical interface of the activities taking place at the quayside, in the storage yard, and on the landside. So-called yard vehicles, transporters, or shuttles are used to perform the transportation through the transport area. The most common types of vehicles used for this are multi-trailer systems with manned trucks, automated guided vehicles, and automated lifting vehicles [11]. Some of the equipment used in the storage yard can also be used in the transport area, e.g., chassis-based trucks and straddle carriers.

Day and night vessels, trucks, barges, and trains arrive and depart, delivering and pickup containers continuously. Depending on the way in which the equipment and the infrastructure within the terminal is used, the performance of the terminal itself will vary, as well as the performance as perceived by the owners and operators of the vessels, trucks, barges, and trains that are using the services of the terminal. It

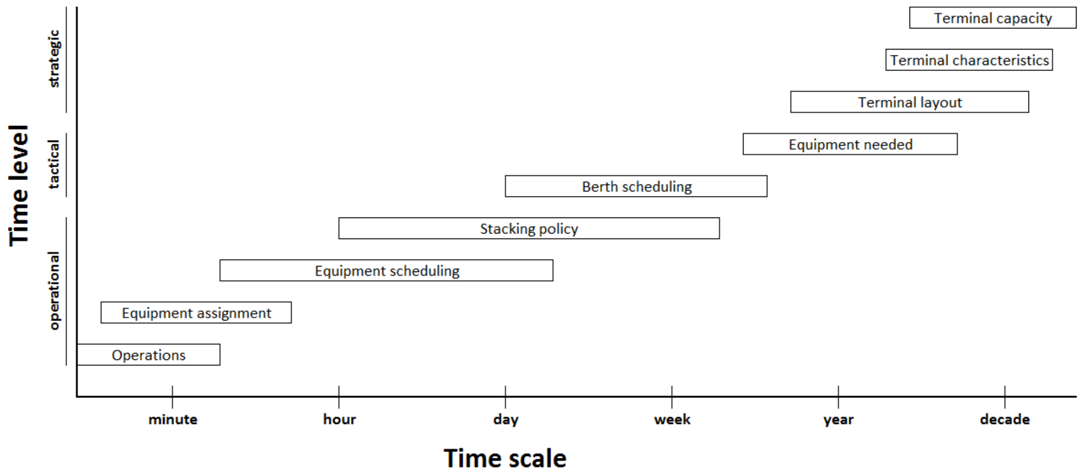

Figure 2: Overview of decisions made at different time scales and time levels.

is the question how the available equipment and infrastructure should be used such that the performance as perceived by each of the parties involved is satisfactorily. This question becomes in particular challenging when things go wrong and unexpected disturbances appear (e.g., due to bad weather conditions, congestion on entry roads, equipment breakdown, delayed arrival of vessels, trains, trucks, etc.). In order to handle such situations in the most satisfactory way, the different areas in a container terminal should be considered as belonging to a single system, rather than as multiple decoupled individual systems, and integrated ways of controlling such a container system in a coordinated way should be employed.

III. CHARACTERISTICS

Only a few studies on integrated views of container terminal control have been published to date, such as [22]. Here, a further discussion of integrated approaches is provided. Table 2 provides the full overview of all characteristics considered. Below we focus in more detail on the following characteristics:

- Time scales and decisions
- Control objectives
- Practical validation

A. Time scales and decisions

For each of the considered papers we have determined what time scales are considered and what related processes and decisions are taken into account. From this the decisions which can be made in order to optimize these processes can be determined. An overview of the decisions categorized by time scale and time level is given in Figure 2.

At the slowest time scale it is necessary to determine future container transportation demand and to make decisions on terminal capacity and design. Then, also the characteristics of a container terminal are determined, including the choices regarding which modes of transportation the terminal will support. Also, the terminal layout is then determined. These decisions take place at a very slow time scale and are made by the terminal design architects. The time scale at which these decisions take place is considered the strategic level. See [1,2,3,18,19].

At faster time scales, the decision making at the tactical level becomes relevant. Depending on the terminal layout the needed equipment has to be determined and berth schedules can be made. Terminal operators can already several months in advance make agreements with customers on container turnovers to make it possible to create at an early stage berth schedules. See [1,2,3,4,12,13,17,18,24,26,28]. It is noted, however, that also during the actual operational phase it may turn out that extra equipment is needed if the current equipment cannot satisfy the demand. It is noted that these schedules can be updated at a faster time scale, as it a more precise arrival time of ships will be known only a few days in advance.

At the fastest time scales, i.e., the operational level, operational decisions are made. When it is known exactly at what time a ship will arrive and containers should be retrieved from the stack it is possible to determine the best stacking policy after which it is possible to determine a schedule for the handling equipment such as loading and unloading plans for quay cranes and yard cranes, and routing plans for transport vehicles. Then, the equipment should be assigned, preferably by the determined schedule, by taking into account possible changes. At the fastest time scale it is necessary to make decisions on real-time operations such as control speed, driving speed, or abrupt route changing for transport vehicles when congestion occurs. See [4,7,13,14,16,17,24,27,28].

B. Control objectives

The papers differ in control goals considered, as is observed in Table 1. The control goal which is considered in most of the papers is the goal of minimizing the ship turnaround time. It can be seen that in four papers [12,16,17,24] attention is paid to the possible occurrence of congestion. Especially when terminals are operating in smaller terminals with higher throughputs this objective becomes more important. Some of the other control goals, namely maximizing quay crane rate, minimizing ship waiting time, maximizing global and net productivity, maximizing throughput of containers and minimizing empty moves of yard cranes may also lead to a decreasing ship turnaround time but an advantage of these more specific control goals, and thus more specific performance indicators, is that also a more specific control is

Table 1: Overview of control goals

Control objective	Occurrence
Minimize ship turnaround time	9
Minimize congestion	4
Maximize quay crane rate	3
Minimize waiting time of ships	3
Minimize number of transfer vehicles	3
Minimize yard occupancy rate	3
Minimize waiting time of trucks	1
Minimize waiting time of quay cranes	1
Maximize throughput of containers	1
Minimize operation time of cranes	1
Minimize difference in volume for rail and road transport	1
Maximize global and net productivity	1
Minimize sea berth length	1
Minimize empty moves of yard cranes	1

possible. Besides these control goals for optimizing the terminal performance focused on decreasing the ship turnaround time, other goals are defined which are more focused on optimization of the required number of equipment or resources. These goals are for example minimizing the number of transfer vehicles, minimizing the yard occupancy rate, minimizing the waiting time of trucks, minimizing the waiting time of quay cranes, minimizing the operation time of quays, and minimizing the sea berth length.

C. Practical validation

The validation in practice (in a real container terminal) of the proposed approaches is limited or absent. Most approaches have been proposed with one specific container terminal in mind and based on this, assumptions on equipment, operations, areas, and other characteristics are made. Some methods have been evaluated and compared with measurements of a real container terminal (such as [4,12,13,14,16,18,19]). However, none of the authors has validated its proposed method on multiple container terminals. The assumptions made in the design of the control system for one particular terminal do not necessarily hold in other container terminals. Validation is then important in order to investigate the applicability of the proposed method in other situations, for other terminals.

D. Overall of all considered characteristics

Table 2 summarizes all characteristics considered for the surveyed papers. The table contains per paper an indication of the level for which an approach is proposed (e.g., strategic, tactical, operational), the modes of transport considered, the components considered when modeling the terminal system, the control goals, a short description of the control strategy employed, and the actions resulting from the control strategy.

IV. Concluding Remarks and Future Research

This paper provides an overview of recent approaches for integrated modeling and control of maritime container terminals, necessarily compact due to space restrictions. A large variety in modes of transportation can be observed in the discussed papers. Furthermore the level of detail in which the system of a container terminal is described varies significantly from one paper to another. Subsequently, also the methods for controlling container terminals are different from one paper to another. Some papers consider automated controllers which perform actions according to a certain optimization algorithm, whereas other papers consider a human controller. Furthermore a variety of different control goals is reported, although most of the discussed papers agree on the importance of minimization of the ship turnaround time. Finally, it is observed that the validation of the proposed approaches is in general limited.

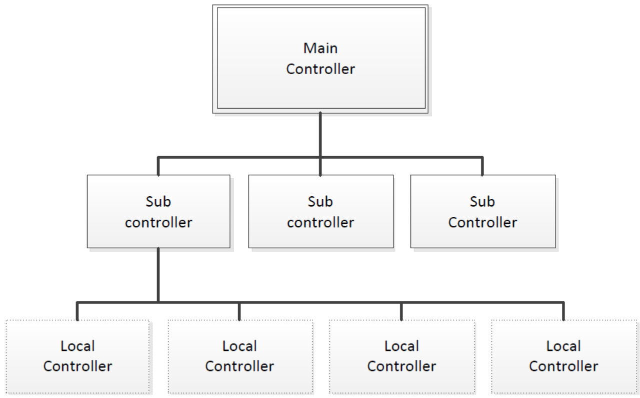

Figure 3: A hierarchical control structure for control within a container terminal or among different container terminals.

The papers considered here each have their own perspective on how container terminals should be operated. The models and control strategies proposed vary in level of detail and level of time scale. Consensus on how the dynamics of container terminals are best captured is lacking. It has also been noted that there can be interaction between control problems at higher levels and at lower levels. The strategies proposed so far each consider control of certain processes and the interaction among these processes. It is hereby assumed that these processes can be directed exactly as desired; however, the processes themselves may in practice require subcontrollers to actually realize what is requested by the controller. From a container terminal-wide point of view an example of a subprocess in a container terminal is the yard stacking process. In this case, the yard crane operators or electronic devices in a yard crane can be considered as the local controllers of the subprocess yard stacking, which is in fact an even lower level of control. Future research should pay more attention to the dynamics in such subprocesses, as these pose constraints on the actions determined at a higher level. Future research should focus on integrating the most promising components from the existing approaches and where necessary develop new approaches. This could then in the end lead to a hierarchical control architecture, as depicted in Figure 3.

Apart from further integrating and coordinating the actions within a container terminal, future research should investigate also modeling in a structured way a larger part of the freight transportation chain in order to obtain improvements. Most current research attention focuses on minimizing the turnaround time of vessels. Taking into account that container terminals are part of a much larger network of transport hubs, it may be beneficial, and in fact necessary, to coordinate transport actions at a larger scale than just the terminal level. In this case, the hierarchical control architecture of Figure 3 can be considered again, but now with at the lowest level controllers for container terminals, at the medium level controllers for regions including multiple terminals (e.g., ports), and at the highest level controllers for coordinating the different regions.

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Table 2: Overview of characteristics of surveyed literature. (CT = container; CTT = container terminal).

Paper	*Description*	*Level*	*Modes*	*Areas*	*Operations*	*Equipment*	*Goal*	*Controller*	*Actions*
[19]	Discrete event simulation method for the planning of a CTT is proposed.	Strategic.	Block trains, trucks, vessels.	Berth, yard, rail yard, truck gate.	Loading/unloading operations, transportation among different CTTs.	Quay cranes, harbor mobile cranes.	Obtain a more equal distribution over rail and road transport.	Port authorities who evaluate three policies based on measurements.	Choice for the optimal policy.
[3]	Linear discrete time-equations model for analyzing design of CCT.	Strategic.	Trains, trucks, three types of vessels.	7 areas representing locations where CTs stand and wait in queues.	CT transfer operations between the 7 areas.	Not specified, equipment is represented via handling rates.	Minimize transfer delay of CTs at areas of terminal, with a focus on delays of ships.	Model predictive controller.	Adjustment of handling rates.
[1,2]	Nonlinear discrete time-equations model for analyzing design of CCT.	Strategic.	Trains, trucks, three types of vessels.	7 areas locations where CTs stand and wait in queues.	CT transfer operations between the 7 areas and rehandling operations.	Not specified, equipment is represented via handling rates.	Minimize lay times of ships, with possibility to minimize queue lengths in areas where CTs are located in a CTT.	Model predictive controller.	Adjustment of handling rates.
[18]	Generic process interaction simulation model with a focus on functional design of multi terminals.	Strategic.	Deep-sea vessels, short-sea vessels, barges, trucks, trains.	Quayside, stacking yard, the gates for barge, rail and truck transfer.	Quay transfer, stack transfer and transportation between quay, stack and landside transport.	Automated guided vehicles, quay cranes, stacking cranes	Minimize number of automated guided vehicles, transport infrastructure required, sea berth length and maximize the stacking capacity.	Humans who determine the required equipment for a multiterminal.	The choice to evaluate a specific conceptual design by the simulation model.
[26]	Model to determine the minimum number of lifting vehicles required.	Tactical.	Vessels.	Quay side with two buffer areas, the stacking yard.	Only transportation from the quay to the stack.	Four quay cranes, sixteen stacking cranes and lifting vehicles.	Avoid delays at the quay cranes and thereby minimize the unloading time of a ship.	Method to determine the influence of the time window on vehicle fleet size.	Create a CT transport scheduling plan.
[13]	Agent based simulator for evaluating operation policies in the transshipment of containers in a CTT.	Tactical.	Vessels.	Terminal area as a whole, storage yard, berths.	Loading/unloading, horizontal transportation and stacking and unstacking.	Quay crane and straddle carrier.	Minimize turnaround time and waiting time of ships and minimize distance traveled by straddle carriers.	Port captain agent, ship agent, stevedore agent and the terminal manager agent.	Sending messages.
[4]	Object-oriented simulation to evaluate different operating policies.	Tactical.	Trucks, trains, vessels.	Storage area, buffer area, yard queue, ship queue.	Quay crane operations, storage yard operations and shuttle truck operations.	Shuttle, input/output truck, quay crane and yard crane.	Minimize the cost function, which is based on performance measurements.	Management policy optimization module based on a cost function.	New management policies.
[12]	Object-oriented 3D real-time-visualization CTT simulation model for assessment of new equipment.	Tactical.	Trucks, vessels.	Berths, storage yard, transportation infrastructure, gates.	Loading, discharging, delivery, receiving and remarshaling, including detailed subprocesses.	Trucks, quay cranes, yard cranes.	Find optimal values for no. of blocks in a storage yard, max no. of yard tractors, average arrival rate external trucks, moving speeds of quay cranes, yard cranes, yard tractors and external trucks, speed of a trolley and a spreader.	Human controllers who vary parameters to determine the influence on the quay cranes productivity.	Varying input parameters such as defined under control goal.
[24]	Distributed agent architecture to develop an automated system for the CTT handling process.	Operational.	Vessels.	Primary and secondary yard storage, stacking yard, quayside, crossings.	Retrieval of CTs from stack, transport from stack to quay and transfer from quay to vessel.	Quay crane, straddle carrier and traffic vehicles.	Maximize quay crane utilization and CTs stored per hectare, minimize yard vehicles.	Area manager agent.	Sending messages.
[7]	Scheduling as hybrid flow shop problem with precedence and blocking constraints.	Operational.	Trucks, vessels.	Quayside, storage yard.	Transfer operations of CTs from/onto ship, of CTs in the yard and transport between yard crane and quay crane.	Quay cranes, yard cranes and yard vehicles.	Minimize total service time of ships.	A tabu search algorithm to solve resulting hybrid flow shop problem.	Create a detailed schedule for all equipment.
[14]	Fuzzy artificial neural network for forecasting the operations of CTTs.	Operational.	Trucks,.vessels.	Quayside, CT yard, truck gate.	Loading and unloading of ships, transit operations and container gate operations.	Quayside cranes, transfer cranes and trailers.	Reduce ship waiting time and total operation time of transfer cranes.	Fuzzy artificial neural network to determine operation rules and control stack height.	Operation plan for the next planning period.
[28]	Distributed agent system for dynamic port planning and scheduling.	Operational.	Vessels.	Berth, container yard.	Allocation of ships, unloading and loading, transportation of CTs within a CTT and stacking.	Shuttle agent and yard storage equipment.	Optimize equipment utilization rate, minimize cost to move a CT and minimize ship turnaround time.	Port planning manager agent.	Sending messages and generate schedules.
[16]	Decision support system for nine interrelated decisions.	Operational.	Trucks, vessels.	Quayside, storage yard, terminal gate, vessels.	Vessel operations and operations by internal/external trucks, yard cranes and quay cranes.	Rubber tyred gantry cranes, internal and external trucks and quay cranes.	Optimize storage space assignment, dispatching policy, routing of trucks, deployment of rubber tyred gantry cranes, allocation of trucks to quay cranes and number of trucks.	Solve subproblems and manage interrelated decisions.	Providing optimal sequence of decisions.
[17]	Resource allocation and operation scheduling aimed at optimizing productivity of a CTT.	Operational.	Trucks, vessels.	Marine side interface, transfer system, container storage and delivery and receipt system.	Quay, yard and transfer operations.	Truck, yard crane and the quay crane.	Assign most cost beneficial berth location, assign trucks to overcome congestion and minimize empty movements of yard cranes and number of restacking.	Quay management agent, transfer management agent, yard management agent and the user agent.	Sending messages.
[27]	CTT logistical operations system optimization using multiple agents.	Operational.	Trucks, vessels.	Berth, storage yard, gate.	Tug boat operations, wharf apron operations, horizontal transport and yard and gate operations.	Twelve types of equipment.	-	Nine types of decision agents.	-