SIMULATION OF TRANSPORTATION ACTIVITIES IN AUTOMATED SEAPORT CONTAINER TERMINALS

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ABSTRACT

A container terminal represents a complex system with highly dynamic interactions between the various handling, transportation and storage units and incomplete knowledge about future events. Hence, decentralized planning is the only realistic mode to govern logistics control of automated container terminals. We classify the specific logistics planning and control issues arising in seaport container terminals with respect to the decision level (terminal design, operative planning, real-time control) and the type of handling equipment involved. In particular, the efficient use of transportation equipment determines the performance of the entire terminal. A simulation study of transportation activities in container terminals is presented, where automated vehicles can be employed in different dispatching modes. The design of the simulation study reflects conditions, which are typical of a real automated terminal environment. Major experimental factors are the size of the terminal and the degree of stochastic variations. The main issues addressed in the simulation experiments are the relative performance of various transportation modes and dispatching strategies and the impact of stochastic variations in handling and transportation times. In addition, directions of future research are highlighted, for instance, the application of local search principles for vehicle scheduling and approaches for integrated scheduling of cranes and vehicles.

Key Words: *Simulation, Transportation, AGV Dispatching*

1. INTRODUCTION

Over the recent years, the use of containers for intercontinental maritime transport has dramatically increased. Figure 1 exhibits the growth of world container turnover. Starting with 50 million TEU (twenty feet equivalent unit) in 1985 world container turnover has reached more than 350 TEU in 2004. A further continuous increase is expected in the upcoming years, especially between Asia and Europe.

Since their introduction in the 1960s containers represent the standard unit-load concept for international freight. Transhipment of containers between different parties in a supply chain involves manufacturers producing goods for global use, freight forwarders, shipping lines, transfer facilities, and customers. Container terminals primarily serve as an interface between different modes of transportation, e.g. domestic rail or truck transportation and deep sea maritime transport. As globally acting industrial companies have considerably increased their production capacities in Asian countries, the container traffic between Asia and the rest of the world has steadily increased (cf. Wang (2005)). For instance, from 1990 to 1996 total container traffic volume between Europe and Asia doubled, whereas in the same period total container flow between Europe and the Americas went up by only 10%.

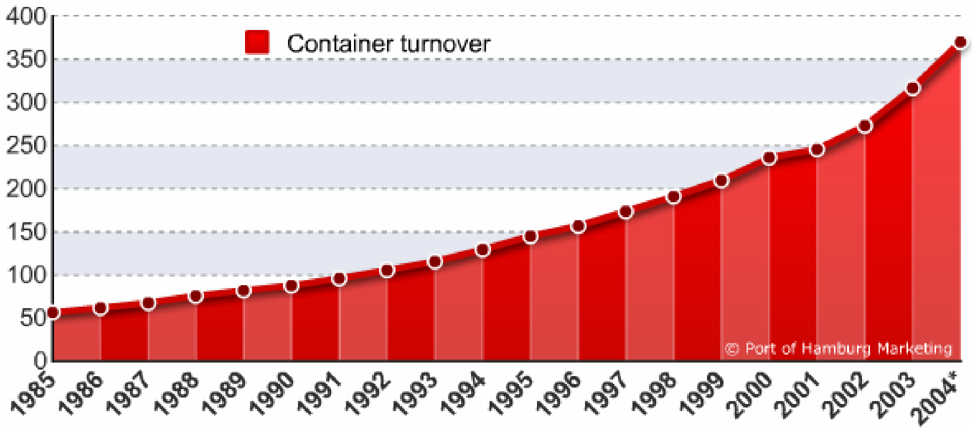

Figure 1. Development of world container turnover

(Source: Port of Hamburg Marketing)

A few facts highlight the ever increasing importance of maritime container transportation (cf. Brinkmann (2005), Lee and Cullinane (2005), and Steenken et al. (2004)).

- Since regular sea container services began 1961 with routes between the East Coast of the United States and ports in Central and South America, the fraction of container transportation in the world's deep-sea cargo rose to more than 60%. Some major maritime freight routes are even containerized up to 100%.
- The transportation capacity of the worldwide container fleet has almost doubled during the past 10 years. At the same time, the transportation capacity of a single vessel rose steeply, culminating in the recent generation of 10,000 TEU container vessels.
- While the worldwide gross national product increased from 1990 to 2003 by about 50%, world container turnover tripled in the same period.
- In 1997 as much as 93.7% of the piece goods handled in the port of Hamburg were packaged in containers.

As a consequence, the number and capacity of seaport container terminals increased considerably, although investments for deep-sea terminals and the related infrastructure expansions almost reach one billion EURO, as it is reported from the latest deep-sea container terminal project at Wilhelmshafen, Germany. At the same time, there is an ongoing trend in the development of seaport container terminal configurations to use automated container handling and transportation technology, particularly, in countries with high labour costs. Hence, manually driven cranes are going to be replaced by automated ones and often automated guided vehicles (AGVs) are used instead of manually driven carts. Figure 2 illustrates the layout of one of the latest highly automated seaport container terminals in Germany.

Driven by huge growth rates on major maritime container routes, competition between container ports has considerably increased. Not only handling capacities of container terminals worldwide got larger and larger. Moreover, significant gains in productivity were achieved through advanced terminal layouts, more efficient IT-support and improved logistics control software systems, as well as automated transportation and handling equipment. For instance, in the port of Singapore, container turnover per employee quintupled from 1987 to 2001.

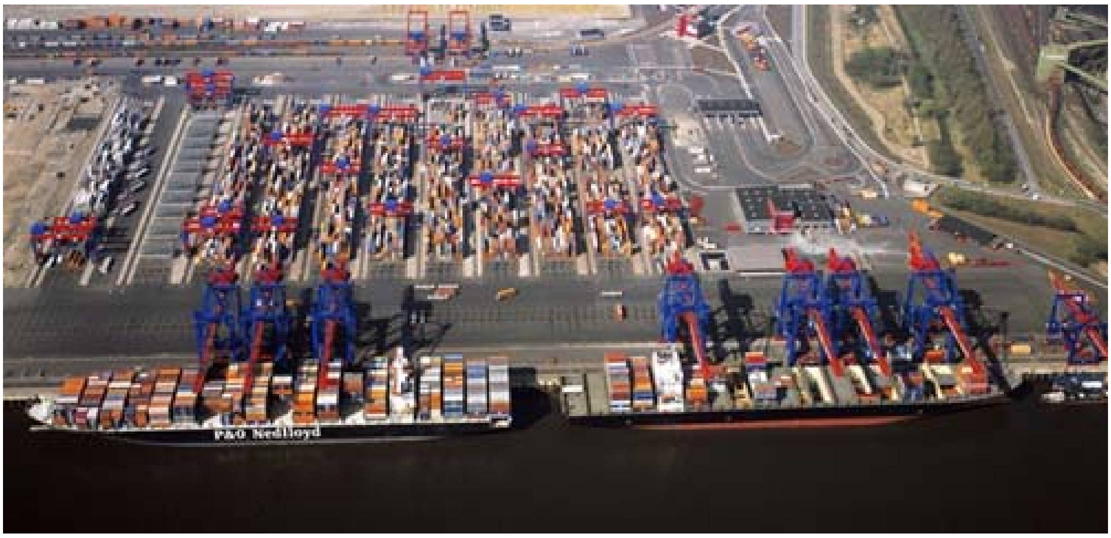

Figure 2. Layout of the Container Terminal Altenwerder (CTA), Hamburg, Germany

(Source: http://www.hhla.de/de/Geschaeftsfelder/HHLA_Container/Altenwerder_(CTA)/Daten_und_Fakten.jsp, visited on December 27, 2005)

In the scientific literature container terminal logistics have received increasing interest. Many papers have been published dealing with individual strategic, operational and control issues of seaport container terminals. Recent overviews can be found in Vis and de Koster (2003), Steenken et al. (2004), Murty et al. (2005) as well as Günther and Kim (2005). Additional OR-oriented papers will be published in the special issue of OR Spectrum on "Design, operation, and logistics control of automated container terminals and transportation systems" edited by Günther and Kim (2006).

2. TRANSPORTATION AND HANDLING EQUIPMENT

Although seaport container terminals considerably differ in size, function, and geometrical layout, they principally consist of the same sub-systems (see Figure 3). The ship operation or berthing area is equipped with quay cranes for the loading and unloading of vessels. Import as well as export containers are stocked in a yard which is divided into a number of blocks. Special stack areas are reserved for reefer containers, which need electrical supply for cooling, or to store hazardous goods. Separate areas are used for empty containers. Some terminals employ sheds for stuffing and stripping containers or for additional logistics services. The truck and train operation area links the terminal to outside transportation systems.

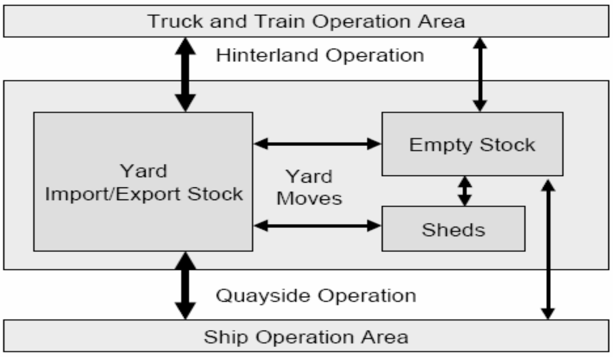

Figure 3. Operation areas of a seaport container terminal and flow of transports

(Source: Steenken et al. (2004), p. 6)

The chain of operations for export containers can be described as follows (see Figure 4). After arrival at the terminal by truck or train the container is identified and registered with its major data (e.g. content, destination, outbound vessel, shipping line), picked up by internal transportation equipment and distributed to one of the storage blocks in the yard. The respective storage location is given by row, bay, and tier within the block and is assigned in real time upon arrival of the container in the terminal. To store a container at the yard block, specific cranes or lifting vehicles are used. Finally, after arrival of the designated vessel, the container is unloaded from the yard block and transported to the berth where quay cranes load the container onto the vessel at a pre-defined stacking position. The operations necessary to handle an import container are performed in the reverse order. Scheduling the huge number of concurrent operations with all the different types of transportation and handling equipment involved is an extremely complex task. In view of the ever changing terminal conditions and the limited predictability of future events and their timing, this control task has to be solved in real time.

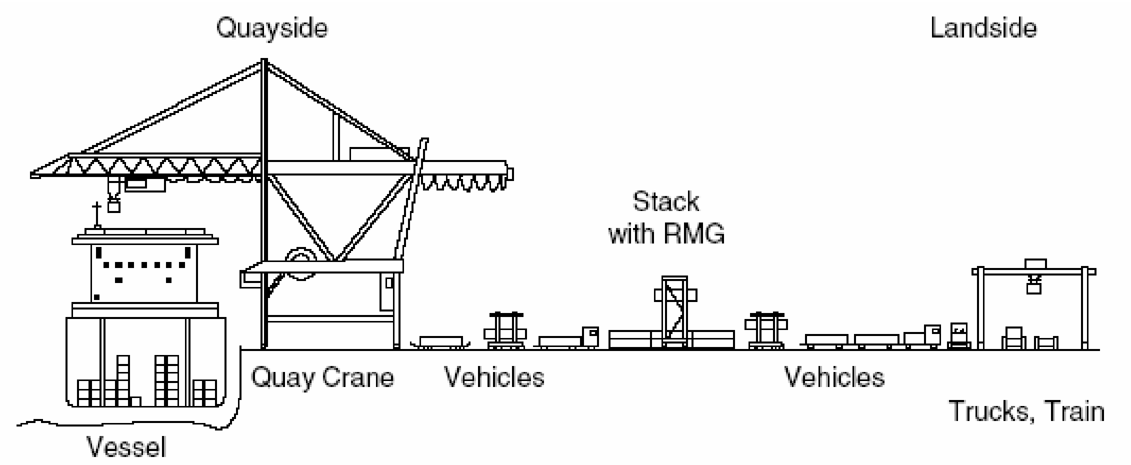

Figure 4. Transportation and handling chain of a container

(Source: Steenken et al. (2004), p. 13)

Seaport container terminals greatly differ by the type of transportation and handling equipment used. Regarding quay cranes, single or dual-trolley cranes can be found. The latter employ an intermediate platform for buffering the loaded or unloaded container. The most common types of yard cranes are rail-mounted gantry (RMG) cranes, rubber-tired gantry (RTG) cranes, straddle carriers, reach stackers, and chassis-based transporters. Of these types of cranes only RMG cranes are suited for fully automated container handling. Figure 5 exhibits the working principle of the different types of handling equipment and their comparative performance figures with respect to the number of TEUs, which can be stored per hectare.

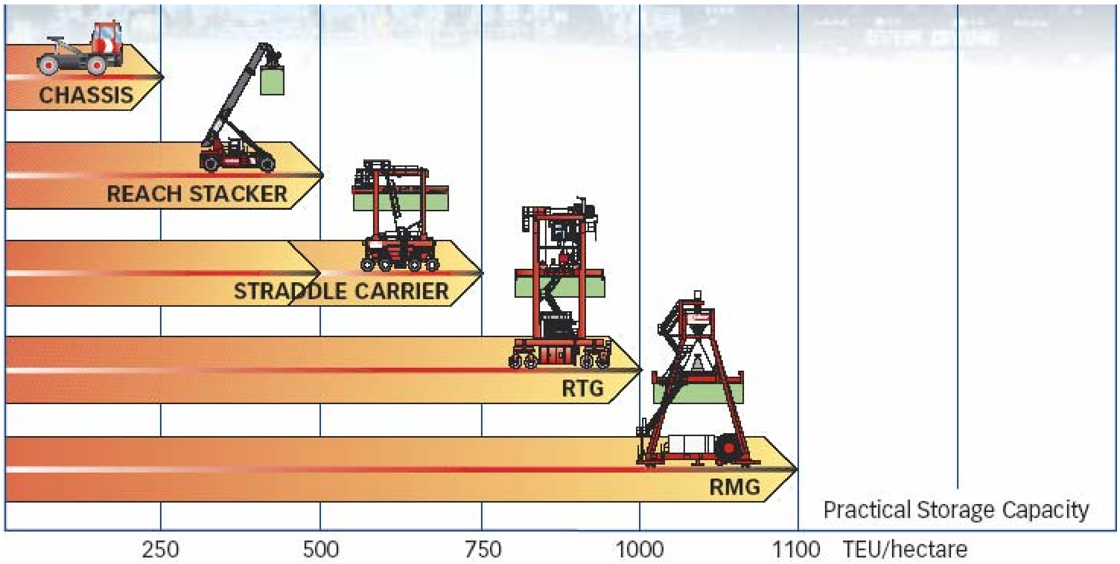

Figure 5. Different types of handling equipment

(Source: www.kalmarind.com; visited on January 2, 2006)

Different types of vehicles can be used both for the ship-to-yard transportation and the interface between the yard and the hinterland. The most common types are multi-trailer systems (MTS) with manned trucks, automated guided vehicles (AGVs), and automated lifting vehicles (ALVs). The latter ones, in contrast to AGVs, are capable of lifting a container from the ground by themselves (cf. Vis and Harika, 2004; Yang et al., 2004). However, despite their superior handling capabilities ALVs have not yet gained widespread use in container terminals.

3. PLANNING AND LOGISTICS CONTROL ISSUES

A container terminal represents a complex system with highly dynamic interactions between the various handling, transportation and storage units, and incomplete knowledge about future events. There are many decision problems related to logistics planning and control issues of seaport container terminals. These problems can be assigned to three different levels as shown in Figure 6: terminal design, operative planning, and real-time control. In the following a brief overview of these planning and control levels and their relationship to the various kinds of terminal equipment is given.

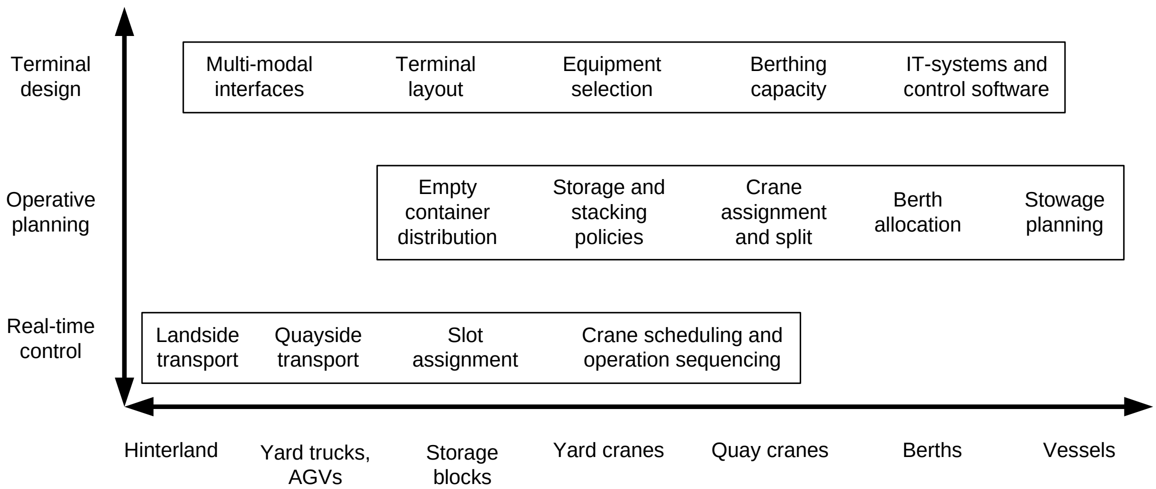

Figure 6. Logistics planning and control issues in seaport container terminals

Terminal design problems have to be solved by facility planners in the initial planning stage of the terminal. These problems have to be analyzed both from an economic as well as a technical feasibility and performance point of view. In particular, construction of a completely new terminal site and the use of automated equipment require huge investments. From the various design problems, only the most important ones shall be highlighted. For a more detailed overview see Steenken et al. (2004).

- *Multi-modal interfaces*: In contrast to their Asian counterparts, most European container terminals are laid out as multi-modal facilities, i.e. they are directly linked to railway, truck and inland navigation systems. The integration of these different modes of transportation has a major impact on the design of the entire terminal.
- *Terminal layout*: The storage yard, transportation guide paths, and quays represent the major entities of each container terminal. Their capacity and spatial arrangement heavily determine the performance of the terminal configuration. Terminal layout also includes the reservation of certain areas for reefer or hazardous goods containers, empty containers or non-standard-size containers.
- *Equipment selection*: Different types of equipment can be used for handling and transportation within the terminal. They primarily differ by their degree of automation and their performance figures. Currently, there is an ongoing trend to make increased use of automated storage cranes und driverless vehicles, although these types of equipment raise complex logistics control problems.
- *Berthing capacity*: The global performance factor of a container terminal is given by its seaside dispatching capacity. The berthing capacity not only determines the number and size of the vessels that can be served, but also the requirements for storage yard space and the fleet size of vehicles etc.
- *IT-systems and control software*: Finally, logistics control in large-sized container terminals is a tremendously complex task, which requires real-time decisions on matching handling tasks with the corresponding equipment units and the provision of detailed information about each individual container. Different modes of software and IT support as well as use of sophisticated optimization tools are issues of considerable importance.

The level of *operative planning* (cf. Steenken et al. (2004)) comprises guidelines and basic planning procedures for performing the various logistic processes at the terminal. Since decentralized planning is the only realistic mode to govern logistics control of automated container terminals, the entire logistics control system is subdivided into various modules for the different types or groups of resources. Hence, specific issues arise in planning and scheduling the use of key resources for a short-term planning horizon of several days or weeks.

- *Empty container distribution*: Since container transportation volumes considerably differ between the various deep-sea cargo routes, circulation of empty container has become a serious concern for international shipping lines. For instance, the container traffic from Asia to Europe is considerably stronger than in the opposite direction. This disparity has also led to significantly different freight rates for major shipping routes.
- *Storage and stacking policies:* Large container terminals in Europe store a total of several 10,000 containers with average dwell times of 3-5 days and daily turnover of 10-20,000 containers. The storage area is separated into blocks, which are organized into bays, rows and tiers. Policies for assigning individual storage locations and stacking of containers are ruled by the objective to expedite the necessary storage and retrieval operations as far as possible and to avoid reshuffling of containers within the

block. Specific issues include the reservation of dedicated storage areas for import and export containers.

- *Crane assignment and split:* To load and unload a large container vessel, several quay cranes are used. First it has to be decided which individual cranes are to be assigned to the various ships considering the accessibility of cranes at the berth and the impossibility to exchange cranes between different berths at the terminal. Second the cranes operating at one ship have to be assigned to different sections or hatches of the ship.
- *Berth allocation:* Before arrival of a ship, the required berthing space has to be allocated taking the prospective time the ship spends in the terminal into account. Additional constraints arise from the availability of cranes and the berthing and crane requirements of other vessels which already moor at the quay or are expected to arrive shortly.
- *Stowage planning:* Shipping lines have to decide which positions within the ship are assigned to specific categories of containers considering container attributes such as destination, weight or type of the container. Based on this given assignment, the terminal operator decides which individual container has to be stored at the specific slots within the vessel. This final slot-assignment heavily affects the loading and unloading sequence of containers and thus represents a major input for determining the yard crane's and vehicle's schedules.

Container terminals represent highly dynamic and highly stochastic logistics systems, which do not allow pre-planning of detailed transportation and handling activities for a look-ahead horizon of more than 5-10 minutes. Hence, *real-time control* of logistics activities is of utmost importance. Real-time control (or real-time planning) is usually triggered by certain events or conditions and requires that the underlying decision problem is solved within a very short time span, in practice usually within less than a second. Real-time decisions include the assignment of transportation orders to vehicles for landside transportation as well as for transportation between the berth and the storage yard, the assignment of storage slots to individual containers, and the determination of detailed schedules and operation sequences for quay and stacking cranes.

4. AGV DISPATCHING

For intra-terminal operation, dual-load AGVs represent a recent development in transportation technology. Such vehicles offer the advantage of being able to transport two 20 ft containers or one 40 ft container at a time. However, in automated container terminals dual-load AGVs are still operated in single-carrier mode, mainly because adequate dispatching strategies, which allow for the efficient use of their enhanced transportation capacity, are missing. Obviously, the dispatching problem for dual-load carriers is considerably more complex than that one for single-load carriers.

Figure 7 shows an example of combining several transportation orders for 20 ft import and export containers. The resulting route starts at quay crane 1, where the first 20 ft import container is picked up. At quay crane 2, the second 20 ft import container is loaded onto the vehicle. Next, one of these containers is dropped off at yard stock 3. This is followed, by picking up the first 20 ft export container at yard stock 4 and dropping off the second import container at yard stock 5. Another 20 ft export container is picked up at yard stock 6. Finally, the export containers are transported to quay cranes 7 and 8, respectively.

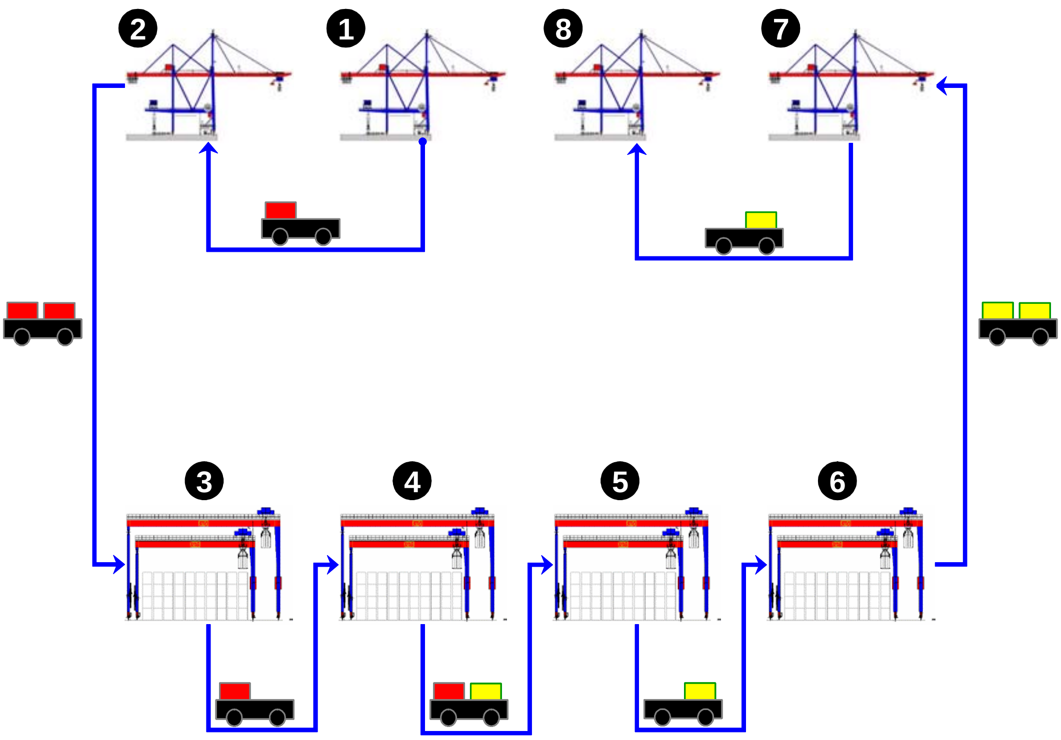

Figure 7. Example of the transportation route of a dual-load AGV

This simple example illustrates the difficulty of dispatching dual-load AGVs. The dispatching task not only requires the assignment of transportation orders to vehicles. In addition, in the case of 20 ft containers, the detailed sequence of all the necessary pick-up and drop-off operations has to be determined. Moreover, the schedules of the AGVs and the affected quay and yard cranes have to be coordinated. In the ideal case, the AGV arrives at the quay or yard cranes, as soon as the crane has completed its previous loading or unloading operation. This way, waiting times of both the cranes and the AGVs can be avoided.

For implementation within a real-time logistics control system, a dispatching methodology is required which guarantees response times of merely a few seconds of CPU time (ideally, even less than a second). Thus, priority rule based approaches seem appealing due to their flexibility and their low computational effort. If the AGVs are used as single-load carriers, one can build upon the dispatching rules known from manufacturing and warehouse applications (cf. Le-Anh and de Koster (2005)). In the simplest case (so-called on-line dispatching; cf. Grunow et al. (2006)), a dispatching request is triggered, when a new transportation order is released (transportation-order-initiated dispatching) or an AGV becomes available (vehicle-initiated dispatching). Certainly the most popular representative for transportation-order-initiated dispatching is the nearest-vehicle (NV) rule, which assigns the vehicle located the closest to the pick-up location whenever a new transportation order is initiated. Vehicle-initiated dispatching normally resorts to the first-come-first-served (FCFS) strategy, which is applied to prioritize waiting transportation orders. Another adequate dispatching strategy is the shortest-travel-time (STT) rule, which is the vehicle-initiated counterpart of the NV rule. By this rule, transportation orders are chosen according to the distance the vehicle would have to travel to service them.

However, in the case of dual-load vehicles as they are employed in the ports of Hamburg and Rotterdam, the entire sequence of pick-up and drop-off operations for a chain of transportation orders must be considered. This is supported by the introduction of assignment patterns which express the feasible options of combining the operations of an already assigned and a new transportation order for the case of 20 ft containers. Grunow et al. (2006)

propose a heuristic dispatching algorithm which utilizes assignment patterns, where pick-up and drop-off operations of the new order are sequenced after those of the already assigned order (assignment pattern "*aann*", read assigned (pick-up) – assigned (drop-off) – new (pick-up) – new (drop-off)), in between them ("*anna*") or alternating ("*anan*"). In Figure 8, the feasible assignment patterns for 20 ft containers are illustrated. Note that, in order to avoid re-routing of a vehicle and to prevent that an already assigned transportation order is infinitely delayed, those patterns which assign the pick-up operation of the new order at the first position in the operation sequence, are not allowed.

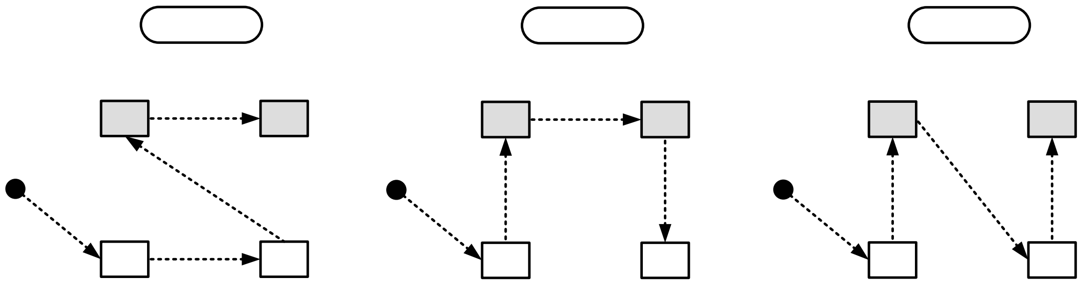

Figure 8. Feasible assignment patterns for 20 ft containers

Given pick-up and drop-off times for all transportation orders, all vehicles and all unassigned orders within a pre-defined look-ahead time window are considered, independently of which event triggers a new dispatching request. The pattern-based dispatching procedure proposed by Grunow et al. (2006) consists of the following basic steps:

1) From all unassigned transportation orders within the given look-ahead time window, determine the one with the earliest service time.
2) For the selected transportation order, consider all feasible assignment patterns to AGVs. Evaluate the assignments according to a given cost function, e.g. penalizing late arrival at the container's destination.
3) Select the order-vehicle-assignment showing the lowest assignment costs, remove the order from the list of unassigned orders, update ready times and prospective locations of the AGV, and go to 1).

The heuristic terminates when all transportation orders in the planning horizon are assigned to a vehicle.

5. SIMULATION MODELLING OF SEAPORT CONTAINER TERMINALS

Today, discrete event simulation is recognized as a powerful tool to improve the performance of seaport container terminals and many other logistics or manufacturing systems. In particular, in the design phase of a new terminal, simulation is applied to compare different layout alternatives and equipment configurations. In strategic simulation studies, logistics operations are usually modelled at an aggregate level, since the focus of the study is on general performance figures rather than on operational control issues. Operational simulation studies, however, target at the comparison of operational policies, the possible gain achieved through the application of optimization methods, or the coordination of logistics activities within the overall logistics control system. Respective simulation models analyse the terminal operations at a great level of detail and also consider specific events, which occur in the dynamic planning environment of the container terminal.

To evaluate the effectiveness of AGV dispatching strategies a comprehensive discrete event-based simulation model has been developed by the authors using the eM-Plant 6.0 simulation software. For modelling a real logistics system through simulation, a major issue in the design of the simulation model refers to the definition of the system boundaries. We decided to build up the simulated system around an AGV guide path and a fleet of vehicles which transport 20 ft or 40 ft containers between quay cranes located at the berth side and automated stacking cranes which operate at the different storage blocks arranged at the opposite side of the guide path. Thus, sub-systems not included in the simulation model are, for instance, the stowage and berth planning for vessels, the storage planning for containers inside the storage blocks, the interface to the hinterland, and the traffic control of the AGVs.

In order to simulate terminals of different size, a basic module was defined which constitutes the building block of a flexible terminal configuration (see Figure 9). Hence, by combining various modules a larger terminal configuration can be generated. The basic module consists of four elements: (1) the AGV guide path laid out as a four-lane uni-directional loop, (2) a fleet of AGVs, (3) a single quay crane, and (4) two storage blocks equipped with two automated stacking cranes each. However, we do not include the detailed operations of the stacking cranes into the simulation model. In optional modules, one or two of the storage blocks or the quay crane are omitted. Thus, an arbitrary combination of quay cranes and storage blocks can be simulated. AGVs are not dedicated to a single module but can freely commute in all modules. To generate a specific terminal configuration, only five parameters are required, (1) the number of quay cranes, (2) the number of storage blocks, (3) the number of AGVs, (4) the AGV travel time between two quay or stacking cranes, and (5) the AGV travel time between the storage area and the berth side.

As an example, Figure 10 displays a medium-sized terminal configuration with 10 quay cranes, 30 storage blocks, and AGV travel times of 20 and 10 seconds between two quay cranes and between two storage blocks, respectively. The trip from the storage area to the berth side or vice versa requires 10 seconds. All cranes in the system are linked by a uni-directional mesh-type guide path in which only the traversals between the quayside and the storage yard show a bi-directional orientation.

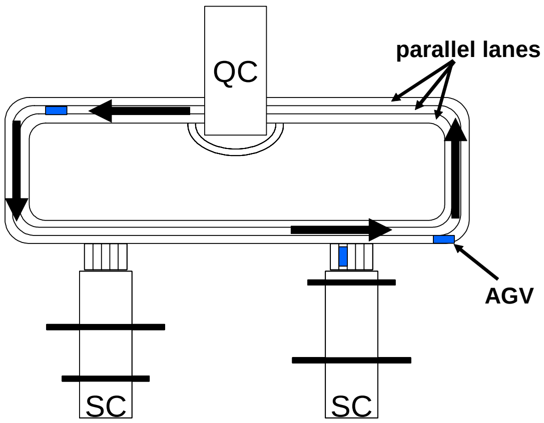

Figure 9. Basic module of a terminal configuration (QC: quay crane; SC: stacking crane)

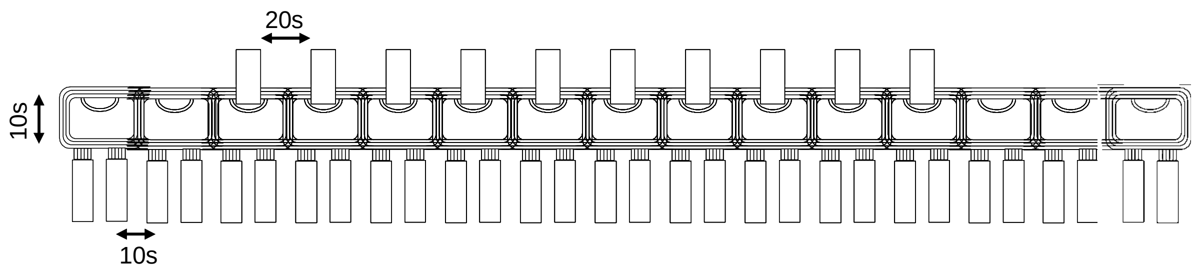

Figure 10. Medium sized terminal configuration generated from basic modules

6. NUMERICAL RESULTS

The scenarios investigated in our simulation study reflect realistic terminal environments and consider stochastic variations in the timing and processing of loading and unloading operations of containers. In order to evaluate the performance of the dispatching strategies in extreme situations, a very high workload was simulated. Throughout the numerical experiments, the degree of stochasticity is varied so that the relative performance of the various dispatching methods can be assessed. Each scenario is characterized by the number of quay and stacking cranes in the terminal configuration and the stochastic variations of the handling time per container. All the detailed data required to feed the simulation model (e.g. container and equipment attributes) were generated according to the guidelines of Hartmann (2004), which were derived from the simulation project of a modern automated container terminal. Specifically, we generated a number of scenarios by varying the following experimental factors:

- Small, medium, and large terminal configurations were generated consisting of 5, 10, and 15 quay cranes as well as 15, 30, and 45 storage blocks, respectively.
- Different degrees of stochasticity were simulated by considering the cycle times of the quay cranes and stacking cranes as random values which are determined according to the empirical distributions observed by Vis and Harika (2004). We distinguish four degrees of stochasticity: deterministic, low, normal, and high.
- AGVs were operated alternatively as single and dual-load carriers. In the latter case, their capability of transporting one 40 ft or two 20 ft containers at a time was utilized.
- The share of 40 ft containers was set to 50%, which is a realistic value for terminals in Europe.

For each scenario, simulation experiments were repeated 10 times with different randomly generated input data. For each data set, the following two approaches were tested once for the single and once for the dual-load mode:

- *on-line dispatching* using the combination of the basic rules “nearest-vehicle / first-come-first-served (NV/FCFS)”,
- *off-line dispatching* using the pattern-based heuristic proposed by Grunow et al. (2006).

While the on-line approach only uses information about the next transportation order of each quay crane or storage block, for the off-line heuristic a look-ahead window of four transportation orders per quay crane was used. All these transportation orders are considered by the pattern-based heuristic for the generation of the actual predictive schedule. Reassignment of all operations scheduled during the last dispatching request is allowed apart from the one to which the vehicle is currently en route (to avoid deviations) and apart from the drop-off of already picked up containers (which clearly must be done by the AGV currently transporting the container).

Since minimizing turnover time of the vessels is the most important performance criterion for AGV dispatching, the different approaches are compared with respect to the overall processing time required to complete all transportation orders. We compare the simulation results to a lower bound which can be determined ex-post upon completion of the entire simulation run, i.e. when the actual handling times generated during the terminal simulation are known (see Grunow et al. (2006) for details).

By examining the detailed simulation results of preliminary numerical tests, we detected deadlock situations, which hampered the system performance. We therefore developed specific deadlock handling strategies and included them in the simulation model used for the numerical investigation. A detailed presentation of these deadlock handling strategies can be found in Lehmann et al. (2006).

The main research questions addressed in our numerical investigation are the following:

- How does the degree of stochasticity affect the performance of the dispatching strategies?
- Does the size of the terminal configuration have a major impact on the relative performance of the dispatching strategies?
- How do the on-line and the off-line strategy perform against each other?
- Can the system performance of the terminal be improved by utilizing the multi-load capability of the AGVs compared to the single-load carrier mode?

Figure 11 shows the final results of the simulation experiments in comparison to the lower bound. As a general result we found that the performance of the investigated dispatching strategies shows similar characteristics for the three investigated terminal configurations. In all cases, the pattern-based heuristic clearly outperforms the on-line ("basic") heuristic. Its overall processing time deviates from the lower bound between 4.5 and 14 % for the small, 2.5 and 10 % for the medium, and 1.5 and 7.5 % for the large terminal configuration. The superior performance for the larger configurations is mainly due to the fact that the scheduling frequency increases, as - due to the increased number of quay cranes - a larger number of transportation orders are considered in the planning horizon. In particular, the result for the most realistic scenario, i.e. the large terminal configuration with a normal degree of stochasticity seems to indicate that the developed approach is appropriate. Here, a deviation from the lower bound of less than 5 % was observed.

The tested on-line heuristics show a deviation from the lower bound between 17 and 33 %. These results clearly demonstrate that the on-line approach, in contrast to the pattern-based heuristic, is unable to exploit the optimization potential which results from coordinated dispatching of the entire AGV fleet over a limited time horizon.

The general effect of an increasing degree of stochasticity is identical for all approaches. It impairs the performance of the heuristics. However, the performance reduction for the pattern-based heuristic is far less than expected. Especially, no convergence of the off-line and on-line heuristics can be observed. Apparently, the off-line character of the pattern-based heuristic is not very distinctive. This is probably due to the high scheduling frequency and to additional triggering of dispatching requests once the delay threshold has been exceeded.

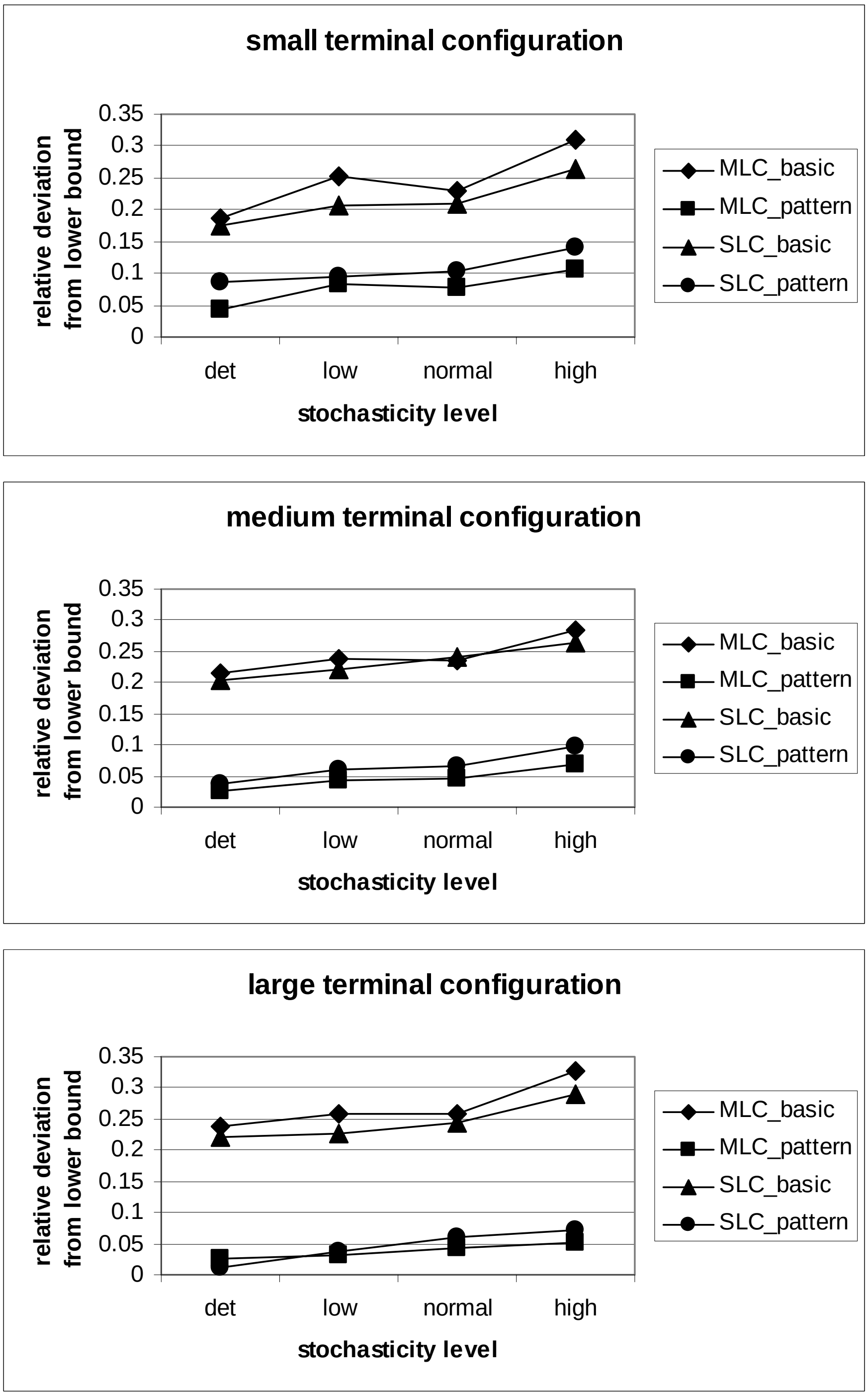

Figure 11. Average performance of dispatching heuristics for different sizes of terminal configurations and different degrees of stochasticity

The version of the pattern-based heuristic, which utilizes the multi-load capability of the AGVs, achieves better results than the pattern heuristic, which treats the AGVs as single-load carriers. This result is highly relevant for terminal operators being currently reluctant to actually use the additional dispatching flexibility and dual-load capability provided by the vehicle technology. As can be seen from our experimental results, the additional scheduling complexity does result in improved system performance. In our simulation study, the advantage of the multi-load heuristic shrinks for the larger terminal configurations (in one case, it even becomes negative). This is mainly due to the random assignment of storage locations employed in our simulation experiments. As a result, the average distance between storage blocks from where a container is retrieved or to where it is to be delivered increases with enhanced terminal size. Hence, combining transportation orders becomes less appealing.

7. CONCLUSIONS

AGV dispatching methods for application in automated seaport container terminals must be capable to react rapidly to changes in the highly dynamic planning environment. In our investigation, the focus is on the development of fast dispatching methods suitable for real-time application. In particular, we examine dual-load AGVs which are able to load either two 20ft containers or one 40ft container. A novel heuristic dispatching approach based on order-vehicle assignments was developed. Comparative simulation studies showed that this approach outperformed myopic priority rules, which are usually applied for AGV dispatching in warehouse or manufacturing applications. Due to its computational efficiency, the pattern-based heuristic is well suited for integration into a real-time AGV control system. Our numerical results also revealed that considerable improvements in AGV performance may be obtained if the AGVs are operated in dual instead of single-load carrier mode.

One direction of future research is to implement improvement heuristics such as neighbourhood search, which further improve the solution found by the pattern-based heuristic. In a real-time application, the improvement heuristics may be run parallel to the handling processes, until the next dispatching request calls for transmitting the actual results to the logistics control system. The authors plan to implement this approach in their future research work. Even without these potential enhancements, the proposed method for AGV dispatching derives close-to-optimum solutions for the case of an AGV system which is regarded as a service system for quay and stacking cranes. However, the lower bound derived in this paper indicates that the quay and stacking crane sequences have a large impact on the utilization of these resources. Our future research will thus aim at integrating the decisions on storage block assignment and sequencing the operations of stacking cranes.

REFERENCES

Brinkmann, A. (2005), *Seehäfen: Planung und Entwurf*, Springer, Berlin, Heidelberg (in German).

Grunow M., Günther H.-O., and Lehmann, M. (2006), Strategies for dispatching AGVs at automated seaport container terminals, *OR Spectrum* (under review).

Günther, H.-O. and Kim K. H. (2005), *Container Terminals and Automated Transport Systems*, Springer, Berlin, Heidelberg.

Günther, H.-O. and Kim K. H. (2006), Design, operation and logistics control of automated container terminals and transportation systems, *OR Spectrum* (to appear).

Hartmann, S. (2004), Generating scenarios for simulation and optimization of container terminal logistics, *OR Spectrum*, **26**, 171-192.

Le-Anh, T., and de Koster, M.B.M. (2005), On-line dispatching rules for vehicle based internal transport systems, *International Journal of Production Research*, **43**, 1711-1728.

Lee, T.-W. and Cullinane, K. (2005), *World Shipping and Port Development*, Palgrave, Basingstoke.

Lehmann, M., Grunow, M., and H.-O. Günther (2005), Deadlock handling for real-time control of dual-load AGVs at automated container terminals, *OR Spectrum* (under review).

Murty, K. G., Liu, J., Wan, Y.-W., and Linn, R. (2005), A decision support system for operations in a container terminal, *Decision Support Systems*, **39**, 309-332.

Steenken, D., Voß, S., and Stahlbock, R. (2004), Container terminal operation and operations research – a classification and literature review, *OR Spectrum*, **26**, 3-49.

Vis, I.F.A. and Harika, I. (2004), Comparison of vehicle types at an automated container terminal, *OR Spectrum*, **26**, 117-143.

Vis, I. F. A. and de Koster, R. (2003), Transshipment of containers at a container terminal: An overview, *European Journal of Operational Research*, **147**, 1-16.

Wang, M. (2005), The rise of container transport in Asia, in: T.-W. Lee, K. Cullinane, K. (eds), *World Shipping and Port Development*, Palgrave, Basingstoke, 10-35.

Yang, C.H., Choi, Y.S., and Ha, T.Y. (2004), Simulation-based performance evaluation of transport vehicles at automated container terminals, *OR Spectrum*, **26**, 149-170.