A Survey on Operations Research Applications in Container Terminal Logistics

Stefan Voß* Robert Stahlbock* Dirk Steenken†

*University of Hamburg
Institute of Information Systems (Wirtschaftsinformatik)
D-20146 Hamburg, Germany
stefan.voss@uni-hamburg.de, stahlboc@econ.uni-hamburg.de

†Hamburger Hafen- und Lagerhaus AG
IS – Information Systems/Equipment Control
D-20457 Hamburg, Germany
steenken@hhla.de

1 Introduction

Containers came into the market for international conveyance of sea freight almost five decades ago. The breakthrough was achieved with large investments in specially designed ships, adapted seaport terminals with suitable equipment, and availability of containers. Today over 60 % of the world's deep-sea general cargo is transported in containers, whereas some routes are even containerized up to 100 %. International containerization market analysis still shows high increasing rates for container freight transportation in the future. This leads to higher demands on seaport container terminals, container logistics and management as well as on technical equipment, resulting in an increased competition between seaports. The seaports mainly compete for ocean carrier patronage and short sea operators as well as for the land-based truck and railroad services. The competitiveness of a container seaport is marked by different success factors, particularly the time in port for ships, combined with low rates for loading and discharging. Therefore, a crucial competitive advantage is the rapid turnover of the containers, which corresponds to a reduction of a ship's time in port and of the costs of the transshipment process itself.

The objective of this paper is to provide a survey and a classification of container terminal operations. Moreover, examples for applications of operations research models – including exact methods, heuristic methods as well as simulation based approaches – are mentioned. For a detailed description and a comprehensive list of references see [1].

2 Terminal Structure and Handling Equipment

Container terminals can be described as open systems of material flow with two external interfaces: the quayside with loading and unloading of ships, and the landside where containers are loaded/unloaded on/off trucks and trains. Stacks for storing containers decouple quayside and landside operation.

Different types of ships have to be served at the quayside. Most important are deep-sea vessels which serve the main ports of different countries and continents. Smaller feeder vessels link smaller regional ports with the oversea ports delivering containers for deep-sea vessels. Inland barges are used to transport containers into the hinterland on rivers and channels. Functionally barges are means of hinterland transportation – like trucks and trains. Operationally they are ships which are served by quay cranes.

After arrival at the port, a container vessel is assigned to a berth equipped with cranes to (un)load containers. Unloaded import containers are transported to yard positions near to the place where they will be transshipped next. Export containers arriving by road or railway at the terminal are handled within the truck and train operation areas. They are picked up by the internal equipment and distributed to the respective stocks in the yard. Additional moves are performed if sheds and/or empty depots exist within a terminal.

The container storage area is usually separated into different stacks which are differentiated into rows, bays and tiers. Some stack areas are reserved for special containers which do not allow for normal stacking (like reefers which need electrical connection, dangerous goods, or overheight/overwidth containers). Often stacks are separated into areas for export, import, special, and empty containers. Some terminals do not only differ in general functions but also in their operational units and, therefore, in their logistic demands.

2.1 Handling Equipment

Handling equipment can be categorized into types of cranes, horizontal transport means, and assisting systems.

Different types of cranes are used at container terminals. Quay cranes for (un)loading ships play a major role. Besides traditional single-trolley cranes, dual-trolley cranes with a second automatic driven trolley are applied at few terminals. This new development may improve productivity: the man driven main trolley moves a container from the ship to a platform. While the main trolley picks up the next container, the second trolley picks up the container from the platform and moves it to the shore (vice versa in case of export containers). The performance in operation is in the range of 22–30 containers per hour.

The stack is served by a second category of cranes, namely rubber tired gantry cranes (RTG), rail mounted gantry cranes (RMG), or overhead bridge cranes (OBC), either man driven or automatic. A new development in RMGs is an automatic Double-RMG consisting of two RMGs of different height and width. They are able to pass each other, avoiding a handshake area. This results in a slightly higher productivity of the system. The technical performance of gantry cranes is approximately 20 moves per hour. Similar cranes are used for (un)loading trains. Forklifts or reachstackers are used to move and stack light, especially empty containers.

A variety of vehicles is used for the horizontal transport at the quayside and at the landside. Passive vehicles like, e.g., trucks with trailers or automated guided vehicles (AGV) – unable to lift containers – are employed in combination with cranes. Active vehicles like, e.g., straddle carriers can be regarded as 'cranes' not locally bound with free access to containers in the yard. Common straddle carriers are manned, but during the last years automated lifting vehicles were developed.

Communication and positioning systems play an important assisting role for organization and optimization. The intense external communication and data interchange between terminal operators and shipping lines, agents, forwarders, truck and rail companies and others, is based on international standards. The main medium for internal communication is radio data communication, which is used, e.g., for transmitting job data from computers to vehicles. Positioning systems, based on the (differential) Global Positioning System or optical systems like Laser Radar, help to localize and keep track of containers in the yard exactly. Transponders and electrical circuits are used to route gantry cranes and automatic vehicles.

2.2 Container Terminal Systems

A great variety of container terminals can be formed by combination of different types of handling equipment. Despite this variety of equipment combinations, two important categories of terminals can be emphasized: pure straddle carrier systems and systems using gantry cranes for container storage.

The decision on which equipment is used depends on several factors. Space restrictions, economical, historical and cultural reasons play an important role. Automated gantry cranes and AGVs may preferably be used in case of high labour costs and new terminal construction, although long term cost oriented studies are not yet made. Because space is becoming a scarce resource, a tendency for higher storage and intensive usage of gantry cranes is to be foreseen.

3 Terminal Logistics and Optimization Methods

The need for using methods of operations research for optimization of container terminal operation has become more and more important in recent years. One reason is a higher degree of complexity of logistics demanding scientific methods for further improvements. A second reason is the need for objective methods in order to compare different logistic concepts, decision rules and optimization algorithms before they are implemented into real systems.

Most of the processes occurring at container terminals cannot be foreseen for a longer time span. Because of the very short planning horizon for optimization, real-time optimization and decision is needed. For example, the exact time when export containers arrive at the terminal is not known. As trucks permanently arrive, recalculation of a job schedule for a crane at the stock has to be performed periodically or event driven. A similar situation occurs for ship (un)loading. In general, data of containers and their positions within the ship are precisely known in advance and the preplanning process allows the calculation of job sequences. But because of operational disturbances, e.g., due to stability constraints during the (un)loading of a vessel, the pre-calculated sequences often have to be changed spontaneously by crane drivers.

3.1 The Ship Planning Process

Ship planning consists of three partial processes: berth planning, stowage planning and crane split.

Before arrival of a ship, a berth has to be allocated to the ship, ideally before the arrival of the first containers dedicated to this ship – on average two to three weeks before the ship's arrival. Technical data of ships and quay cranes have to be considered. All ships to be moored during the respective time period have to be reflected in berth allocation systems. A maximum productivity of ship operation corresponds to a minimization of the total sum of shore to yard distances for all containers to be (un)loaded. Automatic and optimized berth allocation is especially important in case of ship delays: a new berthing place has to be allocated to the ship whereas containers are already stacked in the yard.

Stowage planning is the core of ship planning. The shipping line designs a stowage plan for all ports of a vessel's rotation. The plan assigns container categories to specific positions within the ship. The categories are length or type of a container, discharge port, and weight or weight-class of containers. The objective of optimization from the shipping line's point of view is to minimize the number of shifts during port operation and to maximize the ship's utilization. Constraints to be satisfied mainly result from the stability of the ship. This stowage plan is transferred to the terminal operator by EDI (Electronic Data Interchange). It is used as a pre-plan for the terminal's ship planner, who assigns dedicated containers to respective slots within the ship matching the attribute set of the slot and of the selected container. Different objectives of optimization are possible, e.g., maximization of crane productivity, cost minimization, or minimization of time consuming unproductive yard reshuffles. From a practical point of view the latter one plays an important role. Because the stowage plan is generated before the ship's loading has started, this kind of optimization is offline optimization. But the complex process structure of ship loading demands online optimization, which is not yet in use. It is a future need to enhance the performance of ship loading. Complexity mainly results from the fact that containers usually are more or less spread in the yard. They have different distances to the crane resulting in different transportation times. Additional transportation time is also consumed in many cases: special containers like overheight containers need special equipment which has to be mounted, reefer containers have to be disconnected from the electrical circuit, and yard reshuffles occur to a respective percentage. In manually driven systems the performance additionally depends on the driver's skill and decision which path he travels. Even technical or operational disturbances of the crane operation occur which enforce to change the loading sequence. Therefore, transportation times cannot be calculated exactly, even if automated equipment is in use. Thus, preparing an offline stowage plan which assigns specific containers to ship positions in advance leads often to sub-optimal results. The loading sequence and the sequence of horizontal transport have to correspond with each other in order to avoid crane waiting times and/or queuing of transport vehicles and to achieve a high productivity for the crane operation. In online stowage planning containers are selected for transportation according to the attributes assigned to ship positions in the stowage instruction of the shipping line. Containers with the same attributes are considered as equal. They are loaded according to their arrival time at the quay crane. The specific stowage plan addressing specific container data to specific ship positions is generated simultaneously to the loading activity.

The allocation of quay cranes to ships and the ships' sections is the third step of ship planning. In practice, this crane split has to reflect several constraints, especially technical data of cranes and ships and the accessibility of cranes at a berth. It not only reflects one ship, but principally all ships moored at a terminal in a given period. There is no unique objective for optimization. Minimization of the sum of the delays of all ships can be an objective while maximization of one ship's performance or a well-balanced or economic utilization of the cranes can be others. Besides this schedule the loading mode (horizontally/vertically and starting at the quay/waterside) is decided in this step.

Stowage plan, crane split, and mode of loading together result in a working instruction which defines the loading sequence for every container of a bay. As mentioned earlier, the sequence for the landside transport has to match this loading sequence.

Commonly used operations research models and methods in these fields are, e.g., combinatorial optimization, queueing network models, (mixed) integer programming, (binary) linear programming, branch-and-bound algorithms, and heuristics like genetic algorithms (GA) or simulated annealing.

3.2 Storage and Stacking Logistics

As container traffic grows continuously and space is becoming a scarce resource, more and more containers have to be stored in ports. Therefore, stacking logistics play an important role for the terminals' overall performance. Storage and stacking logistics are becoming more complex and sophisticated. Generally, containers are stacked on the ground in several levels. The maximum number of levels depends on the stacking equipment.

A storage planning system has to decide on the position – addressed by the block, bay, row and level – for a container to be stored. A good storage decision depends on accurate data of containers (e.g., vessel, discharge port, and container weight for export containers). In practice, most unproductive reshuffles are a result of wrong or incomplete data. Moreover, container deliveries follow a stochastic process and, therefore, cannot be foreseen exactly.

To ease the situation and to ensure a high performance of operations, containers sometimes are pre-stowed near to the loading place and in an order fitting the loading sequence. Due to extra transportation, pre-stowage is cost-extensive and should be avoided or limited by optimizing the yard stacking. Two classes of storage and stacking logistics can be distinguished: a system with allocation of stack areas and storage capacities in advance of a specific ship's arrival, and a system with fixed assignment of yard areas to a berthing place. In the latter system, a stack position is selected in real-time. Containers of the same categories are piled up one on top of the other. Containers for one ship are stochastically scattered over the respective stack area. Reservation of yard slots is no longer necessary. This concept results in a higher yard utilization and a remarkable lower amount of reshuffles, because the stacking criteria merge the ship's stowage criteria.

The objective of yard optimization is minimization of the number of reshuffles and maximization of the storage utilization, respectively. Several factors like, e.g., actual workload of a crane, can be integrated into an algorithm and weighted by parameters. Optimization methods like, e.g., tabu search, genetic algorithms, or dynamic programming are discussed in literature.

3.3 Transport Optimization

At a container terminal, horizontal transport and stacking transport can be distinguished. The horizontal transport can be divided into the quayside transport for serving ships, and the landside transport for serving trucks and trains.

Transport optimization at the quayside not only means to reduce times for transports between ship and stack, but also to synchronize the transports with the loading and unloading activity of the quay cranes. A general aim is to enhance crane productivity. Potential for optimization is offered much more in export loading than in import loading. Transport sequences have to take distances, equipment, reshuffles etc. into account, in order to match a given loading sequence, to synchronize (unmanned) equipment and to avoid idle times of cranes and vehicle congestions. A dual-cycle mode, combining transports of import and export containers, is even more complex, and, therefore, demands optimization methods. Due to the dynamic of operations at a terminal, online methods are preferable to offline methods. In any case, the objective of optimization is to minimize the lateness of container deliveries for the cranes and the travel times of the transport vehicles.

The landside transport is split into rail operation, truck operation, and internal transports. Operation at the railhead is analogous to the quayside operation. Therefore, the aim of the terminal operator is to minimize the number of yard reshuffles, the crane waiting times and the empty transport distances of cranes and transport vehicles. Knowing the stowage instruction, the wagon positions and yard situation can be taken into account in order to synchronize transport and crane activities and to avoid unnecessary waiting times of movements.

The objectives of optimization at the truck operation area are minimization of empty distances and minimization of travel times. Empty distances can be minimized if transports of export containers from the truck's transition point to the yard are combined with transports of import containers from the yard to the interchange point. The arrival time of trucks cannot be precisely foreseen. Therefore, transport jobs for the internal equipment cannot be released until the truck arrives at the transition point. Because of the permanently changing traffic volume, flexible and fast online optimization is demanded for.

In general, internal movements are not time critical, although sometimes time-windows have to be kept. Terminals try to execute them at times of less workload. The objective is to minimize empty and loaded travel times.

Another field of application of optimization methods is the transport by gantry cranes operating in stacks. The transport requirements do not differ from those of the horizontal transport described above: sequences of jobs have to be calculated, and jobs have to be assigned to the respective crane. Priority of jobs have to be taken into account, too. Therefore, comparative algorithms can be applied. The objective of optimization is to minimize the waiting times of the transport vehicles at the stack interfaces and the travel times of the stacking cranes. The rapid change of traffic at the interfaces demands online optimization. Job sequences have to be recalculated whenever a new job arises.

Typically applied algorithms for solving those transport optimization problems are, e.g., routing algorithms, learning-based algorithms, agent-based algorithms, GAs, priority rules, beam search and branch-and-bound algorithms.

3.4 Simulation Systems

In recent years, simulation has become an important tool for improvement of terminal operation and performance. With respect to the level of its application, three types of simulation can be distinguished: strategical, operational, and tactical simulation.

Strategical simulation is used to study and compare different types of terminal layout and handling equipment in order to find a combination of high performance and low costs. It is mainly applied if new terminals are planned or the layout or the equipment of existing terminals has to be altered. Realistic scenarios can be designed and tested with real data of existing terminals.

Different kinds of terminal logistics and optimization methods can be tested by operational simulation in order to measure and judge time and cost effects of alternative scenarios objectively, before these methods are implemented in real terminal control and steering systems.

Tactical simulation means integration of simulation systems into the terminal's operation system. Variants of operation shall be simulated parallel to the operation, and advices for handling alternatives shall be given especially if disturbances occur in real operation. Real data of operation then have to be imported and analyzed synchronously to the operation. Because of this ambitious requirement, tactical simulation is seldom or only partially installed at container terminals.

Literature reflects growing acceptance and usage of simulation in the field of container terminal operation. In general, simulation experiments indicate on one hand that automation could improve the performance of conventional terminals substantially at a considerably lower cost. On the other hand, experiments show also that – at a certain point – adding additional equipment can no longer increase productivity (or even lead to decreasing productivity).

4 Conclusions and Outlook

Operations research methods become more and more important in the field of optimizing logistic operations at a container terminal. Until now the focus is not on optimizing the transport chain as a whole but on several isolated parts of the chain. One of the drivers for using these methods is an increased availability of modern information and communication technology that only allows the application of these methods for complex, large problems instances.

High operating costs for ships and terminals and also high capitalization of ships, containers and port equipment demand a reduction of unproductive times at port. Due to severe competition the increasing pressure on terminals to cut costs of operation and to increase productivity enforces the usage of optimization methods. The potential for cost savings is high. A key to efficiency may be the automation of in-yard transportation, storing and stacking to increase the terminal throughput and decrease ships' turnaround time at the terminal.

At terminals which already apply operations research methods to optimize transport and stacking processes, the need for 'integrated' optimization of interdependent processes is becoming more and more relevant. Up to now there are only a few studies on integrated problems, for example with multi-agent systems and/or simulation systems. Integrated optimization, especially stochastic optimization and scenario based planning, should be a field of increased investigation.

Finally, a new challenge is given by advanced security issues. More versatile planning tools for optimization have to be applied. Usage of certain security techniques and procedures and their impact on the logistic chain have to be taken into account.

References

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