Simulation and Optimization of Container Yard Operations: A survey

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Abstract

Management of container terminal operations is essentially the allocation and scheduling of the expensive resources such as berths, quay cranes, storage space, yard cranes, and container carriers. Each of these resources plays an indispensable role in the interlocking processes in a container terminal. In this survey we give a critical review and a comparative study on various decision problems that arise at container terminals and in most cases, the solutions to which go into making up the overall terminal management system. For each problem, an overview of literature is presented, along with a description of the quantitative models that try to solve the problem. We focus our attention on yard management, since the operation on storage yard is the most complicated part at the terminal where both inbound and outbound container flows are handled in this area simultaneously.

1 Introduction and background

Container terminals play a fundamental role in intercontinental cargo transportation by serving as an intermodal interface between the sea and the land carriers. Typically, they

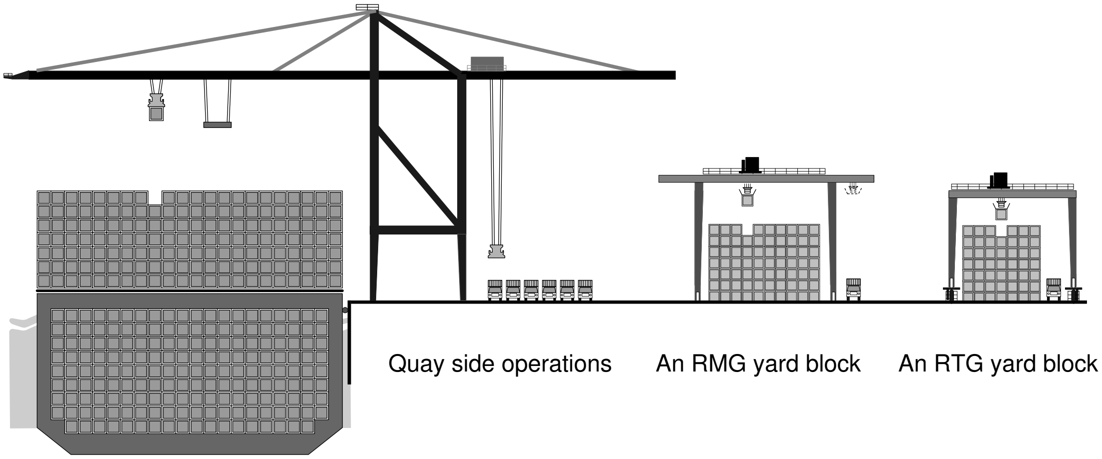

Figure 1: An overview of container terminal port operations

receive cargos in containers from their origins, store them temporarily to account for the differences in arrival times of the sea and the land transport, and route them to their destinations. Figure 1 is a schematic diagram showing the core operations in a container terminal. These operations, in spite of various terminologies, are normally grouped into the following sets of processes that occur simultaneously and interactively:

(a) *Quay side operations*: this includes unloading inbound containers from and loading outbound containers to the vessels via a number of quay cranes (QC), interacting with transport system. The scheduling of vessel berthing and the sequencing of loading/unloading operations are important factors in determining the ship turnaround time.

(b) *Transfer operations*: this focuses on transferring containers between the berth area and the storage yard by container carriers, most popularly by prime movers, yard trucks, or AGVs (Automated Guided Vehicles). An transport system with efficient rules for dispatching, scheduling, and routing the vehicles would effectively reduce congestions to help improve port performance.

(c) *Yard side operations*: this involves the decision of container storage location, the planning and sequencing of stacking or un-stacking, and the allocation of resources (in terms of space and equipment, i.e. yard cranes that store and retrieve containers within yard blocks). Current practice reveals that activities taking place in the storage yard tend to be the bottleneck of port operations due to the limited resources.

There are various performance indices of a container terminal from different perspectives, but ultimately the terminal performance is measured by its service level to the customers. In alignment, port operators are typically look at two objectives [30]:

- to minimize the (average)vessel turnaround time, which is a measure of the service level of a terminal to its customers, i.e. the shipping companies.
- to maximize the (average) throughput of the terminal (reflected by the QC rate), which is a measure of the productivity of a terminal.

In order to achieve satisfactory performance, a number of decisions have to be made at the operational level to manage the involved operations and all these decisions impact each other. For example, decisions on the storage locations of containers directly affect the allocation of yard cranes and the scheduling and dispatching of the prime movers, and indirectly affect the efficiency of QCs. Moreover, the multiple involvement of different action parties and the complex interactions among various service processes further complicate the operation management problem [8]. Therefore, it becomes evident that it is very difficult, if not impossible, to achieve optimal decisions that favor the overall objectives. Logically, hierarchical decomposition of the original problem into simpler sub-problems is an applicable and effective approach to adopt [23].

Before reasonably and effectively breaking the problem into smaller sequential ones, it is necessary to carefully examine the work flows in a container terminal so as to have a full understanding of the problem: starting from the quay side, the container flows are triggered by the vessel arrival event, well before which the number of containers to be handled and the berthing location of the vessel are determined by stowage plan and berth allocation, respectively; the inbound containers are then transferred to the designated yard place and ready for customer pickup (*local import*) or second carrier loading (*transhipment*); following that, the outbound containers (*local export* and *transhipment*) are delivered to the quay side and loaded onto the vessel. Note that the arrival and departure of the *transhipment* containers are decided by vessel schedules and therefore can be known in advance, whereas the departure of *local import* containers and the arrival of *local export* containers are determined by the local customers which makes their arrival time nondeterministic. We can only determine from historical data the distributions when these containers are handled.

Nonetheless, the distinctive feature of the terminal management problem is the great difference in the length of the planning horizons, e.g. yard planning is performed on a time scale of weeks, whereas loading and unloading lists are prepared only a few minutes in advance , or in most cases, in real-time. The different dynamics of these processes (sub-problems), along with the complexity of the problem itself, prevent us from formulating it in an integrated fashion with a sole objective function. It is therefore evident and logical that the separation of the processes with a 'short' horizon from those with a 'long' horizon becomes necessary and helpful. Indeed the hierarchical approach has been recognized as a guideline for solving this problem that divides it sequentially along the time scale, and the input to a sub-problem is actually the output of its immediate predecessor.

These sub-problems (or processes), some of them mentioned in the preceding section, have been commonly identified as follows with different target time domains [29]:

- *Berth allocation* determines the berthing sequence of arriving ships and in turn controls the loading and unloading of containers onboard the ships. It is a multi-objective problem taking care of vessel turnaround time and space utilization. Berth allocation is performed a few days before a ship arrives.

- *Stowage planning* assigns to each bay position a particular outbound container with a type matching the preliminary type-based stowage plan provided by shippers. It is normally done by assigning outbound containers in inverse order of ports to be visited by the ships and changes may be required from the shipping companies. Stowage plans are prepared a few hours in advance.

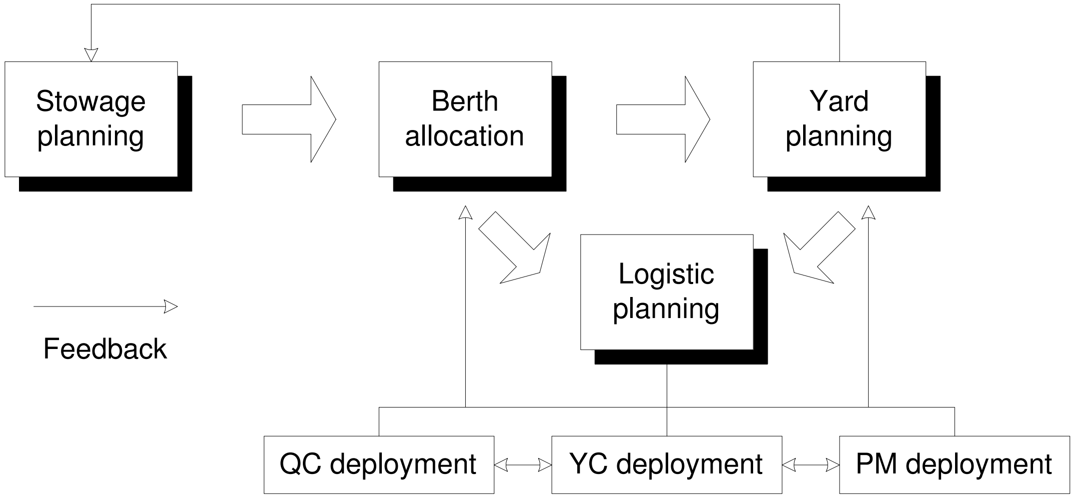

Figure 2: Hierarchical structure of decision-makings in container terminals

- *Yard planning* allocates proper storage locations for the inbound containers, the purpose of which is to integrate all activities within the terminal area into a seamless whole. Though not conclusive, the opinion from most port operators is that it is yard planning that is the key to efficient terminal operations. Yard planning is done on a time horizon of weeks.

- *Logistic planning* coordinates the allocation of resources for handling containers, such as yard cranes, and therefore is also called *Resource allocation* in some literatures. Normally logistic plans are decided days beforehand.

Figure 2 illustrates them in a typical hierarchical structure. As the combined effect of these decision making tasks, the loading and unloading lists of containers for individual vessels are generated with adjustment according to the situation at hand. Once these lists are determined, the productivity of a container terminal becomes assessable, reflecting the level of optimization of the operation policies.

Among these processes, the planning of yard operations plays an important role for efficient port management due to the limited space and high throughput in many terminals. A well designed and planned storage yard would largely improve port performance with high space utilization. In the following we will review various solutions to the different problems arising in yard operations to achieve overall improvement that have been proposed in the literature. On this basis, we attempt to find out the research directions towards the application of simulation and optimization tools and techniques to the problem of container yard management.

2 Yard planning

Operation on the storage yard is the most complicated part at a terminal because both inbound and outbound container flows are handled in this area simultaneously. Yard planning hence determines the port efficiency to a great extent, in which the assignment of storage locations to inbound containers (i.e., *storage allocation*), the usage of yard equipment and the retrieval sequence of outbound containers are resolved.

2.1 stack configuration and storage allocation

In traditional storage yard, containers are stacked by yard cranes side by side and one on top of another to form rectangularly shaped heaps called *blocks*, each of which consists of a number of *rows* in width, a number of *bays* in length and a number of *tiers* in height. The size of each block varies in different terminals, typically with 8 rows and 6 tiers in the port of Singapore using OHBC (overhead bridge crane) as shown in Figure 3. Obviously one of the problems at the strategic level is to determine a good stack configuration, specifically the height of stacking. It's logical to store containers in higher stacking to save necessary ground space, however the more tiers the containers are stacked in, potentially the more reshuffles/rehandles will be required to retrieve a required container.

In [5] it was concluded that the higher stacking needs the improvement on all other relevant conditions at the same time to reduce its possible impact, otherwise large numbers of unproductive container movements are needed. Various storage strategies were then described and tested to tradeoff extra handling efforts for higher stacking against space

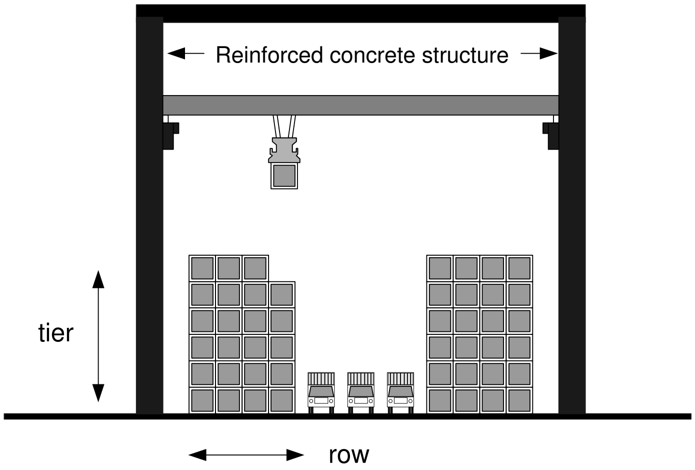

Figure 3: A schematic view of an OHBC yard block

requirement. [1] also studied the stack configuration problem, in which the number of moves to retrieve a container was formulated as a function of stack height and operation strategy, and the best operating strategy could be selected for a chosen configuration. [6] proposed an idea of using a buffer area to store export containers so that the nonproductive movements of yard cranes can be reduced during loading process. A simulation model was built to investigate the effects and 4% reduction in the total loading time was achieved. [11] established a methodology to estimate the expected number of rehandles to pick up an arbitrary container and the total number of rehandles to pick up all containers in a bay for a given initial stacking configuration. Regression equations and an approximation formula were given for evaluation of the number of rehandlings to aid decisions concerning stacking configuration.

Given a stacking configuration, a guideline is needed under for allocation of containers in the yard area. The distribution of containers is normally decided according to container types, which are classified with respect to the origins and destinations of containers as follows:

- *Local import* containers: inbound containers from vessels at predictable times, to be carried out by external trucks at unpredictable times.

- *Local export* containers: inbound containers from external trucks at unpredictable times, to be loaded to vessels at predictable times.
- *Transshipment* containers: discharged from mother vessels and to be loaded to second carriers, both at predictable times.

Taking into account the predictability/unpredictability of container arrival and departure times, in practice various storage strategies are adopted to disperse containers in different terminals according to the portions of different types of containers to be handled. For example, due to the high percentage of *transshipment* containers and the limited storage space, operators in Singapore terminals mix *local export* and *transshipment* containers at the block level by grouping them with certain considerations such as their second carriers, and place containers directly into yard blocks that are near the quayside upon their arrivals. While *local import* containers are segregated according to their importers and stacked in an area close to the gate.

Under this guideline, at operational level storage allocation determines the exact locations in the yard for containers, which is a very critical issue ultimately determining the amount and distribution of workload in individual blocks. The storage allocation policies usually aim at minimizing workload for loading and unloading processes and are tailored for different types of containers, i.e. *export, import,* and *transshipment.* Containers are either put in permanent positions upon their arrivals or stacked in a buffer area before being moved to their permanent positions afterwards. [26] gave a description of handling efforts under different storage allocations for *export* containers and quantified their performance according to the amount of space and the number of moves required. The strategy that puts containers in permanent positions upon their arrivals was found to offer light workload however suffer almost 50% waste of space. [13] discussed how to re-marshal *export* containers in the storage yard to create empty space, which was decomposed into three sub-problems: the bay matching problem matching a specific current bay with a bay configuration in the target layout; the move planning problem determining the number of containers to be moved from one bay to another; the task sequencing problem settling the sequence of container moves. The first two problems were solved by dynamic programming techniques while the third one was formulated as a transportation problem. In [12] the weights of *export* containers were taken as an extra consideration when doing storage allocation. A dynamic programming model was formulated to minimize the number of relocation movements expected for the loading operation and a decision tree was given to support real time decisions. The percentage of wrong decisions, which is a measure of the quality of the decision tree, was found to be less than 5.5%. A generalized approach for dynamic allocation of *export* containers was proposed in [22], in which the problem was formulated as a mixed integer linear programming model to maximize space utilization and to minimize loading time. Two heuristic algorithms were suggested to find the solution based on the least duration of stay (DOS) rule and the subgradient optimization technique, respectively. The DOS-based decision rule was found to be attractive as it delivers same quality of results as the subgradient approach while consuming much less computational time.

[10] investigated the storage allocation problem for *import* containers by segregating them according to their arrival times, with stack height and allocation space as decision variables. The authors extended their findings to cases where the arrival rate of import containers is either constant, cyclic, or dynamic in [15]. It was derived that in the case of constant arrival rate the optimal height of stacks is the total number of containers within the planning horizon divided by the total number of ground slots in the stack. No similar formula was found for the other two cases, but the problem of space allocation was found to be solvable using subgradient optimization techniques. [24] developed simple analytical expressions to estimate the minimum storage capacity needed to ensure infrequent episodes of storage congestion, which also served to identify the effects of changing throughput characteristics on the storage space. [28] provided a method to estimate the number of rehandlings in an import container yard, which leads to an optimal loading/unloading approach.

There are several studies that consider different types of containers as a whole. [3, 4] developed a time-space network to assist in assigning containers to storage locations in advance with an objective of minimizing total costs of operation. The problem was formulated as a two-dimensional packing problem in the sense that a container at the yard can be represented by a time-space rectangle whose height and width are associated with the stay duration and the space occupation. And a *branch and beam* algorithm was proposed to solve it. [9] applied *eco-problem solving* and object oriented paradigms to build a multi-agent model that facilitates the evaluation of allocation policies. [8] took into account the *intrinsic* and *logistic* values of containers and divided them into different priority classes, for each of which the optimal amount of space and price were determined under welfare and profit maximizing rules. The problem was more or less formulated as a demand-supply balancing problem, where demand was introduced by arrival rates, price elasticities and logistic opportunity costs, while supply was brought in through marginal operating costs and land requirements. With a rolling horizon approach, [30] decomposed the allocation problem into two levels and each level was solved by a linear integer programming model. At the first level the total number of containers in each block during the planning horizon was determined to balance the workloads among blocks, while the second level distributed containers to individual blocks for each vessel such that the total travel distance of containers was minimized.

It should be pointed out that in existing research, the *transshipment* containers were regarded as *import* containers during their unloading phases, and as *export* containers during loading phases. The advantage of predictable arrival and departure of *transshipment* containers is not studied and utilized. Due to the high percentage of *transshipment* containers in the Port of Singapore that we are studying for, a new storage allocation policy should be specially designed for them. However, the objectives of balancing workloads and minimizing travel distances are still desirable.

2.2 The number of cranes and their deployment policies

There are several kinds of yard cranes in container terminals to store and retrieve containers in and from the stack, among which rubber tyred gantry cranes (RTG) and rail-mounted gantry cranes (RMG) are most commonly chosen. An RTG moves on rubber tyres over containers and is able to move among blocks. An RMG runs on rails normally serving a single storage block between the rails. Both RTG and RMG provide higher density storage and shorter cycle time than other cranes such as straddle carriers that carry containers between their legs, mobile harbor cranes that are inherited from pre-containerized era, and heavy-duty forklift that are more used for empty containers. Another kind of yard crane, OHBC (overhead bridge crane) with even higher density storage and shorter cycle time is used in Port of Singapore.

One of the decisions to be made at the tactical level determining the number of cranes necessary to ensure an efficient storage and retrieval process. [14] discussed this problem with regard to space requirement for import containers. For a given amount of space, more yard cranes result in shorter response time for a retrieval request but higher facility investment. In other words, there exists an economic tradeoff between the storage density, the accessibility, the investment, and the level of service. A analytical model was developed to resolve the tradeoff by minimizing the sum of relevant cost components associated with the number of cranes and the amount of space. The model was extended in [16] to take care of the operating cost of the cranes and serve the interests of both terminal operators and customers. The minimization of the operation cost was solved with a deterministic model, and a stochastic model was developed to minimize the waiting cost of external trucks and the operating cost of the terminals simultaneously.

Another problem to be considered in yard planning is the deployment of yard cranes, i.e., allocation and routing. As a pioneering research on this problem, [21] used simulation to investigate several yard crane allocation policies with throughput, utilization, and waiting times as performance measures. On routing of yard cranes, several studies have been conducted in [17–19], which considered the single-crane scenario during loading operation of export containers. The container handling time, including the crane setup time and the travel time, was treated as optimization objective and minimized by optimally determining its visiting sequence to the yard bays and the number of containers to be picked up at each yard bay. The loading sequence was constrained to satisfy the work schedule of the corresponding QC that was assumed as an input. The tour of a crane was expressed as a route on a network connected by a series of 'sub-tours', each of which was defined as a sequence of yard bays visited by the crane to pick up all containers that will be loaded together as a cluster onto a ship. In the constructed network, the original routing problem was reduced to finding a path from the source to the sink and to determine the number of containers to be picked up at each node during the tour. It was formulated as a mixed integer program, and was solved by a suggested algorithm that determines the number of containers to be picked up at each bay at the first stage and the route of the crane at the second. It should be noted that the optimal allocation and routing for multiple cranes remains open.

2.3 Retrieval sequencing of containers

Containers in some hub terminals are normally grouped into categories according to their connecting vessels, destination ports, sizes, contents, and weight classes (in this order, named as vvPSCW grouping in PSA). In this case, when a QC asks for a container from a certain category instead of a specific container, a choice can be made among the containers in different blocks taking care of the planned workload of the yard cranes to improve port performance. This is the sequencing problem during loading process that, in its entirety, actually considered crane allocation and routing problems, which is also referred to as the dynamic crane deployment. [31] managed to minimize the total delayed workload in the yard by optimally deciding the times and routes of crane movements among blocks. The problem was formulated as a mixed integer programming model and solved by Lagrangian relaxation technique. A modified Lagrangian relaxation was also proposed to reduce computational time that leads to a near-optimal solution. [20] used genetic algorithms to schedule the retrieval of containers so that the sum of setup times and travel times, and consequently the ship turnaround time, was minimized. Neural networks, tabu search, or other heuristics were also suggested in [20] as possible competing techniques. There are also some studies that covered other aspects with impacts on the loading process such as the packing of containers, see for example in [2, 7, 25]. To the best of our knowledge, the number of papers that focus on the full scope of container loading/unloading process decisions at operational level is very limited. It would be the most useful to look into this area so as to fully understand the impacts of interactions among the decisions. However, it appears that the problem would be too complicated to be solved by analytical methods and the solution heavily depends on the experience of operators.

3 Summary

In this paper, we have presented a comprehensive survey of the operations in container terminals and their simulation and optimization issues from a hierarchy point of view. The management of the manned and automated terminals are discussed by decomposing it into sperate types of decision-makings, for each of which the trends of problem-solving approaches in literature is given. The necessity of integrating these approaches to the overall management is also addressed, and the corresponding studies are listed for reference. This comparative review may give a good source of current trends in simulation and optimization of container terminal yard operations to the researchers for related studies and to the port operators for adopting the mentioned approach to improve the terminal performance.

To the best of our knowledge, most of the related studies have been found to be analytical modelling-based or simulation modelling-based. And it appears that in order to simplify the problem and make it solvable, necessary assumptions are inevitable for the analytical models. Moreover, they are mainly developed to solve stand-alone subproblems, or at most, some of the subproblems. No literature has been located that deals with the overall terminal management problem by pure analytical models. Among the various approaches proposed by the analytical modelling-based studies, most popularly used techniques are mathematical programming, branch and bound method, queueing theory, and network-based method. This finding is consistent to that in [27].

Despite of the numerous research done in this field, there are, however, a few outstanding problems that require further study, say for example, making use of the advantage of predictable arrivals and departures of transshipment containers when doing storage allocation for the terminals that mainly deal with this kind of containers. Furthermore, some of the assumptions made in some models could be relaxed to be more realistic, whereas some models themselves could be extended to become applicable to generalized case.

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