Stowage and Transport Optimization in Ship Planning

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Abstract. We consider the ship planning problem at maritime container terminals where containers are loaded onto and discharged from ships using quay cranes. The container transport between the ships and the yard positions in the terminal is carried out by a fleet of straddle carriers. Based on a stowage plan provided by the shipping company, the dispatcher assigns containers to specified bay positions. Then, subject to operational and stability constraints, he schedules containers in order to avoid waiting times at the quay cranes. We propose an approach combining stowage planning and the selection of "good" loading and transport sequences. For a just-in-time scheduling model, we present computational results based on real-world data of a German container terminal. Moreover, we discuss some real-time and online influences on the daily dispatch situation.

Keywords: stowage planning, transport optimization, just-in-time scheduling, container yards

1 Introduction

Within the last years, the rate of containerization increased by approximately 8 percent per year. Shipping larger number of containers around the world requires matching efficiency improvements in maritime container terminals. Besides the introduction of computer-aided decision systems and infra-structural improvement, the complete logistic chain has to be examined in order to increase the container handling rates. In this article, we focus on a particular problem arising at the quay side.

In maritime container terminals, a large number of containers is handled day by day. The containers arrive at the terminal by truck, ship, or train. Before leaving the terminal, containers are usually stored in the terminal's yard area. In the yard's storage blocks, the containers are arranged in stacks, one beside the other in several rows. Transport between the storage positions in the yard and the terminal's exit points is usually handled by straddle carriers, by automated guided vehicles, or by transtainers. In this article, we only consider straddle carriers as e.g. used at the terminal "Burchardkai" terminal in Hamburg, Germany. The turnover at the terminal "Burchardkai", operated by the Hamburg Port and Warehouse Company (HHLA), increased from 1.1 million container units (TEU) in 1992 to 1.6 million TEU in 1998. It is expected that the number of units handled in 2000 will increase to 2.2 million TEU. This increase requires improved, intelligent logistics. At "Burchardkai", more than 3200 vessel calls are operated per year. Loading and discharging is carried out by quay cranes whereas the transport is performed by a fleet of straddle carriers. The complete dispatch process consists in about 10000 container movements per day.

Combinatorial optimization models apply for instance when assigning vessels to berths, when planning the tours for each transport vehicle, or when computing good storage positions for the containers. The berth planning problem is modelled by Lim [Lim98] as a rectangular packing problem with side constraints. Lim presents a heuristic based on (heuristically) computing longest paths in a graph model. An alternative network flow approach is due to Chen [CH]. Different versions of tour planning models for straddle carriers have been considered by Steenken et al. [Ste92a,Ste92b,SHFV93]. A linear sum assignment model of the dispatch of straddle carriers for discharging and loading trucks is iteratively solved in real-time [Ste92a,Ste92b]. A travelling salesman model combining various hinterland operations is heuristically solved in [SHFV93].

In this article, we discuss the following combination of stowage and transport of containers to be loaded to certain container vessels, named *export* containers. At first, an export container is moved to a respective quay crane. Then, the quay crane loads the container into a suitable position in the bay currently served.

For each export container, the corresponding loading position is specified in accordance with the stowage plan. This stowage plan is derived from information provided by the shipping company. For each bay position, the shipping company defines properties for a container which may be stored at this position. In particular, the shipping company specifies the discharge port, the container type, and its weight. Even restrictions on stored goods may apply.

Today, the transport of export containers to the quay cranes is not taken into account when deciding on the final bay position for a container aboard the vessel. The ship planning process starts two days before the vessel arrives at the terminal. At that time, the responsible dispatcher prepares a stowage plan based on the following information: the onboard storage situation at the previous port and a preliminary list of export containers. In particular, potential information on transportation times is not used.

In section 2, we propose a just-in-time scheduling formulation for combined stowage and transport planning and we introduce a corresponding mixed integer model as well as exact and heuristical methods to solve it. Moreover, we consider different objectives.

In section 3 we discuss how the proposed approach extends to real-time requirements. Particularly flexible update techniques allow adaptation of previously computed schedules with regard to real-time requirements.

2 Ship Planning in Container Terminals

Maritime container terminals form important links in the transport chain of containers. Import and export containers are temporarily stored in the terminal area. Ship planning is very important for the productivity of a container terminal. Ship planning is based on preliminary information provided by the shipping company. The first information, submitted two days before the arrival of a container vessel, consists of a map of the current storage situation at the previously visited port. At the same time, information on *import* containers, i.e. containers which have to be discharged, is made available. For each bay position, the shipping company defines properties for a container which may be stored at this position. In particular, the shipping company specifies the discharge port, the container type, and its weight. Before the vessel's arrival, information about the export containers is updated from time to time.

From the information provided by the shipping company, the dispatcher derives a stowage plan which assigns a particular export container for each loading position. After discharging the vessel, these export containers are moved to the quay cranes by straddle carriers. For each bay, the chosen loading strategy implies a loading sequence of containers for each quay crane. In order to avoid waiting times during the loading process, the transport sequences of the straddle carriers have to match the loading sequence of the respective crane.

For a large number of containers arriving by truck, the exact delivery times are unknown. Up to 30 percent of the export containers arrive at the terminal after the beginning of the loading process. Due to lack of complete information and due to tight timing constraints, the dispatcher has to handle online and real-time versions of the above problems [WZ98].

2.1 Stowage Planning on Container Vessels

In [AP93,APSW98], a stowage plan model for a container vessel visiting several ports is presented. For each bay position, this stowage plan specifies the destination port for the container to be loaded in any given port. Hence, it could be used as the preliminary stowage plan which is provided by the shipping company. In this model, the weights of containers are not taken into consideration. However, for stability reasons, container weights must be considered (see for instance [Asl89,Asl90]): heavy containers should be stored below containers having less weight.

A potential stowage plan for one bay is presented in Figure 1. For each bay position, a container type is specified. Hence, at this position, only a container with prescribed weight and destination can be stored. The required size of the container is defined by the type of the bay. Usually, a bay is restricted to 20' containers or to 40' containers. Some bays may contain both types of containers, whereas all the 20' containers should stand on top of the 40' containers.

In the combined stowage and transport problem, an *abstract* container type is described by: the container's discharge port, the container weight including the weight of the stored goods, the type of the container, i.e., its size (20' or 40') as well as special equipment attributes, the kind of goods stored in the container, and the delivery time of the container.

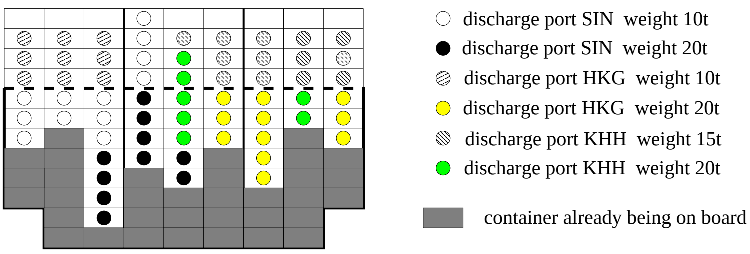

Fig. 1. An example for a stowage plan provided by the shipping company.

We distinguish between the above abstract container types described above and the *real world* container types named in the following list which does not claim to be comprehensive: general purpose container, hardtop container, high cube general purpose container, high cube hardtop container, flat container, open top container, high cube flat container, platform, insulated container, ventilated container, reefer container, bulk container, high cube reefer container, or tank container. Some types require that the container must be stored at a specially equipped position. For instance, reefer containers should be kept cool and must be supplied with electricity. High cube containers differ in height from the standard general purpose containers and will probably occupy two stowage positions.

In the following, we suppose that we know a preliminary stowage plan specifying a container type for each bay position. We assume, that the number of export containers of a specific type exactly matches the number of bay positions of the same container type.

2.2 Stowage Planning in Container Terminals

Ship planning (or stowage planning) in container terminals differs from stowage planning for container vessels. As discussed in the previous section, for container vessels it suffices to specify a certain container type for each bay position. This preliminary type-based stowage plan provided by the shipping company and the list of export containers form the basis for the dispatcher's work at the container terminal. The dispatcher prepares a final stowage plan which assigns to each bay position a particular export container with matching type.

As mentioned above, a large number of export containers arrives after the beginning of the loading process. The dispatcher has to take such difficulties into consideration when assigning containers to bay positions. Additionally, the dispatcher must take into account that containers are stored in stacks (cf. Figure 2). Containers on top of a stack should be moved before a container at a bottom position is required. In order to minimize unnecessary container shifts, stacks of containers of identical type are preferable. Obviously, this may be impossible. In fact, up to 30 percent of the stacks contain containers of differing types.

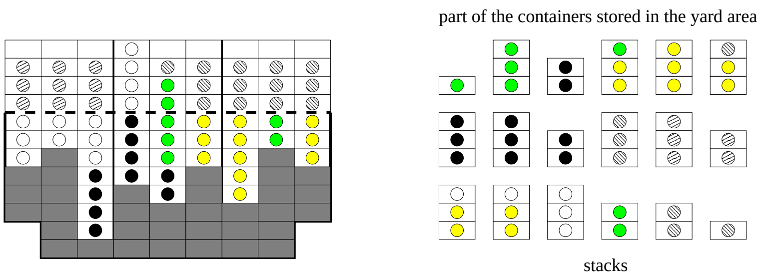

Fig. 2. An example for the storage situation in the yard.

Nowadays, a dispatcher subsequently assigns export containers in inverse order of ports to be visited. First, he chooses a bay. Then, he marks all free positions for containers of the currently considered type. For these positions, the decision support system offers a list of not yet assigned export containers of that type. The dispatcher selects some containers from this list. The final assignment is determined by a simple heuristic in accordance with a specified loading strategy and with regard to container weights. When all containers are assigned, the stowage plan is transmitted to the shipping company which may accept the plan or may ask for some changes.

2.3 Combining Ship and Transport Planning

By now, the stowage plan is generated ignoring loading and transport sequences. In particular, containers are assigned to bay positions without consideration of the necessary transportation times between storage positions in the yard and the quay cranes. As mentioned before, for each bay position, the preliminary stowage plan only assigns a container type. For each bay, the dispatcher chooses a loading strategy which specifies a linear order of export container types. Since bays consists of stacks, there are two straight-forward strategies used in real-world ship planning: loading column-wise or loading layer by layer. For reasons of visibility, the quay cranes always start with the bay positions at the water-side of the vessel. This fixes a loading sequence for both strategies. Two examples of these common loading strategies and the resulting loading sequences are presented in Figure 3.

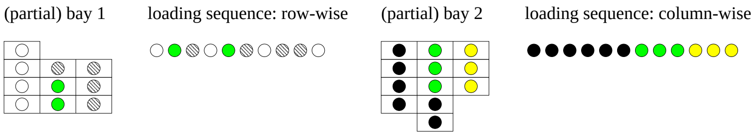

Fig. 3. An example of two loading strategies and the resulting loading strategies.

Each bay may be partitioned into some partial bays which are considered separately. These partial bays correspond to the bay positions on deck or in the hold of the vessel. Moreover, the bay is partitioned into areas that correspond to the hatches. For each partial bay of the vessel, the loading strategy implies a linear list of container types to be loaded.

After the dispatcher has decided for each bay which loading strategy will be used, for each bay we obtain a fixed loading sequence of bay positions. In combination with the stowage instructions provided by the shipping company, this results in a sequence of container types to be loaded into the bays.

2.4 The Crane Split

Next, the bays of a vessel are partitioned into bay areas. Each bay area will be served by one quay crane. This step is called crane split. Based on availability information of cranes, a crane split can be computed by solving a partitioning problem with some operational side constraints. Since the number of cranes available for the loading process is small, an optimal solution of this partitioning problem can be computed within acceptable time.

More formally, we are given a set of bays (or partial bays) $\{1,\ldots,B\}$. b_i denotes the number of containers to be loaded into bay i, $b_i > 0$. This number is defined by the stowage plan provided by the shipping company. The vessel will be loaded using C quay cranes each of which has capacity q_i, $1 \le i \le C$. The capacity corresponds to the time the crane will be available.

We search for a partition $\mathcal{Q}_1, \mathcal{Q}_2, \ldots, \mathcal{Q}_C$ of $\{1,\ldots,B\}$ where each bay area $\mathcal{Q}_i$ contains only consecutive bays, i.e., $\mathcal{Q}_i = \{j_i, j_i+1, \ldots, j_i+k_i\}$ for all $1 \le i \le C$. Obviously, for a given partition, the resulting absolute load is $Q_i = \sum_{j\in\mathcal{Q}_i} b_j$, i.e. the total number of export containers for bay area Q_i. A good choice of a partition may balance the resulting relative loads Q_i/q_i for all quay cranes $1 \leq i \leq C$ as much as possible. Minimizing the maximum relative imbalance, we find

$$\min \max_{i,j \in \{1,\ldots,C\}} \left| \frac{Q_i}{q_i} - \frac{Q_j}{q_j} \right| .$$

For C, a value between 2 and 6 is reasonable for real world container terminals. The number of bays may vary between 20 and 50. Consequently, we may solve this partitioning problem by straight-forward enumeration. An initial upper bound can be derived from the weighted average loads $\mu_i = \frac{q_i}{\sum_{i=1}^{C} q_i} \sum_{j=1}^{B} b_j$. A corresponding "partition" may recursively be constructed. Let $Q_1 := \{1, 2, \ldots, k_1\}$ where k_1 is chosen minimal such that $Q_1 \geq \mu_1$. Then, Q_2 is defined by $Q_2 \geq Q_1 + \mu_2$. The remaining partition is analogously constructed except for the last bay area which contains all remaining bays. Better upper bounds may easily be obtained by slightly varying the values of k_i.

Combining the Loading Strategies For each quay crane and for each bay, we obtain a loading sequence of container types (cf. Figure 4). A loading sequence is served by the straddle carriers available for the crane. We assume that a certain fixed number of straddle carriers is available for each crane. These straddle carriers move containers from their current stowage position in the yard to the crane. Here, pooling of straddle carriers is not considered but may help to stay within real-time bounds at a particular crane where more straddle carriers are required.

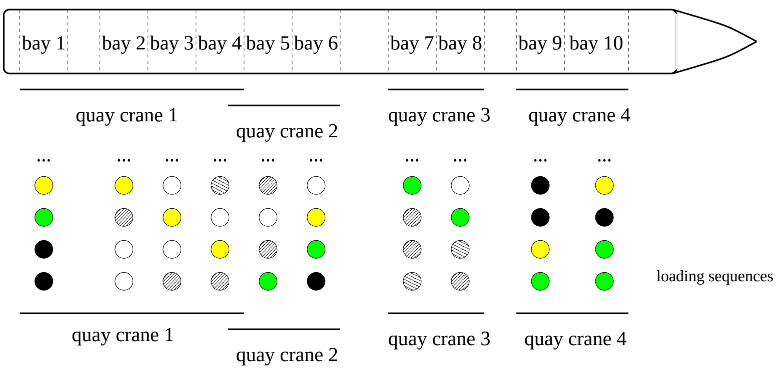

Fig. 4. A crane split and the corresponding loading sequences.

For each loading event of a loading sequence of a quay crane, an export container of the required type is moved to the crane. At the crane, the containers should arrive in the order defined by the loading sequence. If a straddle carrier with a container for a subsequent loading event arrives too early, it may have to wait until all the predecessors of that container have been handled since there is only limited buffer space close to cranes. Usually, at most one or two containers can be placed in this buffer area.

Consequently, only a careful assignment of transportation duties to straddle carriers will optimize the overall loading process. There are several objectives which may be considered. Minimizing the loading time of the last export container corresponds, in the notation of scheduling problems, to the latest completion time. For further improvement it will also be interesting to find the bottleneck of a loading process. Empirical studies and discussions with HHLA showed that the time requirements for the loading process strongly depends on the effectiveness of the quay cranes. Therefore, another promising approach is to minimize the waiting times of the quay cranes, or in other words, to avoid the late deliveries of export containers.

In all experience of HHLA, a quay crane requires between 80 and 120 seconds to load a single container to its bay position. Thus, 30 to 45 containers may be loaded per hour and crane. A more or less regular sequence of loading events ensures a smooth loading process which helps to avoid waiting times. This observation suggests loading events every 80 to 120 seconds and defines reasonable due dates for each loading event. Thus, container transports with m straddle carriers may be modelled as a parallel m-machine scheduling problem with due dates, minimizing late deliveries. Obviously this problem is NP-hard, since it contains parallel machine scheduling problem with due dates (cf. for instance [Lia99,CP99]).

We assign export containers to each loading event of the loading sequence. An export container will be moved by some specified straddle carrier. The respective transportation time corresponds to the distance between the stack position of the container and the position of the quay crane. An example for a schedule of straddle carriers is presented in Figure 5. The respective transportation times are represented by the thick strokes behind the containers. In particular, the first and second straddle carriers will at first move the first and second containers in the loading sequence. Due to the different transportation times, the second straddle carrier should start with some delay in order to arrive at the quay crane later than the first straddle carrier.

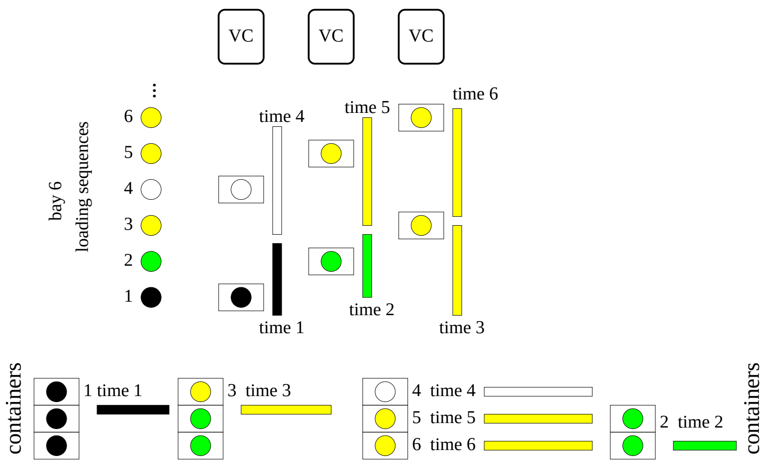

Fig. 5. The scheduling model for the straddle carriers.

2.5 Just-in-time Transport of Containers

Just-in-time scheduling problems have been applied in production by Steiner and Yeomans [SY93], for a single machine by Liaw [Lia99] and for parallel machines by Chen and Powell [CP99] who assume a large common due date. For a related introduction to scheduling we refer to [GKRWZ01].

We present a mixed integer model for just-in-time container scheduling with one quay crane. Here, N denotes the number of export containers, i.e. the length of the loading sequence. $\mathcal{L}$ denotes the set of loading events in the loading sequence. For $1 \leq i \leq N$, the i-th container of requested type $t(i)$ is delivered at the crane at time T_i. $\mathcal{C}$ denotes the set of eligible export containers. For $c \in \mathcal{C}$, the transportation time of container $c \in \mathcal{C}$ from its yard position to the crane is denoted by p_c and its type is denoted by $t(c)$. The set of available straddle carriers is denoted by $\mathcal{V} = \{1, 2, \ldots, V\}$.

A solution of this problem is a schedule assigning the straddle carriers to container transports. By the one-to-one correspondence of container transport and loading jobs, the assignment implies a stowage plan for all bays considered. We call this just-in-time container scheduling problem the *combined container stowage and transport planning problem*. It is NP-hard, since it contains the scheduling problem introduced in [CP99]. We consider the following mixed integer programming formulation (CSTP) of the combined container stowage and transport planning problem:

$$\min \sum_{i \in \mathcal{L}} L_i \tag{1}$$

$$\text{s.t.} \quad \sum_{i \in \mathcal{L}} \sum_{v \in \mathcal{V}} x_{civ} \leq 1 \qquad \text{for all } c \in \mathcal{C} : t(c) = t(i) \tag{2}$$

$$\sum_{c \in \mathcal{C}} \sum_{v \in \mathcal{V}} x_{civ} = 1 \qquad \text{for all } i \in \mathcal{L} : t(i) = t(c) \tag{3}$$

$$\sum_{j \in \mathcal{L} : j \leq i} \sum_{c \in \mathcal{C}} p_c \, x_{cjv} \leq T_i + L_i \qquad \text{for all } i \in \mathcal{L}, v \in \mathcal{V} \tag{4}$$

$$x_{civ} \in \{0, 1\} \qquad \text{for all } c \in \mathcal{C}, i \in \mathcal{L}, t(c) = t(i), v \in \mathcal{V} \tag{5}$$

$$L_i \geq 0 \qquad \text{for all } i \in \mathcal{L} \tag{6}$$

The schedule is defined by assignment variables x_{civ}, where $x_{civ} = 1$ if and only if container $c \in \mathcal{C}$ is assigned to loading event $i \in \mathcal{L}$ and moved by straddle carrier $v \in \mathcal{V}$. An assignment x may imply that the i-th container arrives later at the quay crane than required, i.e. later than at time $T_i = T + (i-1)\frac{3600}{r}$ where r denotes the loading rate per hour in a regular loading sequence. The value of the variable L_i carries the resulting lateness. Since the CSTP contains no precedence constraints, the j-th container may arrive earlier than the i-th container despite of $i < j$. Here, we presume sufficient buffer space at the quay crane. In our computational results for real-world data buffer space for two containers was sufficient.

We discuss computational results for real-world data about four vessels provided by HHLA (cf. Table 1). For each quay crane, we solve the CSTP for different lengths of the loading sequence $\mathcal{L}$. Here, the startup offset value is $T = 90$, and the loading rate $r = 40$ implies a regular loading time of 90 seconds for all loading events of $\mathcal{L}$. We display results for three real-world instances. The lengths of $\mathcal{L}$ vary from 20 to 60 loading events which are the typical lengths of loading sequences dispatched in real-time at container terminals. We apply the standard MIP solver CPLEX 6.6 to the resulting instances of CSTP. We compare the best feasible solution determined within a real-time computation limit of 60 seconds to the final optimum solution. Within this one minute limit, we obtain quite good solutions which are in fact optimum solutions in most cases. We will take advantage of this good computational performance in section 3 where we describe an integrated approach for solving CSTP in a real-time setting. Smaller CSTP will iteratively be solved for each quay crane and for each part of the loading sequence. The number of iterations depends on the length of the partial loading sequence considered in one step. The length of a partial loading sequences strongly depends on the computation time available as well as on the real-time effects influencing the incumbent solution.

Instance	$\lvert \mathcal{L} \rvert$	Constraints	Variables	Nonzeros	1 min. UB	Optimum	CPU sec.
1	20	191	6680	83310	20	20	5.99
	30	231	10020	174915	20	20	21.98
	40	271	13360	299820	20	20	16.48
	50	311	16700	458025	60	20	916.27
	60	351	20040	649530	156	20	6037.04
2	20	130	335	3666	43	43	0.07
	30	199	627	8844	43	43	0.34
	40	248	961	17451	43	43	0.84
	50	298	1607	31797	43	43	2.72
	60	346	1881	49524	43	43	26.50
3	20	186	1844	17571	2894	2894	201.39
	30	396	3219	45306	3074	2894	463.17
	40	443	6274	104138	3002	2894	1289.70
	50	516	6893	170967	3201	2894	1821.24
	60	586	7236	241494	3178	2894	1737.07

Table 1. Computational results for CSTP within a one minute time limit applying CPLEX 6.6 MIP solver on a Pentium-III PC with 700 MHz and 1 GByte core memory. 1 min. UB is the lateness $\sum L_i$ of the best solution obtained within the one minute computation time limit. Opt. is the lateness of an optimum solution, as was proved after CPU sec.

Precedence constraints due to the container stacks As mentioned in section 1, the containers are stored in stacks on the yard. In the considered terminal, these stacks consists of one, two, or three containers. Since straddle carriers can lift containers only up to layer three, a loaded straddle carrier cannot pass a stack of height three. Therefore, some care is necessary when using layer three. In particular, third layer containers are stored in such a way that no deadlocks occur and the third layer containers in a row have the same type. Third layers are only used for a short time periods.

The question whether or not a feasible assignment of containers to loading events without rearranging stacks exists, is equivalent to a certain tram scheduling problem in depots in local transport which is known to be NP-complete [BBHMSW99]. The tram scheduling problem is described in example of [GKRWZ01] in this volume. In [BBHMSW99] a dynamic programming approach is used in order to decide whether or not a linear sequence of type-constrained events (tram departures) can be served by items (trams) stored in stacks (sidings). The resulting algorithm is polynomial in the number of departures (here: containers) and exponential in the number of stacks. For stacks of height two, the problem of minimizing the number of rearrangements can be reduced to a minimum weight perfect matching problem in a related graph and, therefore, it is polynomially solvable [W99]. Due to the small height of container stacks, the related rearrangement problem in container terminals is solvable in reasonable time. For more details on the above mentioned problems, we refer to [BBHMSW99] and [W99].

We may model necessary rearrangements of stacks in CSTP by increasing the transportation times of the affected containers so that additional time needed for the rearrangement is covered. Of course, this simple modification is correct only if the final rearrangement is already known. Alternatively, we may add penalty constraints for rearranging stacks and stack related precedence constraints (c.f. in [W99]) to the CSTP. However, the raised complexity of modified enlarged CSTP reduces its applicability in real-time decision support systems.

Heuristic approaches for more than one quay crane The following best-fit heuristic offers an alternative to the exact algorithms solving the above mixed integer program. The best-fit heuristic can be applied in parallel for all quay cranes available.

Container-Best-Fit (CBF) For each quay crane and each i-th loading event, we select an available straddle carrier and a previously not assigned container c of matching type minimizing the time delay $\max(\Theta - T_i, 0)$ to the actual delivering time Θ of c. We always prefer containers with $\Theta \geq T_i$.

Computational results for CBF are displayed in Table 2. We apply CBF to two real-world instances for different values for the loading rate and the (average) speed of the straddle carriers. We observe that a loading rate of about 40 containers per hour results (i.e. in intervals of 90 seconds) in a reasonable value of cumulative lateness and makespan. Simulation studies covering more side constraints promise a reduction of the time needed to load a vessel.

3 Real-time Ship Planning

Ship planning in the real world has to handle uncertain, changing and missing data as well as general real-time influences. For example, decision support systems must provide proposals within sometimes quite tight time bounds. A short introduction to the general difficulties of combinatorial online optimization in real time can be found in this volume [GKRWZ01].

Here, based on the incomplete information available before the container ship enters the port, a stowage plan is prepared. This stowage plan is sent to the shipping company querying for acceptance. When the vessel has arrived at its berth position, the quay cranes start discharging import containers and those containers that must be reloaded later on, possibly to a different bay position. When a quay crane finishes the discharge process, the loading process starts as described in the above accepted stowage plan. According to the corresponding loading sequences for the bay currently served, export containers are moved from the yard to the quay crane.

		570 containers		758 containers	
Loading rate	VC speed [$\frac{m}{s}$]	Lateness	Last event	Lateness	Last event
45	1.6	3 h 35'	4 h 46'	6 h 18'	6 h 57'
40	1.6	2 h 28'	4 h 53'	4 h 54'	7 h 09'
36	1.6	1 h 46'	5 h 05'	3 h 35'	7 h 21'
33	1.6	1 h 14'	5 h 23'	2 h 24'	7 h 37'
45	1.8	2 h 11'	4 h 20'	4 h 21'	6 h 21'
40	1.8	1 h 54'	4 h 33'	3 h 02'	6 h 33'
36	1.8	57'	4 h 51'	1 h 52'	6 h 50'
33	1.8	33'	5 h 11'	1 h 15'	7 h 05'
45	2.0	1 h 25'	4 h 04'	2 h 52'	5 h 52'
40	2.0	51'	4 h 22'	1 h 42'	6 h 09'
36	2.0	28'	4 h 42'	1 h 07'	6 h 25'
33	2.0	19'	5 h 03'	47'	6 h 49'
45	2.2	54'	3 h 55'	1 h 44'	5 h 32'
40	2.2	27'	4 h 14'	1 h 02'	5 h 48'
36	2.2	17'	4 h 35'	42'	6 h 11'
33	2.2	13'	4 h 57'	18'	6 h 35'

Table 2. Computational results for CBF for different values of loading rate and straddle carrier velocity. Lateness compared with the time of the last loading event ("makespan").

In particular, containers should be moved by straddle carriers as defined in the previously computed optimal or approximative assignment solution of the combined stowage and transport planning problem. Unfortunately, the stowage plan was generated using only incomplete information which is now out of date. Real-time effects influence the performance of the loading process and require a partial or complete update of previous assignments of containers and straddle carriers. Some examples of such real-time influences are:

- delay of a container's delivery to the terminal
- unavailability of a container due to customs regulations
- delay of a container's delivery to the quay crane due to high yard traffic
- delays in the loading process due to unavailable quay cranes

Due to real-time influences transportation times used in the model may differ substantially from the current transportation times. Due to delays, assigned containers may be not available on time. Then, if possible, different containers should be assigned to the loading sequence. Consequently, assignments of containers and straddle carriers must be adapted in real-time to the different online situations. Since the accepted stowage plan should not be changed, the resulting update problem is a just-in-time scheduling problem with due dates for each container.

Update algorithms working in real-time for changing time limits require a high flexibility. We shortly describe a possible algorithmic scheme. Whenever changed transportation times require an update of assignments of containers and straddle carriers, we re-optimize the next Δ, say twenty to thirty, assignments of containers and straddle carriers. The size of the update problem is chosen subject to the real-time requirements, i.e. we may use as much new information as possible in the available computation time.

Then, the complete remaining assignment of containers and straddle carriers is updated accordingly. In an update, we may apply a MIP solver for CSTP, dynamic programming, or heuristics like CBF. Furthermore, we may generate exact solutions to smaller update problems (less new information) or we may generate approximate solutions of larger update problems (more new information). In this way such algorithmic schemes allow to choose the amount of new information with regard to the real-time requirement. Here, as a result, the length of the adapted part of the assignment varies according to the available computation time. Similar "Δ-REPLAN" techniques have previously been proposed in [W99,WZ00] for dispatch problems in local transport.

Failing availability of a quay crane is a severe online event requiring a more global update. Besides technical failure, a quay crane may be withdrawn in order to serve another vessel. In any case, the crane split has to be recomputed and bay areas will be redistributed among the remaining quay cranes. Crane split computation is very fast and can be performed within usual real-time requirements. Of course, updates for the assignment of containers and straddle carriers are required, too. In this way, the proposed combined stowage and transport planning approach allows to handle such failures, too.

4 Conclusion

In this article, we describe and propose an integrated approach for combined stowage and transport planning in container terminals. The basic underlying concept of the resulting model is similar to a certain model for tram dispatch. In ship planning, containers are partitioned into classes of types. The shipping company defines type requirements for stack positions in the bays of a vessel. The dispatcher has to assign the export containers to matching stack positions in the bays. Contrary to tram dispatch in [BBHMSW99,W99], containers do not arrive in a completely predefined sequence. However, the set of export containers is stored in stacks, implying a partial order on the set of containers which may be modelled by precedence constraints. We propose a just-in-time scheduling model (CSTP) combining the stowage plan for the quay cranes and the transportation schedule for the straddle carriers. The resulting model as well as the proposed algorithms for solving the model are particularly suitable for real-time planning in maritime container terminals where various online and real-time influences require flexible response in order to guarantee and improve the overall performance of the terminal.

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