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Inventory based dispatching of automated guided vehicles on container terminals

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Inventory based Dispatching of Automated Guided Vehicles on Container Terminals

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Abstract

This paper deals with automated guided vehicles (AGVs) which transport containers between the quai and the stack on automated container terminals. The focus is on the assigment of transportation jobs to AGVs within a terminal control system operating in real time. First, we describe a rather common problem formulation based on due dates for the jobs and solve this problem both with a greedy priority rule based heuristic and with an exact algorithm. Subsequently, we present an alternative formulation of the assignment problem which does not include due dates. This formulation is based on a rough analogy to inventory management and is solved using an exact algorithm. The idea behind this alternative formulation is to avoid estimates of driving times, completion times, due dates and tardiness because such estimates are often highly unreliable in practice and do not allow for accurate planning. By means of simulation, we then analyze the different approaches. We show that the inventory based model leads to better productivity on the terminal than the due date based formulation.

Keywords: Container logistics, container terminal, automated guided vehicles, simulation.

1 Introduction

In various regions of the world, double-digit growth rates in container handling have been common during the last years and, hence, a substantial number of container vessels is built each year. In addition, new vessels are often larger than older ones—currently, modern vessels can carry more than 9,000 standard containers (twenty foot equivalent unit, TEU), and even larger ships are already planned. Thus, the capacity of the worldwide container vessel fleet increases year by year. This development puts pressure on container terminal operators to enlarge terminal capacities in order to avoid congestion in ports. As a consequence, more container terminals are built, and existing ones are expanded. For reasons of efficiency and stacking density, new and extended terminal facilities increasingly make use of automated equipment. This leads to the necessity of complex terminal control systems which allow for an optimized utilization of the automated resources.

Due to its practical relevance, container terminal logistics has been a prominent field of research. A comprehensive literature survey has recently been given by Steenken et al. [25]. Further overviews have been provided by Meersmans and Dekker [18] as well as Vis and Koster [27]. Important optimization problems include berth planning (see Guan and Cheung [8], Imai et al. [10, 11], Lim [17], Park and Kim [22]), quai crane planning (see Daganzo [5], Peterkofsky and Daganzo [23]), and straddle carrier scheduling (see Böse et al. [4], Kim and Kim [15], Steenken et al. [24]). Moreover, approaches for locating containers in the yard have been developed (see de Castilho and Daganzo [6], Kim and Kim [12], Kim et al. [13], Taleb-Ibrahimi et al. [26], Zhang et al. [29]).

Several papers have studied specific optimization problems arising in container terminals with automated equipment. Automated guided vehicles (AGVs) have been studied by Bae and Kim [1]. Bish et al. [3] propose a greedy dispatching method for AGVs. Grunow et al. [7] consider double load AGVs, that is, AGVs that can carry two 20'-containers at a time. A general model for scheduling equipment such as AGVs or automated stacking cranes (or non-automated resources such as straddle carriers and reefer mechanics) has been proposed by Hartmann [9]. Meersmans and Wagelmans [19] discuss an integrated scheduling approach for automated stacking cranes and AGVs. A simulation study to compare AGVs and automated shuttle carriers has been given by Vis and Harika [28]. Kim et al. [14] employ simulation to provide a test bed for the control system of an automated container terminal.

In this paper, we focus on highly automated terminals which employ AGVs. This study has been carried out in cooperation with the HHLA Container Terminal Altenwerder in Hamburg, Germany (for details on this terminal see Baker [2]). We consider a container terminal configuration similar to the Altenwerder terminal that employs quai cranes, AGVs and automated stacking cranes. Quai cranes are used to discharge containers from and load containers onto vessels. AGVs are means for horizontal transport of containers between the stacking area and the quai, and they are unable to load or unload themselves. The yard is organized in a number of stacks, and each stack (or yard block) is served by one or more stacking cranes. The terminal layout considered throughout this paper is displayed in Figure 1. In this paper, we only deal with the waterside, that is, containers arriving by a vessel which have to be brought to the stacking area and containers being picked up by a vessel which have to be brought from the stack to the quai (the landside with its outside truck and rail operations is not dealt with, hence it is not shown in Figure 1).

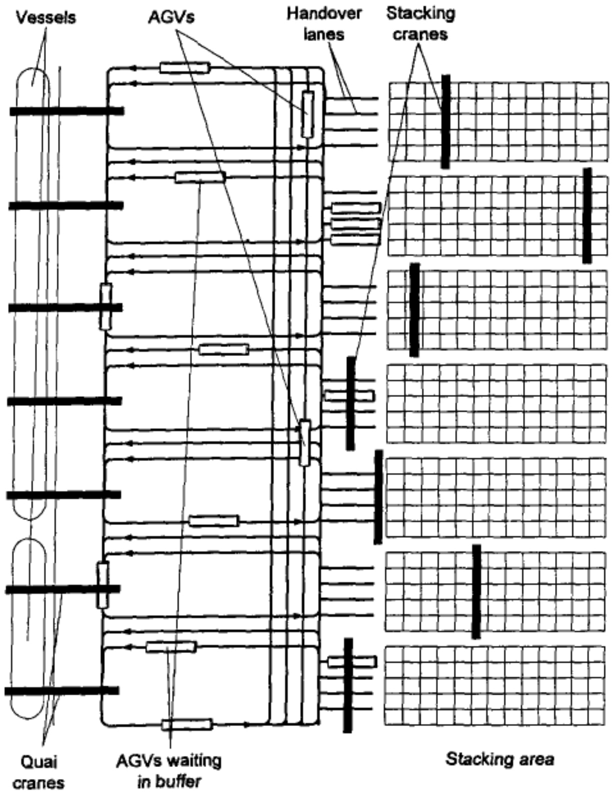

Figure 1: Layout of the container terminal

The goal of the paper is to present a method for assigning AGVs to transportation jobs that is applicable to real world container terminals. Therefore, the main requirements for the method are high waterside productivity, very short computation times and robustness.

High productivity means that the number of container transported per hour should be as high as possible. Short computation times are necessary to allow for real-time application within a terminal control system. Robustness means that the method should perform well in a rather unpredictable environment (which is typical in practice due to quai crane delays, inaccurate estimates for AGV travel times, manual interference etc.).

The outline of the paper is as follows. We first describe a rather conventional approach to the AGV assignment problem which is based on due dates and an earliness-tardiness objective. This formulation will be solved both by a greedy heuristic (such simple methods are often used in practice and are also discussed in the scientific literature, see Bish et al. [3]) and an optimal algorithm. Subsequently, we propose a new approach to the AGV assignment which introduces the idea of inventory related to quai cranes. The motivation for this is to provide a problem formulation that avoids to employ time estimates since the latter are typically inaccurate on real world terminals. Our goal is to define a method that is more robust than a time based one and thus leads to higher productivity. The approaches are then compared in a simulation study. We first point out how much the terminal productivity can be improved by using an optimal algorithm instead of a simple heuristic in the conventional time based formulation. Then we indicate the improvement that can be obtained from using the inventory based formulation instead of the time based one.

2 General Problem Description

We consider the problem of assigning jobs to AGVs. Each job corresponds to the transportation of a container from a pick-up location to a delivery location. An AGV can be assigned one job (and thus a single container) at a time. After completing a job, an AGV can start another job. A job consists of an empty drive from its last position to the pick-up location, a hand-over time at the pick-up location, a drive to the delivery location, and a hand-over time at the delivery location. Two types of processes are distinguished, namely discharging and loading a vessel. For a job related to a discharging operation, the pick-up location is a quai crane and the delivery location is a stack. Analogously, for a job related to a loading operation, the pick-up location is a stack and the delivery location is a quai crane. For each job, the locations are fixed (specific quai crane or spacific stack). Estimates of driving times between any two locations on the layout as well as estimates of the handover-times are assumed to be given (if needed by the actual solution approach).

Depending on the vessel's stowage plan and operational strategies, some container i may have to arrive at the quai crane before some container j when loading a vessel. That is, there may be precedence relations between some (but usually not all) of the jobs related to the same loading quai crane. There are no precedence relations between discharging jobs.

The problem essentially consists of a number of AGVs and a number of jobs. We consider n AGVs, namely those which are currently available and those which will complete their current job within a short time. For the latter, an estimated availability time is given. Due to the problem-inherent rolling planning horizon, only the n most urgent jobs are considered when computing an assigment of jobs to AGVs.

The main goal when assigning jobs to AGVs is to maximize the waterside productivity, that is, the number of containers handled per hour by the quai cranes. This goal cannot be used directly as an objective function for the AGV assigment problem. In fact, different objective functions can be defined to achieve the productivity goal. Two such approaches will be discussed in the following sections. In general, one may achieve high productivities by employing goals such as minimization of the quai crane waiting times for AGV (when AGVs arrive too late), minimization of the AGV waiting times at quai cranes (when AGVs arrive too early), minimization of the empty travel times, and an even distribution of AGVs among the quai cranes. (Note that the loaded travel times cannot be influenced by assigment decisions because the pick-up and delivery locations of each job are fixed.)

The AGV assigment problem is embedded into an overall terminal control system. Whenever a certain event occurs, a new AGV assignment is calculated. Such an event can be the completion of a job or the generation of a new job. Thus, frequent replanning is done. If the assignment procedure assigns a job to an AGV which is currently available, this assignment is fixed and the AGV starts this job. Otherwise, if the assignment procedure assigns a job to an AGV that is not yet available, the assignment is not fixed. In the latter case, the job and the AGV will be considered again when the assignment procedure is started after the next event. This way, the decision to actually execute a job is made as late as possible. This allows for decisions based on actual data, which is important since data are frequently changing in practice due to delays etc. In fact, frequent changes in the data and the inaccuracy of time estimates (which are typical in practice) lead to a short planning horizon and to an assignment problem in which an AGV obtains only one job (instead of a scheduling problem with a sequence of jobs).

In Sections 3 and 4, we present two different formulations of the problem setting described above. Both approaches have essentially the same structure since they are both assignment problems with n jobs and n AGVs (i.e., each AGV must be assigned exactly one job and vice versa) and with an objective to minimize the total assignment costs. They differ only in the way to select the n jobs to be assigned and in the definition of the costs c_{ja} which evaluate the assignment of an AGV a to a job j.

3 Due Date Based Approach

3.1 Problem Formulation

In this section, we provide a formulation of the AGV assignment problem that makes use of due dates for the jobs. This approach is similar to the formulation of Hartmann [9] and will be summarized briefly.

Each quai crane is associated with a sequence of either loading or discharging jobs. Considering the time the quai crane needs for loading or discharging one container, we can define a due date d_j for each job j. The due date reflects the time at which an AGV should arrive at a quai crane either empty (discharging operation) or with a container (loading operation). Note that a job always has a later due date than all of its predecessors.

Since AGVs are unable to load and unload themselves, they should arrive at the quai cranes just in time. Early arrival implies that the quai crane is not yet ready and that the AGV has to wait, which is a waste of AGV capacity. Late arrival means that the quai crane has to wait for the AGV which decreases its productivity. This leads to a traditional earliness-tardiness objective function. Moreover, one may wish to obtain short empty travel times (to save fuel costs and to save AGV capacity for future jobs). Thus, our objective function minimizes the weighted sum of earliness, tardiness and empty travel time.

For a more formal definition, let J be the set of the jobs to be assigned, and let α_E, α_T and α_e be the weights for earliness, tardiness and empty travel time, respectively. Moreover, let f_j^q be the estimated arrival time of job j at the quai crane resulting from the assignment, and let e_{ja} denote the empty travel time of job j when assigned to AGV a. Now the costs c_{ja} of assigning AGV a to job j are defined as

$$c_{j,a} = \begin{cases} \alpha_E \cdot (d_j - f_j^q) + \alpha_e \cdot e_{j,a}, & \text{if } f_j^q < d_j \\ \alpha_T \cdot (f_j^q - d_j) + \alpha_e \cdot e_{j,a}, & \text{otherwise.} \end{cases} \tag{1}$$

Note that the due date d_j does not refer to the completion of the job but to the arrival time f_j^q at the quai crane. In case of a discharging job, the latter corresponds to the end of the drive to the pick-up location. Let us consider a discharging job j with assigned AGV a and availability time τ_a of AGV a (note that we have $\tau_a = 0$ if AGV s is currently available). Then we obtain $f_j^q = \tau_a + e_{ja}$ for discharging jobs. In case of a loading job, however, the due date refers to the end of the drive to the delivery location. Let h_{SC} be the estimated hand-over time at the stacking crane, and let t_{ja} be the estimated transportation time from the pick-up to the delivery location. Then we have $f_j^q = \tau_a + e_{j^a} + h_{SC} + t_{ja}$ for loading jobs.

We consider n jobs and n AGVs for the assignment problem. As outlined in Section 2, the n AGVs are those that are currently available and those which will complete their current job within a short time. The n jobs are determined as follows. We define parameters N_q which reflects the maximal number of AGVs that can be assigned to jobs of quai crane q but have not yet reached q. We then successively pick the most urgent job that has not yet been assigned until we have picked n jobs. The most urgent job is the one with the earliest due date among the remaining jobs. A job related to quai crane q may only be picked if the number of AGVs already driving towards q plus the number of jobs picked for q so far is smaller than N_q. With this approach, we limit the number of AGVs that can be assigned to the same quai crane. The motivation behind this is that this leads to a more even distribution of the AGVs among the quai cranes. This should help to avoid situations in which one quai crane gets too few AGVs while another gets more than it can handle (which causes AGV waiting times). Note that we will usually allow more AGVs for a loading than for a discharging quai crane because it takes longer to reach a loading quai crane.

3.2 Solution Methods

In order to solve the due date based assigment problem, we employ two procedures. Both start by computing the set of jobs J and the set A of AGVs to be assigned as described in the previous subsection.

The first approach is the Hungarian method of [16] which was implemented as described in [20]. This algorithm leads to an optimal assignment with respect to the due date based assignment costs given in (1).

The second approach is a simple greedy heuristic that will be used in order to provide benchmark results for the comparison. We employ a priority rule based procedure similar to that of Hartmann [9]. The procedure repeatedly applies the following steps until each job has been assigned to an AGV, that is, until $J = \emptyset$ and $A = \emptyset$.

1. Select the job j to be assigned next as the most urgent job, that is, the job with the smallest due date $d_j = \min\{d_i \mid i \in J\}$.
2. Select the AGV a that leads to the smallest increase in the objective function, that is, the lowest possible costs $c_{ja} = \min\{c_{jb} \mid b \in A\}$ for job j.
3. Assign AGV a to job j.
4. Remove AGV a from A and job j from J, respectively.

3.3 Implications for Stacking Crane Decisions

The AGV assignment problem decides which empty AGV carries out which job, but it should not decide which container the AGV will actually receive. Consider two empty AGVs a and b with availability times $\tau_a < \tau_b$. Moreover, consider two jobs i and j with the same stack as pick-up location and with due dates $d_i < d_j$. Let us assume that the AGV assigment decision was to assign job i to AGV a and job j to AGV b. It may happen that AGV b arrives at the stack before a (a may have been delayed due to congestion on the layout). Now the stacking crane should put container i on AGV b because container i is more urgent (note that one could say that AGVs a and b switch their jobs).

The stacking crane decisions (i.e., which container is to be moved next) is based on various goals and requirements such as high waterside and landside productivity, short empty travel times, AGVs and external trucks should have short waiting times etc. Considering the interface to the AGVs, we assume that the stacking cranes make use of rules analogous to those employed for the AGVs when deciding which AGV should receive which container. This means that the stacking cranes prefer containers with earlier due dates (in addition to their further goals), an issue which does not have an impact on the AGV assignment problem itself, but which is important when testing the AGV assignment approach in a simulation study as will be done in Section 5.

4 Inventory Based Approach

4.1 Basic Idea

At each quai crane, there is a waiting buffer for AGVs, that is, an area in which arriving AGVs have to wait until the quai crane is ready to serve them. This buffer can be seen as a storage. In this analogy the quai cranes itself are customers which have to be supplied with goods. These goods correspond to AGVs. A loading quai crane requires AGVs with containers to be loaded while a discharging quai crane requires empty AGVs on which a discharged container can be put. Like in inventory management, the supervisors' task is to make sure that no customer has to wait lacking of goods. On the other hand he has to prevent the inventory level from being too high. In our problem this is especially important because among containers AGVs are tied up in stock. Hence, if queues become too long there will be a negative effect on the system's future behavior because less transportation capacity is available.

Considering the buffer as an inventory we say the inventory level of a quai crane is the number of AGVs in the buffer. Furthermore, the inventory level plus those AGVs on their way to the quai crane's buffer can be seen as the quai crane's net inventory level. To keep the analogy, we define a special net inventory level for our problem: The number of AGVs which are busy with a job of a quai crane q and have not reached q equals ila_q. that is the inventory level for assignment decisions (ila) of q. Furthermore, we denote the set of AGVs belonging to ila_q with ILA_q, that is, we have $ila_q = |ILA_q|$. Note that for a loading quai crane q, ILA_q consists of the AGVs that are either waiting in the buffer at q, transporting a container towards q, waiting for a container for q at a stack, or driving to a stack where a container for q is to be picked up. For a discharging quai crane p, ILA_p contains those empty AGVs that are either waiting in the buffer at p or driving towards p (observe that AGVs transporting a container picked up at p do not belong to ILA_p).

Considering the analogy described above, the basic idea for assigning AGVs to jobs can be stated as follows: Whenever an AGV a should get a new job, assign a to the first unassigned job of the quai crane q whose buffer is most probably empty when a would arrive at q. According to the analogy to inventory management we choose the quai crane q with the smallest ila_q. In other words, the next job of that quai crane q for which ila_q is minimal is the most urgent job. One may also say that quai crane q is the most urgent quai crane to receive an AGV. A methodology to assign jobs to AGVs that is based on this basic idea will be presented in Section 4.2.

There is another reason for this idea: If we want to lower waiting times of AGVs at quai cranes we have to shorten the waiting queues. By sending the AGV to quai crane with lowest ila_q we select the shortest expected waiting queue for the AGV to enqueue into.

However, the inventory levels ila_q as described above are not yet suitable for directly comparing the current needs of the quai cranes for further AGVs with each other. Obviously, the time an AGV needs to arrive at the quai crane is much longer for loading quai cranes than for discharging ones. In the former case it contains a drive to the stacking crane, waiting for service and a drive to the quai crane, while in the latter case there is just a direct drive to the quai crane. Naturally, to reach the same supply level for all quai cranes (or, in other words, the same productivity), the inventory level of loading quai cranes must be higher than that of discharging ones. Therefore, we introduce a parameter ϕ called phase factor by which the inventory level of loading quai cranes must be higher. We consider adapted inventory levels for loading quai cranes q by defining $ila'_q = ila_q/\phi$. The inventory levels of discharging quai cranes are not modified, that is, we set $ila'_p = ila_p$ for a discharging quai crane p. The urgency with which a quai crane requires an AGV is now measured by inventory levels ila'_q for all quai cranes q.

So far, we have defined a quai crane q with ila'_q to be more urgent than that of a quai crane p if we have $ila'_q < ila'_p$. Finally, we consider quai cranes having the same inventory level, that is, $ila'_q = ila'_p$. In order to resolve such a tie we define the quai crane for which the last AGV was started a longer time ago to be more urgent.

Note that ila'_q can further be modified to reflect operational issues in practice. One might wish to prioritize some quai crane q, e.g. if q has the longest remaining job list and must accelerated in order to finish the vessel on time. This can be achieved by reducing ila'_q.

This makes the jobs of quai crane q appear more urgent and thus leads to more AGVs for quai crane q. This should provide a higher productivity of q (although, of course, the productivities of the remaining quai cranes may decrease). This example shows the straightforward applicability of the inventory idea with respect to practical needs.

4.2 Assignment Procedure

First, we determine all AGVs, say n, being available within a certain horizon. Next, we find n jobs to be assigned to those AGVs available. Here we employ our basic idea as described in Section 4.1: The most urgent job is a job which belongs to the quai crane q which has the lowest ila'_q. Among all those we select a job all predecessors of which are assigned to an AGV or are in transport or are finished. By paying attention to the given precedence relations while assigning AGVs to jobs we reduce the risk of AGVs waiting at a quai crane where the delay is caused by delayed predecessor containers. We note the job just chosen as assigned, temporarily increase the corresponding ila'_q by one and, once again, determine the most urgent job based on the new data. This process loops until we have n jobs.

To assign the jobs to the available AGVs we create a standard linear assignment problem. The costs $c_{j,a}$ of assigning job j to AGV a consist of three components:

- The AGV has to wait until it finishes its current job to start the next empty travel. These expected w_a time units until then influence the duration until the next job j is picked up as well as the duration until j arrives at its quai crane. Note that w_a is zero if a does not have a current job.
- According to the pick-up location of job j and the current position of AGV a there is an expected empty travel time $d_{j,a}$ if j is assigned to a which affects the containers arrival at the quai crane.
- We introduce $1 \leq o_j \leq n$ as the ordinal number of job j according to the order in which the jobs were chosen for assignment. That is, job j with $o_j = 1$ is the most urgent job with respect to the inventory levels ila'_q, job i with $o_i = 2$ is the second most urgent job and so on.

Now we define the cost as follows:

$$c_{j,a} = (\lambda \cdot (n - o_j) + 1) \cdot (w_a + d_{j,a})$$

λ is a weight to manipulate the impact the job's urgency has on the costs. One part of this objective function depends on the time passing until a container is picked up, the other one on the container's urgency. The lowest value corresponds to the least important container and equals 1. The next containers have coefficients $1 + \lambda, 1 + 2 \cdot \lambda, 1 + 3 \cdot \lambda$ and so on. Having determined the costs c_{ja}, we solve the resulting assignment problem by the Hungarian method of [16] designed as an executable in [20]. This algorithm leads to an optimal assignment in terms of our objective to minimize the total assignment cost.

4.3 Implications for Stacking Crane Decisions

As already discussed in Section 3.3, stacking cranes are involved in the decision which container to load on an AGV. Therefore, we describe a rule for loading containers which is, analogously to the assignment rule, based on net inventory levels.

We distinguish the loading decisions to be made when an AGV receives a container from a stacking crane, and those to be made when the AGV receives a container from a quai crane. In the latter case, the AGV simply receives an arbitrary container from the quai crane it is waiting at. In the former case this decision is much more difficult: The stacking crane may have containers required by different quai cranes, thus it has to decide which to pick first. In order to support the selection we introduce a further inventory level. The inventory level for transport decisions ilt_q of a loading quai crane q is defined as the number of AGVs driving straight towards q after picking up a container for q at the stacking area. Additionally, we define the corresponding set of AGVs as ILT_q.

Then, we select the quai crane in a way similar to the assignment decision: We assume (see Section 3.3) a stacking crane to consider the quai crane q with the lowest ilt_q among all loading quai cranes having containers at the specific stacking crane as the most urgent quai crane. Again, we want to respect the precedence relations, namely only pick up containers whose predecessors are already picked up. However, it is possible that none of the containers to be loaded fulfills this precedence condition because we consider a subset of the containers. For example, it might occur that each container has at least one predecessor not picked up yet which stands at another stacking crane. Then, in order to prevent congestions as much as possible we propose to start with strong requirement formulations and lower them step by step if no container fulfills them. As soon as we find some containers we select the one belonging to the most urgent quai crane.

Sending an AGV to a quai crane q with low ilt_q is motivated by reducing waiting times of quai cranes and AGVs. This idea directly corresponds to the one for selecting containers for the assignment process described in Section 4.2.

4.4 Enforcing Dual Cycles

An AGV's drive to the pick-up location is often necessary but worth avoiding if possible. It ties up AGV capacity and, moreover, leads to more traffic in the terminal so the risk of congestion increases. Therefore, we provide a feature to be plugged in the decision process described so far.

A constellation of an AGV transporting a container to its destination and receiving a new job with a pick-up location equal to the previous job's delivery location is called a dual cycle. Dual cycles are possible only at stacks since quai cranes are either loading or discharging which means they do not discharge a container immediately after loading another one in the same ship bay.

The assignment process described above arranges dual cycles only if there is a container with sufficient urgency at a stack where an available AGV is located. In order to suppress more empty drives we take into account containers stored at a stack which would be ignored when creating the assignment problem in Section 4.2 because of a lack of urgency. Hence, we state an assignment rule as follows: If an AGV is available at a stack, it is assigned to the most urgent job located at this specific stack and whose predecessors already have been assigned or completed. As a result, we might assign a container which would not be considered by the basic method of Section 4.2 but offers a profitable dual cycle. This assignment process is executed right before the basic assignment process in Section 4.2. The jobs and AGVs assigned by this procedure are deleted from the corresponding sets. For the remaining AGVs the assignment problem is created, solved and evaluated as stated in Section 4.2.

Note that the AGV process in case of a dual cycle differs from the stardard process only in that the empty travel to the pick-up location is actually a dummy drive—obviously, it takes no time because the last delivery location of the AGV corresponds to its next pick-up location. Afterwards, we decide which container to load on the AGV and select the most urgent one as described in Section 4.3. Therefore, we always arrange a dual cycle for the most urgent container of the specific stack (to be accurate, the AGV assignment procedure can only decide to leave the empty AGV at that stack, but we assume that the stacking crane scheduling selects the most urgent container with respect to the second inventory level ilt_q). Unfortunately, although this rule reduces empty travel times, it also can also lead to undesirable effects:

- As outlined in Section 4.1 we aim at inventory levels as similar as possible. By partially ignoring the urgency of jobs we risk to disturb this balance. Therefore, we introduce two parameters $0 \leq \sigma, \tau \leq 1$ in order to prevent the balance getting too much disturbed. Furthermore, we consider separate minimum and maximum inventory levels, respectively, for all quai cranes (ila) and for loading quai cranes (ilt) only: $ila_{all}^{min}, ila_{all}^{max}, ilt_{loading}^{min}, ilt_{loading}^{max}$. We employ them to formulate two conditions for a dual cycle concerning a specific candidate job j and its quai crane's q_j inventory levels ila_{q_j} and ilt_{q_j}:

$$\begin{aligned} ila_{q_j} &\leq (1-\tau) \cdot ila_{all}^{min} + \tau \cdot ila_{all}^{max} && (2) \\ ilt_{q_j} &\leq (1-\sigma) \cdot ilt_{loading}^{min} + \sigma \cdot ilt_{loading}^{max} && (3) \end{aligned}$$

  Following these conditions we only choose a container for a dual cycle if it belongs to one of the more urgent quai cranes.

- Dual cycles only support loading quai cranes by more efficient use of AGVs. This leads to change in the relation of AGVs' driving time towards a quai crane (the time for loading cranes is shortened on the average. Hence, we have to adapt the phase factor ϕ described in Section 4.1.

- We arrange dual cycles before solving the assignment problem. Therefore, it might occur that a few loading quai cranes get too many AGVs before discharging quai cranes are taken into account at all. Consider for example ten discharging quai cranes and a single loading one. Each AGV which has been assigned to a discharged container will be assigned to a container to be loaded. Therefore, the loading quai crane gets about ten times more AGVs than each of the discharging ones. Manipulating the phase factor reduces the problem, but cannot solve it completely. In order to remove this effect we introduce a probability ρ with which a potential dual cycle is executed. This will reduce the number of dual cycles. Therefore, we can reserve enough AGVs for the assignment procedure which might assign them to discharging quai cranes.

5 Simulation Study

In order to compare and evaluate the two assignment approaches given in Sections 3 and 4 we developed a simulation model. For a sketch of the terminal layout in the simulation model, we refer again to Figure 1. In the following we give some details of the simulation model, summarize the parameters employed and, finally, discuss the results.

5.1 Model

According to our problem setting, we identify three substantial components of the considered container terminal configuration:

- **Quai cranes**
  Quai cranes load containers onto a vessel or discharge them from it. We can look at their life cycle as an endless loop of either waiting for AGVs or handling containers. When a quai crane holds a container to set it down on an AGV or waits for a container to load on the vessel it has to wait until an AGV arrives at the quai crane. After a quai crane's interaction with an AGV it either transports the container onto the vessel (if loading) or picks the next container from it (if discharging).
  In order to characterize the quai crane's behaviour we employ three distributions: Transfer time for AGVs to be loaded with discharged containers, transfer time to get containers from AGVs to load them on a vessel and the time the quai crane needs to start the next transfer. The former two contain the processes of adjusting to the AGV, grabbing the container and lifting it up to a height that allows the AGV to leave (if loading) or adjusting to the AGV, setting the container down and releasing it (if discharging). The latter includes the container's travel to or from the vessel.
  A quai crane reports an estimated availability time of an AGV for the assignment procedure when the AGV leaves the buffer.

- **Stacking cranes**
  Stacking cranes manage the stacking area and therefore receive containers from AGVs after they were discharged from vessels. Additionally, stacking cranes provide containers for AGVs to be loaded onto vessels. Both processes are modeled by distributions for the transfer times, that is, the times the AGVs have to wait at the stacks. Since the behaviour of the stacking cranes is not modelled explicitly, these distributions implicitly contain all other activities such as shuffling containers and serving the landside. Similarly to the quai cranes, stacking cranes report an estimated availability time for an AGV. This happens a certain time, according to a given distribution, before the transfer is assumed to be finished.

- **AGVs**
  AGVs transport containers from quai cranes to the stacking area and vice versa. Their only activity to be modelled is driving. Therefore a distribution for the driving time from each possible starting position to each possible destination position is registered in the model. These distributions cover interferences of AGVs on the layout, especially congestions.

The simulation model has been implemented in Desmo-J, a discrete event based simulation framework in Java (see Page et al. [21]). The distributions mentioned above were taken from statistics of the Container Terminal Altenwerder. The original statistics were modified for reasons of confidentiality, but the resulting distributions still allow for a realistic simulation.

5.2 Scenarios

In order to evaluate our approach we compare four different methods to assign jobs to AGVs. First, we implemented the greedy heuristic described in Section 3 which we will refer to as "dueDatePrio". Our own approach which was described in Section 4 was realized both with ("invDualCycle") and without forcing dual cycles ("inv"). Because we want to get results concerning the different methods to select containers for assignment, namely the due date based rule and the inventory based idea, we have to eliminate effects caused by different assignment methods. We achieve this by using the Hungarian method for assigning containers selected by the due date idea in a fourth method, "dueDateHung".

We apply these approaches to scenarios which differ by the structure of the containers' precedence relations. Varying this structure gives a hint about the capability of an approach because the structure defines the degrees of freedom which are left for it. Obviously, precedence relations between containers i and j can solely exist if i and j belong to the same quai crane. We considered five structures of precedence relations:

- The lowest requirement level is given in a scenario without precedence relations. The approaches can randomly choose containers to load or discharge when available.
- The strongest requirement level is given by "linear" precedence relations between the containers of each quai crane. Then at each point of time there is just a single container for each quai crane which can be loaded or discharged.
- In addition, we have three settings with partial precedence relations. They are different with respect to the number of precedence relations per job, leading to scenarios with "many", "medium", and "few" precedence relations per job.

In each scenario there are twenty stacking cranes and fourty AGVs. Ten quai cranes, of which five are loading and five are discharging, are randomly distributed on the twenty possible positions. We created sixty jobs per hour and quai crane. The corresponding stacks associated with the jobs are randomly distributed on the ten nearest stacks cranes for containers to discharge and on the twelve nearest ones for containers to load on vessels. For the simulation runs we identify four goals resulting from the discussion in Section 2. We use them in order to compare the approaches:

- Increasing the container terminal's waterside productivity, i.e. the number of containers loaded onto and discharged from vessels per hour, is the main goal of our approach.
- Waiting times of quai cranes increase the time in port of the vessels. Hence, we want to reduce them.

- Waiting times of AGVs tie up capacity without having any positive effect on the system's productivity, so we want to reduce them.
- Empty travel times should be shortened because, like waiting times, they tie up capacity without supporting the main goal. Besides, they increase traffic on the AGV layout and therefore the probability of congestion.

We carried out two series of simulation runs. In preliminary experiments we tested a broad variety of values for each parameter while fixing others. After evaluating these runs we fixed all parameters for further experiments to get reliable results in order to evaluate the different approaches. Tables 1 and 2 give the fixed values of essential parameters. Note that phase factor ϕ has to be adapted according to Section 4.4 when dual cycles are forced.

parameter	symbol	value
earliness cost	α_E	1
tardiness cost	α_T	7.5
empty driving cost	α_e	1

Table 1: parameters for due date approach

parameter	symbol	value
phase factor	ϕ	1.6
cost step	λ	3
dual cycle	τ	1
dual cycle	σ	0.5
dual cycle	ρ	1

Table 2: parameters for inventory approach

For each approach we performed 100 simulation runs with a simulation time of eleven hours per run which were preceded by two hours to let the system get in balance and followed by two hours to make sure containers were not running out in the period to be evaluated. Solely the period of eleven hours is evaluated by means of statistics.

5.3 Results

In the following we present the results of the simulation runs taking into account our four approaches and five different scenarios.

Precedence relations	dueDatePrio	dueDateHung	inv	invDualCycle
linear	1	1.010	1.050	1.049
many	1	1.014	1.046	1.059
medium	1	1.015	1.045	1.183
few	1	1.014	1.075	1.229
without	1	1.018	1.047	1.190

Table 3: Quai crane productivity

Table 3 gives an overview of the productivity resulting from the different approaches. Productivity is measured as average number of containers loaded or discharged per hour and quai crane. Although we did not use the original approach employed at the Container Terminal Altenwerder nor the original statistics, we cannot give absolute productivity figures here in order to avoid misinterpretations. Therefore, the results are given as relative figures. We selected "dueDatePrio," the simplest method in our study, as a base and set its productivity index to 1.0 for each of the five scenarios. The productivities resulting from the other methods are given relative to those of "dueDatePrio" (e.g., 1.015 of "dueDateHung" for the "medium" scenario indicates a productivity improvement of 1.5 % over "dueDatePrio").

One can clearly observe that productivity using "dueDateHung" is slightly higher in each scenario than when "dueDatePrio" is applied. Remember that these approaches only differ in the algorithm, not in how the most urgent jobs are determined or how job assignments are evaluated. The results show that the Hungarian method is better suited than the greedy heuristic, although the productivity is increased only by 1.0–1.8 %. Furthermore, "inv" reaches a higher productivity than "dueDateHung". These two approaches employ the same algorithm (i.e., the Hungarian method) but employ different problem formulations. Therefore, we can say that the inventory based concept is more promising than the due date approach. In particular, we can see that the improvement due to the inventory concept is higher than the improvement that can be obtained from using an optimal algorithm in the due date based model. When comparing "inv" and "invDualCycle", we observe that using the option to enforce dual cycles in the inventory based approach seems to be extremely promising. Also note that the superiority of the dual cycle approach further increases if there are less precedence relations.

Precedence relations	dueDatePrio	dueDateHung	inv	invDualCycle
linear	1	0.955	0.906	0.876
many	1	0.951	0.906	0.814
medium	1	0.943	0.924	0.580
few	1	0.952	0.914	0.559
without	1	0.950	0.919	0.529

Table 4: Empty travel times of AGVs

Table 4 gives an impression of the influence the approaches have on the total empty travel time of AGVs. Again, the Hungarian method in "dueDateHung" is superior to the simple priority rule in "dueDatePrio". The inventory based approach leads to smaller empty travel times than the due date based approach. Obviously, enforcing dual cycles strongly reduces empty driving times. The effect of dual cycles on the empty travel times increases with decreasing number of precedence relations. This is because less precedence relations make it more likely to fulfill the conditions for arranging dual cycles on a higher requirement level (see Section 4.3) which will reduce congestions in front of the quai crane.

Precedence relations	dueDatePrio	dueDateHung	inv	invDualCycle
linear	1	1.032	0.860	0.944
many	1	1.027	0.881	1.036
medium	1	1.075	0.666	0.696
few	1	1.039	0.911	0.964
without	1	1.007	0.601	1.052

Table 5: AGV waiting times in buffer at quai crane

Table 5 is arranged like Tables 3 and 4 and shows the waiting times of the AGVs in the buffer at the quai crane. Recall that AGVs have to wait in this buffer if more AGVs than the quai crane can handle have been assigned to this quai crane or if AGVs have to wait for delayed predecessors. We can see that the inventory based approach reduces waiting times of AGVs significantly. If the dual cycle extension is considered, the waiting times of the AGVs are higher than otherwise. The latter results from the drawback discussed in section 4.4: By enforcing dual cycles we partially ignore the urgency of containers. Therefore, it becomes more likely that we send AGVs to quai cranes with higher ila_q. Hence, AGV queues get longer and waiting times in the buffer increase.

Precedence relations	dueDatePrio	dueDateHung	inv	invDualCycle
linear	1	1.032	0.860	0.944
many	1	0.990	0.974	0.955
medium	1	0.982	0.957	0.800
few	1	0.990	0.962	0.837
without	1	0.987	0.977	0.838

Table 6: Quai crane waiting times for AGVs

The waiting times of the quai cranes are given in table 6. Again, the inventory based idea leads to better results than the due date approach. Moreover, enforcing dual cycles reduces the quai crane waiting times even further.

Finally, we have a brief look at the impact of the precedence relations on the productivity, empty travel times, waiting times of AGVs in the quai crane buffer and quai crane (QC) waiting times for AGVs. The results are displayed in Table 7. We consider only the greedy priority rule based heuristic for the due date approach (dueDatePrio) which has been the benchmark in our study. As in the previous tables, we give relative results. Here, we have selected the linear precedence relations as a basis for the comparison. We observe a significant influence of the precedence relations' density on the results. In particular, having less precedence relations leads to higher productivities. If we have no precedence relations at all, the productivity (with the same heuristic) is 11.8 % higher compared to the case of linear precedence relations. This is because less precedence relations make it less likely that an AGV has to wait for a delayed predecessor in the buffer at a loading quai crane. This is confirmed by Table 7 which shows that the AGV waiting times in the quai crane buffer decrease drastically when we have less precedence relations.

Precedence relations	productivity	empty travel	AGV waiting	QC waiting
linear	1	1	1	1
many	1.035	1.000	0.744	0.982
medium	1.065	0.981	0.370	0.973
few	1.071	0.993	0.256	0.964
without	1.118	0.989	0.242	0.943

Table 7: Impact of precedence relations (method: dueDatePrio)

6 Conclusion and outlook

In this paper we proposed an approach to schedule container transports between quai cranes and the stacking area. We captured the problem of assigning transportation jobs to AGVs by introducing a concept related to inventory management. The essential idea is to assign an AGV to a job that belongs to a quai crane to which a relatively small number of AGVs is currently assigned. This problem formulation was compared to a more traditional formulation which is based on due dates for the jobs and an earliness-tardiness objective. Both formulations differ only in how the jobs to be considered are determined and in the way the assignment costs of jobs to AGVs are calculated, but not in the underlying mathematical structure.

In a simulation study, we found that the problem formulation has an impact on the resulting terminal productivity. Even when both problem formulations are solved with the same algorithm (the well-known Hungarian method), the inventory based concept outperformed the due date based approach with respect to waterside productivity (although only by a few percent). At first glance, the due date approach seems to allow for more precise scheduling because it accurately plans events and durations on the terminal. However, our results indicate that the bad time estimates which are common in practice (and which were considered in our simulation model in a realistic way) lead to suboptimal decisions in the due date approach and thus to lower productivities. The inventory based approach which avoids the use of estimated times appears to be more robust and thus better suited for application in practice.

Additionally, we introduced a feature to enforce dual cycles of AGVs at stacks (that is, a stacking crane unloads a container from the AGV and puts another on the AGV). This allows to reduce the empty travel times of the AGVs and, as shown by our results, leads to higher waterside productivities.

Furthermore, we analyzed the impact of the precedence relations both on the productivity and on the performance of the different approaches. Less precedence relations between containers to be loaded onto vessels lead to higher productivities. This is due to more degrees of freedom for the AGVs, that is, in case of fewer precedence relations, AGVs can directly proceed to the quai crane without having to wait for a delayed predecessor to pass. Moreover, the additional productivity gain of the dual cycle extension increased with a decreasing number of precedence relations.

Considering the good results of the inventory based concept for AGV dispatching, an objective of further research should be the application of this approach to other types of equipment for container handling. In particular, inventory based optimization would be promising for stacking cranes and straddle carriers. In both cases, the inventory idea would have to be adapted in order to reflect the specific requirements of those types of equipment.

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