Efficiency considerations for sequencing and scheduling of double-rail-mounted gantry cranes at maritime container terminals

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Abstract: The current decade has seen a considerable growth in worldwide container transportation and with it, an indispensable need for optimisation. This paper seeks to investigate to which extent double-rail-mounted gantry cranes can help to improve a container terminal's efficiency. A simulation study is conducted for evaluating different online algorithms for sequencing and scheduling of jobs for automated double-rail-mounted gantry cranes serving a terminal's storage block. The experiments are based upon scenarios that are derived from the real world (Container Terminal Altenwerder, CTA, Hamburg, Germany) in order to investigate advantages as well as problems and limits of our algorithms and the specific crane systems. Furthermore, the influence of the horizontal transport at the block's interfaces is examined.

Keywords: maritime container terminal; crane scheduling; storage block; double-rail-mounted gantry crane; simulation; crane interference; crane assignment; shipping; transport logistics; job sequencing.

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1 Introduction

The current decade has seen a considerable growth in worldwide container transportation and with it an indispensable need for automation (especially in regions with high labour costs) and optimisation. The containerisation until 2008, as well as forecasts for the next decade, clearly show a (steep) trend upwards (see Figure 1). This is also supported by the figures of the top ports of the world (see Figure 2), although current news report a decrease with respect to the collapse of financial markets and an economic recession.

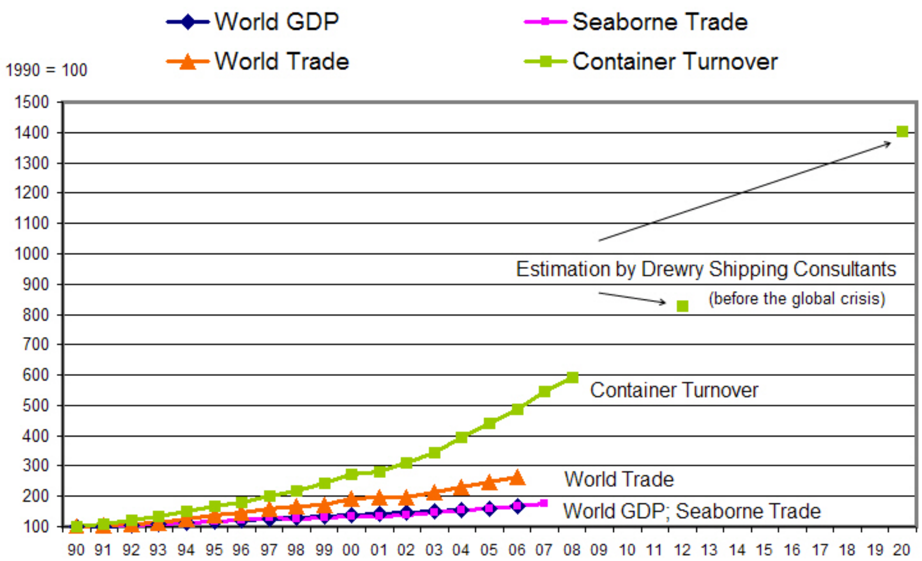
Seaports are faced with limitations in space as well as with high labour costs (in particular in Europe). The main objectives for container terminals in order to fulfil the clients' requirements are:

- reliability (being on time is more important than trying to be fast)
- decrease vessels' berth time (transshipment time)
- low rates (therefore, low costs) for loading and discharging
- use scarce space more efficiently
- increase throughput and reduce unproductive times.

The potential of cost savings is high. Derived objectives for terminal equipment are related to the efficient use of equipment as well as the synchronisation of horizontal transports. Furthermore, the focus is clearly on the waterside having priority compared to the landside. Means to achieve the goals are the use of modern equipment for handling containers accompanied by sophisticated planning and scheduling methods as well as the use of information technology and automation.

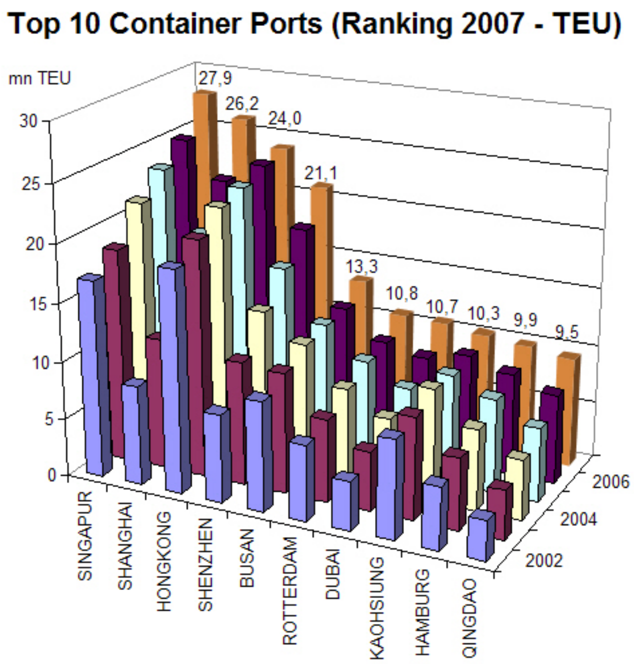
Why is automation of interest? Successful examples can be found in the manufacturing industry which is highly automated. Automation promises, e.g., stable quality, cost savings, etc. Container handling is similar to manufacturing in its repetition of tasks, simplicity of tasks, well-defined physical boundaries or even the unattractive environment for workers (working three shifts, noise, industrial areas, pollution, etc.). Hence, container handling at a terminal indeed seems to be very appropriate for automation. As a matter of fact, examples in our modern real world can be observed, e.g., at the CTA or at Rotterdam. The key to efficiency seems to be the automation of in-yard transportation, storing and stacking. This can help to increase the terminal throughput and to decrease the ship turnaround time at the terminal. This paper focuses on the import/export stock in the yard with its interfaces to the landside transhipment process and the waterside transhipment process (see Figure 3).

Figure 1 Containerisation trend: high growth of container turnover (see online version for colours)



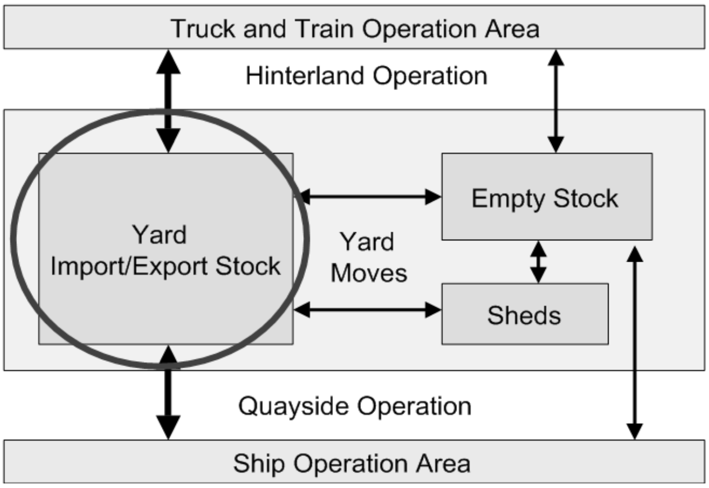
Source: Data retrieved from Volk (2002) and United Nations Conference on Trade and Development (UNCTAD) – Secretariat (2008)

Figure 2 Container turnover of the ten largest seaport terminals in the world from 2002 to 2007 (see online version for colours)



Source: Data retrieved from Port of Hamburg (n.d.)

Figure 3 Operation areas of a maritime container terminal and flow of transports



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

This paper investigates double-rail-mounted gantry cranes (DRMGs) regarding possible impacts on improving a container terminal's efficiency. A simulation study is conducted for evaluating different online algorithms for sequencing and scheduling of automated DRMGs serving a terminal's storage block. The experiments are based upon scenarios that are derived from the CTA in order to investigate advantages as well as problems and limits of our algorithms and the specific crane systems. Furthermore, the influence of the horizontal transport at the block's interfaces is examined.

The paper is organised as follows. We present gantry cranes serving a storage block in the yard and discuss related literature in order to show the research deficit. Then, we propose solution methods for our scheduling approach within a simulation experiment. We discuss our calculation of crane movements with and without taking crane interferences into account. We present our simulation setup and discuss our results. Finally, we provide a conclusion and outlook for further research.

2 Gantry cranes processes in a storage block

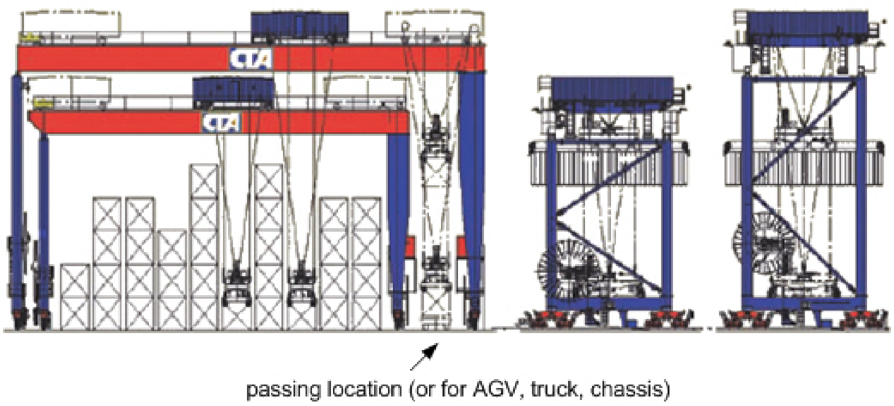
We focus on the storage of containers in a yard block and stacking operations performed by gantry cranes. We refer to Steenken et al. (2004), Henesey (2004, 2006) and Stahlbock and Voß (2008) for a detailed description of the equipment and the processes at a maritime container terminal as well as for a very comprehensive literature survey with respect to container logistics with focus on container terminals.

2.1 Gantry crane systems

Each storage block in a container yard has a specified number of bays, rows and tiers. In each block either man-driven vehicles such as straddle carriers or cranes are responsible for the storage and retrieval of containers into and out of the block. Three types of cranes are commonly known: rubber-tyred gantry cranes (RTGs), rail-mounted gantry cranes (RMGs) and automated stacking cranes (ASCs).

An RTG moves on rubber tyres. It provides flexibility since it is able to move between blocks and react on different situations of workload among the blocks. An RMG moves on rail tracks that are installed along a block. Therefore, an RMG is not able to move between different blocks. An ASC is similar to an RMG. Additionally, it is fully automated in all of its operations and works without the assistance of a driver. Thus, an ASC may be called automated RMG, too. To improve block operations, there are many ports using two cranes in each block instead of just one single crane. In most of these cases, the two cranes are of the same size and type. Therefore, they are unable to cross each other (e.g., twin RMG). Sharing railways results in crane interferences. Thus, a common approach is to distinguish between a waterside and a landside working area with a buffer zone (handshake area) in between. This requires some containers to be handled twice. Two cranes of different heights serving the same block (DRMG, cross-over twin RMG) are more flexible since they both can serve the landside and the waterside. Moreover, there are obvious advantages regarding reachability of containers in case of maintenance of the cranes. Avoiding a handshake area may result in a slightly higher productivity of the entire system. A DRMG is either man-driven or (semi)automatic. At the CTA, it spans up to ten rows and allows for stacking up to a height of four to five containers. The technical performance of one crane is approximately 20 moves per hour. The newest development [e.g., planned for the renovated Terminal Burchardkai (Hamburg, Germany) in 2012] are triple RMGs with two cranes of the same height (twin RMG) and one higher crane able to crossover both smaller cranes. A schematic view of a DRMG is shown in Figure 4.

Figure 4 Schematic view of a DRMG at the CTA (see online version for colours)



Source: Koch (2004, p.632)

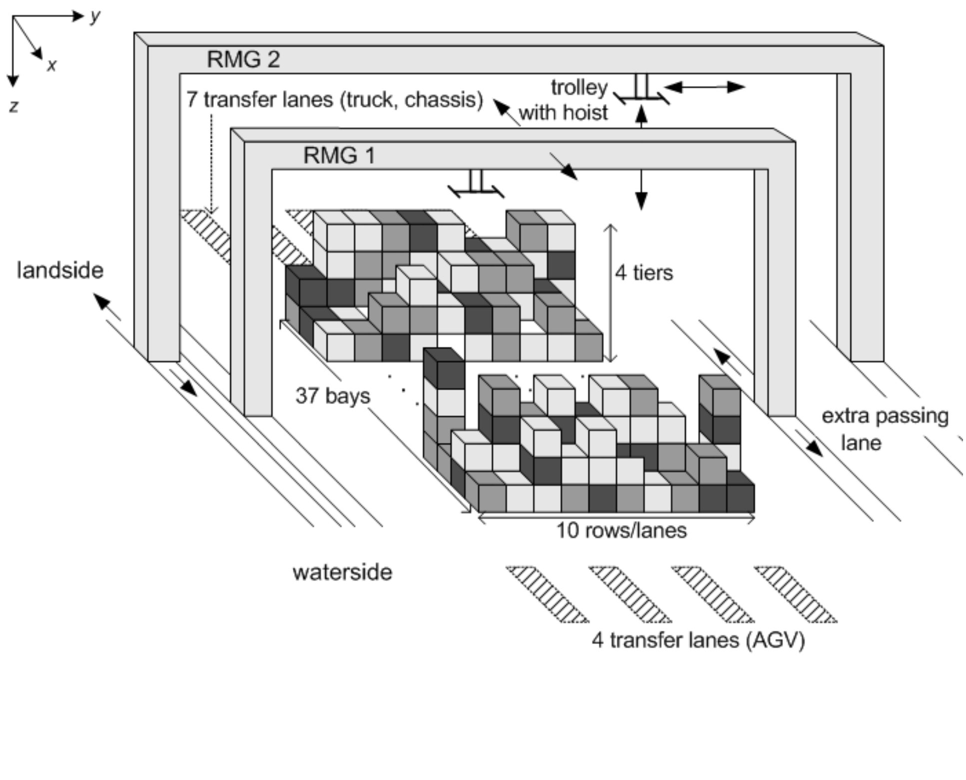
The main technical data for a DRMG are for the outer large crane and the inner small crane, respectively [see, e.g., Koch, (2004), p.633]: width 40 m/31 m, height 27 m/22 m, lift height 21.5 m/15.5 m, weight ≈310 tons/≈250 tons, maximum lifting capacity 42 tons, driving speed 3.0 m/s, trolley speed 1.0 m/s and hoisting speed (loaded) 1.5 m/s.

2.2 Block system and block layout

In this paper, we focus on one block that is served by a DRMG. We consider a semiautomatic DRMG (installed at the CTA), i.e., only the movements of the very last metres during pick up/delivery from/to a truck at the landside are manually operated via remote control due to safety reasons. For our purposes, a block includes handshaking areas at the waterside and landside. At the waterside, particular lanes are reserved for parking automated guided vehicles (AGVs) that transport containers to/from the bay and ship. At the landside, containers are passed to/from trucks or chassis from/to the gantry crane. Those lanes can be regarded as system borders. For simplicity (but without loss of generality), we assume for our research that the block is designed for stacking 20 ft or 40 ft standard containers. Reefers, oversized containers, etc., are not considered. Containers are stacked on the ground of the block area without any chassis. Therefore, a container is not always directly accessible. This sometimes results in the necessity to perform unproductive restacking operations in order to pick up a container which is stored below another container.

A container block has three dimensions. We refer to bays and rows in x- and y-dimension forming a layer of containers and tiers in z-dimension for counting the layers that can be stacked on top of each other. Our block (according to the layout used at the CTA) has ten rows and 37 bays. Therefore, the basic layout consists of 370 positions for 20 ft containers to be stacked. A 40 ft container uses two positions. Furthermore, a block has four tiers. The considered block layout is shown in Figure 5.

Figure 5 Layout of a storage block served by a DRMG



2.3 Processes within the block system

Within a yard block, different processes can be identified. For each process a DRMG has to perform several moves which can be considered as an ordered sequence of steps. While additional tasks may be performed between processing two adjacent steps the sequence of the steps is fixed. The main processes and steps are as follows:

- Import of a container from the waterside:
  1. movement to the pre-parking position at the waterside
  2. synchronisation with the AGV if the AGV has arrived (i.e., movement to the transfer lane and pick up of the container)
  3. movement to the stacking position
  4. delivery (positioning and release) of the container.
- Export of a container to the waterside:
  1. movement to the container that has to be exported
  2. pick up of the container
  3. movement to the pre-parking position at the waterside
  4. synchronisation with the AGV if the AGV has arrived (i.e., movement to the transfer lane and delivery of the container).
- Import of a container from the landside:
  1. movement to the pre-parking position at the landside
  2. synchronisation with the truck if the truck has arrived (i.e., movement to the transfer lane and pick up of the container)
  3. movement to the stacking position
  4. delivery (positioning and release) of the container.
- Export of a container to the landside:
  1. movement to the container that has to be exported
  2. pick up of the container
  3. movement to the pre-parking position at the landside
  4. synchronisation with the truck if the truck has arrived (i.e., movement to the transfer lane and delivery of the container).
- Restacking operation, i.e., a pick up and delivery of the same container within one block:
  1. movement to the container that has to be restacked
  2. pick up of the container
  3. movement to the container's target position within the block
  4. delivery of the container.

- Crane's movement into its parking position:
  1. movement of the spreader/hoist to the top position (highest z-position)
  2. movement of the trolley to its parking position
  3. movement of the crane to its specific parking bay (defined by the parking position's logical address).

While all the above mentioned processes include crane operations, the first four processes incorporate additional vehicles for horizontal transport. Thus, a synchronisation between crane operations and vehicles at the interface lane becomes necessary. Assignments or reservations of a container's block position as well as the vehicle coordination in order to be at the expected lane at the expected time are controlled by a central system. The state of the system is time dependent since the behaviour of all components and therefore their states are highly interdependent. This dynamic cybernetic system is complex due to its very large number of different system states.

Jobs cannot only be distinguished with respect to the direction of the container movement but also with respect to their load. Therefore, a crane can perform an empty travel, that usually is performed in order to pick up a container and a loaded travel with a container already picked up.

Jobs have a target time defining the time for a container to be at a specific transfer lane. We refer to the planned time or real time when a transfer is performed as performance time. In case of an import job, this is the start time of the loaded travel. For an export job, this is the end of the job. For a restacking job, we define this time according to the start of the loaded travel. The target time for a restacking job is the time of the following job (i.e., the export of the container below the container to be restacked). If necessary, a predefined period of time is subtracted. An earliness or tardiness refers to the difference between a job's performance time and its target time.

Jobs are assigned to cranes indirectly by a sequencing component (called sequencer) of the control system. The sequencer is not able to directly control crane actions. That is, after the sequencer has transmitted a job to a specific crane, the crane performs its job autonomously. The performance of the DRMG is only influenced by the sequence of jobs resulting in a particular sequence of movements of both cranes. A sequence can be disadvantageous or advantageous. For example, a particular sequence can result in a high number of empty travels or unproductive times due to crane inferences or it can result in fluent work with many productive moves and double cycles. Double cycles depict a combined export and import transfer at one end of a storage block assigned to one crane. In theory, preferring double cycles or penalising non-double cycles saves or shortens the time for empty runs and shall increase the productivity of a block.

2.4 Related literature

While the problem of scheduling single yard cranes and RTGs is discussed in several papers the problem of handling DRMGs is hardly addressed in literature. In this section, we present a brief overview of related work. There are papers on single gantry cranes, for exporting containers, for RTGs, for single RMGs, twin RMGs, and DRMGs.

Kim and Kim (1997) present an algorithm for routing a single gantry crane loading export containers out of the stack onto waiting vehicles. The objective is to minimise the crane's total transfer time including set-up and travel times. The model's solution determines the sequence of bay visits for pick up operations and the number of containers to be picked up at each bay simultaneously. It is stated that the developed algorithm is 'efficient' and shows solutions to problems of practical size 'within seconds'. In a more detailed paper, Kim and Kim (1999) use the same algorithm for solving the mixed integer program of a 'practical problem of a moderate size'. The load sequence of individual containers within a specific bay remains undetermined. Kim and Kim (2003) extend their problem shown in Kim and Kim (1997, 1999) to general yard-side equipment, such as gantry cranes or straddle carriers. Numerical experiments show that the proposed beam search algorithm outperforms a genetic algorithm. The pick up sequence for individual containers in a bay remains undetermined as in Kim and Kim (1999).

Lin (2000) as well as Chung et al. (2002) focus on the scheduling of RTGs among different blocks.

Narasimhan and Palekar (2002) consider the minimisation of a single yard gantry crane's handling time for executing a given load plan with a given bay plan for export containers. A mathematical programming formulation is provided. An exact branch-and-bound-based algorithm and a heuristic method are developed and tested by computational experiments on randomly generated problem instances. It is shown that the algorithm is practical for solving large size problems. Furthermore, it is proven that the single transtainer routing problem is $\mathcal{NP}$-hard.

Liu and Ioannou (2002) present a simulation approach for operations of an automated terminal. They aim at a comparison of four different concepts:

1 AGV/single RMG

2 conveyance system/single RMG

3 overhead grid rail/AGV

4 rack/AGV in terms of performance and costs.

The results show that automation could improve the performance of conventional terminals substantially at a considerable lower cost. It turns out that the AGV/RMG-system is the most cost-effective one.

Kim et al. (2002) present a simulation study on operation rules for automated container yards. In particular, they investigate container stacking rules as well as operational rules of DRMGs in an AGV-based system with AGVs driving in an extra lane of the large crane beside the block. They aim at testing two sequencing rules [first-in-first-out (FIFO) rule and minimum empty travel distance rule] and two crane dispatching rules with and without differentiating the two cranes based upon their capabilities.

Zhang et al. (2002), Linn et al. (2003) and Murty et al. (2005) consider the deployment of RTGs between blocks with one or two RTGs per block.

Ng (2005) deals with the problem of scheduling of multiple yard cranes to perform a given set of jobs with different ready times. The cranes share only a single bidirectional travelling lane in a yard zone. That is, the paper is focused on the concept of twin RMGs, not on DRMGs. Ng and Mak (2005a, 2005b) consider problems of scheduling a single yard crane.

Zyngiridis (2005) proposes approaches for optimising container movements using one and two automated stacking cranes (RMGs) in a single block.

Bohrer (2005) is focused on crane scheduling in container terminals, but his research only considers RTGs and (single) RMGs and no DRMGs.

Saanen and Valkengoed (2005) present a comparison of single RMG, twin RMG and DRMG. Different stacking alternatives are evaluated by means of simulation in terms of throughput, flexibility, complexity, operational costs and investment costs. Overall, the DRMG appears to be the best performing one but it needs the largest amount of space. Saanen (n.d.) compares twin RMG, DRMG and triple RMG. Overall, his results show that the twin RMG is the best performing one, at least when the storage capacity is taken into account. Per stack module, the triple RMG is the most productive one.

Lee et al. (2007) present an approach for the scheduling of two RTGs serving the loading operations of one quay crane at two different container blocks. It is similar to Cao et al. (2008), a paper by the same group of authors that had been submitted in 2005 but published later in 2008. Here, deployment strategies of DRMG systems for loading outbound containers in traditional yard truck-based terminals (without AGVs) are proposed. The authors present an integer programming model and a greedy heuristic, a simulated annealing (SA) approach and a combined DRMG scheduling heuristic for solving the problem.

Yang and Gen (2008) propose an approach based upon using genetic algorithms for scheduling a single yard crane in each block.

It can be resumed, that there are obviously some papers focusing on yard cranes. But only a few papers deal with the particular DRMGs. To the best of our knowledge, no systematic optimisation approach can be found in the literature.

3 Problem characteristics and solution methods

In reality, operations of a DRMG are complex. Reasons are, e.g., different speeds of different parts of different RMGs (RMG/bay, trolley/row, hoist/tier, acceleration and deceleration) and different handling times depending on the exact storage position. Furthermore, a prediction of exact entry/exit times of containers is impossible. About 50% of the information are either unknown beforehand or become obsolete (mostly after checking a container). Hence, most of the operations at a container terminal can only be planned shortly before execution. Any change at the terminal regarding devices or jobs may change the data of the planning problem. These online/real-time characteristics require solutions on demand. Therefore, online algorithms have to be developed that are restricted to very short runtime in order to immediately deliver results. Adequate planning and scheduling methods with fast algorithms have to be developed and evaluated by simulation prior to implementation into real systems.

With 11 transfer lanes, 11 jobs plus restacking jobs can emerge at one point in time to be served. An exact solution for 11 jobs cannot be found in sufficient time. A net workload of 30 box/h (i.e., gross workload up to 42 box/h – including necessary relocations) results in a maximum computation time of almost 90 minutes on average without taking changes of data into account. Hence, our approach is to compute a solution if a crane becomes idle after finishing a job. This requires very quick algorithms for delivering a solution within seconds, such as constructive priority rule-based algorithms or quick metaheuristics.

In general, the objectives to be achieved by scheduling DRMGs are, e.g., the minimisation of the remaining unfinished workload at the end of each time period and the minimisation of delays or of empty travels. With respect to DRMGs the following problems have to be solved:

- sequencing of jobs
- assigning jobs to the large/small crane
- considering possible blocking situations of the two cranes when operating in the same area.

Our main objective is to prevent delays in the horizontal transport of waterside import and export containers. This goal can be achieved by minimising the weighted earliness and lateness as well as empty travels. Further objectives are the prevention of unnecessary restacking operations and the maximisation of the productivity (similar to minimising empty travels).

In this section, we present priority rule-based procedures and ways to restrict the problem size by preprocessing problem data in order to use quick algorithms for solving the real-time online DRMG scheduling problem.

3.1 Operational interactions and preprocessing problem data

For the components of the terminal to work properly the transfer operations between areas have to be synchronised. In order to achieve this, time windows are calculated by a superordinate process manager and have to be met as efficiently as possible by the operational components (see Section 4.1). Otherwise the productivity of the system might be affected negatively.

On the other hand, the definition of those time windows or transfer due dates artificially bound the productivity since a container may hardly be transferred earlier than the due date.

3.1.1 Synchronisation with AGVs

For having smooth processes at the waterside, a synchronisation of cranes and AGVs may be more important than adherence to time limits provided by the automated terminal and logistics system (TLS) (see Section 4.1). A good synchronisation minimises waiting times for cranes and AGVs. For synchronisation, predicted arrival times (arrival hints) are used. They are provided by the AGV job managing component and communicated via the TLS. Arrival hints are updated in case of large delays. Ideally, the target times predicted by the TLS are (approximately) equal to arrival hints for AGVs. Potential for optimisation seems to be given by anticipatory assignments of jobs to cranes so that cranes arrive at the block interfaces simultaneously with horizontal transport vehicles. Hence, it has to be guaranteed that the vehicles arrive at the same transfer lane in the announced sequence. Otherwise, deadlock situations can occur. Guaranteeing the sequence is important particularly for import jobs at the waterside since AGVs are assigned to specific jobs. Furthermore, it should be ensured that the difference between the true arrival times of the AGVs and the predicted arrival times are not too large in order to avoid long waiting times for a crane. In case of large differences a job should be assigned only if the transport vehicle has already arrived at the transfer lane.

3.1.2 Eligibility of jobs

The list of all jobs is filtered for reducing the complexity and improving an algorithm's runtime. Jobs to be excluded are results from the structure of the problem (e.g., with respect to preceding jobs) and interaction with systems at the landside or waterside. Therefore, the number of eligible jobs is reduced by taking only jobs with specific attributes into account:

- jobs without preceding (restacking) jobs
- jobs with already executed preceding jobs
- jobs at the landside and waterside and corresponding restacking jobs with respective vehicles that are already in a transfer lane
- jobs at the waterside and corresponding restacking jobs with already communicated arrival hints for corresponding vehicles.

Basically all kinds of jobs with time windows lying quite far ahead may be neglected for the time being. The set of eligible jobs is referred to as J_e in the following.

3.1.3 Restacking problems

Necessary restacking operations can block export movements and result in additional restacking operations. In case of resulting cycles, endless restacking operations can occur. Since the simulation model does not solve this problem, the original problem is modified in order to achieve the full productivity for the cranes. Simple rules are applied on the sequencing level in order to avoid restacking cycles:

- export jobs are only eligible if there are no other jobs with the same start slot
- export jobs are only eligible if there are no other jobs with a target slot that is identical to the export job's start slot
- import jobs are only eligible if there are no other jobs with the same target slot
- import jobs are only eligible if there are no other jobs with a start slot that is identical to the import job's target slot
- an export job has higher priority to a restacking job with the same start slot.

However, more sophisticated approaches for handling restacking problems may be of interest for further experiments.

3.1.4 Multiple slots

An additional approach for gaining better solutions may be the consideration of multiple slots having quality figures for import and restacking jobs. Then, the sequencer can use slots that are worse at first sight with respect to the import or restacking job but that are nearer (i.e., better) with respect to the following job's starting slot. However, some slots have to be reserved for each import and restacking job. Early in the simulation process, this may result in a situation where no more slots are available for reservation. Hence, this approach is omitted in our first experiments. For further experiments, similar approaches with multiple slots may be satisfactory.

3.2 Priority rule-based methods

These methods order the jobs according to a priority rule. Our approach schedules jobs according to the following rules (importance of criteria in descending order):

a earlier target time (i.e., the latest delivery time for the job) first

b higher priority first

c waterside before landside.

The simplest method is a serial scheduling and assignment scheme sorting the complete list of jobs according to a FIFO scheme. The first job of the list (i.e., the most urgent job) is assigned to the next idle crane demanding for a job.

In addition to FIFO, a parallel scheduling and assignment method (PAM) that is time and machine oriented is applied. For each iteration, a point in time for the next sequencing of jobs, that may be planned, is determined. It is the later one of:

1 the time when the next crane is available

2 the starting time of the job that has to be started next with regard to the target time.

So both conditions are fulfilled at that point.

3.3 Simulated annealing

In addition to the priority rule-based methods, the well-established local search-based SA approach is applied to the DRMG problem. SA is a metaheuristic based upon an analogy to the cooling process of materials from liquid to solid state. Depending on the decreasing temperature the acceptance of worse solutions, in order to overcome local optima, becomes more unlikely. SA is proposed in Kirkpatrick et al. (1983) as well as in Černý (1985). A pseudocode for various metaheuristics including SA is provided in Fink and Voß (2002).

For real-time online scheduling, the annealing process has to be kept short (see, e.g., the study of Gutenschwager et al. (2004) for the online scheduling of electric monorail load carriers). A general parameterisation may not be given, since the runtime depends on the simulation speed and the computational power of the scheduling system.

Solutions are represented by vectors $S = \langle S_1, S_2, \ldots, S_n]$ and $C = \langle C_1, C_2, \ldots, C_n]$ with n being the number of jobs. S depicts the sequence in which jobs $S_j \in J_e$ shall be executed whereas C depicts the respective sequence of cranes, i.e., C shows the assignments of a crane $C_j \in M$ to job S_j with $M = \{1, \ldots, m\}$ being the set of cranes and m being the number of RMGs. As minimal moves, we may then apply shifts of single jobs in order to change the sequence marginally as well as switching single crane assignments (see Figure 6).

If jobs have to fulfil a specific rule of precedence this rule has to be kept by allowing only appropriate job shifts. For example, if job S_j has to be performed after job S_{j-k} and before job S_{j+l} then in one iteration job S_j can only be shifted within the positions $j-k$ and $j+l$: $S = \langle S_1, \ldots, S_{j-k}, \ldots, S_j, \ldots, S_{j+l}, \ldots, S_n|$.

Both vectors S and C for encoding the job sequence and the crane assignments have to be transformed into a schedule for calculating the objective function based upon start and end times of jobs, times for crane movements and idle times of cranes.

Figure 6 Example: representation of solution and minimal moves for SA

Initial solution							
Index:	0	1	2	3	…	$n-1$	
S:	123	122	124	121	…	128	job sequence
C:	2	1	1	2	…	2	crane assignment
Index:	0	1	2	3	…	$n-1$	
S:	123	122	124	121	…	128	
C:	**1**	1	1	2	…	2	switch of a single crane assignment
Index:	0	1	2	3	…	$n-1$	
S:	**122**	**123**	124	121	…	128	marginal change of job sequence by shifting a single job
C:	2	1	1	2	…	2	

3.4 Extended procedures

As described above, a crane assignment is changed by switching an element of vector C. As a simple extension to all methods, we implemented a procedure for a complete enumeration of all 16 combinations of job-to-crane assignments for the four most urgent jobs according to some sorted job list or current solution. Instead of generating numerous solutions by switching crane assignments arbitrarily we reduce the search space by only changing the job sequence and subsequently enumerating the crane assignments for the first jobs. By integration of this approach into the FIFO approach we created an additional serial assignment method (SAM). Since this method dominated the simple PAM in preliminary tests we omitted the simple PAM and used the extended PAM in our final experiments as well as the extended SA.

3.5 Schedule without crane interferences

The calculation of a schedule is based upon the target time for a container handover ted_j. A crane c with $c = 1$ for the inner small crane and $c = 2$ for the outer large crane has to perform the following subtasks in order to fulfil a job:

1 Empty travel (duration a_{jc}). The crane is moving from its current position to the start position of the job.

2 Lift off container (duration u_c).

3 Loaded travel (duration t_{jc}). The crane is moving to the target position of the job.

4 Deliver the container (duration u_c). The numerical value for the handling time u_c of a container is set as a parameter.

The calculations of the times for empty and loaded travels are presented in the following subsections.

3.5.1 Empty travels

The time duration a_{jc} for an empty travel of crane c approaching a starting position of job j results from the distances between the finishing position of the last executed job (or the parking position that has to be estimated) and the starting position of job j as well as of a crane's speed. For keeping the model simple, we assume the rectilinear Manhattan metric, i.e., a crane is performing a movement only in one direction (x: crane on railway, y: trolley, z: hoist/spreader) at a time. The trolley of the large crane $(c = 2)$ should generally move to the passing lane (y-coordinate 20) resulting in a different calculation in the y-direction. For the calculation of a_{jc} we seek an index i as the maximum of a set of possible candidates l where each candidate has to fulfil all of the following three conditions:

1 $S_h = j$

2 $l < h$

3 $C_l = c$, for $h = 1, \dots, n$.

Thus, the calculation of a_{jc} is as follows (with four tiers used for stacking, i.e., the z-coordinate of the passing tier is 5):

$$a_{jc} = \begin{cases} \dfrac{d^x(e_{S_i}^x, i_j^x)}{v_-^x} + \dfrac{d^y(e_{S_i}^y, i_j^y)}{v_-^y} + \dfrac{d^z(e_{S_i}^z, 5)}{v_-^z} & \text{if } c = 1, \\ \dfrac{d^x(e_{S_i}^x, i_j^x)}{v_-^x} + \dfrac{d^y(e_{S_i}^y, 20)}{v_-^y} + \dfrac{d^y(20, i_j^y)}{v_-^y} + \dfrac{d^z(e_{S_i}^z, 5)}{v_-^z} & \text{if } c = 2, \end{cases} \tag{1}$$

with $i = \max\{l | S_h = j \wedge l < h \wedge C_l = c\}$, for $h = 1, \dots, n$,

i_j^x, i_j^y, i_j^z coordinates (x, y, z) of starting position of job j

e_j^x, e_j^y, e_j^z coordinates (x, y, z) of target position of job j

$d^x(x_1, x_2)$ distance in x-direction

$d^y(y_1, y_2)$ distance in y-direction

$d^z(z_1, z_2)$ distance in z-direction

v_-^x speed of crane in x-direction, without load

v_-^y speed of trolley in y-direction, without load

v_-^z speed of hoist in z-direction, without load.

3.5.2 Loaded travels

The time duration t_{jc} for loaded transport travels can be calculated similarly by taking pick up and delivery positions and speeds into account:

$$t_{jc} = \begin{cases} \dfrac{d^x(i_j^x, e_j^x)}{v_+^x} + \dfrac{d^y(i_j^y, e_j^y)}{v_+^y} + \dfrac{d^z(5, e_j^z)}{v_+^z} & \text{if } c = 1, \\ \dfrac{d^x(i_j^x, e_j^x)}{v_+^x} + \dfrac{d^y(i_j^y, 20)}{v_+^y} + \dfrac{d^y(20, e_j^y)}{v_+^y} + \dfrac{d^z(5, e_j^z)}{v_+^z} & \text{if } c = 2, \end{cases} \tag{2}$$

with

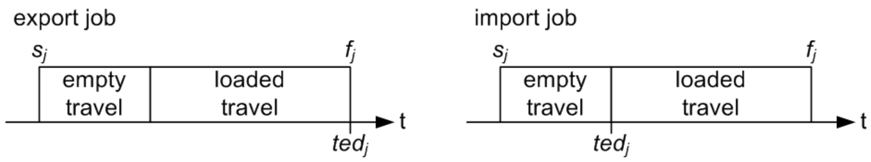
v_+^x speed of crane in x-direction, with load

v_+^y speed of trolley in y-direction, with load

v_+^z speed of hoist in z-direction, with load.

For export jobs, the target time for a container handover ted_j relates to the time f_{jc} of finishing job j (end of loaded travel). For import and restacking jobs, the target time refers to the time of finishing the empty approach travel (starting the loaded travel). This concept is displayed in Figure 7.

Figure 7 Concept of target time for a container handover ted_j for export and import jobs



Thus, the starting time s_{jc} and finishing time f_{jc} are calculated as follows:

$$s_{jc} = \begin{cases} ted_j - a_{jc} & \text{if } twr_j = 0, \\ ted_j - t_{jc} - \dfrac{d^z(i_j^z, 5)}{v_+^z} - u_c - a_{jc} & \text{if } twr_j = 1, \end{cases} \tag{3}$$

with

u_c processing time for pick up/release of a container

ted_j planned time for handover container of job j (target time)

twr_j time window reference, i.e., reference to point in time for the handover

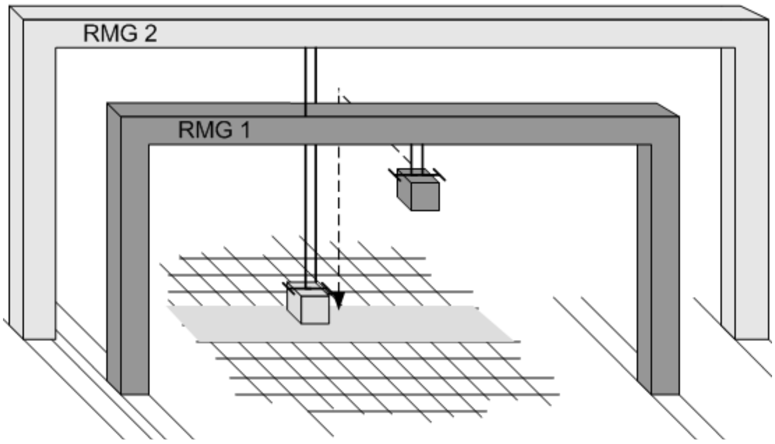
$$twr_j = \begin{cases} 0 & \text{if } ted_j \text{ is referencing the start of a transport (import, restacking),} \\ 1 & \text{if } ted_j \text{ is referencing the end of a transport (export),} \end{cases}$$

and

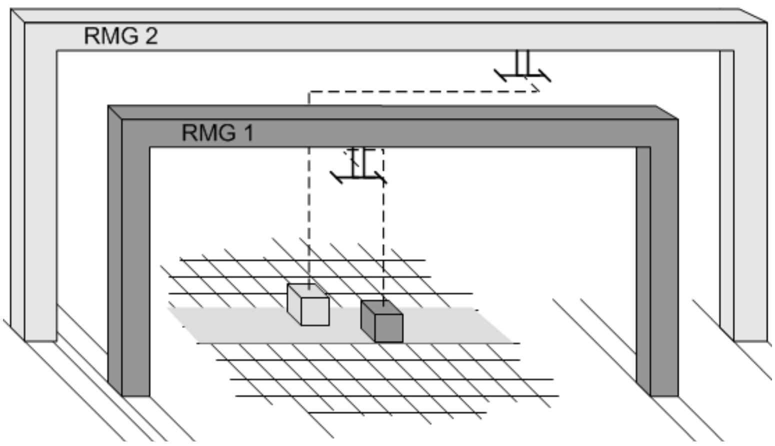
$$f_{jc}=\begin{cases} ted_j+u_c+\dfrac{d^z(i_j^z,5)}{v_+^z}+t_{jc} & \text{if } twr_j=0,\\ ted_j & \text{if } twr_j=1.\end{cases} \tag{4}$$

If the crane is available later than s_j the start and finishing times have to be shifted by this time difference, resulting in $s'_{jc}=s_{jc}+\max\{0,f'_{ic}-s_{jc}\}$ and $f'_{jc}=f_{jc}+\max\{0,f'_{ic}-s_{jc}\}$ with $i=\max\{l|S_h=j\wedge l<h\wedge C_l=c\}$, for $h=1,\dots,n$.

Figure 8 Crane interferences – delay due to blocking situation



(a) trolley of large crane is located in storage area of small crane



(b) both cranes working in nearby bays (within safety clearance)

3.6 Crane interferences

The specific problems of a DRMG in comparison to a single crane or even to twin RMGs are interferences of both cranes. These interferences will occur if both cranes have to operate at the same bay (or at two nearby bays within a safety clearance) at the same time. Furthermore, the cranes will be blocked if the trolley of the larger crane is positioned above the block (i.e., not in the particular parking position beside the block) since then both cranes cannot cross each other (see Figure 8).

In order to calculate the movements of the cranes as exactly as possible it is helpful to calculate possible interferences in advance and consider resulting time shifts (delays, retarding). Therefore, exact times for the work of a trolley/hoist in a bay have to be taken into account. We calculate an empty travel along the block for performing job j with crane c as follows:

$$a_{jc}^{x} = \frac{d^{x}(e_{S_i}^{x}, i_j^{x})}{v_{-}^{x}} \tag{5}$$

with $i = \max\{1|S_h = j \wedge l < h \wedge C_l = c\}, h = 1,\ldots,n.$

Thus, the other crane is potentially blocked after an empty travel at the time $b_{jc}^{a} = s'_{jc} + a_{jc}^{x}$. The duration of that blocking is the crane's time at the corresponding bay (duration of empty travel in yz-direction). It can be calculated by:

$$a_{jc}^{yz} = \begin{cases} \dfrac{d^{y}(e_{S_i}^{y}, i_j^{y})}{v_{-}^{y}} + 2 \cdot \dfrac{d^{z}(e_{S_i}^{z}, i_j^{z})}{v_{-}^{z}} + u_c & \text{if } c = 1, \\ \dfrac{d^{y}(e_{S_i}^{y}, 20)}{v_{-}^{y}} + \dfrac{d^{y}(20, i_j^{y})}{v_{-}^{y}} + 2 \cdot \dfrac{d^{z}(e_{S_i}^{z}, i_j^{z})}{v_{-}^{z}} + u_c & \text{if } c = 2, \end{cases} \tag{6}$$

with $i = \max\{l|S_h = j \wedge l < h \wedge C_l = c\}$, for $h = 1,\ldots,n.$

A blocking situation can occur after a loaded travel along the block, too. The travel takes the time $t_j^{x} = \frac{d^{x}(i_j^{x}, e_j^{x})}{v_{+}^{x}}$. Hence, the start of the blocking can be calculated by $b'_{jc} = b_{jc}^{a} + a_{jc}^{yz} + u_c + t_j^{x}$. The duration of that blocking is the time the trolley is in the bay:

$$t_{jc}^{yz}(j) = \begin{cases} \dfrac{d^{y}(i_j^{y}, e_j^{y})}{v_{+}^{y}} + 2 \cdot \dfrac{d^{z}(i_j^{z}, e_j^{z})}{v_{+}^{z}} + u_c & \text{if } c = 1, \\ \dfrac{d^{y}(i_j^{y}, 20)}{v_{+}^{y}} + \dfrac{d^{y}(20, e_j^{y})}{v_{+}^{y}} + 2 \cdot \dfrac{d^{z}(i_j^{z}, e_j^{z})}{v_{+}^{z}} + u_c & \text{if } c = 2. \end{cases} \tag{7}$$

A blocking situation shown in Figure 8(a) can occur in the intervals $[b_{k2}^{a}, b_{k2}^{a} + a_{k2}^{yz}]$ with j being the current job of the small crane $(c = 1)$ and k being the current job of the outer large crane $(c = 2)$. If one of the interval boundaries is within the time interval for an empty or loaded travel with respect to the current job of the small crane, the small crane will be delayed by the time of this overlapping. A blocking situation shown in

Figure 8(b) occurs when containers in the same area (±15 m safety clearance) are served simultaneously. This is the case when the following equations are satisfied:

- $i_j \pm 15$ m $= i_k \pm 15$ m

  If $[b_{j1}^a, b_{j1}^a + a_{j1}^{yz}]$ and $[b_{k2}^a, b_{k2}^a + a_{k2}^{yz}]$ are overlapping the job with the crane driving later into the bay will be retarded:

  - $b_{j1}^a > b_{k2}^a \Rightarrow$ retard crane 1/job j
  - $b_{k2}^a > b_{j1}^a \Rightarrow$ retard crane 2/job k.

- $i_j \pm 15$ m $= e_k \pm 15$ m

  If $[b_{k1}^a, b_{k1}^a + a_{k1}^{yz}]$ and $[b_{k1}^t, b_{k1}^t + t_{k1}^{yz}]$ are overlapping the job with the crane driving later into the bay will be retarded.

- $e_j \pm 15$ m $= i_k \pm 15$ m

  If $[b_{k2}^t, b_{k2}^t + t_{k2}^{yz}]$ and $[b_{k2}^a, b_{k2}^a + a_{k2}^{yz}]$ are overlapping the job with the crane driving later into the bay will be retarded.

- $e_j \pm 15$ m $= e_k \pm 15$ m

  If $[b_{k1}^t, b_{k1}^t + t_{k1}^{yz}]$ and $[b_{k2}^t, b_{k2}^t + t_{k2}^{yz}]$ are overlapping the job with the crane driving later into the bay will be retarded.

The duration of retarding equals the duration of interval overlapping.

3.7 Earliness and lateness

The sequencer component calculates deviations from target times, i.e., earliness and lateness, based upon calculated starting and finishing times by taking calculated processing times into account. Lateness is given by $l_{jc}^{+} = \max\{0, f_j - ted_j - twr_j \cdot t_{jc}\}$ while earliness is calculated by $l_{jc}^{-} = \max\{0, ted_j - f_j - twr_j \cdot t_{jc}\}$. Since the optimisation aims at synchronisation with AGVs the arrival hints for AGVs are considered as point in time for the handover instead of ted_j communicated by the process manager (see Section 4.1).

3.8 Objective function

There are two complementary objectives to be achieved. First of all the yard cranes should be synchronised with the corresponding vehicles arriving at the transfer areas. For this purpose, time windows are defined for the transfer of containers at the block ends. For restacking operations this is done for the start of a restacking process. Secondly, the productivity of a block has to be maximised. This objective may also be formulated as minimising the duration of empty travels of the cranes. It is obvious that meeting these time windows results in a lower bound for the block productivity although the synchronisation promotes less waiting times at block ends and thus the terminal's overall productivity. The mathematical formulation of these objectives is as follows:

$$\text{Minimise} \sum_{j \in S} \left(\alpha_1 \cdot l_j^{+\beta_1} + \alpha_2 \cdot l_j^{-\beta_2} + \gamma \cdot a_{jc} \right) \tag{8}$$

The synchronisation is supported by minimisation of earliness l_j^- and lateness l_j^+ of jobs according to their time windows. The last term ensures the minimisation of the duration a_{jc} of empty crane movements. The parameters α_1, α_2 and γ are weights for each component. The weights β_1 and β_2 allow for control of the trade-off between a single large delay/earliness versus several small time differences.

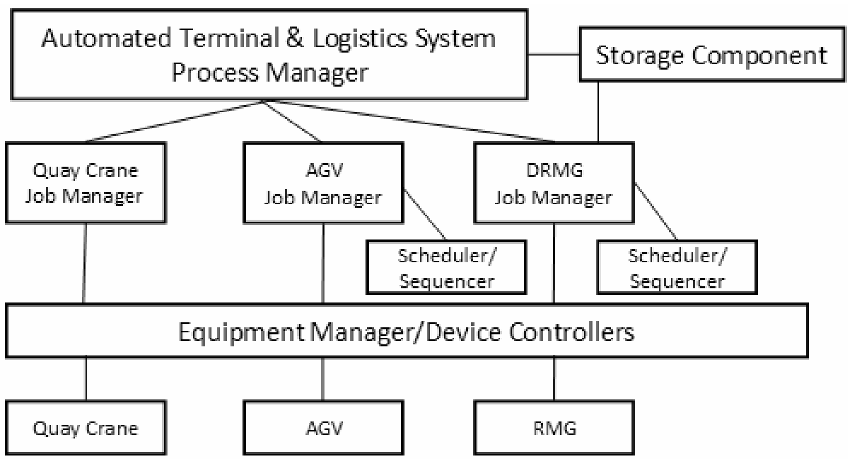
4 Simulation experiment

Data of the DRMG scheduling problem continuously changes over time. Therefore, a classical offline approach might solve a problem instance according to the currently known jobs exactly. But ex post the solution might turn out not to be optimal, if all data were known beforehand. For investigating this it is common to develop a simulation model of a facility and test algorithms more realistically for the online situation. In this regard, online algorithms have to be adapted to suit the needs of the changing data. In this section, we present the setup of the simulation model and results of the conducted simulation study.

4.1 Simulation model, architecture and implementation

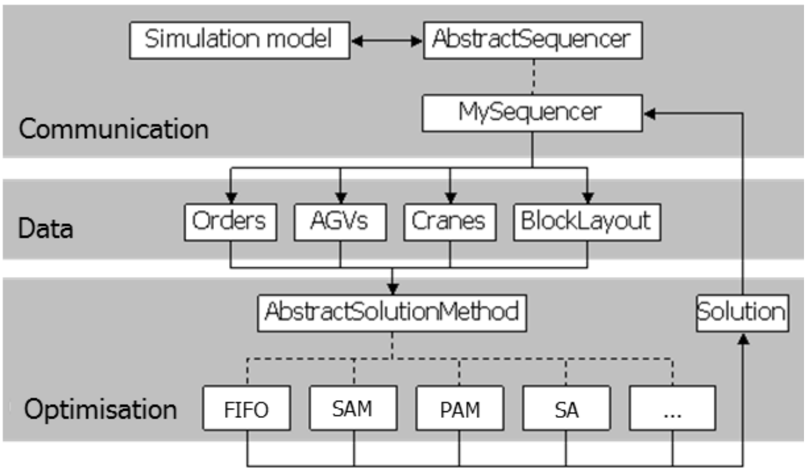
The simulation model is implemented with Tecnomatix eM-Plant and Java. It depicts one stacking block only. In order to map the real system, important components are built into the model as far as needed. Superordinate and adjacent systems within an automated TLS are shown in Figure 9.

Figure 9 Architecture of an automated container terminal system



The process manager is a superordinate component which synchronises the quay cranes, the AGV area and the storage area of the terminal by distribution of jobs. This is basically done by using scenario files that contain all important data for each container move in order to perform the scheduling, e.g., the source and destination location and the due date. Furthermore, a storage component handles and keeps track of storage allocations, which completes the functionality on the highest planning layer. The scheduling information produced by the process manager is distributed to the operational components, which in this particular case is the task manager of the storage block. The arrival time of trucks and trailers (serving the railway) on the landside as well as the AGVs on the waterside are stochastically altered in order to adopt the fluctuations of the real system. Afterwards the data is passed through an interface to the scheduling component (sequencer) of the storage block, which does the operational scheduling autonomously and returns the result whenever a resource is becoming idle and jobs have still to be processed. The result is forwarded to the execution layer by the task manager and the task is being dispatched. For the sequencer component different algorithms are implemented in Java. The coupling is done according to the real system via TCP/IP. The architecture of the sequencer component and the link to the simulation model are shown in Figure 10.

Figure 10 Architecture of the simulation system



All algorithms are derived from the abstract sequencer class allowing an easy exchange of solution methods. The solution class encapsulates all methods to generate and alter solutions. All data is held in the data layer in order to accelerate and link data objects, such as AGVs, jobs, block layout data and crane velocities.

4.2 Setup

Two different objectives are analysed in this study. The first is the quality of synchronisation of a storage block and the horizontal transport depending on the average load. The second is the maximum productivity of one storage block that can be achieved permanently. This is done by approaching the limit of productivity in the margin workload levels (33–36 box/h).

For the study on synchronisation the following setup is chosen:

- Different average loads of 20, 25 and 30 jobs per hour are simulated. These loads are to be understood as the net throughput of a block without restacking jobs.
- Five scenarios with two different random seeds are used.
- Simulation runs are terminated when a total number of 2,000 jobs is reached. This allows for comparability among the simulation runs.
- The container block is prefilled before the simulation run starts.
- The setup is oriented at the real configuration at the CTA. The real block layout as well as the technical data of cranes are simulated (see Section 2).

The methods FIFO, SAM, PAM and SA are analysed. For the analysis of the marginal productivity only SAM and SA are applied due to preliminary results. Two runs per load level are performed summing up to eight runs per method.

The initial solution for the SA is generated by SAM. The SA control parameters are set as follows based upon appropriate and promising results of preliminary experiments taking our simulation and scheduling system into account:

- initial temperature: 10
- cooling rate: 0.95 (commonly used exponential temperature schedule with $\text{Temperature}_{t+1} = \text{Temperature}_t \cdot 0.95$)
- stopping temperature: 2.

The weights α_1, α_2 and γ in the objective function [see equation (8)] are set to 1 so that earliness, lateness and the duration of empty crane movements are weighted equally. The weights β_1 and β_2 are set to 1 as well so that several arrivals with each having a small time difference have the same influence as a single large delay or earliness. The simulation system is configured so that computation times for the simulations are 60 times faster compared to the real world (on a personal computer with 2GB RAM and an Intel Xeon® CPU, 3.2 GHz). That is, as an example, one second of computation time simulates one minute of the real environment. This allows for a proper trade-off between running times and utilisation of appropriately defined parameters in the SA (see, e.g., Gutenschwager et al., 2004).

4.3 Results

In this subsection, the results for the synchronisation analysis are presented with respect to:

- lateness with respect to horizontal transport
- restacking ratio
- double cycles
- empty travels.

Furthermore, the results with respect to the maximum productivity are presented.

4.3.1 Lateness with respect to horizontal transport

The lateness with respect to horizontal transport denotes a job's timewise deviation from the best possible processing time for a transfer, e.g., from entering the system until storage is completed for import transfers and for export transfers vice versa.

The average delays in total and for the waterside as well as for the landside are presented in Table 1 for different scenarios. Up to a load of 25 box/h the results do not deviate significantly. The deviations are within the scope of stochastic fluctuations of modelling.

Table 1 Performance (average delay in seconds) with different loads and 2,000 jobs

Load (box/h)	*Indicator (sec)*	*FIFO*	*SAM*	*PAM*	*SA*
20	Average delay total	25	23	24	24
	Average delay landside	9	7	8	9
	Average delay waterside	35	32	34	33
25	Average delay total	39	35	35	36
	Average delay landside	16	13	13	16
	Average delay waterside	54	48	49	48
30	Average delay total	256	69	88	*62*
	Average delay landside	346	*31*	45	36
	Average delay waterside	195	93	115	*79*

For a load of 30 box/h, Table 1 shows that SAM and SA both outperform PAM. The best results are different with respect to the service at the landside and the waterside. The SA approach yields better results for the waterside whereas SAM provides better services for the landside. The simple procedure FIFO is dominated by all other methods. This procedure considers neither the restacking loops nor the extended crane assignment scheme. Hence, these extensions really start influencing the solution quality from 30 box/h onwards.

4.3.2 Restacking ratio and double cycles

Here we try to investigate the impact of the structure of job sets on the schedule. Therefore, the ratio of unproductive restacking jobs to export transfers and the number of advantageous double cycles are investigated. The results are shown in Table 2. As expected, FIFO generates more restacking jobs than the other methods, since this procedure does not try to avoid unnecessary restacking jobs by any means. Surprisingly, this effect does not bear on the scenarios with a load of 25 box/h. FIFO is excluded from further analysis.

Besides FIFO, all methods try to force double cycles. This is obvious in the results. The SA approach generates the highest number of double cycles. In particular, in the high workload case, more advantageous job pairs are built.

Table 2 Performance (ratio of restacking jobs and export jobs; double cycles) with different loads and 2,000 jobs

Load (box/h)	*Indicator*	*FIFO*	*SAM*	*PAM*	*SA*
20	Ratio restacking/export jobs	0.5896	0.5760	0.5744	0.5740
	Number of double cycles	0	115	120	*128*
25	Ratio restacking/export jobs	0.6478	0.6470	0.6347	0.6386
	Number of double cycles	0	189	181	*220*
30	Ratio restacking/export jobs	*0.8206*	0.7069	0.7035	0.7060
	Number of double cycles	0	239	232	*309*

4.3.3 Empty travels

The empty travel times are presented in Table 3. The table shows the deviation of PAM and SA with respect to the results of SAM.

Table 3 Performance (empty travels) of PAM and SA with different loads and 2,000 jobs

Load (box/h)	*Indicator*	*SAM*	*PAM*	*SA*
20	Duration empty runs – total	0%	–1.85%	*–2.65%*
	Duration empty runs – landside	0%	–2.04%	*–5.03%*
	Duration empty runs – waterside	0%	–1.74%	–1.27%
25	Duration empty runs – total	0%	1.51%	*–3.96%*
	Duration empty runs – landside	0%	3.07%	*–6.64%*
	Duration empty runs – waterside	0%	0.56%	*–2.34%*
30	Duration empty runs – total	0%	1.48%	*–10.36%*
	Duration empty runs – landside	0%	1.32%	*–15.55%*
	Duration empty runs – waterside	0%	1.62%	*–6.81%*

Note: Relative results (difference to SAM)

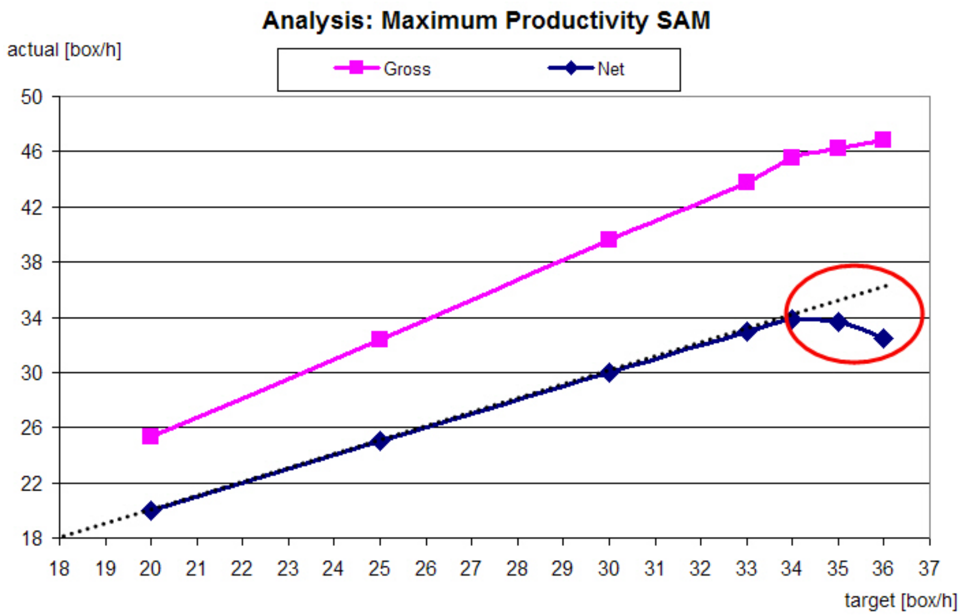
The SA approach generates shorter empty travels than the priority rule-based procedures, particularly in the high workload case. This is due to the objective function used by the metaheuristics since it explicitly tries to minimise the empty run times whereas the priority rule-based procedures do not assist minimisation of empty runs at all.

4.3.4 Maximum productivity

In addition to the synchronisation aspect, the maximum productivity of a DRMG system is of interest. The idea is to consider the difference between the target of the applied workload and the actual productivity resulting from the simulation as an indicator for the maximum productivity. It is assumed that this difference to the productivity will increase with an increasing workload and will start to rise disproportionately high near the maximum productivity. Therefore, the results of a performance test approximating the productivity margin for the best solution methods so far (SAM and SA) are presented. For this analysis, we started with a load of 33 box/h and increased the load continuously until the productivity was falling behind.

In the following two figures, the simulated productivity is plotted against the applied workload. Observations for 20, 25 and 30 box/h are copied from the first study regarding the horizontal transport. The results for SAM are shown in Figure 11. Up to a load of 34 box/h, the productivity hardly differs (maximum difference is 0.195). With increasing load, the productivity is falling below the administered load more and more. With the maximum load of 36 box/h, it is observed that jobs are queuing to an extent so that it is impossible to reserve any storage position for further stacking. Some simulation runs abort.

Figure 11 Maximum productivity SAM (see online version for colours)



For the SA approach, the results are similar, i.e., the performance is stable up to a load of 34 box/h (see Figure 12). With a load of 36 box/h, several simulation runs abort again.

The simulation experiments indicate that an average net productivity of 34 box/h (gross 45.5 box/h, i.e., including restacking operations) may be assured. This is the maximum net productivity that can be achieved on a continuing basis. The highest observed productivity was net 34.4 box/h and gross 47.2 box/h. None of the tested algorithms is able to reach a net productivity of more than 35 box/h.

Finally, the ratio of unproductive reshuffle jobs to export jobs is analysed in order to ensure that the found maximum productivity is not influenced by restacking operations. Obviously, the number of restacking jobs has to increase about proportionally with the increasing load. The result is plotted in Figure 13.

For SAM, the ratio shows a disproportionate rise at 36 box/h. Hence, the problem of restacking operations may influence the result at 36 box/h. For different loads and for SA it seems that restacking is not an issue.

Figure 12 Maximum productivity SA (see online version for colours)

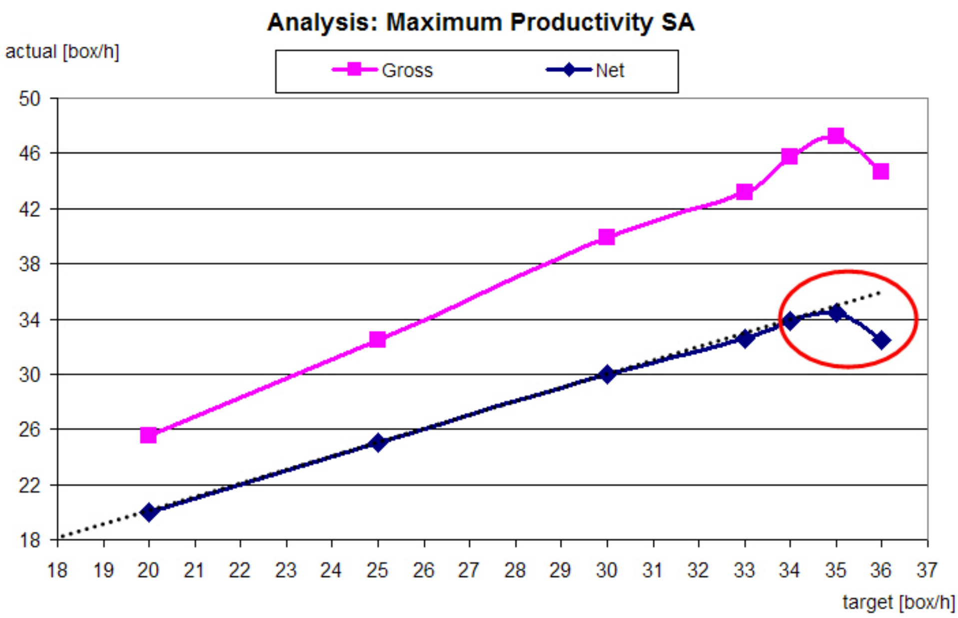


Figure 13 Ratio of restacking jobs and export jobs (see online version for colours)

5 Conclusions and outlook

The simulation experiments show that up to a workload of 25 box/h the results of the proposed algorithms are not significantly different. For high workload, which is the more interesting problem since it reflects problematic real world situations, the SA dominates the priority rule-based heuristics, in particular with respect to the important waterside. Hence, an idea for future experiments is to incorporate a weight into the objective function according to the workload in order to control the trade-off between efficiency and synchronisation with AGVs.

The proposed methods are able to increase the reliability of synchronisation of the horizontal transport. The terminal equipment is used more efficiently. The exact calculation of crane assignments for only four jobs in advance has increased the solution quality significantly. The sequence of jobs is strongly determined by the predefined transfer times for jobs. Switching the crane may imply a sequence change as well. To overcome the disadvantages of a complete enumeration, one may consider designing an efficient exact procedure.

Further research should focus on reshuffles and stacking strategies, accelerating algorithms, exploring the influence of the weights in the objective function, developing a mathematical model (and solution) which can serve at least as a reference model/benchmark, integration of AGVs and an integrated optimisation.

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