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Scheduling of Different Automated Yard Crane Systems at Container Terminals

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Abstract. In this work, different variants of a branch-and-bound procedure for yard crane scheduling at seaport container terminals and their effect on the terminal's performance are studied. In particular, this work investigates the level of detail needed to take the exact crane characteristics, e.g., movements and crane interference, into account in the scheduling algorithm. This is examined for four different automated yard crane systems with one or more cranes that operate on rectangular yard blocks with transfer positions at both ends of the block and with the yard blocks arranged orthogonally to the quay. Using a simulation model with realistic scenario data and an automated guided vehicles system for horizontal transport, the results are compared with respect to different key performance indicators, e.g., yard crane productivity and average lateness of jobs. It turns out that especially the consideration of crane interference leads to significant improvements in yard crane productivity. As a result of the long computation times for some crane systems that render the practical application of the algorithm difficult, an approximation procedure is also developed that generates good results in reasonable time and hence allows for real-time application at a container terminal.

Keywords: container terminal • scheduling • RMG • yard crane • branch-and-bound

1. Introduction

Container terminals form a main link in intercontinental supply chains. Hence, they are highly affected in periods of strong economic growth. Increasing deep-sea vessel sizes have an impact on the terminal, as have strongly growing container flows that have to be handled by the terminal in a limited time period. A similar effect occurs during periods of decreasing or stagnating container flows, as caused, e.g., by the financial crisis: overcapacities on large deep-sea vessels lead to stronger competition between shipping companies and container-shipping rates drop to the economic limit. This competitive pressure also affects container terminals, because guaranteed service times and high vessel handling rates are required. This results in demand for higher berth productivity and leads to greater peak volumes in the storage area of the terminal. Hence, independent of the development of the global economy, there is a requirement for increasing the productivity of container terminals.

Several terminal enhancements, like twin and tandem operations (Saanen and de Waal 2007) or dual-cycle operations (Goodchild and Daganzo 2006) can help to significantly increase quay crane productivity without high investments in new terminal devices (Stahlbock and Voß 2008). Moreover, the capacity of horizontal container transport between the berth and storage area can be adjusted by using additional vehicles. Thus, the container yard that is often operated by automated stacking cranes (Saanen 2004, Saanen and de Waal 2007) most likely becomes the bottleneck of a terminal, because adding additional stacks or cranes to improve yard productivity is—if at all possible—extremely cost intensive. Therefore, high productivity of the existing yard modules is an important objective, and the scheduling of the cranes is a major optimization problem in this context.

In this study, a branch-and-bound algorithm for planning the work schedules of automated yard cranes in a single yard module is presented. This work builds on Speer, John, and Fischer (2011) who present the basic idea of the algorithm and apply it to a double rail mounted gantry crane (DRMG) system, where two yard cranes operate on two rails. In the present work, the approach is extended to the Single rail mounted gantry crane (RMG) and the Twin RMG where one or two cranes work on the same rail, and to the Triple RMG (TRMG) system where three cranes work on two rails.

While Speer, John, and Fischer (2011) focus on avoiding crane interference, in this work all parts of the crane cycle times are considered in the scheduling; e.g., waiting times for horizontal transport and crane synchronization at the transfer positions are taken into account, which is important for DRMG and TRMG. To our knowledge, these aspects have not been integrated into yard crane optimization studies before. As the major new contribution of this paper, the benefits of considering each of these parts of the crane cycle times and the impact on terminal performance and on service times for terminal vehicles and external trucks are analyzed for all four crane systems. Hence, the primary research question is whether taking into account the different parts of crane cycle times has a significant impact on the resulting terminal performance or if the standard assumption of constant cycle times is sufficient. This question is answered by a comprehensive simulation study, using realistic scenarios for a medium-sized container terminal. With this approach, also the impact of considering different levels of detail on the computation times of the branch-and-bound algorithm is evaluated. As short computation times are of high relevance in practice, it is important to judge practical relevance and applicability of the approach. To generate solutions within a limited amount of time, a new heuristic procedure is developed that leads to promising results.

The rest of the paper is organized as follows: The process flow at an automated container terminal, the characteristics of the four crane systems, a formal description of the scheduling problem considered in this work, and the relevant objectives are given in the following section. Section 3 provides a literature overview on yard crane scheduling approaches. In Section 4, the branch-and-bound algorithm for solving the scheduling problem is developed. In Section 5, the simulation model is specified. Section 6 compares the different variants of the optimization procedure for the various crane systems. Section 7 gives a summary of the results and suggestions for future research.

2. Yard Crane Scheduling at Container Terminals

2.1. Process Flow at an Automated Container Terminal

The discharging and loading of deep-sea vessels are usually handled by several quay cranes, which move the containers between the vessel and the quay area of the terminal. Internal transport vehicles—terminal trucks, automated guided vehicles (AGVs), or straddle carriers—carry containers between the quay cranes and the stacking area.

In the case of automated yard blocks, the containers are transferred to a yard crane that moves the containers from the transfer area into the yard block or vice versa. Usually a second transfer area on the opposite side of the yard block is used for handling the landside containers that are normally delivered by rail or external trucks. By these two transfer areas, a separation of terminal-owned and external vehicles is accomplished. The main disadvantage of this design is that many containers pass the whole length of the yard block during their dwell time. This leads to long traveling distances for the RMGs and decreases crane productivity (usually measured in container movements per hour) significantly. To overcome this problem, sometimes two or more cranes operate on the same yard block. Four different RMG systems for single yard blocks exist; these are described in Section 2.2. Other RMG applications, e.g., cranes with sidewise cantilevers, are often used for specially shaped terminals (Johnson 2007) or intermodal facilities (Gutenschwager, Böse, and Voß 2003). These are not considered in this work.

2.2. Different Yard Crane Systems for Automated Container Yards

In Figure 1, four different kinds of automated yard crane systems are shown. Because of the different requirements with respect to block length, width, and the different number of rails, the terminal operator has to choose one of the RMG systems in the planning phase of an automated container terminal. The following characteristics of the four RMG systems have to be taken into account:

- Single RMG: Only one crane operates on the block, which is responsible for the service on both ends of the block. This is a very simple layout, but it is rarely

Figure 1. (Color online) Schematic View of an Automated Container Terminal with Different Yard Crane Systems

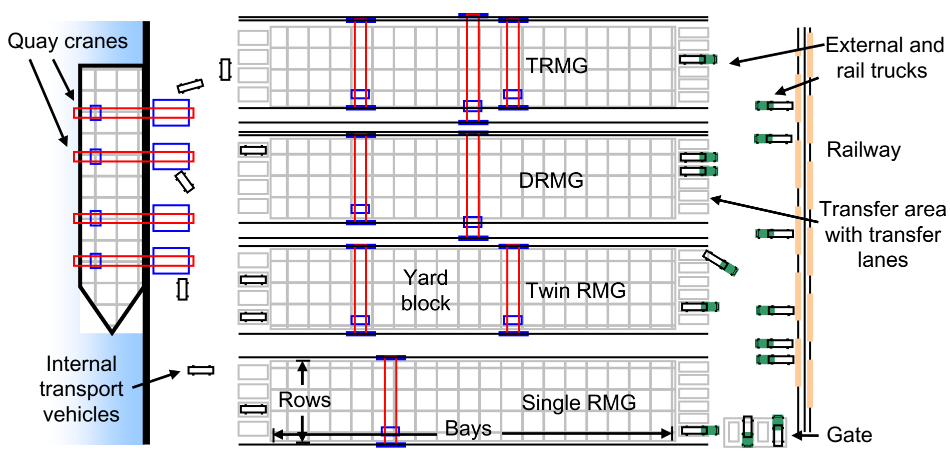
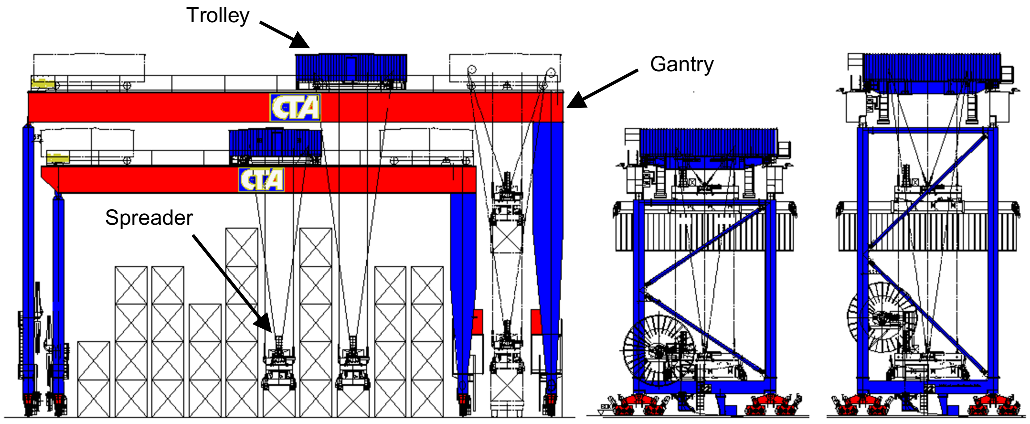


Figure 2. (Color online) DRMG Cranes



Source. HHLA CTA (2011).

used because, when the crane fails, the containers in the respective block are no longer accessible. Actually, Single RMG cranes are only used at the ECT terminal in Rotterdam, Netherlands (Saanen 2004, 2008).

• Twin RMG: Two cranes operate on the same rail; one is responsible for the waterside and the other for the hinterland service. This can increase the number of operations carried out in a block, compared to the Single RMG setting (Gharehgozli et al. 2013). However, the two cranes cannot operate at the same end of the block nor can they pass each other. This is a limitation, especially in peak situations. However, when one crane fails, the other crane can continue the service of the block, after the failed crane has been towed to its maintenance position. Twin RMGs are in use in Portsmouth, Virginia (Kemme 2012).

• DRMG: Two cranes operate in the block, but each crane has its own rail. The cranes are designed in such a way that the large outer crane can pass the smaller inner crane after the trolley with the container has been driven to a sidewise transfer position (see Figure 2). In this way, both cranes can serve the entire block. This arrangement enhances availability of the entire facility, since if one crane fails, service of the affected block is still possible, even if at reduced handling rates. Additionally, both cranes can operate on both sides of the block, reaching higher productivities in peak situations, e.g., when there is no hinterland service at night. Such DRMGs are used at the container terminal Altenwerder (CTA) in Hamburg, Germany (John and Witte 2010). A description of the technical details and parameters for the DRMG system at CTA can be found in Koch (2004). The settings used for the evaluation in Section 6 are similar to these settings.

• TRMG: Three cranes operate in the block. Two smaller cranes operate on the same rail track (similar to the Twin RMG) and a larger crane operates on its own rail (similar to the DRMG). This ensures a high service level in peak situations and also during crane failures. TRMGs are in use at the container terminal Burchardkai (CTB) in Hamburg, Germany (Dorndorf and Schneider 2010, Kemme 2012).

2.3. Description of the Yard Crane Processes

In typical processes at a container terminal, the following types of moves occur for an (automated) RMG system:

• Inbound move: A yard crane picks up a container from a transfer area (e.g., from a transport vehicle or the ground), moves it into the stack, and sets it down at a position in the stack determined by the terminal operating system (TOS).

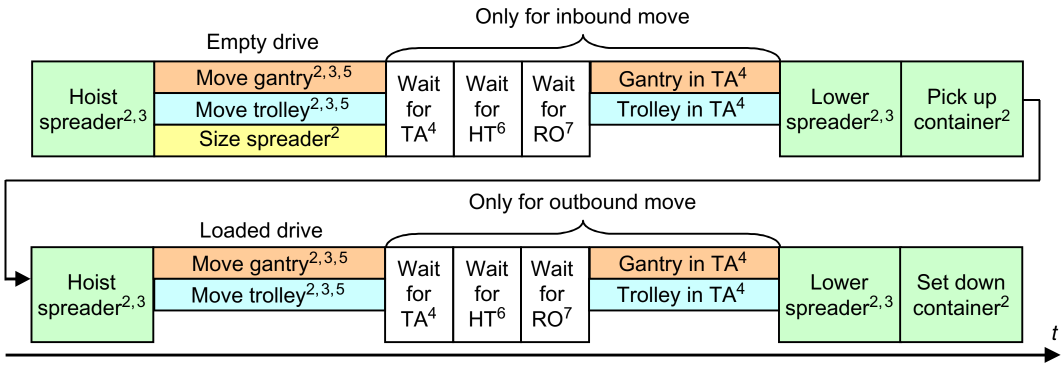
• Outbound move: A yard crane picks up a container in the yard stack, moves it to a transfer area, and sets it down on a transport vehicle or on the ground.

• Reshuffle: For an outbound move, additional reshuffles can occur for the yard crane when the outbound container is not accessible for the crane because one or more containers are stacked on top of it and have to be removed prior to the outbound move. To allow for a higher flexibility in the creation of job sequences, reshuffles are treated as independent moves that can be executed by another crane. In this way, effective cooperation of the cranes becomes possible. Many approaches found in the literature apply a more static assignment of reshuffles (Dell, Royset, and Zyngirdis 2009) but it was shown by Park et al. (2010) that the flexible approach leads to better results.

• Housekeeping move: Housekeeping moves aim to improve the storage position of containers (Kemme 2012, p. 571) so that they can be delivered with a minimum number of reshuffles and short travel times (Van Valkengoed 2004, p. 15). These moves have a lower priority than other moves and are executed during times of low workload (Kemme 2013, Van Valkengoed 2004).

Figure 3 shows the pattern of a typical RMG movement for an inbound or outbound move or a reshuffle, i.e., for one job. The first row shows the empty drive

Figure 3. (Color online) Pattern of a Typical RMG Movement (Cycle Pattern)



while the RMG's loaded drive is pictured in the second row. Apart from the adaptation of the spreader size, the empty and loaded part of the job are performed analogously. A similar movement pattern can be found in Saanen (2004, p. 209), where the resizing of the spreader is not treated as a separate step. Yet, as the resizing can take 20 to 30 seconds, and often takes longer than the gantry drive, especially in situations with short gantry drives between reshuffles or when combining outbound and inbound moves (double cycle), it should be explicitly taken into account. (The superscript numbers indicate the level of detail at which the time consumption for the respective step is considered by the branch-and-bound procedure, see Section 4.2.) In the case of two or more cranes, interference can occur during the movement of the gantry and trolley, and can result in a significantly longer driving time. For an inbound or outbound move, the crane must often stop at a waiting position in front of the transfer area (TA). After some waiting time at this position, travel is continued into the TA to finish the job. The waiting of the crane is necessary when another crane is currently working in the TA; when the horizontal transport vehicle (HT, e.g., the AGV) has not yet arrived and the synchronous transfer cannot take place; or when the assistance of a human remote operator (RO) is necessary (e.g., in the case of external trucks or disturbances).

For the control of the service times and the coordination with loading sequences for quay cranes, a so-called "due date" for each job is determined by the TOS, and a job is called "late" when the set down of the container by the RMG exceeds it.

2.4. Objectives and Problem Definition

In the literature, several different objectives for crane scheduling at container terminals are suggested:

- Maximization of the yard block productivity (Kemme 2011).
- Minimization of the makespan (Briskorn and Angeloudis 2016, Gharehgozli et al. 2013, Vis and Carlo 2010).
- Minimization of service times for external (inbound and outbound) jobs (Steenken, Voß, and Stahlbock 2004).
- Minimization of empty drives of the RMGs (Steenken, Voß, and Stahlbock 2004).
- Minimization of lateness (relative to the due date) (Kemme 2011).
- Minimization of earliness (relative to the due date) (Kemme 2011).

Some of these criteria have a similar effect, whereas others do not agree, e.g., short empty drives often relate to high productivity of the RMGs but may be in conflict with minimization of lateness. For the problem defined next, the following three objectives are used:

1. Minimization of cycle times: total RMG time spent working on jobs.
2. Maximization of external productivity: Minimization of the sum of the estimated times required for job completion, for all external jobs.
3. Minimization of lateness: the delay relative to the due date, squared and summed up for all scheduled jobs.

In the first objective, the duration of empty drives is included, because the empty drives are part of the cycle times (see Figure 3). For an efficient crane operation, the total cycle time must be considered, especially the parts of the cycle time that depend on the assigned crane and the position of the job in the schedule. These are the duration of the loaded drive that is influenced by crane interferences, the waiting times for entering the TA, waiting times for HT, and for ROs. This requires a detailed estimation of all parts of the cycle time which has to be carried out repeatedly for each job during the scheduling. (It should be noted that an explicit minimization of earliness is not necessary in this approach, because earliness of the RMG leads to a waiting time that is measured as part of the cycle time.)

The minimization of the cycle times leads to efficient, and in many cases, energy saving operations of the RMGs. However, the use of cycle times as the only objective turned out to be misleading during this study, particularly for crane systems with more than one crane. In this case, schedules may occur in which only one crane is active and can operate with short empty drives and without any interference or waiting times, but resulting in long waiting times for the vehicles. To avoid these effects, the second objective, the maximization of the external productivity through the minimization of job completion times, is introduced. It turned out that this objective works better than the classical makespan minimization. When a single job cannot be completed for a long time (because of a long waiting time for the HT), fast completion of the other jobs is not assured by makespan minimization, whereas the new objective works properly for these cases that often occur in practical scheduling instances.

The third objective, the minimization of lateness with respect to due date, is necessary, because high external productivity and low cycle times do not guarantee the observance of planned sequences (often presented by due dates). Jobs with long durations tend to be delayed without the third objective, which might result in interruptions of ship loading processes or long waiting times of external trucks. If exceeding of the due dates cannot be avoided, delays should be evenly distributed among the jobs. Therefore, delays are squared, an approach that is also described by Stahlbock and Voß (2010).

Hence, in combination with the second objective, the third objective ensures low and evenly distributed service times for trucks and other means of HT, and all six objectives mentioned at the beginning of this section are directly or indirectly covered by the suggested approach.

Consequently, for the purpose of this work, the *crane scheduling problem* is defined as follows: A set of available cranes C that work in a yard block and a set of jobs J for this block, i.e., for stacking of inbound containers, delivery of outbound containers, additional reshuffles, and housekeeping moves are given. The problem is to find an assignment of the jobs to the cranes and a sequence of jobs for each crane that is feasible according to predecessor relations (e.g., in the case of reshuffles), such that the service times for the vehicles at the transfer lanes and the cycle times of the stacking cranes are as small as possible, and external productivity is maximized.

A mathematical model for this problem can be found in Heitmann (2015).

3. Literature Review

Optimization at container terminals is an important area of research. A good overview is provided by Vis and de Koster (2003), who categorize the optimization problems based on their different decision horizons. A survey of different simulation and optimization approaches for container terminals is found in Chen, Hsu, and Huang (2003). Steenken, Voß, and Stahlbock (2004) give an extensive overview and a widely accepted classification. An update is provided by Stahlbock and Voß (2008), which also contains references for newer technologies like dual cycle operations and an overview of crane scheduling approaches for rubber tired gantries (RTG), Single RMG, Twin RMG, and DRMG.

Carlo, Vis, and Roodbergen (2014) provide a survey of various publications on yard strategies and handling equipment. They give a classification according to various aspects such as the decision problem, yard layout, type of handling equipment, and objective function.

In addition to giving an overview, Kemme (2011) describes the online character of the crane scheduling problem (cf. Grötschel et al. 2001, Steenken, Voß, and Stahlbock 2004), and presents a classification of the different approaches for yard crane scheduling. Petering et al. (2009) compare simulation results for several different priority rules for the yard crane scheduling problem and address many aspects of the online problem, e.g., the importance of arrival information for horizontal traffic and deadlock problems.

3.1. Scheduling of Single RMGs

Single RMGs are rarely used at automated container terminals and therefore little research has been done on this topic. However, many approaches for manually operated RTGs can be found. The scheduling problem for an RTG has similar characteristics as for the RMGs, except for the sidewise container transfer to transport vehicles. Kim and Kim (1997, 1999) were the first who examined this problem and published several studies.

Guo et al. (2011) present an approach for yard crane scheduling, considering RTG blocks parallel to the quay. Similar to the algorithm presented in Section 4, a sequence of jobs for the yard crane is iteratively created and the problem is formulated as a tree search problem. Several search strategies are investigated.

3.2. Scheduling of Twin RMGs

The scheduling problem for Twin RMGs is a special case of the multiple crane scheduling problem. This problem is addressed in several articles (Mak and Sun 2010, Ng 2005, Wu et al. 2015). The main characteristics of the Twin RMG system is that it only allows a transfer at the heads of the block, not at the long sides. This leads to longer travel distances and therefore to more crane interference than in multiple crane systems and to the additional constraint that each crane can only operate on one side of the block.

Choe et al. (2007) and Park et al. (2010) address the scheduling problem for Twin RMGs for a terminal with AGVs on the quayside and external trucks in the hinterland. AGV delay and truck waiting times are used to compare different algorithms for the crane scheduling problem.

Dell, Royset, and Zyngirdis (2009) provide a scheduling approach for RMGs on yard blocks perpendicular to the quay with straddle carriers as transport vehicles. They compare one and two cranes and they also deal with the assignment of storage locations and the scheduling of housekeeping moves. A similar approach is followed by Gharehgozli et al. (2013), who provide an integrated optimization of Twin RMG scheduling and determination of stacking positions for inbound containers, using the makespan as the objective.

3.3. Scheduling of DRMGs

Vis and Carlo (2010) develop a mixed integer linear program for the scheduling of DRMGs and use the makespan as the only objective. They neglect reshuffles and assume that the sequence of jobs has no influence on their duration. The authors develop a heuristic based on simulated annealing. They find that limited crane interferences occur with their test data and the results are only 2 to 6% above the lower bound.

Stahlbock and Voß (2010) evaluate the scheduling of DRMGs using CTA as the example. In contrast to Vis and Carlo (2010), they discover that crane interference is an important issue for the DRMG system and conclude that the duration of loaded drives should not be assumed to be constant. Nevertheless, in addition to lateness and earliness, only the duration of empty drives is considered for the objective in their approach. Furthermore, the authors assume that cranes and trolleys cannot move simultaneously and every move of the passing crane is routed via the passing lane. Both conditions may lead to an overestimation of crane driving times. Speer, John, and Fischer (2011) suggest a branch-and-bound approach for the scheduling of DRMGs, also using data from CTA for their evaluation. They focus on a detailed modeling of crane interferences and evaluate the impact of sequence length and technical breakdowns on crane cycle times using a simulation model. The cycle times is compared with operational data from CTA. The major finding is that crane interference is a considerable part of the cycle times, especially in scenarios with technical breakdowns.

3.4. Scheduling of TRMGs and Crane Routing

Very few authors deal with the scheduling of TRMGs. The only algorithmic approach is provided by Dorndorf and Schneider (2010), who suggest a beam search algorithm in which the weighted sum of the mean tardiness, crane driving, and interference times is considered for the objective. An increase of yard crane productivity between 20 and 30% compared to simple priority rules is achieved. In addition to the scheduling, an optimal routing for the cranes is also determined. The routing problem is integrated as a subproblem, which is solved for each step of the beam search algorithm. The objective of the routing subproblem is the minimization of the makespan for the given job sequence.

Briskorn and Angeloudis (2016) deal with the problem of crane routing for Twin RMGs and DRMGs. They minimize the makespan for a fixed job sequence and given job assignments to the cranes and achieve an optimal solution in polynomial time.

Carlo and Martinez-Acevedo (2015) use priority rules for the routing of Twin RMGs and achieve results which deviate by only 1.3% from the optimal makespan.

Heitmann (2015) develops a mixed integer linear program for the integrated optimization of crane scheduling and routing for Twin RMGs, DRMGs, and TRMGs.

A disadvantage of all four approaches for crane routing is that trolley movements are neglected. However, these movements are necessary for each passing of a large crane with a container in the DRMG and TRMG system and need considerable time (Koch 2004).

3.5. Comparison of the Different Crane Systems

Several authors compare different yard crane systems on a single yard block by means of productivity and service times. Van Valkengoed (2004) compares Twin RMGs and DRMGs and describes a routing approach with a system of rules, by which the priority of the cranes is determined based on their position, direction, and distance to the crane's target. The author compares different priority rules and evaluates a variety of job assignment strategies for the DRMG system, e.g., the fixed assignment of each crane to one side of the block. Surprisingly, with this setting he attains better results than with a flexible crane assignment for the DRMG and than for the Twin system. However, for a complete container terminal with eight yard blocks, he finds that DRMGs with flexible assignment perform best, particularly for a scenario with a high peak at the quayside.

Saanen and van Valkengoed (2005) give recommendations concerning cost, land requirement, and flexibility of the crane systems. Saanen and de Waal (2007) provide several suggestions to improve the performance of automated container terminals and to quantify the potential, using a simulation model of an RMG-AGV-terminal. Among these suggestions is the substitution of DRMGs by Twin RMGs, especially because of lower land requirements and therefore higher possible turnaround on given space.

Saanen and Rijsenbrij (2007) also compare the productivity of different crane systems, neglecting the Single RMG, but including the TRMG. They find that TRMGs perform best, but the contribution of the third crane is in the range of only two additional moves per hour.

Kemme (2012, 2013) provides the only publications in which all four crane systems are considered and that also contain a detailed description of their characteristics. By use of simulation, various combinations of yard block dimensions and crane systems are compared. A notable result is that the Twin RMG achieves lower service times than the DRMG for wider yard blocks in particular, because of the time consuming passing of the cranes.

3.6. Conclusions from Literature Review

The analysis of the existing literature presented previously shows that there are some limitations that are surpassed in this work. For example, in some publications, only one objective is used (Guo et al. 2011, Vis and Carlo 2010); here multiple objectives are taken into account (cf. Section 2.4). Others make simplifying assumptions for the modeling of the yard cranes (Dell, Royset, and Zyngirdis 2009, Guo et al. 2011, Stahlbock and Voß 2010), e.g., trolley movements (Briskorn and Angeloudis 2016, Dorndorf and Schneider 2010, Heitmann 2015), or crane waiting times are neglected (Guo et al. 2011, Speer, John, and Fischer 2011).

While the branch-and-bound approach used in this study is based on the ideas of Guo et al. (2011) and Speer, John, and Fischer (2011), by contrast to these publications, all relevant parts of the crane cycle times (Figure 3) are modeled in the simulation model and the algorithm presented next (see Sections 4 and 5). This feature and its impact on productivity and computation times are not evaluated in any previous publication. This is the focus and also the major new contribution of this work.

Moreover, few papers compare the different crane systems and their effects on terminal performance, on service times for terminal vehicles, and external trucks, and there are no contributions so far that consider the influence of crane interferences or waiting times for all crane systems. Except for Kemme (2012, 2013), who uses only one scheduling procedure, never before have all four systems been studied; hence, this paper also extends the existing literature in this respect.

4. A Branch-and-bound Algorithm for the Crane Scheduling Problem

The main issue with solving the crane scheduling problem for realistic situations is the large number of jobs in J. As a result of the 24 hour-operation of an automated container terminal, there is no intuitive definition of a finite set of jobs that should be used in the planning process. Moreover, only some jobs are usually known in advance, because the exact arrival times of internal horizontal transports and of external trucks cannot be planned and forecasted reliably. The same is true for the container data, which often only becomes known when the container arrives.

Because of these online aspects of the (realistic) crane scheduling problem (Steenken, Voß, and Stahlbock 2004), finding efficient solutions to the problem at hand appears impossible for a longer planning horizon. A common approach is the repeated solution of a crane scheduling subproblem, where the set of jobs J under consideration consists of only a subset of a few (usually the most urgent) requests with reliable data. This approach is also suggested by Grötschel et al. (2001) who call it "replan." Therefore, in the procedure presented next, such a subproblem is solved whenever a crane becomes available, or when a new job becomes known while a crane is available. Each time, only the first job of the calculated sequence is permanently assigned to the available crane; the rest of the sequence can be re-optimized with the next call of the procedure. Finding an appropriate size for the subset of jobs is part of the computational study presented in Section 6.1.

Of course, this approach does not guarantee an efficient solution to the original problem of scheduling *all* jobs, as the solution depends on the number and choice of jobs used in the subproblems. Moreover, different optimization problems result, depending on the level of detail to which the components of the cycle time (see Figure 3) are taken into account in the calculation of the job durations. To compare the results of the different problems, key figures for the original problem, i.e., block productivity, etc., are calculated and compared for the whole planning horizon.

The subproblem described previously is a multi-objective problem that can be transformed into a single-objective minimization problem by the weighting method (Ehrgott 2006, p. 345). Suitable weights for the three objectives that were described in Section 2.4 are the values: 0.69, 0.3, and 0.01; they were determined in a comprehensive sensitivity analysis that has not yet been published and is not the focus of this study. Using these weights, every subproblem can be solved as a single-objective problem. This leads to nondominated solutions of the respective subproblems (Ehrgott 2006, pp. 244–245).

Next, a branch-and-bound approach for the subproblem of the crane scheduling problem, based on Speer, John, and Fischer (2011), is presented. The approach provides optimal solutions for the single-objective subproblems and can be applied to all four crane systems mentioned previously. As a result of the insights of Speer, John, and Fischer (2011) and Kemme (2013, pp. 278–279), optimal approaches for a subset of jobs outperform priority rules for all jobs in most cases. However, the often used priority rules FIFO (first in-first out) and EDD (earliest due date) will be used as a benchmark for the branch-and-bound algorithm presented in this study.

4.1. Branching

The idea of the branch-and-bound algorithm is the iterative construction of a job sequence for each crane (Guo et al. 2011, Speer, John, and Fischer 2011). The algorithm starts with an empty sequence for each crane or a fixed assignment of a job if the crane is currently executing a job. By each assignment of a job to a crane, a new, so-called partial solution is generated. The branch-and-bound algorithm operates on a set of these partial solutions. Such a partial solution s_i (node of the search tree) consists of a job sequence for each crane and a set $F_i \subset J$ of jobs that have not yet been assigned to a crane. The set F_i is named "free jobs." Initially, the set F_i is equal to J (root of the search tree).

In each branching step, the crane that becomes available first is considered. Each of the free jobs is assigned to this crane, if the assignment is feasible for the crane. Waiting times are considered, if the assigned job has a predecessor, which still has to be finished by another crane (for further details, see Speer, John, and Fischer 2011). This results in up to $|F_i|$ new partial solutions. Another partial solution is developed by the assumption that no further job will be assigned to the earliest available crane. A complete solution (leaf of the tree) is found when the set of free jobs is empty, i.e., each job is assigned to a crane at a specific position in the sequence. Hence, the leaves of a partial solution are all solutions whose job sequences start with the same job assignments. Figure 4 illustrates the development of a new partial solution. Each rectangle represents a job and its length d displays its duration.

4.2. Different Levels of Detail for the Calculation of Job Durations

In most approaches to the crane scheduling problem in the literature, the duration d of a job is assumed to be constant (e.g., Guo et al. 2011, Mak and Sun 2010, Vis and Carlo 2010). Of course, this assumption does not hold in reality for systems with more than one crane and hence it can be expected that this approach does not lead to high quality solutions. Therefore, the following configurable levels of detail are implemented for the calculation of job durations in the branch-and-bound approach, to evaluate their relevance for the quality of the resulting solutions. (Note that the heuristic approaches FIFO and EDD get the numbers 0 and 1 and the further numbering corresponds to the superscript numbers in Figure 3).

2. BB (Default): The time consumption for hoisting, lowering, and resizing of the spreader, for moving the trolley and gantry and for pick up and set down of a container are considered, based on the technical parameters and the movement pattern of the cranes (see Figure 3). The movement of the gantry, trolley, and lift is modeled with constant speed, i.e., acceleration, deceleration, and crane interferences are neglected. Waiting times at the transfer area are also neglected. But to avoid crane waiting times for HT, for the first position of the scheduling sequence only those jobs can be chosen for which the HT has already arrived at the transfer position (if such a job exists). This precondition for the start of a job is also suggested by Choe et al. (2007) and Park et al. (2010).

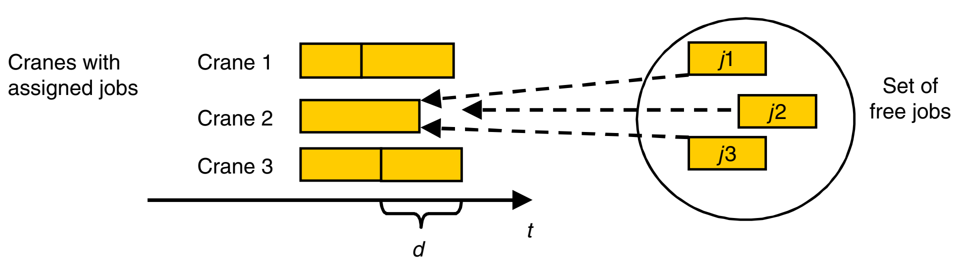
3. BB KIN (Kinematics): In addition to the preceding, acceleration and deceleration of the gantry, trolley, and lift are considered for scheduling.

4. BB HP: In addition to the preceding, the fact that only one crane can work in a transfer area at a time (see Section 2.3) is taken into account. To guarantee the clearing of the transfer area, a crane is sent to the nearest parking position if its last job in the sequence ends in a transfer area.

5. BB CI: In addition to the preceding, crane interference is taken into account. If an intersection of the crane routes occurs in a solution, the movement of the cranes is estimated using a rule-based routing strategy (e.g., give-way to the other crane, wait for the other crane, overtake the other crane, crossing of cranes). The strategy is calculated subject to the position and target of the involved cranes and has to guarantee that all cranes can reach their target successively. A strategy can consist of different steps, e.g., for the overtaking strategy of the passing crane (in the DRMG or TRMG system) these steps are (1) driving the trolley to the passing lane (and simultaneously starting the gantry travel, if possible), (2) overtaking the small crane on the passing lane, and (3) leaving the passing lane and approaching the target position after overtaking.

For the TRMG system, considerably more sophisticated strategies are necessary, because the third crane multiplies the number of possible situations, e.g., if one

Figure 4. (Color online) Development of a New Partial Solution by Assignment of a Job to the Earliest Available Crane



small crane must overtake the passing crane, it may also be in conflict with the other small crane. Therefore, the calculation of strategies and the estimation of job times becomes a problem for the TRMG (Kemme 2011). Of course, this rule-based calculation of routing strategies does not provide optimal solutions for the crane routing (cf. Section 3.4). However, this approach is also pursued by other authors (Van Valkengoed 2004) and Carlo and Martinez-Acevedo (2015) find that it often leads to nearly optimal solutions.

6. BB AH (Arrival hint): In addition to the preceding, the estimated time of arrival for the HT (in the case of AGV) is used to estimate the waiting time of the crane at the holding position (Petering et al. 2009). The precondition that an AGV for the first job in the sequence has arrived (see 2) is omitted, because waiting times are now explicitly estimated.

7. BB RO: In addition to the preceding, a forecast of the waiting time for an RO is used to estimate the waiting time of the crane at the holding position. This forecast is estimated by a central component that receives requests for ROs from all yard blocks and returns a forecast for the waiting time of each job.

It could be argued that taking these different pieces of information into account means to solve different problems. However, the underlying crane scheduling problem remains the same (see Section 2), only the level of detail taken into consideration in the solution process changes.

4.3. Bounding

For each partial solution created during the branch-and-bound procedure, a *lower* bound for the objective function has to be calculated. In all cases, for each assignment of a job to a crane, times for empty and loaded drive have to be determined, dependent on the selected level of detail (see Section 4.2). For the free jobs, the exact duration cannot be calculated because, for example, the duration of the empty drive depends on the predecessor in the sequence and cannot be calculated until the job is assigned to a crane. Yet a lower bound for the empty driving time can be estimated with regard to the possible starting positions, which are the last positions of the cranes or the target locations of the free jobs. For example, for the partial solution shown in Figure 4, the empty drive for job $j1$ can start at the target locations of job $j2$ or $j3$ or at one of the last positions of crane 1 to crane 3. The location with the shortest driving time is used for the bound. As with every assignment of a job the number of free jobs decreases, this bound becomes tighter with every step.

Interference times during empty or loaded drives are not considered for the lower bounds of free jobs because they cannot be estimated before a job is assigned to a crane. Waiting times for transport vehicles and remote operators are estimated based on arrival and forecast announcements from the AGV and the TOS.

Because of the occasionally long times for crane interference and waiting times, a tight *upper* bound for the duration of the free jobs can hardly be found and hence also the calculation of an upper bound for the objective function value of a partial solution does not provide good results. Instead, a starting solution is generated by a heuristic approach, which creates partial solutions similar to the branch-and-bound, but discards all solutions except the best after each branching step. This corresponds to a beam search with beam 1 (Dorndorf and Schneider 2010). The objective function value of this heuristic solution is used as an initial upper bound; this is very important for an effective pruning. Of course, the upper bound is adjusted every time a better full solution is found.

5. Simulation Model Description and Assumptions

5.1. Simulation Model Description

In this section, the simulation model that was developed with Plant Simulation and its assumptions are described. At a berth of 800 m length, 8 quay cranes are positioned for the handling of deep-sea vessels and smaller vessels (feeders and barges). For the transport between the quay cranes and the container yard, an AGV system with synchronous transfer is modeled with a detailed layout. Each yard block is equipped with an automated RMG system. The relevant parameter settings are shown in Table 1. There are four AGV/RMG transfer lanes on the quayside of each block. On the landside of the block, there are three transfer lanes for internal rail chassis and four lanes for external trucks. The containers inside a yard block are stacked in 37 bays, 10 rows, and up to 4 containers high. Similar dimensions of a yard block have been shown to be suitable for the crane systems considered here (Kemme 2012), and they have become accepted for practical use (Dorndorf and Schneider 2010, Koch 2004).

To simplify the model and to allow for a sufficient number of simulation runs, only 1 of 10 yard blocks in the model is activated. This approach is also taken by Saanen and van Valkengoed (2005). Quay cranes, 15 AGVs, and hinterland operations are nevertheless included in the model, but they do not form a bottleneck because their workload is limited by the single yard block. Quay cranes and rail cranes have random

Table 1. Parameter Settings for the Simulation

Device	Speed (m/s)	Acceleration (m/s^2)	Pick/set-time
Gantry RMG	3	0.5	
Trolley RMG	1	0.33	
Lift RMG	1.5	0.4	
Spreader RMG	0.2 (resizing)		5 s

cycle times, as these are operations that are carried out by human operators, while the other parts of the model, i.e., the automated operations, are deterministic. For the quay and rail cranes it is assumed that cycle times vary by ±10% around a given value (90 and 120 s, respectively).

Because of the fact that cranes are scheduled for each block separately, results can be easily transferred to multiple yard blocks. The only difficulty with this approach is the correct modeling of remote operators. The simulation runs are executed with one remote operator, which is too much for one yard block and results in an immediate connection of a remote operator whenever one is required. Hence, a scenario with several blocks should be used for a comprehensive evaluation of this aspect.

To measure the productivity of a yard block, which is the most important output of the simulation model, total productivity including reshuffles is used. Also Stahlbock and Voß (2010) suggest this key figure, while other authors prefer the external productivity excluding reshuffles (Kemme 2011). For this study, the total productivity is used because reshuffle moves are internal moves inside the block and a high productivity for these internal moves is worthwhile, particularly with regard to housekeeping moves. Moreover, the number of reshuffles has been shown to be relatively independent of the job sequence and therefore the results should be comparable. Further output measures used in the evaluation are the number of crane interferences and the average lateness.

5.2. Scenario and Due Dates

The simulation data (scenario) for the evaluation is generated for a medium size container terminal with 8 quay cranes, 10 automated yard blocks, and an annual turnaround of 1 million twenty-foot equivalent units (TEU). To enable the simulation of a single yard block, the data is generated for a period of 3 weeks and downscaled to one block, i.e., only 10% of the containers (approximately 5,400 inbound and outbound moves plus additional reshuffles) are considered. These containers are selected at random. A so-called synthetic scenario generator is used to generate realistic data for the simulation model. The data generation is based on a timetable for the deep-sea vessel services with five visits per week that are periodically repeated every week. The times at which the container moves at the vessels take place are equally and randomly distributed over the ship's service time. Deliveries of rail and external trucks are generated based on these times, using an equally distributed dwell time of the containers between one and seven days, which is added (for inbound moves) or subtracted (for outbound moves). About 3,000 of the 5,400 movements are used to fill the yard and hence to generate a predefined yard allocation (Stahlbock and Voß 2010), on which the remaining moves that correspond to one week can be performed without a warm-up period for each simulation run (Kemme 2013, p. 182). Table 2 shows the average remaining number of moves for each type. Attributes for each container such as size, type, weight, shipping company, and destination are generated using realistic data distributions. A similar concept for generating scenarios is described by Hartmann (2004). However, Hartmann (2004) does not use a periodic deep-sea vessel timetable.

It turned out that the observed key figures (output) for each simulation run become sufficiently stable when only 1,000 jobs are taken into account; hence, as each simulation run contains about 2,400 external jobs, the results from the simulation are highly reliable. Using the approach suggested by Lorscheid, Heine, and Meyer (2012), the deviation of both the mean value and the coefficient of variation was studied. Both deviations are significantly less than 1% for all key figures when considering five simulation runs per configuration. Hence, 2,400 external jobs per run and 5 replications are sufficient for drawing valid conclusions.

To simulate a continuous peak situation for the single yard block, the moves are generated consecutively and without idle times in between, resulting in a queue of pending jobs and a continuously high workload. At each point in time, only the first 12 jobs of the queue are known and the next job is only announced when a job has been carried out and has left the queue. For inbound moves, the announcement to a yard block takes place after the yard location has been assigned. A peak scenario is an important instrument for simulation purposes, as the differences between scheduling algorithms become most apparent with this type of scenario (Speer, John, and Fischer 2011). Housekeeping moves are neglected in the simulation model. This is realistic because housekeeping is not an issue in situations of high workload.

The right column of Table 2 shows the due date definitions for the different move types. Due dates form an important instrument for scheduling, as they are used for considering and comparing the urgency of jobs.

Table 2. Scenario and Due Date Settings

Carrier	Move type	No. of moves	Due date
Vessel	Inbound	792	10 min after AGV arrival at transfer lane
	Outbound	806	Planned load time less the estimated travel time of the AGV and time for the transfer
Rail	Inbound/Outbound	211/194	30 min after arrival at transfer lane
External truck	Inbound/Outbound	204/188	15 min after arrival at transfer lane
All	Reshuffle	~860 (depending on stacking)	30 s prior to successor

They are defined with respect to the mode of transport. Usually, jobs for the quayside are more urgent than hinterland jobs, because their timely execution is important to meet productivity agreements with the shipping companies and to reach an intended departure time for the vessel. Hence, for loading moves, the due date is determined by the planned time of loading at the quay crane, from which the estimated driving time of an AGV and an additional buffer time for the transfer between the devices are subtracted. For the storage of quayside containers, the due date is set to 10 minutes after the arrival time of the AGV at the yard block. According to the lower urgency, for external trucks the due date is defined as 15 minutes, and for rail containers as 30 minutes after arrival at the yard block. To ensure the timely execution of reshuffles, so-called predecessor relations between the jobs are defined and the due date for a reshuffle is set 30 seconds prior to its successor.

6. Simulation Experiments

In this section, the simulation results for the different crane systems are presented and the effects of the distinct levels of detail considered in the scheduling are discussed. At the end of this section, an approach is developed that tries to overcome problems with long computation times that occur with the TRMG system in particular. Because of the online character of the problem, at most two seconds are acceptable for the assignment of a new job when a crane is idle.

The results presented below were achieved on a workstation with an i7-CPU with 3.4 GHz. Because the tool Plant Simulation does not support the use of multiple kernels for a simulation process, up to six simulation runs were executed simultaneously. In the figures in the following sections, every data point represents the mean value of the results of five simulation runs.

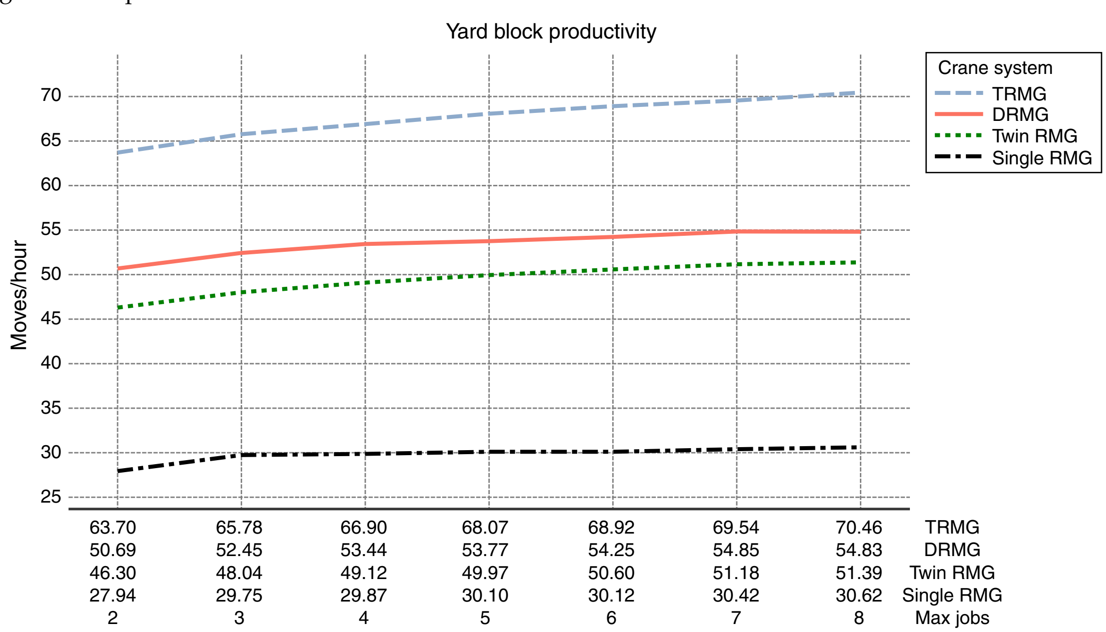
6.1. Impact of Sequence Length on the Different Crane Systems

First of all, the number of jobs, which is necessary to reach an appropriate solution quality and which therefore should be considered in each subproblem and be used in the branch-and-bound approach, is evaluated. For this analysis the branch-and-bound approach with the maximum level of detail (7 BB RO) is used. This investigation is also used to compare the productivity and the characteristics of the different crane systems.

In Figure 5, on the x-axis the number of jobs considered for scheduling in the subproblems is shown, and on the y-axis, the average productivity of the yard block (measured in moves per hour including reshuffles), i.e., the average result for the whole planning horizon, is displayed. The productivity is one of the most important performance indicators for container handling equipment (Saanen 2004). One line is plotted for each RMG system and the numbers under the x-axis are the mean productivity values for the four systems, shown in the same order as in the legend. The data points for each crane system are connected for a better illustration, although non-integer values for the number of considered jobs are not feasible.

As expected, the Single RMG provides the lowest yard block productivity with about 30 moves per hour, including reshuffles. The TRMG system attains

Figure 5. (Color online) Yard Block Productivity for Different Crane Systems and for Various Numbers of Jobs Considered for Scheduling in the Subproblems



the highest performance, but with 70 moves per hour it achieves less than triple the performance of a Single RMG. Nevertheless, the contribution of the third crane is clearly higher than evaluated by Saanen and Rijsenbrij (2007). Twin RMG and DRMG reach productivities between 50 and 55 moves per hour, which is in the middle between Single and TRMG and, in the case of the DRMG, significantly closer to double the Single RMG value (60 moves per hour).

Surprisingly, for all examined sequence lengths, the DRMG outperforms the Twin RMG by at least 6%. This contradicts the results found by Saanen and de Waal (2007) as well as Saanen and van Valkengoed (2005), who obtained better results for the Twin RMG. An explanation might be that the DRMG benefits from the typical import-export scenario considered here that generates a lot of long distance travel for the RMGs, whereas the Twin RMGs may have an issue with giving way to each other in this case. This effect becomes even more obvious when average lateness, relative to the due date, is compared (see Table 3), as the Twin RMG generates more than twice as much delay as the DRMG. Nevertheless, the Twin RMG might be a better choice for terminals with a lower transshipment rate, and it has the further advantage of lower land requirements (Saanen and van Valkengoed 2005, Saanen and de Waal 2007).

The number of jobs considered for scheduling has a considerable effect on productivity, but only for small numbers of jobs and depending on the crane system. For the Single RMG, considering three jobs seems to be enough, while for the Twin and DRMG system, the saturation limit is reached at six to seven jobs (Figure 5). For the TRMG, no saturation can be noticed. Overall, at least three jobs per crane should be considered in the subproblems to reach reasonable productivity.

The examination of the crane utilization (see Table 3, bottom) allows similar conclusions. The Single RMG reaches a utilization of nearly 100%; this can be explained by the simulated peak scenario with an extreme workload that allows the assignment of jobs to the crane at any time. For the remaining crane systems, crane utilization increases with the number of jobs considered. For the DRMG, a utilization near 100% is reached when at least four to five jobs are considered. Only in a few situations, the algorithm finds no jobs to be started or decides to work with only one crane (e.g., because the operation of the second crane does not pay off as a result of high crane interference). For the Twin or TRMG system, these situations occur more often, because the small cranes cannot execute all jobs. Therefore, a crane utilization of only about 94% is reached in the best case.

As computation times are an important issue in real-time applications, Figure 6 shows the mean computation times for the four crane systems and for different numbers of jobs. The mean computation time strongly increases with the number of jobs considered.

Overall, it is found that at least three jobs per crane should be considered for the scheduling to reach high productivity and low delays. However, consideration of more than six jobs results in long computation times for the TRMG and DRMG system which prohibits practical application of the algorithm. Nevertheless, considering more than six jobs can make sense in practice, because in many situations good solutions can be found after a few seconds and only the optimality proof takes a lot of time (see Section 6.3).

6.2. Evaluation of Different Levels of Detail for the Algorithm

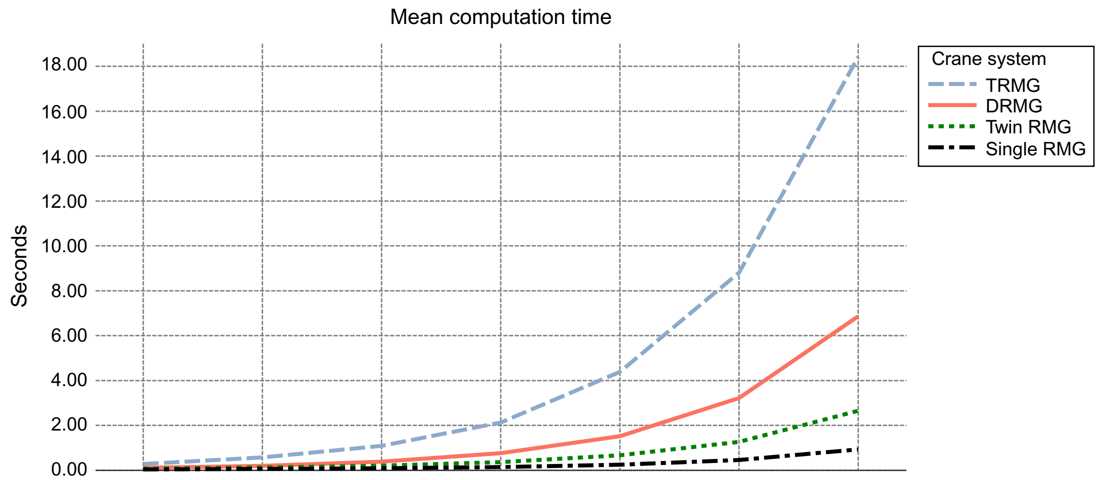
For the TRMG system, the limit of two seconds computation time is already exceeded with five jobs (Figure 6), but the potential of productivity is not exhausted with this setting (Figure 5). Therefore, in this section the impact of the level of detail considered in the scheduling algorithm on the results and computation times will be analyzed. The aim is to discover parts of the algorithm leading to high time consumption, but to small improvements of the results, and to find a compromise for the application in practice.

In Figure 7, the productivities (scaled on the y-axis) of different variants and algorithms are compared; these are shown on the x-axis. The priority rules (0 FIFO and 1 EDD) act as a reference. Variants 2

Table 3. Average Lateness Compared to Due Date (in Minutes) and Crane Utilization for Different Crane Systems and for Various Numbers of Jobs Considered in the Subproblems

Jobs	2	3	4	5	6	7	8
Lateness							
TRMG	1:39.92	1:20.09	1:12.27	1:07.19	1:03.89	1:04.09	1:04.34
DRMG	3:35.60	2:21.76	1:59.38	1:45.78	1:35.94	1:34.48	1:33.04
Twin RMG	5:47.74	5:00.98	4:37.76	4:08.16	4:01.50	3:53.13	3:42.05
Single RMG	12:13.38	13:01.86	12:54.09	12:49.25	12:25.00	12:05.01	12:02.44
Utilization							
TRMG (%)	85.41	89.32	91.20	92.40	93.36	93.74	94.36
DRMG (%)	97.76	99.25	99.65	99.68	99.73	99.70	99.75
Twin RMG (%)	86.60	89.21	90.96	92.01	93.16	93.81	94.39
Single RMG (%)	99.96	99.94	99.98	99.97	99.95	99.97	100.00

Figure 6. (Color online) Mean Computation Time for the Scheduling for Different Crane Systems and for Various Numbers of Jobs Considered in the Subproblems

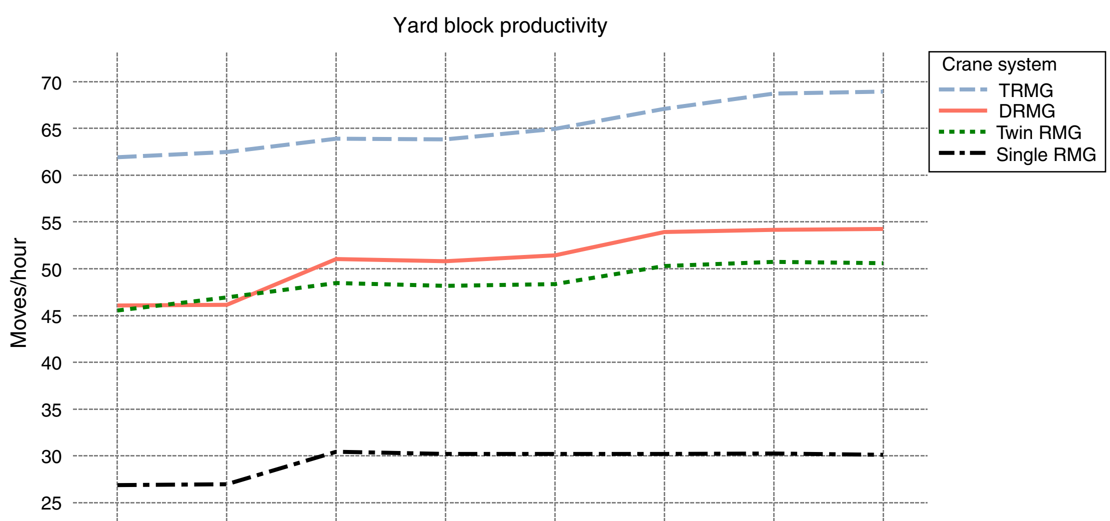


0.28	0.57	1.09	2.13	4.38	8.81	18.42	TRMG
0.11	0.20	0.38	0.76	1.52	3.22	6.86	DRMG
0.07	0.12	0.20	0.36	0.67	1.27	2.65	Twin RMG
0.03	0.05	0.09	0.15	0.25	0.45	0.93	Single RMG
2	3	4	5	6	7	8	Max jobs

to 7 match with the levels of detail of the branch-and-bound algorithm described in Section 4.2. As in the previous section, one curve is plotted for each crane system. In all cases considered in this section, six jobs were taken into account in the subproblems.

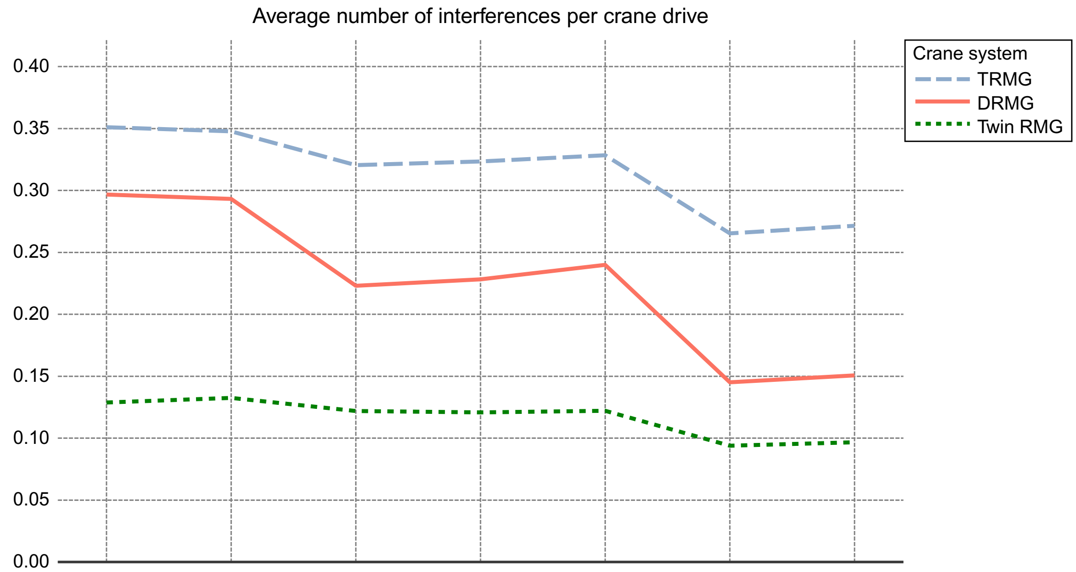
The productivity of the DRMG and the Twin system is very similar when priority rules are used; this is consistent with the results of Saanen and van Valkengoed (2005) and Van Valkengoed (2004). The branch-and-bound approach outperforms the priority rules for all four crane systems even on the basic implementation level (2 BB). The largest gain in productivity when going from 0 FIFO to 2 BB is reached for the DRMG, which shows clearly higher productivities than the Twin system with all branch-and-bound variants. In other words, the higher investment in the passing option of the cranes only pays off when a sophisticated algorithm—as branch-and-bound in contrast to a heuristic approach—is used. Moreover, the DRMG is the system where crane interference is reduced most through the branch-and-bound approach (see Figure 8). Obviously, the minimization of the duration

Figure 7. (Color online) Yard Block Productivity for Different Crane Systems and Scheduling Algorithms



61.91	62.49	63.91	63.83	64.95	67.10	68.73	68.92	TRMG
46.08	46.16	51.04	50.81	51.44	53.92	54.16	54.25	DRMG
45.55	46.94	48.47	48.17	48.36	50.29	50.74	50.60	Twin RMG
26.89	26.96	30.44	30.20	30.21	30.21	30.25	30.12	Single RMG
0 FIFO	1 EDD	2 BB	3 BB KIN	4 BB HP	5 BB CI	6 BB AH	7 BB RO	Algorithm

Figure 8. (Color online) Average Number of Interferences per Crane Drive for Different Crane Systems and for Various Scheduling Algorithms



	0 FIFO	1 EDD	2 BB	3 BB KIN	4 BB HP	5 BB CI	6 BB AH
TRMG	0.350	0.350	0.320	0.320	0.330	0.270	0.270
DRMG	0.300	0.290	0.220	0.230	0.240	0.150	0.150
Twin RMG	0.130	0.130	0.120	0.120	0.120	0.090	0.100
Algorithm	0 FIFO	1 EDD	2 BB	3 BB KIN	4 BB HP	5 BB CI	6 BB AH

Note. If a crane drive lasts longer than the driving time that is estimated based on starting position and target of the crane, this is counted as an interference.

of empty drives as part of the cycle times not only leads to a higher productivity but also to more unhindered and effective work of the cranes in comparison to the priority rules.

While the inclusion of kinematics (3 BB KIN) and holding position (4 BB HP) in the scheduling approach seems to have a minor influence on the productivity of the RMGs, taking into account crane interference (5 BB CI) results in a considerably rising productivity and clearly reduced crane interferences by up to 39% for the DRMG system (see Figure 8). This step leads to the largest gain in productivity. On the other hand, the implementation of routing strategies in the scheduling component for the present study has been shown to be very time consuming and costly, in particular for the complex TRMG system. Furthermore, computation times increase significantly with this step (see Figure 10). As expected, the consideration of crane interference has no influence on the Single RMG.

The consideration of waiting times for transport vehicles (6 BB AH) brings only small advantages in productivity (most for the TRMG system) and, as expected, taking into account waiting times for remote operators (7 BB RO) shows no significant effect for the scenario with one yard block. Hence, this configuration is not displayed in Figures 8 and 9.

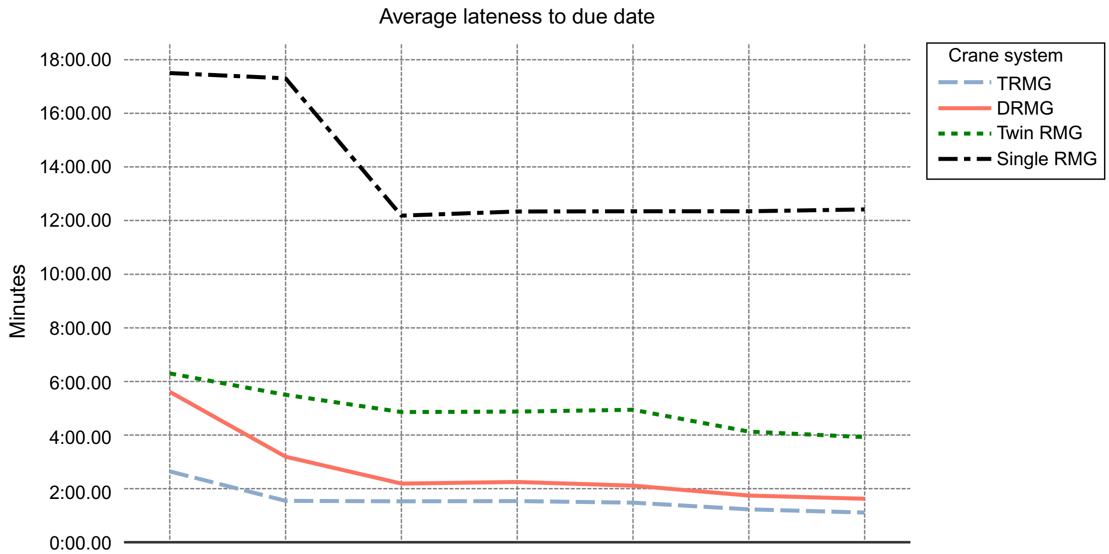
Another important key figure is the average lateness relative to due date that is also used by Stahlbock and Voß (2010) and shown in Figure 9. In the present study, it turned out that this key figure shows similar characteristics as the service times of AGVs and other vehicles which are mentioned as an important key figure by Steenken, Voß, and Stahlbock (2004). Hence, vehicle waiting times for AGVs and other vehicles are not separately displayed in this study.

Similar to productivity, the largest improvements in terms of lateness are achieved by the branch-and-bound procedure in contrast to the priority rules and by the consideration of crane interference (see Figure 8). Yet also the modeling of the holding position leads to slight improvements for the DRMG and TRMG system. As expected, there is no such effect for Single and Twin RMG, as these cranes cannot operate in the same transfer area.

In Figure 10, the mean computation times of the various algorithms for the different crane systems are presented. The computation times for the priority rules are nearly null and the computation of a solution with the basic branch-and-bound procedure (2 BB) takes less than one second. Considering crane interferences (5 BB CI) needs the most additional computation time among the branch-and-bound variants, but it also leads to a major improvement of the results. Hence, it can be concluded that it is worthwhile to consider a high level of detail in the scheduling approach and that neglecting computation-intensive details leads to significantly worse results.

In the last column of Figure 10, the computation times of a full enumeration of the solution space

Figure 9. (Color online) Average Lateness Relative to Due Date for Different Crane Systems and for Various Scheduling Algorithms

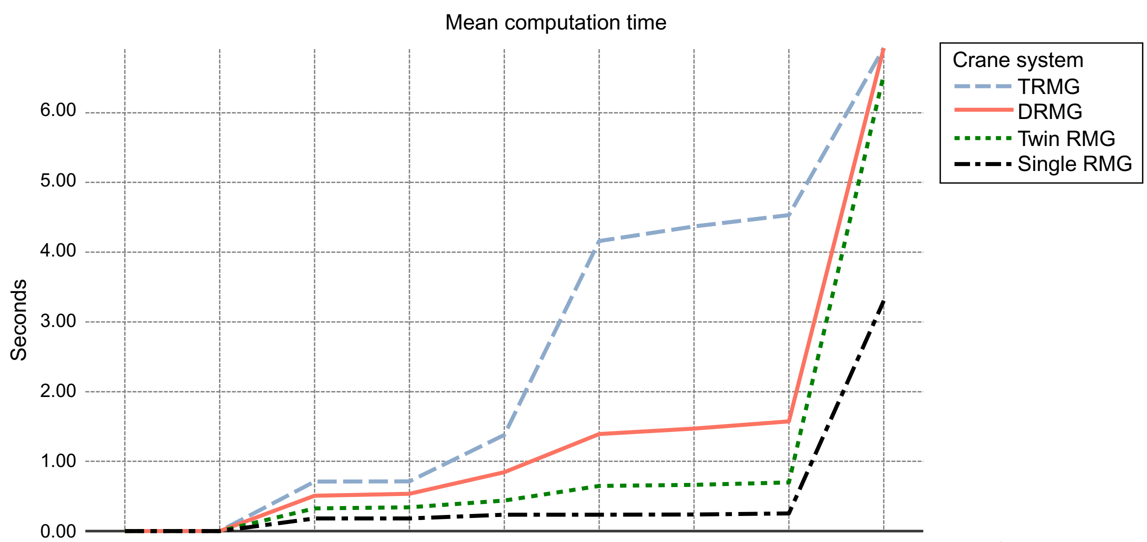


0 FIFO	1 EDD	2 BB	3 BB KIN	4 BB HP	5 BB CI	6 BB AH	Algorithm
2:38.35	1:32.71	1:31.77	1:32.04	1:28.49	1:13.83	1:06.46	TRMG
5:36.54	3:11.36	2:11.45	2:14.93	2:06.48	1:44.56	1:37.13	DRMG
6:17.66	5:29.91	4:51.35	4:52.61	4:56.30	4:07.78	3:55.51	Twin RMG
17:30.30	17:18.30	12:10.87	12:20.14	12:20.99	12:20.99	12:24.83	Single RMG

are shown (not to scale for the DRMG and TRMG). It shows that the branch-and-bound variants with high level of detail consume only 3 to 10% of the computation time of a full enumeration. This is due to the fact that most of the possible solutions can be pruned during the branch-and-bound process.

In summary, it can be stated that the suggested branch-and-bound algorithm with replanning is an expedient approach for the crane scheduling problem that provides up to 18% higher yard block productivity and a reduction in delays of up to 50% compared to the priority rules (for the DRMG). Nevertheless, the computation times for the TRMG system and in some cases also for the DRMG system are prohibitive for the application under real-time conditions. Therefore, in Section 6.3 a new approach is presented that can

Figure 10. (Color online) Mean Computation Time for Different Crane Systems and for Various Scheduling Algorithms



0 FIFO	1 EDD	2 BB	3 BB KIN	4 BB HP	5 BB CI	6 BB AH	7 BB RO	8 ENUM	Algorithm
0.00	0.00	0.70	0.71	1.37	4.15	4.37	4.53	97.58	TRMG
0.00	0.00	0.50	0.53	0.84	1.39	1.47	1.57	58.64	DRMG
0.00	0.00	0.32	0.34	0.43	0.64	0.66	0.69	6.54	Twin RMG
0.00	0.00	0.18	0.18	0.23	0.23	0.23	0.25	3.30	Single RMG

be used to derive a good approximation for these two crane systems in reasonable computation time.

6.3. Different Search Strategies and Limitation of Computation Time

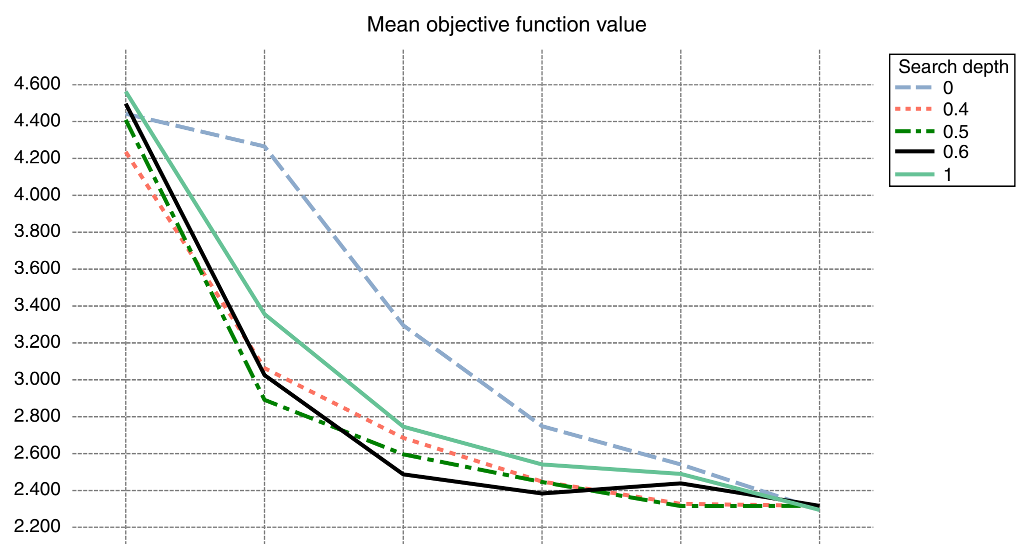
When calculating an optimal solution takes too long, it is a common approach to abort the algorithm after a certain time and to use the best solution found so far. With the heuristic starting solution (see Section 4.3), a feasible solution that can be used is available after some milliseconds. How much this solution can be improved during the branch-and-bound procedure depends on the strategy used for node selection in the solution tree. In most branch-and-bound implementations, the next node to be branched is the one with the lowest lower bound. For the problem under consideration, this often leads to a breadth-first search, because some parts of the crane cycle times, e.g., interference times, cannot be estimated by the bound (see Section 4.3) and hence, complete solutions are often found only late during the branch-and-bound process. This is especially unfavorable when the process is aborted before the whole tree is investigated. Hence, in addition to the objective function value, here the number of free jobs f_s is used as a second, dynamically weighted criterion: The number f_s is normalized and multiplied with a (fixed) weight w and with the objective function value of the respective solution. Then the result is added to the objective function value and the solution with the lowest sum is investigated next. The weight w is called "search depth," because a higher value of w results in a more depth-first search of the solution tree.

Figure 11 shows the mean objective function value (scaled on the y-axis) of the best solution found so far, when the procedure is aborted after a certain time, for different search depths. The limit for the computation time (in seconds) is scaled on the x-axis. The results are shown only for algorithm 7 BB RO for the DRMG system with six jobs. An evaluation of different tree search strategies for the scheduling of a single RTG can also be found in Guo et al. (2011).

It should be noted that a time-dependent abort of the algorithm does not guarantee deterministic results. Moreover, with unlimited computation time (600 s), the different search strategies can cause the selection of different solutions (with the same objective function values). This results in differing job assignments during a simulation run and therefore in different problem instances for the subproblems with different mean objective function values. (This explains the slight differences between the results shown previously and those presented next.)

From Figure 11, it can be concluded that the consideration of the number of free jobs in the search strategy provides better solutions than a breadth-first search (search depth 0) when computation time is limited. Hence, a search depth of 0.5 is used for the following evaluation, as this value leads to good results in most cases (see Figure 11). Analysis has shown that the best solution is often found after 20 to 30% of the

Figure 11. (Color online) Mean Objective Function Value of the Best Solution for Different Search Depths with Various Limits of Computation Time (s) for the DRMG System and Algorithm 7 BB RO



4.442	4.265	3.296	2.749	2.541	2.294	0
4.236	3.064	2.685	2.448	2.327	2.316	0.4
4.409	2.892	2.595	2.446	2.315	2.316	0.5
4.497	3.026	2.487	2.384	2.438	2.316	0.6
4.563	3.356	2.746	2.541	2.490	2.294	1
0.5	1	1.5	2	3	600	

Max comp. time

computation time with this setting. The remaining time is necessary to prove optimality of the solution. From the terminal operator's point of view, this proof is only of inferior importance. Hence, this new search strategy is a good choice for practice; this also applies for the TRMG system.

The results in Section 6.1 have shown that the computation times for calculating an optimal solution of a subproblem considerably grow with the number of jobs taken into account. However, it was not evaluated how many jobs should be considered when computation time is limited. As the value of the objective function depends on the number of jobs considered, the average lateness in relation to the due date is compared instead. Figure 12 shows the average lateness for the DRMG system for a variety of jobs and for different limits of computation time which is scaled on the x-axis.

The more computation time is available, the more jobs should be considered in the subproblems to reach a low average lateness. When only one second is available, taking into account five jobs achieves the best results. For up to two seconds, six jobs are preferable, for more than two seconds seven jobs are best, and when computation time is unlimited, considering eight jobs achieves the best results. An evaluation for the TRMG (not shown in the figure) has shown a similar trend, just with higher time limits. It is important that the time limit for a run of the sequencing algorithm is defined with respect to the current situation of the cranes. In general, the result of the scheduling algorithm is required as quickly as possible, particularly if at least one crane is idle when a new job is received. However, in this situation, normally only a few jobs are available. For this case, the time limit is defined as two seconds. In peak scenarios, the situation is different, because all cranes are occupied and the jobs are queued. Whenever a crane finishes his current job, i.e., the set down of a container on a transport vehicle or in the stack, the scheduling has to decide with which job from the queue the crane should continue. But the first step of a new job is always the hoisting of the spreader (see Figure 3). Depending on the position of the container, this step can take between 2 and more than 10 seconds. Hence, during the hoisting of the spreader the next job for the crane does not have to be known. Moreover, the time needed for the hoisting of the spreader can be accurately estimated and can be used as a time limit for the scheduling. Hence, this limitation was implemented in the simulation model and the results are presented in the following figures. Figure 13 shows the yard block productivities (y-axis) with limited computation time. On the x-axis, different numbers of considered jobs (5 to 8), a variant with a dynamic number of jobs based on the results of Figure 12 (dynamic), and a reference with unlimited computation time (8–unlimited) are shown.

For both crane systems, the variants with seven and eight jobs, as well as with a dynamic number of jobs, achieve similar productivities. For the DRMG, the

Figure 12. (Color online) Average Lateness for Different Numbers of Jobs Considered in the Subproblems and for Various Limits of Computation Time (s) for the DRMG System and Algorithm 7 BB RO (Search Depth 0.5)

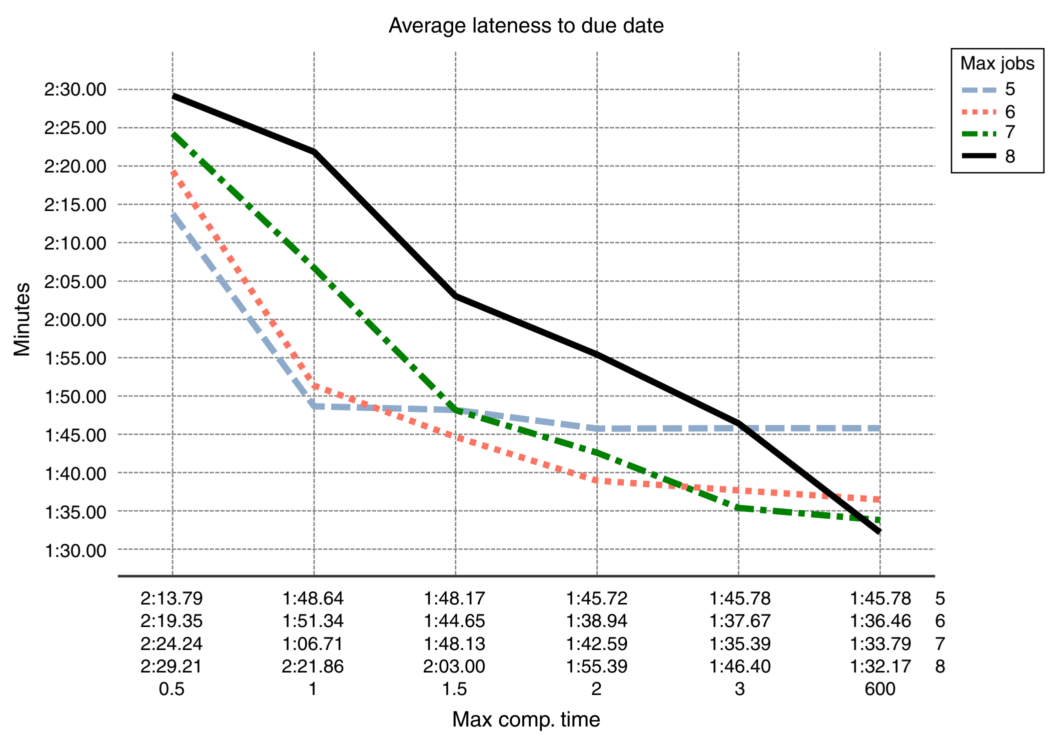
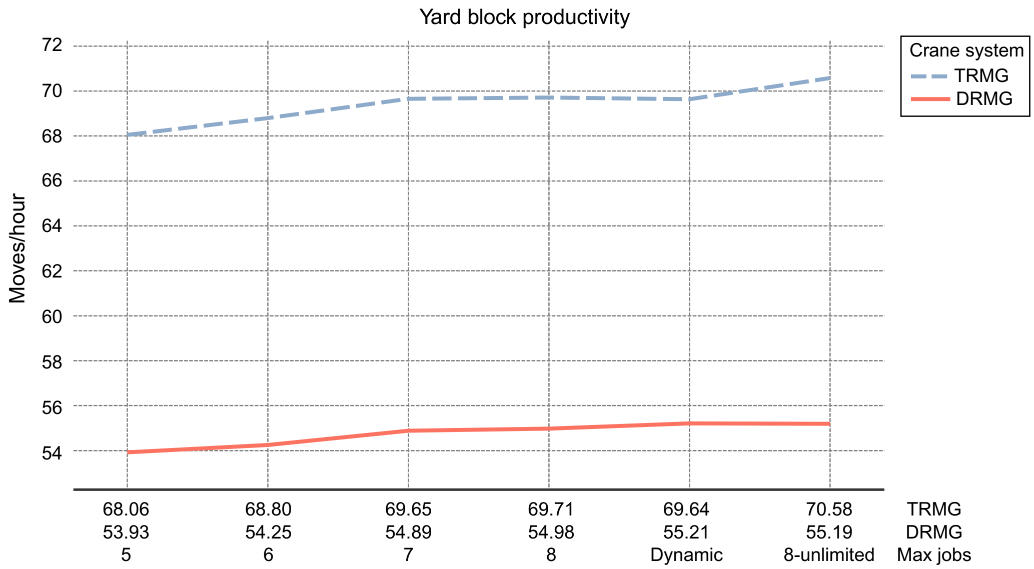


Figure 13. (Color online) Yard Block Productivity with Algorithm 7 BB RO with Computation Time Limited by the Hoisting Time of the Spreader for Different Numbers of Considered Jobs (5 to 8), Dynamic Number of Jobs, and Without Time Limit (8–Unlimited)

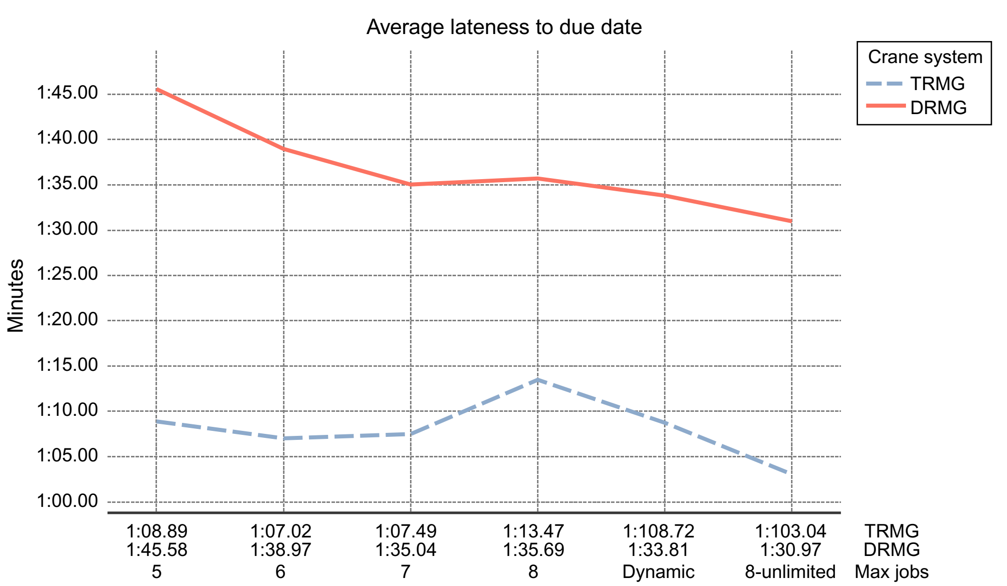


productivities are nearly equal to the variant without time limit, while for the TRMG system there still is a small difference.

The average lateness relative to the due date which is shown in Figure 14 shows a different result. For the DRMG, the variant with a dynamic number of jobs provides the best results with limited computation time and the average lateness is only 3 s above the optimal value. For the TRMG, the dynamic variant is still good, but considering only six or seven jobs achieves slightly better results with respect to lateness. It should be noted that considering eight jobs results in the maximum lateness for the TRMG with limited computation time. This might be a result of the significantly higher number of possible solutions.

It can be concluded that the branch-and-bound algorithm provides good results when computation time is limited. For the DRMG, the variant with a dynamic setting for the number of jobs to be considered for the scheduling reaches the best results, coming very close

Figure 14. (Color online) Average Lateness Relative to Due Date with Algorithm 7 BB RO with Limited Computation Time for Different Numbers of Jobs Considered (5 to 8), for a Dynamic Number of Jobs, and Without Time Limit (8–Unlimited)



to the results without a time limit, while for the TRMG a small gap remains with respect to productivity and lateness.

7. Summary and Future Research Prospects

In this work, a branch-and-bound algorithm for real-time yard crane scheduling was used to study the performance of four different automated crane systems within a simulation model. The algorithm was applied repeatedly to a limited number of known jobs, using a replanning approach. The performance of the crane systems was compared with respect to different key figures. All parts of the crane cycle times were taken into account successively in the procedure and it could be shown that integration of most of them is worthwhile. An increased yard block productivity of up to 18% and a reduction in delays of up to 50% can be achieved, compared to the well-known priority rules (for the DRMG). The highest gain in productivity was reached by considering crane interferences, which at the same time caused considerable increases in computation times, particularly for the DRMG and TRMG system. Therefore, different search strategies were evaluated for these two systems and a strategy was found that can almost exhaust the potential also when computation time is limited, and hence allows the application of the algorithm in practice.

Future research might focus on an improvement of the computation times, which would allow to take into account a higher number of jobs for the TRMG system. With respect to the enhancement of multiprocessors in the past decade, a parallel search of the solution tree seems promising. Moreover, for crane systems with more than one crane, an integrated optimization of the crane routing might be advantageous.

Furthermore, the impact of considering crane waiting times for remote operators on the scheduling should be analyzed using a scenario for an entire container terminal with many yard blocks. This is left for future research.

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