Agent-Based Support for Container Terminals to Make Appointments with Barges

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Abstract. We consider a container terminal that has to make appointments with barges dynamically with only limited knowledge about future arriving barges, and in the view of uncertainty and disturbances. We study this problem using a case study at the Port of Rotterdam, considering a proposed multi-agent system for aligning barge rotations and terminal quay schedules. We take the perspective of a single terminal participating in this system and focus on the decision making capabilities of its intelligent agent. Using simulation, with input settings based on characteristics of the larger terminals within the Port of Rotterdam, we analyze the benefits of our approach. We conclude that a terminal can increase its utilization significantly by using various sources of flexibility in the operational planning.

Keywords: Terminal planning · Quay scheduling · Dynamic assignment · Multi-agent system · Simulation

1 Introduction

The Port of Rotterdam, located in the Netherlands, is the largest port in Europe and the world's tenth-largest container port in terms of twenty-foot equivalent units (TEU) handled. Over the past years there has been a tremendous growth in container transportation, going from less then 0.4 TEU in 1970 to over 12 million TEU in 2015. During these years, the quality and accessibility of hinterland transportation has become increasingly important. The number of transported containers to the hinterland has grown tremendously, and nowadays the hinterland services form a large share in the total transportation bill [11]. To reduce the pressure on the current road infrastructure as well as to reduce greenhouse gas emissions, the port aims for a modal shift from road to barge or train. Here we focus on barge hinterland container transportation. Specifically, we take the perspective of a terminal operator on how it can improve its operational performance when making appointments with barges dynamically and in real-time.

A major problem in the port is the poor alignment of barge and terminal operations. This poor alignment results in uncertain dwell times of barges and a significant loss of capacity for terminal operators. Typically, barges have to visit

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about eight terminals when visiting the port. The sequence in which the terminals are visited, determines to a large extent the time a barge needs to complete all its loading and unloading activities. An additional problem is that a delay at one terminal propagates quickly to the other terminals. The alignment of barge and terminal operations, the so-called barge handling problem, is considered to be the most urgent problem in hinterland barge container transportation by the Port of Rotterdam. Solving this problem improves the hinterland connectivity and thereby the attractiveness of the port significantly, and stimulates a modal shift towards barge transportation.

To provide a solution for the barge handling problem, an agent-based decision support system has been proposed [5,6]. The reason to use a multi-agent (or distributed planning) system is that players are reluctant to share information with their competitors and prefer to have control over their own operations. In earlier research, the focus was on decision support for barge operators. However, the new way of working will have a major impact on the way terminal operators make appointments with barge operators. Opposed to the old situation, where appointments were made manually and the terminal planning was made off-line, the new situation requires real-time (partly) automated decision making.

The objective of this paper is to come up with operational planning rules for terminals to efficiently utilize their capacity given the changed setting in which they have to operate, i.e., a setting in which they have to make reliable appointments with barges taking into account future events and disturbances, e.g., delayed arrivals of container vessels. To support the operational planning rules, we present various sources of flexibility and provide numerical results on the impact of using them on quay utilization and barge waiting times.

The remainder of this paper is structured as follows. In Sect. 2, we give a brief overview of the relevant literature. In Sect. 3, we present our model, the decisions involved, and our solution approach. We present our simulation model, with corresponding numerical results, in Sects. 4 and 5. We close with conclusions in Sect. 6.

2 Literature Review

During the last decade, a substantial amount of research has been conducted to increase the efficiency of container terminal operations. Different subjects within this area include the berth allocation problem, quay and yard cranes assignment and scheduling, and yard storage management and container stacking. Extensive literature reviews on these subjects can be found in [1,24,28].

A closely related problem is the berth allocation problem (BAP), which concerns the assignment of berths to ships such that berth utilization is maximized or the waiting time for ships are minimized. Extensive literature reviews on this subject can be found in [2,23,24,26]. The literature on the BAP makes assumptions which do not hold for the barge handling problem. First, the arrival times of vessels are generally assumed to be known [1,19,26]. This assumption is made for the so-called static BAP, where ships are waiting at the start of the planning horizon, but also for the dynamic BAP where ships arrive during the planning horizon [2,10], as also considered in this paper. The planning of quay cranes is called the quay crane assignment problem (QCAP) and the quay crane scheduling problem (QCSP). A recent trend in the BAP literature is to combine these three problems, see, e.g., [1,9,14,20,21] for an overview.

Although our focus is on a terminal as a single decision maker, research on multi-agent systems is relevant since we aim at an implementation environment where the single terminal participates in such a system. In the area of road transportation, many examples of agent-based approaches can be found [16]. However, applications of agents in transportation via water are scarce and most papers have focused on the alignment of activities at a single terminal [3]. Examples include the optimal placement of containers in the yard [7], strategies for the cranes to minimize the trucks' wait time [27], simulation of ships and their allocation [25], and simulation of various strategies regarding the movement of containers from the ship into the yard [8]. A multi-agent cooperative planning system between multiple intermodal transport operators is considered in [13].

Agent-based or distributed planning approaches for inland barge traffic in the port of Rotterdam have been suggested by various authors. Initially, the focus was on creating an off-line planning system, where barge rotations were planned one day in advance [22]. From this work it became clear that a decentralized control structure offers an acceptable solution for the parties involved [18]. Next, the focus was on real-time agent-based planning [6]. Based on these agent-based systems, two multi-player games have been developed [5,17] that contributed to the acceptance among barge operators of the proposed multi-agent system.

In this paper, we contribute to the existing literature by studying how to schedule ships (barges and container vessels) such that a high quay utilization is realized. We take the perspective of a single terminal that operates within a port-wide multi-agent system for the barge handling problem as described in [6]. A consequence of using this system is that the terminal agent has to respond to barge handling requests dynamically, in real-time, and partly automatic.

3 Model Description

First, we describe the environment within which the terminal operates (Sect. 3.1). Next, we present our modeling assumptions and notation (Sect. 3.2), our objective (Sect. 3.3), and the decisions we have to make (Sect. 3.4).

3.1 Multi-agent Environment

We illustrate our approach using the multi-agent system from [6]. In the remainder of this section, we briefly explain this system to understand the decisions a terminal has to make in this specific case.

Starting point of the distributed planning approach is improving the reliability of appointments. The basic idea of the proposed system is that terminal and barge operators get a software agent that act on their behalf. This planning approach is preferred by the operators, because it enables them to stay in control of their own operations and share only limited information. The crucial information shared by the terminal agents are the so-called service-time profiles. A service-time profile (STP) is issued on request of a barge operator and denotes a guaranteed maximum service time given a certain arrival time at the terminal, where service time is defined as the sum of the waiting and handling time at this terminal. Hence, an STP is barge and time specific. Barge operators can use the STPs to optimize their rotation (sequence of terminals visits). Terminal operators in turn can use the STPs to indicate preferred handling times thereby optimizing their capacity utilization.

Barges arrive in the port over time. On arrival in the port, the barge operator requests STPs at all terminals he has to visit. A terminal has to reply instantaneously and has to do so with only limited knowledge about future arriving barges. After receiving all STPs, the barge operator determines its best rotation and announces its preferred arrival time at the terminal. The terminal operator makes an appointment by confirming the barge's latest arrival time and a guaranteed maximum service time. By making the appointment, the barge commits to a latest arrival time and the terminal commits to a latest departure time (namely the latest arrival time plus the guaranteed maximum service time). When barges arrive after their latest arrival time, the appointment will be canceled, regardless of the reason for the delay. During the whole process from planning to execution, the terminal has to deal with uncertainty and disturbances, such as uncertain arrival times and handling times of barges and container vessels, as well as cancellations and no-shows.

3.2 Assumptions and Notation

As stated earlier, we take the perspective of a single terminal. We assume that the activities at other terminals are reflected in the arrival process of barges at the terminal of interest. This assumption is not unrealistic, since terminals do not share their operational information with each other for competitive reasons. As point of reference, we consider the large terminals within the Port of Rotterdam. These terminals are characterized by high volumes, large numbers of quay resources, and high utilization rates. Our focus is on the operational planning level of the terminal. This means that decisions made at the tactical level (such as the amount of capacity deployed) are considered fixed.

The planning process starts with a barge $n \in \mathcal{N}$ requesting an appointment at the terminal. We assume that this barge has a preferred (or earliest) arrival time e_n. When the barge cannot be scheduled within a given planning period, it will be rejected ($r_n = 1$). Obviously, rejection is often not possible in practice and the terminal has to assign additional capacity to handle these requests. However, using the number of rejected requests, we can gain insight in the amount of additional capacity that needs to be assigned. If the barge is not rejected, ($r_n = 0$), we provide the barge an STP. This STP gives for each possible latest arrival time l_n a service-time $s_n = d_n - l_n$, with d_n being the latest departure time.

The latest departure time d_n is guaranteed by the terminal when the barge arrives on time ($a_n \leq l_n$), with a_n being the actual arrival time. When the barge arrives too late ($a_n > l_n$), the appointment will be canceled ($r_n = 1$). We further introduce a handling time h_n for the time required to load/unload the containers from barge n, and a planned starting time b_n, with $l_n \leq b_n \leq d_n - h_n$. The actual starting time might take place before l_n in case of an early arrival. We illustrate the notation using the example schedule of Fig. 1. Here, the first ship arrives earlier than its latest arrival time ($a_1 < l_1$) and handling of the ship is started earlier than its latest arrival time ($b_1 < l_1$). The other ships have a planned starting time b_n equal to their latest arrival time l_n. For ship 3, we have the possibility to postpone the starting time b_3 by two time units because the service time s_3 is two time units longer than the handling time $h_3 = 3$.

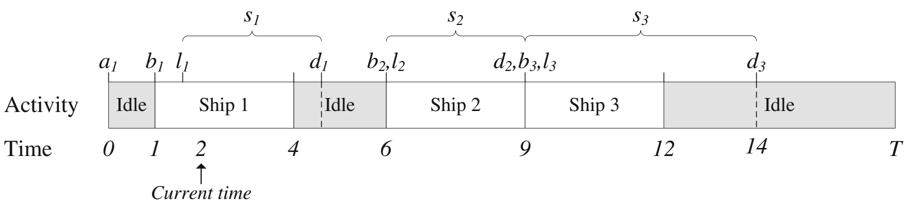

Fig. 1. Illustration of a schedule

3.3 Objective

The objective of the terminal operators we interviewed in the Port of Rotterdam is to maximize the utilization of their quay resources. More specifically, to maximize the utilization of crew, crane(s), and berthing position(s), and in this sequence. We make two comments regarding the utilization rate as terminal objective. First, maximizing the utilization of quay resources cannot be done without keeping an eye on the waiting time of barges. Given the variability in barge arrivals, a utilization rate of 100 % will definitely lead to infinite waiting times for the barges. Second, if the capacity of the terminal is fixed during a certain time period by decisions made at the tactical level, as we assume in this paper, then the utilization rate of a terminal only depends on the barges we accept to handle within this period. Therefore, the main objective is to make appointments, in such a way that the utilization rate of the terminal within a given time period is maximized. Since we assume the capacity to be fixed, this results in the maximization of the sum of the handling times of all accepted barges within the given time period, i.e., $\max(\sum_{\forall n \in \mathcal{N}} (1 - r_n) h_n)$, subject to having an average waiting time for the accepted barges below a reasonable bound.

3.4 Decisions

The main decision of the terminal is to set the service-times $s_n = d_n - l_n$, for all possible latest arrival times l_n, as part of the STP. To create the STP in real-time, we assume that the terminal starts with a list of intervals in which barges can be handled. These intervals depend on, e.g., opening times, scheduled ships, and resource capacities, and do not depend on a specific barge. Without loss of generality, we assume that the intervals are given by the maximum length of the idle periods between planned ships as shown in Fig. 1. Since the terminal has some flexibility in choosing the planned starting times (see Sect. 3.5), the interval between ship n and ship $n+1$ is given by planning the starting times of ships before ship $n+1$ as early as possible and for ships after ship n as late as possible, resulting in an interval $[b_n + h_n, b_{n+1}]$. These intervals are determined for each possible insertion position. Upon a barge request, the terminal (i) makes a selection of intervals to offer to the barge operator and (ii) constructs the STP using these intervals, see [6]. These two decisions are based on the amount of buffer and slack to be used respectively (see Sect. 3.5). After an appointment has been made, the terminal has to schedule the starting times b_n and has the option to re-schedule barges (see Sect. 4).

3.5 Sources of Flexibility

We approach the problem from a practical point of view by considering various sources of flexibility. We define a source of flexibility as a factor that offers planning flexibility in the terminal schedule. From multiple interviews with barge and terminal operators within the Port of Rotterdam, we conclude that sources of flexibility are used frequently to deal with real-time decision making under uncertainty. With this approach, we aim to provide insight into the benefits of deploying these sources of flexibility to improve terminal performance.

There are several factors in the planning and execution of barges that potentially improve the planning flexibility of the terminal. We mention the following instruments terminals might use:

- *Buffer*. The terminal might only consider intervals that are at least a buffer w_n longer then the required handling time h_n, i.e., intervals shorter then $h_n + w_n$ are not offered to the barge.
- *Slack*. The terminal can add slack v_n to an appointment with a barge, such that the latest departure time becomes $d_n = l_n + h_n + v_n$. This way, the terminal has flexibility in choosing the planned starting time b_n and postpone it up to $l_n + v_n$.
- *Re-scheduling*. The terminal may reschedule barge appointments thereby improving its quay schedules.
- *Cancellation*. The terminal can cancel appointments, e.g., when a schedule becomes infeasible.

Even though the terminal as no (or little) influence on it, the characteristics of barges might also provide a potential source of flexibility. We mention the following:

- *Early arrival.* A barge arrives earlier than its latest arrival time ($a_n < l_n$).
- *Cancellation.* A barge cancels an appointment at the terminal, meaning that the terminal can use the time that comes free for other purposes.
- *Deviation in handling time.* The handling time distribution of a barge may impact the flexibility of the terminal to fill an interval.

Note that not all of these sources of flexibility are desired by the terminal. For instance, a cancellation by a barge is usually a disturbance in the schedule, although it can sometimes be welcomed when the terminal deals with delays. Here we assume that cancellations just take place and therefore consider it as a potential source of flexibility.

4 Simulation Model

To investigate the impact of the different sources of flexibility, we use discrete event simulation. To provide realistic insights, we use the large terminals within the Port of Rotterdam as point of reference. The simulation settings are based on these terminals and on interviews with barge operators as reported in [4]. An overview of our simulation model is given in Fig. 2.

We determine the arrival rate of barges and container vessels using a desired utilization rate (instead of the other way around). The desired quay utilization rate in the simulation is set to 85 %, with a share of 45 % for barges and 40 % for container vessels. These numbers are based on 2006 figures from two large terminals within the Port of Rotterdam, see [4]. The 85 % is also close to the average utilisation of 86.6 % for North European deep seaports [15] and in line with the Drewry Maritime Research forecasts for average container terminal utilization world wide. We choose to control the utilization rate and derive from that the mean interarrival time for both barges and container vessels:

$$\text{mean interarr. time} = \frac{\text{mean handling time} \cdot (1 - \text{cancellation rate})}{\text{terminal capacity} \cdot \text{desired utilization rate}}, \quad (1)$$

where the terminal capacity is given by the amount of time this terminal is open multiplied with the number of quays.

Barges arrive with exponentially distributed interarrival times upon which a preferred arrival time is determined and announced to the terminal. The preferred arrival time is drawn uniformly between the current time and 48 h later. This way, we mimic a realistic arrival process, i.e., a barge that arrives later may be processed earlier than another barge that arrived earlier. The number of containers to load/unload, announced by a barge, is distributed according to a Weibull distribution (parameters shown in Table 1). The handling time per container is assumed to be 3 min. We assume that the exact number of containers to load/unload is known at the start of handling a barge.

Container vessels arrive according to a Poisson process. They announce their arrival time and total number of containers to load and unload three weeks prior to their initial planned arrival time. The handling of a container vessel has

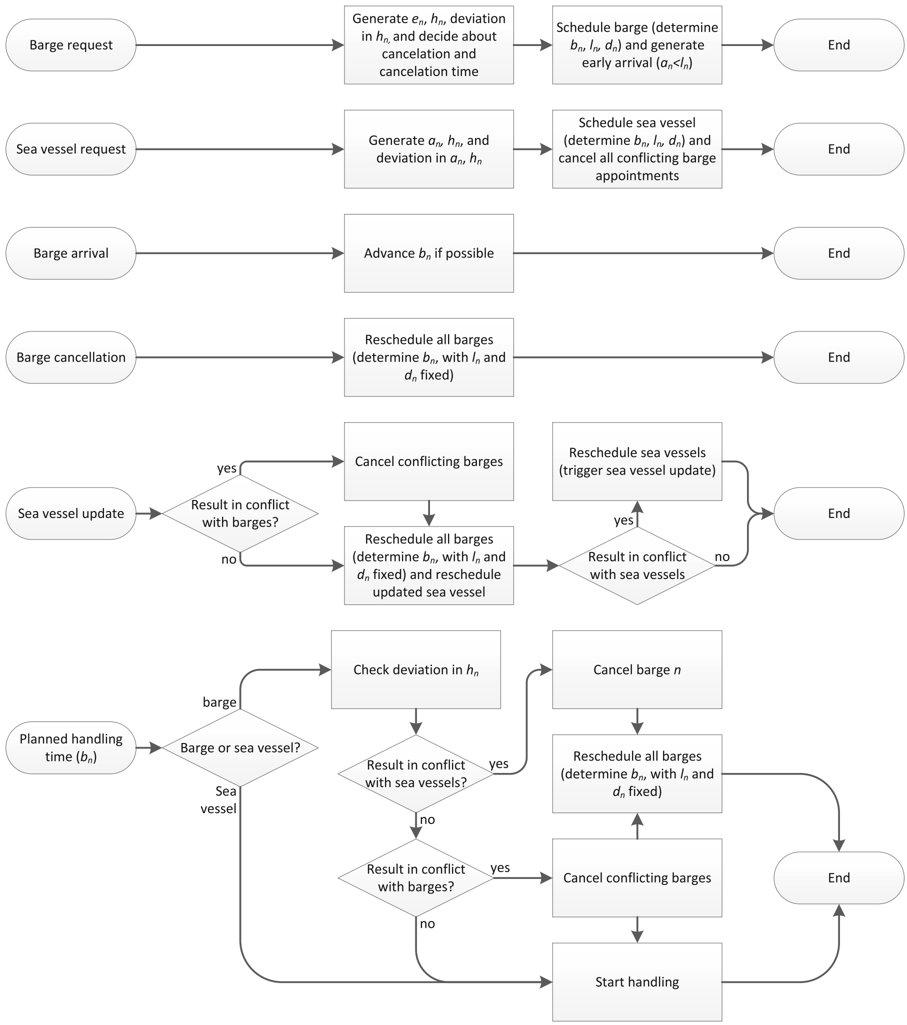

Fig. 2. Overview of the simulation model

priority over the handling of barges. The handing time, in minutes, is drawn from the Beta distribution with $\alpha = 1.14$, $\beta = 8.3$, multiplied by 6400.

Without loss of generality, we assume the terminal is open 24 h per day and has 4 quays. A quay is a combination of resources that are all necessary to handle a ship; both sea vessels and barges are handled at one quay. The schedule of the terminal will consist of several gaps (intervals), since it is not likely that barges are scheduled directly after one another. When the terminal receives an announcement of the barge preferred arrival time e_n at the terminal, it schedules the latest arrival time l_n of this barge at the first possible starting time after e_n. Initially, the terminal schedules each barge with starting time $b_n = l_n$ and latest departure time $d_n = a_n + h_n + v_n$. The terminal can start the handling of a barge earlier than its latest arrival time if the barge arrives earlier and when no appointments with other barges are violated.

During the simulation, four types of disturbing events may take place that require an action of the terminal. First, a barge arrives earlier than planned, this becomes known upon arrival. Earliness in minutes is drawn uniformly from $[0, x]$, where x is an experimental factor (see Table 1). Second, a barge cancels its appointment. The fraction of barges that cancel their appointment is an experimental factor (see Table 1), and cancellation by a barge happens at a uniform time $[0, 5]$ h prior to its latest arrival time. Third, the handling time of a barge might be different than announced before, this becomes known upon the start of handling. We use a uniform deviation $[-4, 5]$ in the number of containers, using a lower bound of 1. Fourth, a container vessel arrives at a different moment or has a different handling time, this information will be announced by the container vessel 48 h prior to its latest arrival time. Regarding the deviation in total handling time of a container vessel, we assume a uniform deviation $[-20\,\%, 20\,\%]$. Regarding the deviation in arrival time, we assume a uniform delay $[-8, 8]$ h, using the current time as lower bound.

In case of a disturbance, the terminal applies a policy as shown in Fig. 2 and described below.

- *On arrival of a barge.* The terminal checks if it can start handling the barge without violating other appointments. If not, the barge will be cancelled.
- *On cancellation of a barge.* In case of cancellation by a barge, the terminal can perform two actions, namely not to reschedule or to reschedule. Not to reschedule means that the terminal plans all barges in one specific quay schedule as early as possible while keeping the sequence of scheduled barges on a specific quay the same. To reschedule means that the terminal reconsiders all quay schedules, and may change the timing, the sequence, and the quay where barges are planned. The rescheduling procedure is as follows. The terminal makes a list of all candidate barges that could be scheduled in the new gap that arose after the cancellation. Candidate barges are barges of which (i) the handling has not been started, (ii) the planned starting time is greater than the start of the new gap, and (iii) that fit into the new gap. The barge with the lowest latest arrival time of all candidate barges is scheduled in the new gap. If this barge does not fill the gap completely, then the terminal looks for the next candidate barge until either the gap is filled or the list of candidate barges is empty. The same procedure is then applied for all gaps that arise after moving the barges to the new gap until all gaps are filled or no candidate barges for rescheduling are available anymore.
- *On handling a barge.* Upon the start of handling a barge, it might appear that the handling time will be longer then planned. As a result, other appointments might become infeasible. The terminal will not cancel the barge currently in process. Instead, the terminal will check for each barge and container vessel planned after this barge whether the appointment is going to be violated. If an appointment with a barge is violated, then this appointment is cancelled.

Table 1. Experimental factors with their corresponding low and high values

No.	Factor	Low	High	Comment
1	Early arrival	120	0	The barge arrives in the low scenario a uniformly distributed time between 0 and 120 min earlier, and in the high scenario at its latest arrival time
2	Handling time	−	+	Weibull distribution for the number of containers to load and unload, with parameters $\lambda = 2.1$ and $\kappa = 33.9$ for the low value and with parameters $\lambda = 1$ and $\kappa = 30$ for the high value (corresponding with a mean of 30 min and standard deviation of 15 and 30 min)
3	Cancellations	0	0.2	Fraction of barges that cancel an appointment
4	Re-scheduling	No	Yes	Re-schedule on cancellation of a barge, see the policy for 'on cancellation of a barge'
5	Slack	0	40	Minutes slack to add to appointments
6	Buffer	0	30	Minutes buffer to use between appointments

If an appointment with a container vessel is violated due to a scheduled barge, then the barge appointment is cancelled.

– *On receiving an update from a container vessel.* When a container vessel announces its real arrival time and the required handling time, then the terminal updates the quay schedules. In case the container vessel appointment conflicts with scheduled barges, then the barge appointments are cancelled. If the appointment conflicts with an earlier scheduled container vessel, then the arrival time of the container vessel is updated with the completion time of the earlier scheduled container vessel. If the appointment conflicts with later scheduled container vessels, then the appointments with later scheduled container vessels are postponed.

To analyze the effects of the different sources of flexibility, without considering the computationally intractable full-factorial design, we split our analysis in two parts. In the first part, we use a $2k$ factorial design [12], where we choose two levels (high and low) for each of the six factors (sources of flexibility), which means that we have $2^6 = 64$ possible factor-level combinations. Table 1 denotes the six sources of flexibility that are considered, with their respective high and low values. The values 120 min early arrival, 40 min slack, and 30 min buffer correspond with roughly the 95^{th}, 87^{th}, and 86^{th} percentiles of the distribution in handling time deviations of all ships, respectively. In the second part of our analysis, we perform a full factorial experiment using the most promising factors found in the first part.

We validated our model by comparing it with [4] under similar conditions without using the various sources of flexibility. To provide accurate results, we replicate each experiment five times, where each replication has a warm-up period of 10 days and a run length of 365 days.

5 Numerical Results

In this section, we present the results from the simulation experiments described in the previous section.

Factorial Analysis. The results (averaged over all replications) of each scenario considered with respect to both, the utilization rate and the average barge waiting time, are shown in Fig. 3. The design points follow the logic from [12]; using '−' and '+' to denote the low and high level respectively, the first five design points are given by: $(-,-,-,-,-,-)$, $(+,-,-,-,-,-)$, $(-,+,-,-,-,-)$, $(+,+,-,-,-,-)$, and $(-,-,+,-,-,-)$.

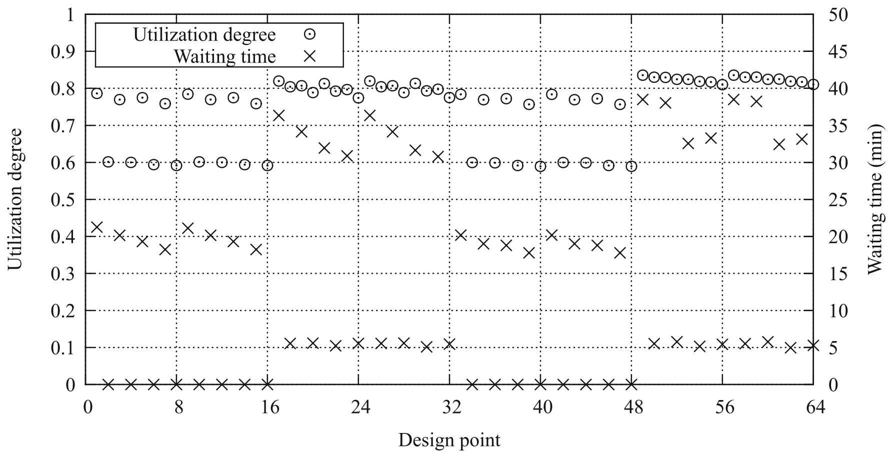

Fig. 3. Results for the 2k factorial design

We draw the following conclusions. First, scenarios with slack (scenarios 17–32 and 49–64) result in the highest average quay utilization rate. Clearly, a relatively low amount of slack provides enough flexibility to deal with disturbances; a slightly lower value for the buffer and a much higher value for earliness have a much lower impact on the utilization rate. Second, in scenarios where barges arrive early (the uneven scenarios), we observe a higher utilization rate than the corresponding scenarios in which barges arrive at their latest arrival time. This is different when also slack is added to appointments (compare, e.g., scenarios 1–16 with 17–32). Third, if barges arrive early, they usually have more waiting time. When also slack is added to the appointments, then the waiting time increases even further (compare, e.g., scenarios 1–16 with 17–32). Fourth, a buffer seems to have effect only when also slack is used in the appointments (small differences between scenarios 49–64 and 17–32 with slack and almost no differences between scenarios 33–48 and 1–16 without slack). Finally, re-planning on cancellations seems to have no visible impact (compare, e.g., scenarios 1–8 with 9–16, or scenarios 49–56 with 57–64).

The above mentioned observations are confirmed by the main effects and the two-way interaction effects (results not shown). The two sources of flexibility with the largest positive impact on the terminal performance are early arrivals and slack. The buffer has a much lower impact, but may be interesting to have a closer look at. The factors 2 (handling time distribution), 3 (fraction of cancellations), and 4 (re-scheduling on cancellation), have hardly any impact on the utilization rate of the terminal or on the average barge waiting time. This explains why there are many scenarios with almost similar results.

Zooming in on Three Sources of Flexibility. In this section we focus on three sources of flexibility that have the highest impact on the terminal performance, namely slack, early arrivals, and the buffer. We evaluate these factors in all combinations using broader ranges then considered in the $2k$ factorial analysis: slack $\in \{0, 40, 80, 120\}$, early arrival $\in \{0, 30, 60, 120\}$, and buffer $\in \{0, 20, 40, 60\}$. For clarity of presentation, we fix one parameter at a time to its second lowest value while varying the other two (the remaining combinations exhibit similar patterns).

Figure 4 shows, for a given buffer of 20 min, the impact of early arrival and slack on the utilization rate and the waiting time of the barge respectively. We draw the following conclusions. First, early arrival of barges positively impacts the utilization rate of the terminal, but worsens the average waiting time of barges. Second, the extent to which early arrivals contribute to an improvement of the quay utilization rate depends on the amount of slack used. If slack is being used ($\geq$40), then early arrivals only have a limited effect on the utilization. Third, if 40 min slack is used (in case no barge arrives early), then the quay utilization rate improves from about 60 % to more than 80 %, whereas the average waiting of barges increases with less than 10 min.

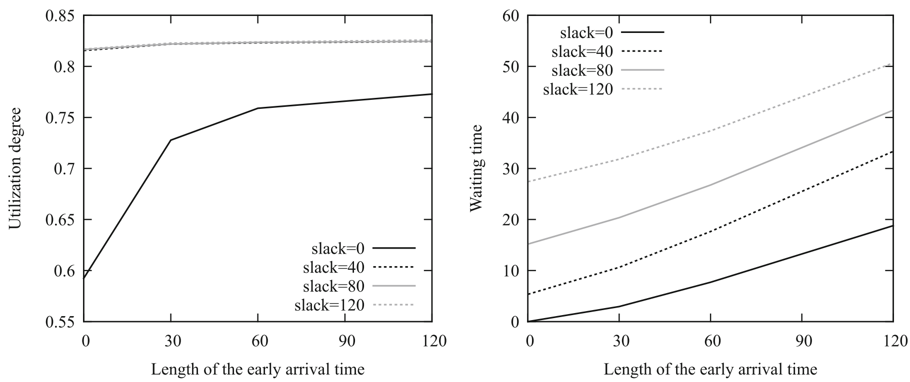

Fig. 4. Varying length of early arrival time for given buffer of 20 min

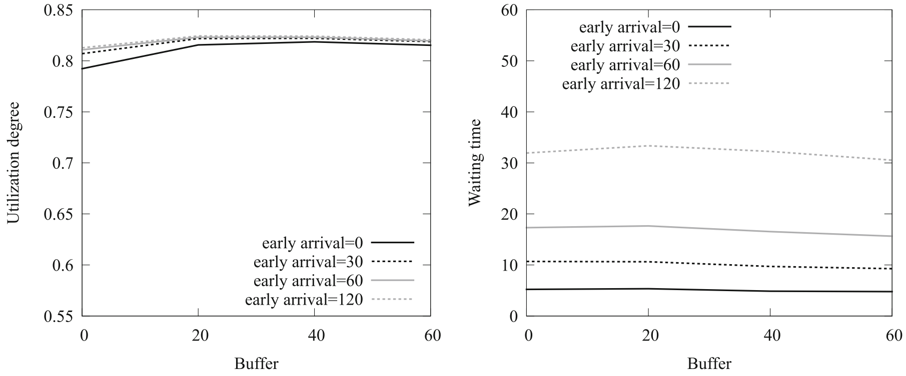

Fig. 5. Varying buffer for given slack of 40 min

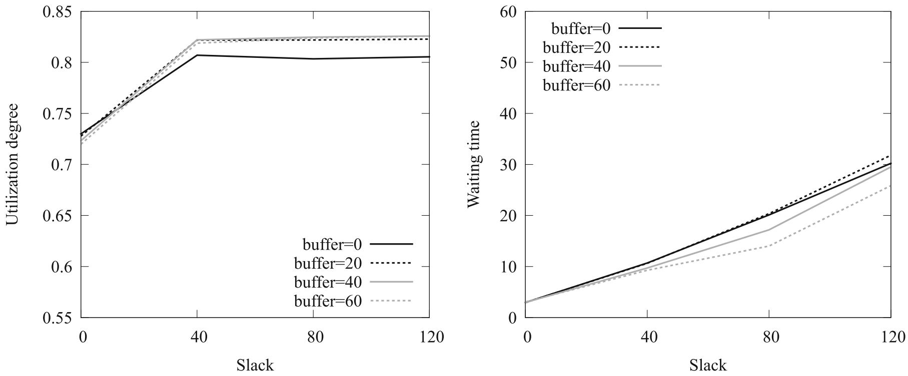

Fig. 6. Varying slack for given length of 30 min early arrival time

Figure 5 shows, for a given slack of 40 min, the impact of early arrivals and the buffer on the quay utilization rate and the average waiting time. We conclude that a positive buffer improves the utilization rate of the terminal for different levels of early arriving barges. Moreover, a small buffer of 20 min already leads to the greatest improvement of the utilization rate if barges arrive 30 min or more early. We further see that a larger buffer leads to a minor decrease in waiting times.

Figure 6 shows, for a given maximum of 30 min earliness, the impact of slack and the buffer on the quay utilization rate and the average waiting time. We conclude that a buffer does not add value when slack is zero. When using a positive amount of slack, the buffer improves the utilization rate of the terminal with a few percent points. With respect to the average waiting time, we also find that the impact of a buffer is relatively small.

Summarizing we conclude that, within the experimental setting considered, a quay utilization rate of 82 % can be realized with a minimum use of three sources of flexibility, namely slack (40 min), a buffer (20 min), and early arrivals (uniformly between 0 and 30 min). Without the use of these sources of flexibility, the quay utilization rate is as low as 60 %. Note that the maximum utilization rate that could be realized in our experimental setting is 85 %. The main takeaway from these results is that in environments with uncertainty and disturbances, dynamic appointment making can be supported by the relatively simple concepts of slack and buffers. We belief that these insights also apply to other settings, such as dynamic appointment scheduling in hospitals.

6 Conclusions

We focused on the operational planning of a terminal operator that has to plan dynamically and partly automatic. As a case of reference, we assumed that the terminal has to make appointments by means of an intelligent software agent that is part of the multi-agent system as described in [6]. The main challenge for the terminal agent is to make appointments with barges dynamically with only limited knowledge about future arriving barges. During the whole process from planning to execution, the terminal has to deal with uncertainty and disturbances, such as uncertain arrival and handling times of barges and container vessels, as well as cancellations and no-shows.

Using simulation, we explored the deployment of various sources of flexibility that are naturally available to the terminal. To give realistic insights, we used the large terminals within the Port of Rotterdam as point of reference for our experimental setup. From our numerical results, we found three major sources of flexibility, namely (i) early arrivals of barges, (ii) the use of slack in appointments, and (iii) the use of a buffer between appointments. For the instances considered, we found that a terminal, with a target utilization of 85 %, could significantly increase its performance using these sources of flexibility. Specifically, an increase in utilization rate from 60 % to 82 % can be realized with a minimum use of the two sources of flexibility (slack of 40 min and a buffer of 20 min). This major increase in utilization is achieved under a minor increase in barge waiting times (5 min).

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