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Albert Douma, Martijn Mes

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# Strategies for dynamic appointment making by container terminals

Albert Douma

Dinalog  
Dutch Institute for Advanced Logistics  
Breda, The Netherlands  
douma@dinalog.nl

Martijn Mes\*

School of Management and Governance  
University of Twente  
Enschede, The Netherlands  
m.r.k.mes@utwente.nl

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## Abstract

We consider a container terminal that has to make appointments with barges dynamically, in real-time, and partly automatic. The challenge for the terminal is to make appointments with only limited knowledge about future arriving barges, and in the view of uncertainty and disturbances, such as uncertain arrival and handling times, as well as cancellations and no-shows. We illustrate this problem using an innovative implementation project which is currently running in the Port of Rotterdam. This project aims to align barge rotations and terminal quay schedules by means of a multi-agent system. In this paper, we take the perspective of a single terminal that will participate in this planning system, and focus on the decision making capabilities of its intelligent agent. We focus on the question how the terminal operator can optimize, on an operational level, the utilization of its quay resources, while making reliable appointments with barges, i.e., with a guaranteed departure time. We explore two approaches: (i) an analytical approach based on the value of having certain intervals within the schedule and (ii) an approach based on sources of flexibility that are naturally available to the terminal. We use simulation to get insight in the benefits of these approaches. We conclude that a major increase in utilization degree could be achieved only by deploying the sources of flexibility, without harming the waiting time of barges too much.

*Keywords* Multi-agent system, Terminal planning, Quay scheduling, Dynamic assignment, 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 than 0.4 TEU in 1970 to over 11 million TEU in 2011. 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 (Konings 2007). However, the share of the different modes of transportation for the Port of Rotterdam is rather stable over the last decade (around 60% truck, 30% barge, and 10% train). 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

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\*Corresponding author. Tel.: +31 534894062; Fax: +31 534892159.

in the Port of Rotterdam. 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.

One of the main problems in barge handling today is the poor alignment of barge and terminal operations in the port. This poor alignment results in uncertain dwell times of barges and a significant loss of capacity for terminal operators. Typically, barges have to visit 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. Barge operators anticipate this domino effect by adding large margins in their plans to ensure reliable services to their customers. The alignment of barge and terminal operations, the so-called barge handling problem (see Douma, Schutten & Schuur 2009), is considered to be the most urgent problem in hinterland barge container transportation by the Port of Rotterdam. The poor alignment of barge and terminal operations leads to high direct costs (about 27 million euro a year only for barge operators) and has even more indirect effects, such as environmental pressure and congestion on the road and rail infrastructure. 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, a project has been started in 2011, called BATMAN, which stands for Barge Terminal Multi-Agent Network. This project, in which the authors of this paper participate, aims to design and implement a multi-agent system that solves the barge handling problem through intelligent and partly automated alignment of the barge and terminal operations. 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. A multi-agent system can facilitate these requirements. The project builds on earlier research (e.g., Douma et al. 2009, Douma, Schuur & Schutten 2011), in which a proof-of-concept multi-agent system was developed, evaluated, and demonstrated. The primary goal of this project is to make the step from conceptual model to a system that is ultimately fully-operational. To our knowledge, this will be the first realized large-scale distributed planning system between competing players in a supply chain.

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. These changes are welcomed by the terminal operators, since it enables them to respond dynamically to events and disturbances, to lower their administrative burden, and to improve the reliability of barge handling. On the other hand, dynamic also means that decisions have to be made with limited knowledge of future events, which could mean that the terminal operator sometimes will regret decisions that are just made in the view of new information.

The objective of this paper to come up with operational planning rules for terminals to efficiently utilize their capacity given the changed setting in which the terminal has to operate. In earlier work, we studied relatively simple terminal operator algorithms to make appointments with barges, under the assumption of deterministic sailing and handling times (no disturbances). In this paper, we go a step further by exploring two alternative solution approaches for improving the terminal performance. Here we take into account disturbances that can take place, such as delayed arrivals of sea vessels. These disturbances may have a negative impact on the performance of the terminal. This paper makes the following contributions. First, we present an analytical approach to gain insight in the value of having certain gaps in a schedule. Second, we present various sources of flexibility that can be used by terminals to increase their capacity utilization. Third, we provide numerical results on the impact of using these sources of flexibility on terminal utilization and barge waiting times.

The remainder of this paper is structured as follows. In Section 2 we give a brief overview of the relevant literature. In Section 3, we present our model, the decisions involved, and a sketch of our solution approach. We present our solution approaches, with corresponding numerical results, in Section 4 and 5. We close with conclusions, remarks on generalizations, and directions for further research in Section 7.

## 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. Extensive literature reviews on these subjects can be found in (Vis & Koster 2003, Bierwirth & Meisel 2010, Steenken, Voß & Stahlbock 2004).

The berth allocation problem (BAP) concerns the assignment of berths to ships under certain constraints such that berth utilization is maximized or the waiting time for ships are minimized. Extensive literature reviews on this subject can be found in (Steenken et al. 2004, Cordeau, Laporte, Legato & Moccia 2005, Stahlbock & Voß 2008). The literature on the BAP makes assumptions which do not hold for the barge handling problem. A first important assumption is that the arrival times of vessels are generally assumed to be known (c.f., Bierwirth & Meisel 2010). 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 (Imai, Nishimura & Papadimitriou 2001, Cordeau et al. 2005). In our problem, the arrival time of a barge is uncertain since it depends on the available slots at this terminal as well as at other terminals this barge has to visit. As a result, terminals have to plan their quays taking into account possible future barge arrivals. This brings us at a second important assumption within BAP, namely that the operations of a terminal are not influenced by other terminals. In our problem setting we deal with multiple terminals which mutually depend on each other because barges have to visit, in general, more than one terminal. This means that the arrival time of a barge at a terminal is also a result of decisions made at other terminals. A final important difference is that in the BAP the planning of vessels can be optimized, since we know exactly when vessels arrive, how much handling time they require and so on. In our problem setting, the barge operators eventually decide when they are processed at the terminal. This means that we cannot optimize the handling of barge in the same way as in the BAP, but instead we have to act indirectly by offering the ‘right’ set of time slots.

Although there are important differences with the BAP, we can also learn from the way the BAP is modeled. For instance the dimensions of the BAP and the issues we have to take into account. Bierwirth & Meisel (2010) identify different dimensions. First, how to deal with the spatial attribute, i.e., can we treat the quays as being discrete entities, a continuous line, or something in between? Second, how to deal with the temporal attribute, since that determines what information about the vessels we have at what point in time? Third, how to approach the handling time, is it fixed, does it depend on the berthing position, or does it depend on the quay crane operation schedule? Fourth, how to we measure the performance of our algorithm? All these questions have not been answered yet for the barge handling problem.

To plan a barge, we need at least one crane, one crew, a quay space, and time. The planning of quay cranes (and crew) 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., Park & Kim 2003, Lokuge & Alahakoon 2007, Imai, Chen, Nishimura & Papadimitriou 2008). A literature overview on integration approaches for BAP, QCAP, and QCSP is given by Bierwirth & Meisel (2010). The planning of quay space depends on the choice whether a quay is a continuous line or consists of discrete berths. Moreover, in case of a quay as a continuous line, we have to apply advanced methods to determine the times upon

which we have sufficient time and space available to handle a barge. This problem is related to the Maximum Empty Rectangle (MER) problem (Chazelle, Drysdale & Lee 1986, Handa & Vemuri 2004). An extension of this problem is required to deal with the fact that planned ships may be moved, either in space or in time (depending on the appointments that are made).

In case of discrete berths, the BAP can be modeled as an parallel machine scheduling problem where a ship is treated as a job and a berth as a machine (Cordeau et al. 2005). Closely related to our problem is the online parallel machine scheduling problem where jobs have to be scheduled in real-time without (or with little) knowledge of future jobs. The effectiveness of an online algorithm is usually measured by its competitive ration (Pinedo 2008). This ratio describes the worst the online algorithm can do compared to the optimal case of solving the problem offline with all data known. An overview of literature on online parallel machine scheduling is given by Hall, Schulz, Shmoys & Wein (1997). Some recent examples can be found in (Liu, Zheng, Chu & Xu 2011, Schulz & Skutella 2002, Megow, Uetz & Vredeveld 2005, Megow & Schulz 2004). A major difference with problems in online (or real-time) scheduling is that in the PAT-system the terminal operator can only indirectly influence the time the barge is handled, since a barge operator planner eventually decides for which time slot he opts. Additionally, we should not neglect the role of the planner who may intervene in the schedule, reallocate capacity, or make other decisions to improve the utilization of the terminal.

In this paper we approach the problem using a multi-agent system, see Wooldridge & Jennings (1995) for an introduction into this topic. In an extensive survey on existing research on agent based approaches in transport logistics, Davidsson, Henesey, Ramstedt, Törnquist & Wernstedt (2005) state that especially applications of agents in transportation via water are scarce and most papers have focused on the alignment of activities at a single terminal. For example, Gambardella, Rizzoli & Zaffalon (1998) try to find optimal solutions for the placement of containers in the yard while assuming that the cranes use a fixed policy. Vidal & Huynh (2010) present strategies for the cranes to use to minimize the trucks' wait time given random truck arrivals. Some preliminary work on simulating the ships and their allocation is presented in (Rebollo, Julian, Carrascosa & Botti 2001) and similarly in (Thurston & Hu 2002). Henesey, Davidsson & Persson (2009*b*) investigate the the movement of containers from the ship into the yard and considers various policies for the sequencing of ships, berth allocation, and the use of simple stacking rules (Henesey, Davidsson & Persson 2009*a*). We agree with Davidsson et al. (2005) that most agent based approaches (especially in the maritime industry) are not evaluated properly and comparisons with existing techniques are rare. Most papers stay at the level of a conceptual agent model and sometimes draw conclusions about the (expected) performance of the model without presenting experimental results. Examples of two recent papers that apply a quantitative evaluation of their multi-agent model for the optimization of terminal operations are Henesey et al. (2009*a*) and Lokuge & Alahakoon (2007).

Finally, 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 and not updated during execution (Melis, Miller, Kentrop, Van Eck, Leenaarts, Schut & Treur 2003, Schut, Kentrop, Leenaarts, Melis & Miller 2004). From this work it became clear that a decentralized control structure offers an acceptable solution for the parties involved (Moonen, Van de Rakt, Miller, Van Nunen & Van Hillegersberg 2007). Next, the focus was on a real-time agent based planning system, as presented in the work of Douma and co-authors (Douma et al. 2009, Douma, Schuur & Jagerman 2011, Douma, Schuur & Schutten 2011). They show that a distributed planning approach using an interaction protocol based on service-time profiles performs very well, even compared to central coordination. The presented solution was received with great enthusiasm by the terminal and barge operators.

In this paper we contribute to the existing literature by studying how to schedule ships (barge and sea vessels) such that a high terminal utilization is realized. We take the perspective

of a single terminal which operates within a port-wide multi-agent system for the barge handling problem as described by Douma, Schuur & Schutten (2011). A consequence of using this system is that the terminal agent has to respond dynamic, in real-time, and (partly) automatic to barge handling requests. In contrast with our earlier work, we explicitly focus on operational planning from the side of the container terminals taking into account disturbances. The purpose of this paper is explorative, namely to get insight in the most promising solution approaches for the research objective at hand.

### 3 Model description

In this paper we take the perspective of a single terminal, which is located in a port where also other terminals operate. We assume that the activities at other terminals can be modeled as a black box and are reflected in the arrival process of barges at the terminal of interest. As point of reference, we consider the largest terminals in the Port of Rotterdam. These terminals are characterized by high volumes, large numbers of quay resources, and high utilization degrees (say more than 80%). A quay is defined as a combination of three resources, namely crew, crane(s), and berthing position(s). We assume that a ship (barge or sea vessel) is handled at one quay, and that the berth length of a quay is never restrictive. We focus on the operational planning level of the terminal. This means that several decisions made at tactical level (such as the amount of capacity deployed) are a constraint at the operational planning level.

We present the proposed new way of working by means of a multi-agent system in Section 3.1, after which we present our objective and performance indicators (Section 3.2), the decisions we have to make (Section 3.3), and our solution approach (Section 3.4).

#### 3.1 Multi-agent system

The generic setting of this research is a terminal operator that has to plan dynamically, in real-time, and partly automatic. To meet these requirements, the terminal uses planning software to make appointment with barges, plan its resources, and monitor the various processes. Although the insights from this article apply to the generic setting, we illustrate our approach using the multi-agent system proposed by Douma, Schuur & Schutten (2011). In the remainder of this section, we shortly explain this system, which is being implemented within the BATMAN project, to understand the decisions a terminal has to make in this specific case.

Starting point of the distributed planning approach, proposed by (Douma et al. 2009, Douma, Schuur & Schutten 2011), is improving the reliability of appointments. Making appointments only makes sense when they are reliable (Douma, Schuur & Jagerman 2011). The basic idea of the proposed system is that terminal and barge operators get a software agent that act on their behalf. The distributed planning approach is preferred by terminal and barge operators, because it enables them to stay in control of their own operations (autonomy) and share only limited information. The crucial information shared by the terminal agents are the so-called service-time profiles. A service-time profile is issued on request of a barge operator and denotes a guaranteed maximum service time given a certain arrival time at the terminal during a certain time period, where service time is defined as the sum of the waiting and handling time at this terminal. Hence, a service-time profile is barge and time specific. Barge operators can use these profiles to optimize their rotation (sequence of terminals visits). Terminal operators in turn can use the profiles 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 service-time profiles at all terminals that he has to visit. A terminal has to reply instantaneously by issuing a service-time profile. The terminal has to do so with only limited knowledge about future arriving barges. After receiving all service-time profiles, 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 latest arrival time and a guaranteed maximum service time. By making the appointment, the barge commits itself 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, irrespective of the reason of the delay. The reason we do so is that in a network of terminals it is very hard to point the initial cause of a delay due to the dominoes effects that take place. Without this implication of being late, there is no incentive for barges to uncouple terminal operations by including slack time between terminal visits. This way, we make the network as whole more robust against (small) disruptions. This is desirable from a system perspective. During the whole process from planning to execution, the terminal has to deal with uncertainty and disturbances, such as uncertain arrival time and handling times of barges and sea vessels, as well as cancellations and no-shows.

### 3.2 Objective and performance indicators

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. For the terminal it is less important that a berthing position is not used than that a crew is idle. However, as stated by Imai, Zhang, Nishimura & Papadimitriou (2007), decision making at a container terminal has a multi-objective nature. There is a balance between terminal utilization and the waiting times of barges. For example, a terminal can make poor decisions resulting in a growing queue of waiting barges. This queue can be used efficiently by the terminals to fill their capacity leading to a high utilization. Another complicating fact in the barge handling problem is that a terminal cannot be considered in isolation. Because barges have to visit multiple terminals in one rotation, domino effects of disturbances are likely to happen. A network of terminals also means that waiting time at the terminal is not by definition a problem for a barge, since other terminals can possibly be visited in the mean time.

We make two comments regarding the utilization degree 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 degree 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, then, at an operational level, the utilization degree of a terminal is more or less given by the workload of barges that visit the terminal during that period of time. We state ‘more or less’ given, since the latter only holds when the terminal does not reject the handling of barges. This might be necessary if the terminal applies a poor scheduling policy.

Let us give an example. Suppose that a terminal schedules three barges successively on a single quay as depicted in Figure 1 and suppose that there are hardly any ships with a call size smaller than or equal to two time units. Then it is very unlikely that the idle times in the schedules will be filled. The terminal will therefore waste capacity, which leads to increasing waiting times of barges. The situation would have been different if all ships were scheduled immediately after each other.

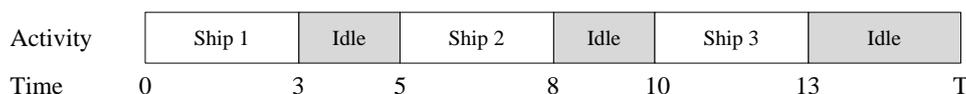


Figure 1: Illustration of the value of idle time

Taking the two comments into account, we operationalize the objective function using the

following performance indicators:

1. *Average utilization degree*: This is the sum of the handling time of all accepted barges (in minutes) divided by the capacity deployed by the terminal (in minutes) in a certain period of time.
2. *Average waiting time barges*: Waiting time is measured as the difference between the start of handling of a barge and its arrival time at the terminal.

These two indicators reflect the trade-off the terminal will make when planning their terminal resources.

### 3.3 Notation and decisions

Throughout this paper we use several time variables. The process starts with a barge  $n$  requesting an appointment at the terminal. We assume that this barge has a preferred (or earliest) arrival time  $e_n$  at this terminal. An appointment consists of a latest arrival time  $l_n$  and a latest departure time  $d_n$ . The latest departure time  $d_n$  is guaranteed by the terminal when the barge arrives on time ( $a_n \leq l_n$ ). When the barge arrival too late ( $a_n > l_n$ ), the appointment will be canceled. We further introduce a handling time  $h_n$  for the time required to load/unload the containers from a barge or sea vessel, 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  $a_n$  in case of an early arrival.

To cope with disturbances, the handling times for the different ships should not be scheduled too close to each other. To do so, we propose the use of slack and buffers. Terminals might include slack  $s_n$  in the latest departure time  $d_n$ , such that  $d_n = l_n + h_n + s_n$ . This way, the terminal has some flexibility in choosing the planned starting time  $b_n$ . By using a buffer  $w_n$ , the terminal only consider time intervals which are at least  $w_n$  longer then the required handling time  $h_n$ , i.e., intervals shorter then  $h_n + w_n$  are not offered to the barge. The buffer is used to avoid a situation in which a newly inserted ship makes later scheduled ships critical. Critical means that a ship is planned to be completed at its latest departure time. Any delay in the schedule will therefore results in a departure of the ship later than its latest departure time.

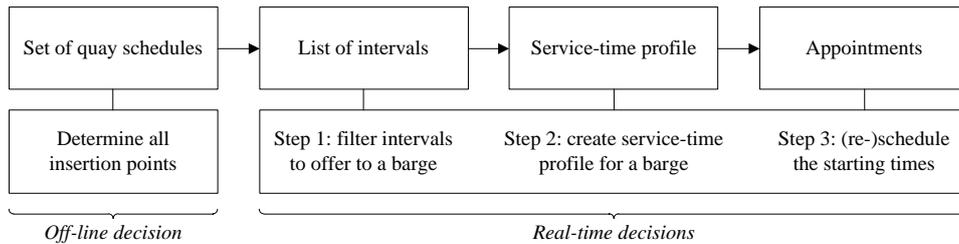


Figure 2: Decisions steps for terminals

To create a service-time profile in real-time, we propose that the terminal follows the steps depicted in Figure 2. The terminal starts with considering all quay schedules and determines all possible intervals in which a barge could be handled. These intervals depend on the scheduled ships as well as on the resource capacities (which are set by decisions made on the tactical planning level). This process can be performed off-line and is irrespective of a specific barge.

In this paper we focus on the real-time operational decisions with respect to the planning and handling of barges. When a specific barge requests a service-time profile, then the terminal operator considers the list of intervals and selects those intervals (or sub intervals) that will be offered to the barge operator via a service-time profile (step 1). Based on these intervals, the terminal can construct a service-time profile in real-time (step 2), see Douma, Schuur & Schutten (2011). After an appointment has been made, the terminal has to schedule the starting times

$b_n$  and has the option to re-schedule barges (step 3). To summarize, we consider the following decisions:

- Which intervals to offer via a service-time profile (step 1).
- How much buffer to use between scheduled ships (step 1).
- How much slack to use in the agreed service times (step 2).
- To schedule the starting time of barges (step 3).
- Whether to re-schedule the barges (step 3).
- Whether to cancel an appointment (step 3).

We assume that decisions with respect to resource capacity (e.g., the working times of crews) are made up front on a tactical planning level. Hence, these decisions are out of the scope of this research.

### 3.4 Solution approach

To reach our objective, to come up with operational planning rules for terminals given the changed setting in which they have to operate, we explore two solution approaches. The reason we consider these two approaches, which we describe below, is that we expect that the most promising solution, both in terms of efficiency as well as acceptability, consists of a combination of these two.

First, we explore an analytical approach that can be used for the operational decisions from steps 1 and 2 (see Section 3.3). The idea is that we attach values to intervals (also called gaps in the schedule) by computing a gap value for each interval. A similar approach is considered by Mes, van der Heijden & Schuur (2010) for the planning of full-truckload transportation. Our objective with this approach is (i) to investigate whether the concept of gap values is useful to support the terminal in its operational decisions regarding the filtering of intervals (step 1) and (ii) to get insight in the added value of using slack in the agreed service times (step 2). This approach is meant to be explorative; a full and more realistic analytical derivation is part of future research.

Second, we approach the problem from a more practical point of view by considering various sources of flexibility. A source of flexibility is for example slack that is added to the service-time profile. This slack enables a terminal to move appointments in time to create new planning possibilities. From practice, we observed 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 enhance the performance of the terminal. These insights can then be used (i) to support ‘rules of thumb’ for the terminal operators and (ii) form a basis for the extension of our analytical approach.

The two solution approaches are presented in Section 4 and 5 respectively.

## 4 The value of gaps in a schedule

In this section we explain the concept of gap values and explore the usefulness of this concept to evaluate (i) the value of scheduling an appointment at different positions within a gap and (ii) of adding slack to an appointment. First, we describe how the gap values can be computed (Section 4.1) after which we describe how these gap values can be used by terminal operators to influence the appointment times a barge might opt for (Section 4.2). We end with a numerical example in Section 4.3.

## 4.1 Determining the gap values

At each point in time, the terminal has a schedule containing all appointments with ships. To simplify the presentation, we assume that the terminal can be considered as a single machine, i.e., has only one berth. Without loss of generality, we also ignore the scheduled opening and closing times of terminals, which in principle can be scheduled in a similar manner as the handling of ships. Formally, we define a schedule  $\Psi$  by an ordered list of 4-tuples  $\Psi_n = (l_n, d_n, b_n, h_n)$  where  $n$  refers to the  $n^{\text{th}}$  ship in the schedule.

We define a gap with length  $\omega$ , as the maximum amount of idle time between two scheduled ships. We mention “maximum” because the terminal has flexibility in the starting time  $b_n$  of a ship  $n$  when using slack ( $s_n > 0$ ). For the gap immediately after ship  $n$ , we have  $\omega = (d_{n+1} - h_{n+1}) - (l_n + h_n)$ . An illustration can be found in Figure 3. For instance, gap 2 has a length  $\omega = (d_3 - h_3) - (l_2 + h_2) = (12 - 3) - (5 + 3) = 1$ . Besides this length, a gap is also defined by a time-to-go  $\tau$ , which is the difference between the earliest departure time of the ship just before this gap and the current time. Using the example of Figure 3, the time-to-go  $\tau$  for gap 2 is 8.

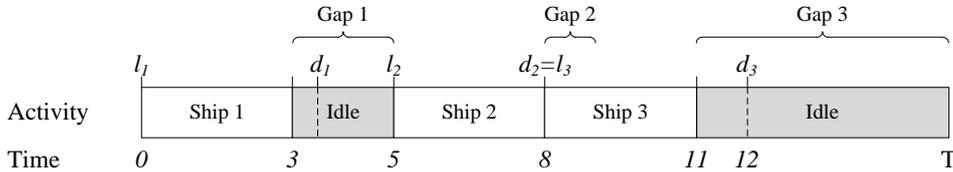


Figure 3: Illustration of the value of idle time

We define the value  $V^g(\tau, \omega)$  of a gap as the expected number of time units within the gap that will be filled. This value can be computed if the terminal has some knowledge about future barge requests in the form of probability distribution functions. In principle, this information could be derived from historical data. However, the main difficulty here is that the arriving barges can decide for themselves on their position in the schedule, both within a gap as well as between gaps. Hence, the probability that a certain barge opts for a particular gap depends on the characteristics of the other gaps at this terminal as well as on the availability of other terminals in the port.

To provide an idea how these gap values can be computed, we make several simplifying assumptions. A comprehensive analytical approach to compute these gap values in a more realistic way is part of future research. First, assume that the individual gap values are independent. Then, the probability distributions for new request depend on the gap length  $\omega$  and the expected number of ships  $k$  that opt for an appointment time within this gap during the time-to-go  $\tau$ . Now suppose the terminal has some knowledge about future barge requests in the form of the following two distribution functions:

$p_{\tau, \omega}(k)$  = probability of receiving exactly  $k$  request for arrivals for the gap characterized by  $\tau$  and  $\omega$ .

$q(h)$  = probability that a ship has a handling time of  $h \in \mathcal{H}$ .

Next, assume that ships arrive one-by-one and that upon each request a decision has to be made whether to schedule or reject the arrival request. We assume that ships can be put in a gap as long as the total handling times of all ships does not exceed the gap length. This also means that we reject ships that do not fit. With respect to the scheduling of ships arriving in the time-to-go, we assume that all ships are planned right after one another. We introduce  $G(\omega, k)$  to denote the value of a gap with length  $\omega$ , given that we receive exactly  $k$  request for

arrivals within this gap. The gap value  $V^g(\tau, \omega)$  can now be computed recursively using

$$V^g(\tau, \omega) = \sum_{k=0}^{\infty} p_{\tau, \omega}(k) \cdot G(\omega, k),$$

where

$$\begin{aligned} G(\omega, k) &= \sum_{h \in \mathcal{H} | h \leq \omega} p(h) \cdot [h + G(\omega - h, k - 1)] + \sum_{h \in \mathcal{H} | h > \omega} p(h) \cdot G(\omega, k - 1) \\ G(\omega, 0) &= 0 \\ G(0, k) &= 0. \end{aligned}$$

Note that  $G(\omega, k)$  is non-decreasing for increasing values of  $\omega$  and  $k$ , i.e., for larger values of  $\omega$  and  $k$  it is more likely that the time within this gap will be utilized.

## 4.2 Using the gap values

Gap values can be used to decide (i) where to put a barge in the schedule, (ii) which intervals to offer to a barge, and (iii) how much slack to use in the agreed latest departure times. Without introducing formal mathematical notation, we here define  $V(\Psi)$  as the value of schedule  $\Psi$ , which is given by the sum of all gap values  $V^g(\tau, \omega)$  within this schedule. Adding a new appointment to the schedule  $\Psi$  will result in a new schedule  $\Psi'$  with an updated value. The best choice regarding the appointment time and the amount of slack can be found by maximizing  $V(\Psi')$ .

The difficulty here is that gap values depend on each other. So, if we insert a ship in one gap and postpone the handling time of the next ship, then this will have an influence on the next gap. However, in principle this can be solved. First, assume that postponing the handling times will have no effect on the time-to-go  $\tau$  for the other gaps. Then, the impact of delaying an appointment, only has an impact the lengths  $\omega$  of the gaps after this appointment time. We can then compute all gap values recursively, starting with the last gap, for all intermediate values of  $\omega$ . This idea is illustrated, although for another problem class, in Mes et al. (2010).

		Gap length	
		Small	Large
Time-to-go	Short	+-	+
	Long	-	+-

Figure 4: Division of gap priorities

In the before mentioned solution approach, we treat all gaps equally important. However, the urgency to fill a gap may vary. In Figure 4 we illustrate two dimensions for the urgency to fill a gap, namely the length of the time-to-go and the length of the gap. If the length of a gap is large and the time-to-go is short, then filling the gap may get high priority. Gaps with lower priority are gaps with a long time-to-go that have a small gap length. The insights from Figure 4 can be used within a simple policy that focuses on filling the most urgent gaps first (by making these gaps more attractive within the service time profiles, or even removing the non-urgent gaps from the profile). Investigating this statement is part of future research.

## 4.3 Numerical example

Let us do a quick exploration to see whether the concept of gap values is useful. Specifically, we want to find out what the impact is of (i) scheduling an appointment time at different positions within a gap and (ii) of adding slack to an appointment.

For the purpose of our exploration, we use Monte-Carlo simulation to give a rough indication of the value  $V(\Psi)$  after scheduling a new ship. We take the following approach. Consider a terminal having a schedule with one gap, starting at time  $\tau$  from now and ending at the end of the planning horizon  $T = \tau + 10$ . Now, a ship request an appointment time, which is  $\tau + x$  time units from the current time, with  $0 \leq x \leq 10$ . For simplicity assume that the ship has a handling time of zero. The insertion of this ship will result in two gaps, namely one with a length of  $x$  and one with a length of  $10 - x$ . Further assume that during the time-to-go  $\tau$  exactly  $K$  arrivals take place. Each of these arrival requests has a random handling time which is drawn from a Normal distribution  $\mathcal{N}(6, 3)$ , rounded up to the nearest integer, and using the bounds  $[1, 10]$ . The probability that this request opt for one of the two gaps is proportional to the length of this gap. If the ship does not fit in this gap, we consider the other gap. If it does not fit on both gaps, then we cancel this request. If the ship fits in gap 1, then we schedule the ship directly at the start of gap 1. If the ship fits in gap 2, then we schedule the ship right at the end of gap 2. So a new arriving ship never results in splitting gap 1 or gap 2 in two new gaps. The value of the schedule is now given by

$$V(\Psi) = V^g(\tau, x) + V^g(\tau + x, 10 - x),$$

where the gap values  $V^g(\tau, \omega)$  are computed using the simulation described above.

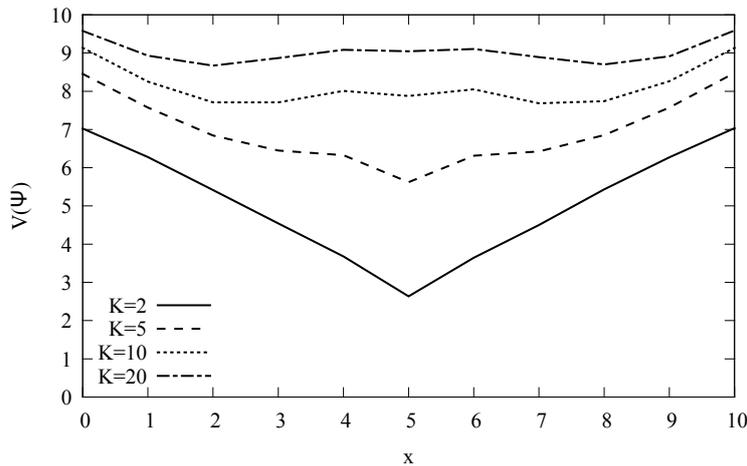


Figure 5: Value of a schedule after scheduling the new ship

We perform 10,000 replications for different values of  $x$  and  $K$ . The results can be found in Figure 5. From this figure we make the following, rather intuitive, observations:

1. Splitting a gap in two smaller gaps usually leads to a lower value for the schedule. The reason is that the smaller gaps can only be filled with ships having a length smaller than or equal to the length of each of these gaps.
2. The value of inserting a ship at different positions in the gap depends on the request rate, the handling time distribution, the time-to-go, and the total gap length. The best positions in general are insertions at the start or end of a gap.

Without showing the results, we found similar figures when running the experiment for other values of  $T$  and other process time distributions. Also, for the case in which we do not allow a ship to be scheduled outside the gap of its choice, we find similar figures, with the exception of having a smoother shape and lower minimum.

Now let us evaluate the value of a gap when we use slack in making appointments. By adding slack to an appointment, the terminal has the possibility to extend the starting time  $b_n$

of ship  $n$  with a time period equal to the slack  $s_n$ . In our example, this means that the length of gap 1 has a minimum of  $x$  and a maximum of  $x + s$ . The length of gap 2 is equal to 10 minus the length of gap 1.

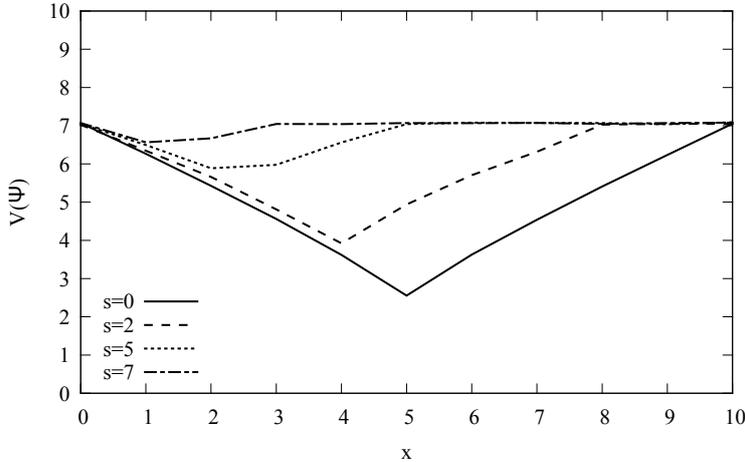


Figure 6: Value of a schedule using slack

Figure 6 shows the results for  $K = 5$  and different values of  $x$  and  $s$ . We observe that adding slack to appointments leads, on average, to an increase of the value of a schedule. Insertion points at the end of the gap show the biggest increase in value when positive amounts of slack are added. The reason for this is that the starting time  $b_n$  of a ship can always be postponed from  $l_n$  to  $l_n + s_n$ , whereas it cannot be processed earlier than its latest arrival time (unless the barge arrives early which is not known in advance).

Note again that the above mentioned analysis is due to several non-realistic assumptions, such as the assumption that ships arriving in the time-to-go never split a gap into two new gaps. Nevertheless, the insights we derived from the single gap analysis can be applied by the terminal operator using the proposed multi-agent system. The terminal can do so by varying the amount of slack added to the service-time profile. For example, the terminal can use a slack policy where a relative large amount of slack is used for appointment times that have a large impact on the value of the schedule. By doing so, the terminal becomes more indifferent to the final choices made by the barge agents.

## 5 Potential sources of flexibility

In the previous section we explored the usefulness of gap values for terminals to make appointments with barges dynamically. One of our findings is that the value of the schedule can be increased significantly when adding slack to appointments with ships. Through slack we improve the flexibility of the terminal to reschedule barges when new events happen. In fact, adding slack reduces the probability that the terminal regrets a past decision in the view of a new situation.

In this section we consider another approach, which builds further on these insights, by focusing on various sources of flexibility. We define a source of flexibility as a factor (that can be influenced by the terminal or not) that offers planning flexibility in the terminal schedule. For instance, slack is a source of flexibility, since the terminal can still move the starting times of ships thereby creating possibilities for later arriving ships. In this section we analyze the effects of these sources of flexibility. The results from this analysis can be used (i) as ‘rules of thumb’ for the terminal operators and (ii) form a basis for the extension of our analytical approach as presented in Section 4.

First, we discuss potential sources of flexibility (Section 5.1). Then, we describe the simulation model we use to evaluate the impact of using the different sources of flexibility (Section 5.2). In Section 5.3 we present the numerical results.

## 5.1 Potential sources of flexibility

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

- *Slack*. The terminal can add slack  $s_n$  to an appointment with a barge, meaning that the terminal gets some freedom to postpone the starting time  $b_n$  up to  $l_n + s_n$ .
- *Buffer*. The terminal might only consider intervals that are at least  $w_n$  longer then the required handling time  $h_n$ .
- *Re-scheduling*. The terminal may reschedule barge appointments thereby improving its quay schedules.
- *Cancellation*. The terminal can cancel appointments, e.g., when a schedule is not feasible anymore.
- *Multiple quays*. Multiple quays at the terminals give the terminal operator planner the possibility to (re)schedule barges over the quays.

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 a gap.

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 also be welcome when the terminal deals with delays. Here we assume that cancellations just take place and therefore consider it as a potential source of flexibility.

## 5.2 Simulation model

To investigate the impact of the different sources of flexibility, we use discrete event simulation. In the simulation we consider a terminal which handles barge and sea vessels, and has to deal with disturbances like cancellations and deviations in the handling time of ships. To provide realistic insights, we use the large terminals within the Port of Rotterdam as point of reference for our experimental setup. The parameter settings used for the simulation can be found in Appendix A.

We choose to consider one terminal in ‘isolation’, i.e., we model the rest of the port as a black box. As a result, we do not model barge rotation planning. Instead we assume that barges arrive at the terminal as follows. Barges arrive at a fictitious port entrance point with exponentially distributed interarrival times. When a barge arrives at this entrance point, it determines a preferred arrival time at the terminal and announces this time to the terminal. The preferred arrival time is drawn uniformly between the current time and several hours later.

In this way we mimic a realistic arrival process at the terminal, i.e., a barge that arrives later in the port may be processed earlier at the terminal than another barge that arrived earlier in the port. Moreover, the schedule of the terminal will consist of several gaps, 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  $e_n$ . The terminal schedules each barge with starting time  $b_n$  equal to the latest arrival time  $l_n$  and the latest departure time  $d_n = a_n + h_n + s_n$ . 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.

The number of containers to load/unload, announced by a barge, is subject to uncertainty. We assume that the exact number of containers to load/unload is known upon the start of handling a barge. With respect to sea vessels, we assume that they announce their real arrival time and total number of containers to load and unload several hours prior to their initial planned arrival time. The handling of sea vessel has priority over the handling of barges.

We assume that a certain fraction of the terminal capacity is reserved for handling of the sea vessels. We determine the arrival rate of barges and sea vessels using a desired utilization degree (instead of the other way around). The desired terminal utilization degree in the simulation is 85%, of which 45% is reserved for barges and 40% for sea vessels. Reasons to choose for a 85% utilization degree are (i) to resemble a realistic utilization degree for the terminals under study and (ii) to create a situation in which the scheduling of barges will be non trivial. We choose to control the utilization degree and derive from that the mean interarrival time. For both, barges and sea vessels, this interarrival time is computed by

$$\text{mean interarrival time} = \frac{\text{mean handling time} * (1 - \text{cancellation rate})}{\text{terminal capacity} * (\text{desired utilization degree})}, \quad (1)$$

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

During the simulation, several disturbing events may take place which require an action of the terminal. We consider four types of disturbances. First, a barge arrives earlier than planned, this becomes known upon arrival. Second, a barge cancels its appointment, this will be announced by the barge prior to its arrival. Third, the handling time of a barge appears to be different, this becomes known upon the start of handling. Fourth, a sea vessel arrives at a different moment or has a different handling time, this information will be announced by the sea vessel prior to its arrival. In case of a disturbance, the terminal applies a policy as mentioned in the list below.

- *On arrival of a barge.* The terminal checks if it can start handling the barge without violating other appointments.
- *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 barge 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 that fits in the gap until either the gap is filled or the list of candidate barges is empty. The same procedure is then applied for

No.	Factor	Low	High	Comment
1	Early arrival	0	120	The barge arrives in the low scenario at its latest arrival time, in the high scenario a uniformly distributed time between 0 and 120 minutes later.
2	Deviation in handling time	-	+	Weibull distribution for the number of containers to load and unload, with parameters $\lambda = 2.1$ and $\kappa = 33.9$ (mean of 30 and variance of 15) for the low value and with parameters $\lambda = 1$ and $\kappa = 30$ as high value (mean of 30 and variance of 30).
3	Cancellations by barges	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.

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

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 than 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 sea 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 canceled (no new appointment with this barge is made). If an appointment with a sea vessel is violated due to a scheduled barge, then the terminal cancels the barge appointment.
- *On receiving an update from a sea vessel.* When a sea vessel announces its real arrival time and the required handling time, then the terminal updates the quay schedules. In case the sea vessel appointment conflicts with scheduled barges, then the barge appointment is canceled. If the appointment conflicts with an earlier scheduled sea vessel, then the arrival time of the sea vessel is updated with the completion time of the earlier scheduled sea vessel. If the appointment conflicts with later scheduled sea vessels, then the appointments with later scheduled sea vessels are postponed.

Potential sources of flexibility may reduce the negative effect of disturbances on the terminal performance. In Section 5.1 we mentioned several sources of flexibility. A full-factorial analysis with respect to these factors is computationally intractable. We therefore choose for a  $2k$  factorial design (Law 2007). In a  $2k$  factorial design we choose two levels for each factor, which means that we have  $2^k$  possible factor-level combinations. The two levels of a factor are usually denoted by a plus and a minus sign, denoting the high and the low level respectively. The choice for the plus and minus value of a factor should be not too far from each other, to avoid that important effects in the response are not noticed. One combination of all factors at a certain level is called a design point, the list of all design points is called the design matrix.

We choose to consider six factors (sources of flexibility) in all combinations, where each factor can have two levels (high and low). Table 1 denotes the six sources of flexibility that are considered, with their respective high and low value. Sources of flexibility we treat as fixed input are (i) the number of quays, (ii) the cancellation policy of the terminal, and (iii) the

deviation in handling time and arrival time of sea vessels (see Appendix A for this input). The total number of design points considered equals  $2^6 = 64$ , which is still tractable. The resulting design matrix can be found in Appendix B. Each of the designs is replicated five times and one replication has a length of 365 days. The warm-up period for each replication is 10 days.

### 5.3 Numerical results

In this section we present the results from the simulation experiments described in the previous section. First, in Section 5.3.1, we present the results of the  $2k$  factorial design. As we will see, this analysis shows that there are three factors that have a significant higher impact on the performance. Therefore we consider a full factorial experiment with respect to these factors in Section 5.3.2.

#### 5.3.1 $2k$ factorial analysis

To evaluate the impact of the potential sources of flexibility we did several analyses. We start with depicting the results (averaged over all replications) of each scenario considered with respect to both performance indicators, the utilization degree and the average barge waiting time.

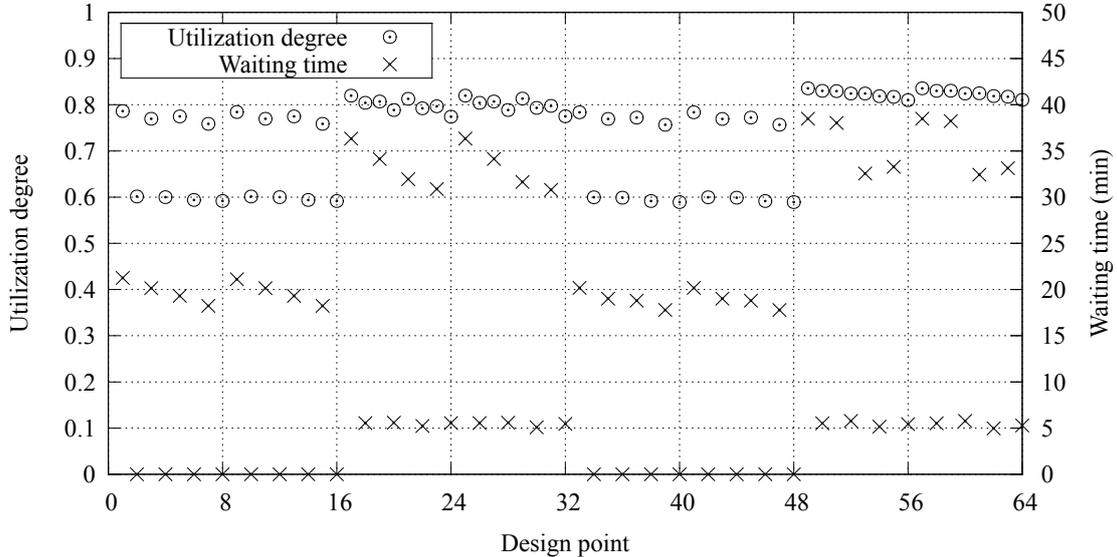


Figure 7: Results for the  $2k$  factorial design

From Figure 7 we draw the following conclusions:

1. The scenarios 17-32 and 49-64 result in the highest average terminal utilization degree. These scenarios correspond with a high value of factor 5, i.e., adding slack to appointments.
2. In scenarios where barges arrive early (the uneven scenarios), we observe a higher utilization degree than the corresponding scenarios in which barges arrives at their latest arrival time. This is different when also slack is added to appointments (compare, e.g., scenarios 1-16 with scenarios 17-32).
3. 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 scenarios 17-32).
4. A buffer seems to have effect only when also slack is used in the appointments (compare scenarios 49-64 with 17-32, and scenarios 33-48 with 1-16).

5. Re-planning on cancellations seems to have no visible impact (compare for instance 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-factor interaction effects. We consider these effects with respect to both performance indicators for each of the six factors considered. The complete analysis can be found in Appendix C. Here we only mention the main conclusions. 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 degree of the terminal or on the average barge waiting time. However, they do impact the flexibility of the terminal in the short term.

In the next section we choose to take a closer look at the factors that have the highest impact, i.e., factors 1, 5, and 6, to see how the performance of the terminal depends on different values for each of these factors.

### 5.3.2 Zooming in on three sources of flexibility

In this section we focus on three sources of flexibility, namely slack, early arrivals, and the buffer. We evaluate these factors in all combinations, where each factor has four different values: slack  $\in \{0, 40, 80, 120\}$ , early arrival  $\in \{0, 30, 60, 120\}$ , and buffer  $\in \{0, 20, 40, 60\}$ . The reason we study these factors in more detail is that we are interested in the impact of each of these factors (and the factors in combination) on the utilization degree of the terminal and on the waiting times of barges.

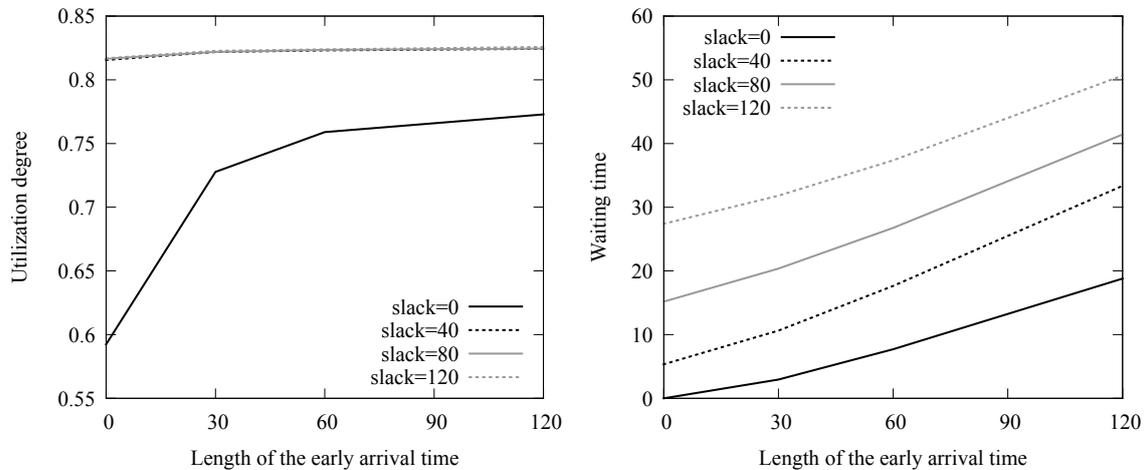


Figure 8: Varying length of early arrival time for given buffer of 20 minutes

Figure 8 shows, for a given buffer of 20 minutes, the impact of early arrival and slack on the utilization degree and the waiting time of the barge respectively. We draw the following conclusions:

- Early arrival of barges positively impacts the utilization degree of the terminal, but worsens the average waiting time of barges.
- The extent to which early arrivals contribute to an improvement of the terminal utilization degree depends on the amount of slack used. If a positive amount of slack is being used ( $\geq 40$ ), then early arrivals only have a limited effect on the utilization.

- If 40 minutes slack is used (in case no barge arrives early) then the terminal utilization degree improves from about 60% to more than 80%, whereas the average waiting of barges increases with less than 10 minutes.

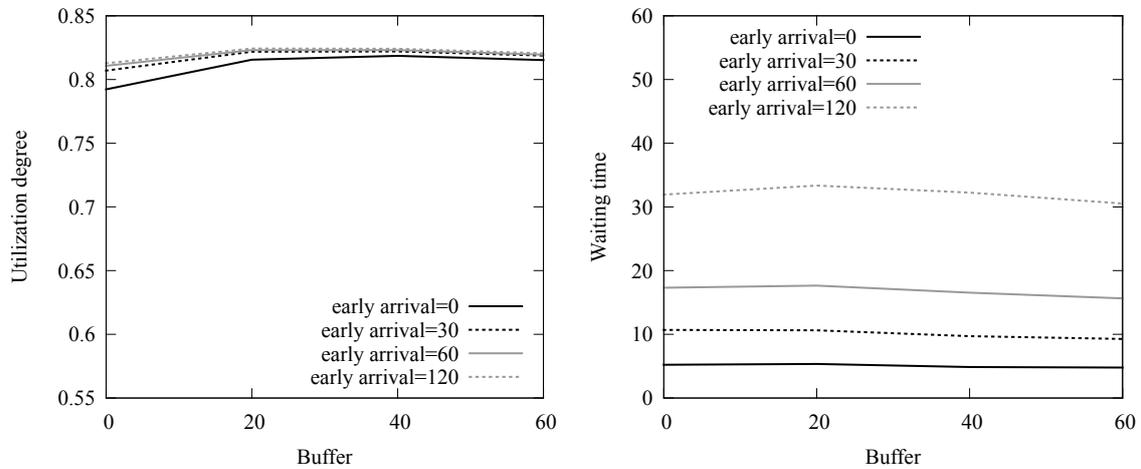


Figure 9: Varying buffer for given slack of 40 minutes

Figure 9 shows, for a given slack of 40 minutes, the impact of early arrivals and the buffer on the terminal utilization degree and the average waiting time. We conclude that a positive buffer improves the utilization degree of the terminal for different levels of early arriving barges. Moreover, a small buffer of 20 minutes already leads to the greatest improvement of the utilization degree if barges arrive 30 minutes or more early. We further see that a larger buffer leads to a minor decrease in waiting times.

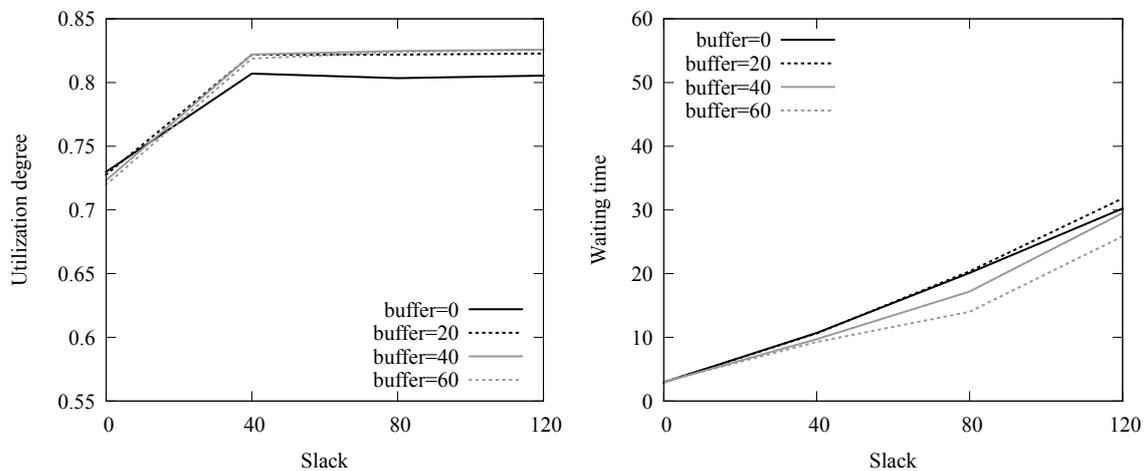


Figure 10: Varying slack for given length of 30 minutes early arrival time

Figure 10 shows, for a given maximum of 30 minutes earliness, the impact of slack and the buffer on the terminal utilization degree and the average waiting time. We conclude that a buffer does not add value when slack is zero. This is similar to the results found in the previous section. When using a positive amount of slack, the buffer improves the utilization degree 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 terminal utilization degree of 82% can be realized with a minimum use of three sources of flexibility, namely

slack (40 minutes), a buffer (20 minutes), and early arrivals (uniformly between 0 and 30 minutes). Without the use of these sources of flexibility, the terminal utilization degree is as low as 60% (in the experimental setting considered). Note that the maximum utilization degree that could be realized in our experimental setting is 85%.

## 6 Conclusions

In this paper 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 proposed by Douma, Schuur & Schutten (2011). The main challenge for the terminal agent is to make appointments with barges in 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 sea vessels, as well as cancellations and no-shows.

We explored two solution approaches, (i) an analytical approach based on the value of having certain intervals within a schedule and (ii) an approach based on sources of flexibility that are naturally available to the terminal. The reason we considered these two approaches, is that we expect that the most promising solution, both in terms of efficiency as well as acceptability, consists of a combination of these two.

The analytical approach is based on the concept of gap values, which describe the value of having certain intervals within a schedule. By using the gap values, a terminal can decide (i) which appointment times to offer to the barges and (ii) how much slack to add to the different appointment times. Through a numerical example, we showed that the gap values can be used efficiently for making appointments dynamically. In the second approach, we further explored the deployment of various sources of flexibility to enhance the terminal performance. To evaluate the sources of flexibility, we used a discrete event simulation model. 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 degree from 60% to 82% can be realized with a minimum use of the two sources of flexibility (slack of 40 minutes and a buffer of 20 minutes). This major increase in utilization is achieved under a minor increase in barge waiting times (5 minutes).

The promising results for both solution approaches give rise for further research in which we combine these approaches. Specifically, we aim to include the sources of flexibility, such as slack, within an analytical approach. The resulting methodology can then be used to support decisions regarding the amount of slack to be used, depending on the barge characteristics, other appointments, resource capacities, etc. More specifically, we aim to (i) extend the stochastic dynamic programming formulation by taking into account the dependencies between gaps and (ii) perform an in-depth analysis of the performance of such an approach compared to current way of working as well as to the heuristic approach considered in this paper.

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## Appendix A

An overview of the simulation settings can be found in Table 2 - 4.

Parameter	Value
Arrival distribution	Poisson arrivals with mean interarrival time given by Equation 1.
Handling time distribution	The number of containers to load/unload follows a Weibull distribution with their parameters as experimental factor (see Table 1). The handling time is given by multiplying the number of containers by 3 minutes.
Deviation in handling time	We deviate from the number of containers to load/unload by adding a number drawn uniformly between -5 and 5, using a lower bound of 1 for the total number of containers to load/unload.
Planning horizon	48 hours. This time is used to generate the preferred arrival time of a barge, which is drawn uniformly between 0 and 48 hours later than the arrival time of the barge at the port.
Early arrival	A barge may arrive earlier than its latest arrival time. The amount of earliness is drawn uniformly between 0 and $x$ minutes, where $x$ is a experimental factor (see Table 1).
Cancellation rate	Fraction of barges that cancel their appointment at the terminal. This is a experimental factor (see Table 1).
Time of cancellation	A barge may cancel an appointment at a time drawn uniformly between 0 and 5 hours prior to its latest arrival time.

Table 2: Barge settings

Parameter	Value
Arrival distribution	Poisson arrivals with mean interarrival time given by Equation 1.
Handling time distribution	The time in minutes is drawn from the Beta distribution with $\alpha = 1.14$ , $\beta = 8.3$ , a minimum of 0, and a maximum of 6400.
Deviation in handling time	The handling time is multiplied with a factor drawn uniformly between -0.2 and 0.2.
Planning horizon	Sea vessels plan their appointment 3 weeks in advance. The barge appointments are canceled in case of conflicts.
Early/late arrival	Sea vessels can arrive a certain amount of time early or late. This amount is drawn uniformly between -8 and 8 hours, using the current time as lower bound from the arrival time.
Announcement time	48 hours prior to the latest arrival time, the real arrival time of the sea vessel is announced together with the real number of containers to load and unload.
Cancellation rate	0%

Table 3: Sea vessel settings

Parameter	Value
Number of quays	4
Opening times	24 hours a day
Utilization degree	85%, where 40% is reserved for sea vessels and 45% for barges.
Re-scheduling	This is a experimental factor (see Table 1).
Slack	This is a experimental factor (see Table 1).
Buffer	This is a experimental factor (see Table 1).

Table 4: Terminal settings

## Appendix B

The design matrix for the  $2^6$  factorial design can be found in Table 5.

## Appendix C

We calculate the main effects and the two-factor interaction effects for each of the 6 experimental factors considered, using the design matrix from Appendix B. The main effect of a factor  $i$  gives the average change in response (outcome of the simulation) due to moving factor  $i$  from its minus to its plus level, while keeping all other factors fixed. The two-factor interaction effect is a measure for the interaction effect of two factors, and is defined as half the difference between the average effect of factor  $i_1$  when factor  $i_2$  is at its plus level and the average effect of factor  $i_1$  when factor  $i_2$  is at its minus level (keeping all other factors fixed). For more information we refer to (Law 2007). The results can be found in Table 6.

We can see that two factors have the biggest impact on the utilization degree when these factors are put from a low to a high value. These factors are factor 1 (early arrival of barges) and factor 5 (slack). However, there is a strong interaction effect between factor 1 and 5 of about -8%. The reason is that the terminal utilization degree in the simulation can never get higher than 85%, i.e., one of the two factors already puts the utilization degree of the terminal close to 85%. We also observe that a larger standard deviation in the handling time negatively impacts the utilization degree, although this impact is limited compared to the impact of factor 1 and 5. The same holds with respect to factor 3, the fraction of barges that cancels an appointment. A buffer has a limited but positive impact on the utilization degree of the terminal. However, we also see that the interaction effect between factor 5 and 6 is equally strong as the first order effect of factor 6. This means that a buffer only makes sense if slack is used in the appointments. This makes sense since applying a buffer without using slack simply results in small gaps with a length equal to the buffer.

When analyzing the impact of the potential sources of flexibility on the average barge waiting time, we find again that factor 1 and 5 have the biggest impact. The interaction effect of both factors is positive, in contrast to the analysis with respect to the utilization degree. This means that the average waiting time of a barge increases even more when both slack is added to the appointments and barges arrive early. The interaction effect between factor 0 and 2 indicates that the main effect of factor 3, i.e., a reduction of the waiting time due to barges that cancel appointments, can only be observed when barges arrive early. The other effects measured on the average barge waiting time are similar to the effects observed by the analysis on the impact of the utilization degree.

Until now, we defined the waiting time as the difference between the actual arrival time  $a_n$  (which equals the latest arrival time  $l_n$  minus the earliness) and the actual start time of handling the barge. However, we are also interested in the flexibility of the terminal regarding the preferred arrival time  $e_n$  of barges. Therefore, we define an alternative waiting time by the difference between the preferred arrival time  $e_n$  and the actual start time of handling the

		Experimental factor								Experimental factor					
Design point		1	2	3	4	5	6	Design point		1	2	3	4	5	6
1		+	-	-	-	-	-	33		+	-	-	-	-	+
2		-	-	-	-	-	-	34		-	-	-	-	-	+
3		+	+	-	-	-	-	35		+	+	-	-	-	+
4		-	+	-	-	-	-	36		-	+	-	-	-	+
5		+	-	+	-	-	-	37		+	-	+	-	-	+
6		-	-	+	-	-	-	38		-	-	+	-	-	+
7		+	+	+	-	-	-	39		+	+	+	-	-	+
8		-	+	+	-	-	-	40		-	+	+	-	-	+
9		+	-	-	+	-	-	41		+	-	-	+	-	+
10		-	-	-	+	-	-	42		-	-	-	+	-	+
11		+	+	-	+	-	-	43		+	+	-	+	-	+
12		-	+	-	+	-	-	44		-	+	-	+	-	+
13		+	-	+	+	-	-	45		+	-	+	+	-	+
14		-	-	+	+	-	-	46		-	-	+	+	-	+
15		+	+	+	+	-	-	47		+	+	+	+	-	+
16		-	+	+	+	-	-	48		-	+	+	+	-	+
17		+	-	-	-	+	-	49		+	-	-	-	+	+
18		-	-	-	-	+	-	50		-	-	-	-	+	+
19		+	+	-	-	+	-	51		+	+	-	-	+	+
20		-	+	-	-	+	-	52		-	+	-	-	+	+
21		+	-	+	-	+	-	53		+	-	+	-	+	+
22		-	-	+	-	+	-	54		-	-	+	-	+	+
23		+	+	+	-	+	-	55		+	+	+	-	+	+
24		-	+	+	-	+	-	56		-	+	+	-	+	+
25		+	-	-	+	+	-	57		+	-	-	+	+	+
26		-	-	-	+	+	-	58		-	-	-	+	+	+
27		+	+	-	+	+	-	59		+	+	-	+	+	+
28		-	+	-	+	+	-	60		-	+	-	+	+	+
29		+	-	+	+	+	-	61		+	-	+	+	+	+
30		-	-	+	+	+	-	62		-	-	+	+	+	+
31		+	+	+	+	+	-	63		+	+	+	+	+	+
32		-	+	+	+	+	-	64		-	+	+	+	+	+

Table 5:  $2^6$  factorial design matrix

Exp. effect	Utilization		Waiting time		Alternative waiting time	
	95% conf. interval		95% conf. interval		95% conf. interval	
$E(e_1)$	0.094	± 0.002	24.162	± 0.622	-69.325	± 6.035
$E(e_2)$	-0.010	± 0.001	-0.386	± 0.141	-150.175	± 34.636
$E(e_3)$	-0.011	± 0.004	-1.655	± 0.117	393.532	± 41.298
$E(e_4)$	0.000	± 0.000	-0.036	± 0.010	0.101	± 1.291
$E(e_5)$	0.128	± 0.002	10.267	± 0.354	-93.526	± 3.206
$E(e_6)$	0.011	± 0.000	0.379	± 0.106	180.954	± 33.187
$E(e_{12})$	-0.003	± 0.001	-0.504	± 0.121	3.098	± 2.556
$E(e_{13})$	0.000	± 0.000	-1.489	± 0.132	-16.694	± 4.110
$E(e_{14})$	0.000	± 0.000	-0.001	± 0.009	-0.647	± 0.999
$E(e_{15})$	-0.081	± 0.002	4.833	± 0.184	16.605	± 4.693
$E(e_{16})$	-0.003	± 0.000	0.389	± 0.063	-3.221	± 2.547
$E(e_{23})$	-0.001	± 0.001	0.173	± 0.055	-73.735	± 28.009
$E(e_{24})$	0.000	± 0.000	0.019	± 0.021	0.765	± 1.234
$E(e_{25})$	-0.001	± 0.001	0.153	± 0.060	9.283	± 2.412
$E(e_{26})$	0.002	± 0.000	0.226	± 0.076	-18.231	± 10.557
$E(e_{34})$	0.000	± 0.000	-0.039	± 0.006	1.120	± 0.779
$E(e_{35})$	-0.001	± 0.001	-0.856	± 0.099	-37.484	± 3.897
$E(e_{36})$	-0.001	± 0.000	-0.144	± 0.078	68.311	± 18.666
$E(e_{45})$	0.000	± 0.000	-0.027	± 0.026	1.246	± 1.016
$E(e_{46})$	0.000	± 0.000	0.011	± 0.016	0.358	± 1.510
$E(e_{56})$	0.013	± 0.001	0.766	± 0.110	4.045	± 6.892

Table 6: 95% confidence intervals for the expected effects

barge. The results with respect to the alternative waiting time can be found in the last column of Table 6. Note that a high values observed in the last column are not necessarily a problem, since barge operators may visit other terminals in the mean time.

The effects related to the alternative waiting times are quite different from the others. We see that the first order effect of factor 1 (early arrival of barges), factor 2 (larger dispersion of the barge handling time), and factor 5 (slack) is negative. This means that these factors positively impact the flexibility of the terminal in the sense that terminals have more possibilities to handle barges in the short term. Factor 3 (fraction of cancellations) and factor 6 (buffer) both reduce the flexibility of the terminal in the sense that the terminal has less possibilities to handle barges in the short term. In particular the effect of factor 3 is strong in this respect. This can be explained as follows. If factor 3 is at its high level, then we generate 120% barge arrivals. Part of these barges (20%) cancel their appointment at a random time prior to their latest arrival time. Newly arriving barges therefore face a highly occupied terminal when they make appointments, but shortly before execution of the planning it turns out that 20% of the barges cancels its appointments. In practice this would mean that a barge decides to visit several other terminals first before visiting our terminal, due to the fact that our terminal seems to be highly occupation in the short term. However, when executing its rotation, the barge will find out that the terminal is not occupied as much as the terminal suggested when making the appointment. The interaction effect of factor 2 and 3 shows that the impact of factor 2 is a bit larger if the dispersion in the barge handling time is larger. The interaction effect between factor 3 and 6 indicates that the impact of factor 3 increases when a buffer is used.

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