

Flexibilisation of Intra-port Container Transport with Time Slot Bookings

Flexibilisierung von hafeninternen Containertransporten mit Zeitfensterbuchungen

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Abstract: Truck appointment systems are a well-studied approach to reduce queues in front of container terminals and on their yard. Traditional systems are lacking in flexibility and tend to favour the terminal operators over other partners in the maritime supply chain. To enable a better fit of appointment systems to ports and to increase their flexibility, a systematic analysis of different parameters and strategies and their interdependencies is executed. The results show that longer time slots benefit terminal operators as well as trucking companies. Furthermore, the so-called flexibility options show some promise to increase efficiency with little extra effort. As there are many interdependencies, the parameters and strategies need to be chosen with care for every container terminal.

1 Truck Appointment Systems at Container Terminals

In today's ports, the necessary container transports between the logistical nodes represent a significant challenge. These inter-terminal transports mainly include movements between container terminals, empty container depots and container packing stations. Even if only short distances are covered by these transports, there are frequent trips to the logistical nodes. If traffic jams or waiting times occur at nodes in the port, delays can quickly accumulate and lead to missed deadlines. Considering the role of port logistics as a critical link in global supply chains, the efficient handling of these processes is not only important from an operational point of view but also has economic and ecological implications. (see Heilig, Voß 2017; Lange et al. 2023) One proven measure for reducing waiting times at logistics nodes is the implementation of a truck appointment system (TAS). These systems enable trucking companies to book specific time slots in advance for the delivery or pick-up of containers. By distributing arrivals more evenly, traffic flow can be improved and waiting times can be reduced. These systems have the potential to bring efficiency gains not only within the confines of the port but also in connection with the extensive logistics network. However, it is often the case that the previous implementations of these systems lack flexibility,

which in particular results in reduced use by truckers (Huynh et al. 2016). Stakeholders such as truckers, freight forwarders and terminal operators often have different requirements and daily schedules. A system that offers flexibility can promote wider adoption and user satisfaction. Given the dynamic nature of port operations, such as unforeseen delays caused by weather conditions or operational disruptions, flexible time slot systems can act as a buffer to smooth out such fluctuations. Therefore, this research aims to develop strategies to improve the flexibility and thus the attractiveness of TAS. By means of a simulation study, different parameter constellations are tested to identify the most promising settings for different port structures and actor constellations. The results will help to develop practical recommendations to increase the efficiency of container logistics in ports. The article first presents the current state of research and describes the identified alternatives for solving the above-mentioned problems in Section 2. In doing so, it addresses the different approaches discussed in the research literature. In Section 3, the simulation study is explained in detail, including its methodology and the design of the experiment. The main results of the study are presented in Section 4, with a special focus on the relevant parameters identified for further simulation studies. The paper concludes in Section 5 with a discussion of the practical relevance of the research results and provides an outlook on possible future research directions that can contribute to further optimising internal container logistics in port structures.

2 State of Research

Thanks to advancing digitalisation, many paperless processes have been implemented in ports over the last few decades, making the handling of transport modes more efficient. At the same time, there is still considerable potential for optimisation, which can be exploited in particular by taking an integrated approach to various issues and methods (see Kastner et al. 2024; Raeesi et al. 2023). In existing research concerning TAS, the focus is often either on the container terminals or the trucking companies in isolation. Simultaneous consideration of several actors in the port is rare. Yet the port is a highly complex, mutually influential system of diverse stakeholders. Although they work together, they are often characterised by conflicting objectives, which makes a holistic analysis necessary. Time slots, as used in today's TAS, are usually static and inflexible. The only notable step towards flexibility is the initiation of collaborative booking systems (for example Gharegozli et al. 2017; Wasesa et al. 2024). These are approaches that promote synergies between the stakeholders, but here, too, there is often a lack of practical implementation and empirical data. Structured comparisons of different characteristics of time slots have not been sufficiently researched so far (Lange et al. 2022). Another gap in research is the investigation of the influence of flexibility options of the trucking companies on the overall handling process (Lange et al. 2019). This work closes both gaps by conducting a comprehensive, structured investigation of the influence of such options. In doing so, various flexibility parameters are compared and examined for their suitability.

3 Design of the Simulation Modell and the Experiments

A structured literature review to identify potential measures for increasing flexibility in the use of a time slot system was conducted, also considering approaches from other

industrial sectors especially production and healthcare. Based on that, the relevant parameters (describing the underlying logistics network) and strategies for the simulation study (flexibility options of the TAS) are defined (Tab. 1).

To evaluate these factors, a discrete event simulation model is created in Tecnomatix Plant Simulation Version 16.0.3.2087 that maps the operations of a typical trucking company within a port. The model is based on data from companies in the Port of Hamburg and is, therefore, limited to its area. In addition to four container terminals (CTs) using TAS and a trucking company, 17 other logistics nodes such as packing stations and empty container depots are represented. The routes between the locations are simplified as dwell times in model modules based on dynamic travel time matrices. Route times are limited by statutory rest breaks and shift times, during which the truck must return to the depot. At the logistics nodes and terminals, only those land-side processes that are directly relevant to truck handling are taken into account. A transport order consists of picking up and delivering a container. A simulation run comprises one to three shifts, with all necessary bookings being made in the TAS at the start of each run.

Table 1: Selected factors for the 2⁹-factorial experimental design

Factors	-	+
<i>Input parameters</i>		
Opening hours	As-Is in Hamburg	Min. 5 am – 10 pm
TAS characteristics (scope of time slots)	1h ± 30min	2h ± 60min
No. drivers/shift	60 drivers, 1 shift	36 drivers, 3 shifts
Traffic	High	Low
<i>Strategies</i>		
Swapping slots for transport orders	No	Yes
Adding a follow-up transport	No	Yes
Rebooking cancellation & new booking	No	Yes
Overbooking of capacity per time slot	No	20 %
Open Access with no booking	No	Yes

The central aspects of this study are time slot booking and route planning for transport orders. Time slot booking is triggered in the simulation model. Once the parameters have been set in accordance with the experiment plan, a new random order list with pick-up and delivery addresses is generated in Excel. Afterwards, the required time slots are booked randomly based on the information in the order list considering the number of shifts set by the trucking company. The capacity of the individual time slots is limited. Apart from booking before the start of the simulation model, it may also be necessary to book new time slots during the simulation run.

The tour planning is vehicle-initiated, i.e. it is triggered by vehicle events. A new order is assigned at the start of a shift, after a driving break or waiting time following a failed order assignment, or when an order has been successfully completed or

cancelled. Tour planning, i.e. the search for the best open, feasible order, is controlled by rule-based heuristics in the simulation model. The priority rules search for the most suitable follow-up order for the triggering truck. To this end, all open orders in the order list are evaluated according to two criteria: urgency and necessary travel time. The urgency is determined by the opening and closing times or the booked time slots of the source and sink of the order in relation to the current simulation time. During assignment, the system checks whether execution is still feasible based on the predicted arrival times and conditions at the nodes.

The chosen strategies to increase the flexibility of all actors in intra-port transports are here called flexibility options. The options of *swapping*, *adding* and *rebooking* expand the possibilities for order assignment and are implemented directly at the trucking companies. The design options of *overbooking* and *open access* are offered by the terminal. If a time slot has been assigned to a truck for an order, the simulation model will attempt to keep to this time slot, as this is where the shortest possible waiting time is expected. If the *swapping* of time slots is activated, the system checks whether the truck's empty runs can be minimised by exchanging time slots. To do this, a forecast is made as to when the current order will be completed at the sink and whether a follow-up order could be assigned in the course of a new order allocation. The best follow-up order is reserved by the triggering truck, whereby the necessary exchanges of the time slots involved must be feasible.

If, during the execution of a transport, it becomes apparent that a time slot cannot be met, an attempt is made to book another one, taking into account the available flexibility options. First, the system checks whether it is possible to *add* to the current or future order. To do this, the sink of the current order and the source of the subsequent order must match. If this is not the case, a *rebooking* attempt is made, if permitted. A random number is drawn. If this random number is less than the capacity limit specified for the time slot, the old time slot can be cancelled and the new one booked. If this is also not possible, the flexibility option of *overbooking* is checked. Here, too, this is done by drawing a random number. For simplicity, it was assumed in the simulation model that overbooking is successful with a probability of 10 %. If successful, the new time slot is entered in the order list. With *open access* approach, trucks that have not been assigned a suitable time slot for a transport order after 20 attempts in the initial booking process in Excel are directed to their preferred time in the simulation model. Furthermore, if open access trips are possible, only one attempt is made to rebook in the simulation model. If this rebooking attempt is unsuccessful, the open access option is selected immediately. Trucks that use the open access option at a node generally have a longer waiting time than trucks with a valid time slot. The waiting time is calculated based on the current utilisation at the node. To enhance the chances of developing an error-free model, multiple verification and validation methods were integrated. These methods include animation, limit value testing, desk testing, and structured walkthroughs.

The experiment design is set up so that the simulation model can be used for factor screening (Sanchez et al. 2020). To examine the influence of the selected parameters and strategies on CTs and trucking companies, a 2^9 -factorial experimental design is developed. This design requires only two values for each factor. These can be low and high, often referred to as - and + (see Table 1). The comprehensive factor screening allows to evaluate the effect of the factors (in this case parameters and strategies) on the target variable and their interaction with each other. The target variable for this

study is the number of completed orders per truck driver and shift, as this allows conclusions to be drawn about the efficiency of terminals and trucking companies. (cf. Gutenschwager et al. 2017, p. 178) After determining the nine factors and their two respective characteristics, 2^9 simulation runs are performed, each with 50 replications. The result values E_1 to E_{512} can be used to determine the effect of each factor on the overall result and their respective interactions.

4 Analysis of the Simulation Results

The first step of the selected 2^9 -factorial experimental design is to analyse the effects (e_i) of the factors (f_i) on the target value, the number of completed orders per driver and shift. Table 2 shows the effect of every factor calculated as the difference (Δ) between the average result of the target value in simulation runs with the chosen factor at the high level and the average result of the target value in simulation runs with the factor at the low level.

Table 2: Effects of factors on the target variable

Factors	Category	Sign	Effect [Δ compl. orders]
<i>Input parameters</i>			
Opening hours	Input nodes	e_1	0.0867
TAS characteristics	Input nodes	e_2	0.6219
No. drivers/shift	Input nodes	e_3	-0.5507
Traffic	Input nodes	e_4	0.8329
<i>Strategies</i>			
Swapping	Flex. opt. truck	e_5	0.0488
Adding	Flex. opt. truck	e_6	0.0642
Rebooking	Flex. opt. truck	e_7	0.0483
Overbooking	Flex. opt. nodes	e_8	0.0104
Open access	Flex. opt. nodes	e_9	0.0021

When considering the effects, it becomes clear that the factors called input parameters have a significantly greater influence on the number of completed orders than the strategies examined. In the case of opening hours (f_1), the design of the TAS (f_2) and travel times (f_4), higher values lead to a higher number of completed orders. This means that, as expected, longer opening hours, longer time slots and lower traffic loads have a positive effect on the number of completed orders. In contrast, when it comes to the number of drivers per shift (f_3), a lower value, i.e. only one shift with many drivers instead of three shifts with a medium number of drivers, is more advantageous. Of the four input variables, travel time has the greatest effect, with an increase of $e_4 = 0.8329 \Delta$ completed orders.

The strong effect of the input variables is not surprising, as most of them are the levers that companies use to try to increase their profitability. At the same time, these input

variables are subject to many external restrictions. For example, the opening hours of the nodes depend on the available personnel, the opening hours of competitors and noise protection regulations. Longer opening hours also lead to higher costs, which may not be covered by the higher number of orders completed. The input variable of traffic is particularly challenging, as it cannot be influenced by any of the port operators. It is interesting to look at the interactions with other input variables to determine whether a difficult traffic situation can be offset by one of the measures considered.

All strategies considered have a positive effect on the number of completed orders. The flexibility options relating to the trucking companies have a significantly greater effect than those relating to the nodes. The option of adding (f_6) has the greatest effect with $e_6 = 0.0642 \Delta$ completed orders. This is followed by swapping ($e_5 = 0.0488 \Delta$ completed orders) and rebooking ($e_7 = 0.0483 \Delta$ completed orders) with similarly high values. The possibility of overbooking ($e_8 = 0.0104 \Delta$ completed orders) and open access ($e_9 = 0.0021 \Delta$ completed orders) have only a very minor effect on the number of completed orders when considered individually. The flexibility options differ in terms of the complexity of their application. For the factors f_5 to f_7 and f_9 trucking companies and node operators must agree on suitable procedures and integrate these into their own systems. Factor f_8 can be implemented directly by node operators without much effort.

In the second step, the interactions between two factors are calculated and evaluated. If the interaction is positive, then values of the same level must be selected for the two examined factors to increase the number of completed orders. If the value of the interaction is negative, the number of completed orders can be positively influenced by selecting different levels for the respective factors. When evaluating the interactions, a higher absolute value indicates a greater interaction between the input variables. If, for example, the interaction between parameters f_1 (opening hours) and f_2 (TAS design) is to be calculated, the results of the runs in which both parameters have different characteristics are subtracted from those in which they have the same characteristics. In this case, the interaction is 0.0032, which is on the low side. To make the results easier to interpret, they are presented in standardised form as a heat map in Figure 1. For standardisation purposes, the highest interaction value was defined as 100 % and the other values were scaled accordingly.

Looking at the heat map, it can be seen that the interactions between the input variables vary in size. The greatest interaction is between travel times and the number of drivers per shift ($e_{34} = -0.137$). The value for normalisation was set to -100 %. Since the value is negative, different factor levels are appropriate for this factor pair. In conjunction with the analysis of the effects ($e_3 = -0.5507$ and $e_4 = 0.8329$), it can be concluded that the higher level of driving times, i.e. shorter driving times due to less traffic, and the lower factor level of drivers per shift, i.e. more drivers per shift, result in an increase in the number of completed orders.

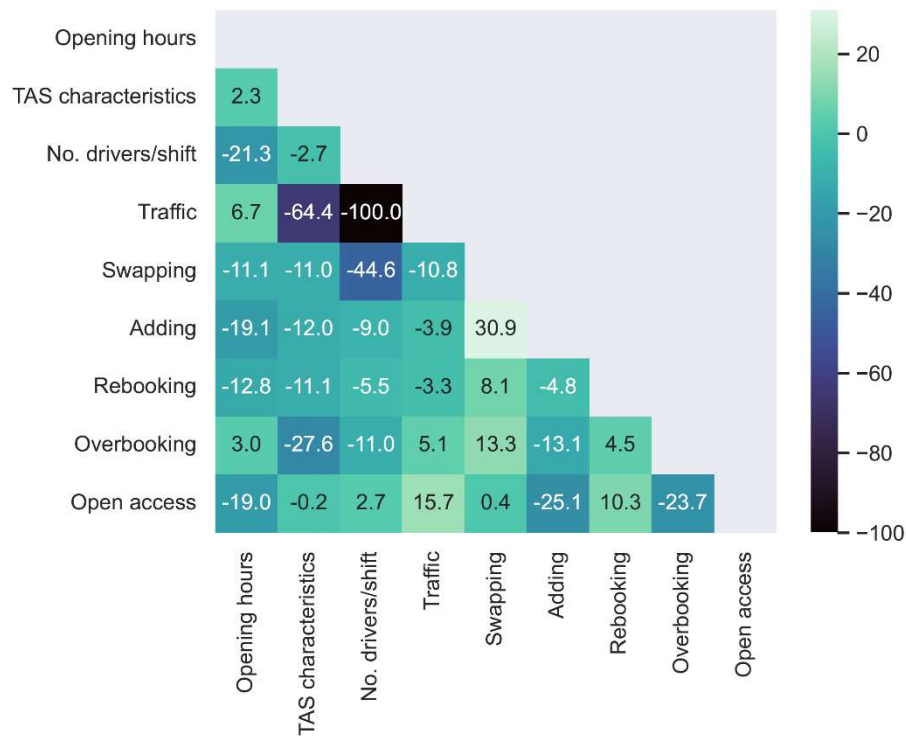


Figure 1: Heat map of the normalized interactions of the factors as a percentage of the highest value in terms of amount

Different levels also have a positive effect on the factor pair with the second highest interaction ($e_{24} = -64.4\%$). These are travel times and the design of the TAS. Determining the respective factor levels is much more difficult here, as the higher level was rated more positively for both when considering the effects. It can be deduced that the effect of longer time slots for TAS is less helpful when the traffic situation is better, whereas when the traffic situation is poor, longer time slots have a more positive effect on the number of completed orders. If the traffic situation cannot be improved, longer time slots should be made available at the nodes.

The input variables with the third highest interaction ($e_{35} = -44.6\%$) are number of drivers per shift and the flexibility option of swapping. Here, too, different factor levels are helpful in achieving a higher number of completed orders. Based on the determined effects of the input variables, it can be concluded that a low level of drivers per shift, i.e. many drivers in only one shift, should be combined with the option of swapping. A high number of drivers per shift also increases the number of orders that are eligible for swapping. This means that better alternatives can be found by using the flexibility option.

The flexibility options of swapping and adding bookings have the highest positive interaction ($e_{56} = 30.9\%$). This is the fourth highest value for interactions overall. Since the analysis of the effects for both input variables shows that the higher factor

level has a positive effect on the number of completed orders, it makes sense to choose this option for both input variables.

The fifth highest interaction, the interaction between the TAS characteristics and the overbooking option ($e_{28} = -27.6\%$), is again negative. Here, too, it must be taken into account that the higher factor level was rated more positively in the analysis of the effects of both input parameters. The two input variables have very similar effects and therefore compete for orders. With a TAS with long time slots, the overbooking option is therefore not necessary. Similarly, if overbooking is possible, it does not make sense to extend the length of the time slots.

The flexibility options of adding and open access also have a negative interaction ($e_{69} = -25.1\%$). In principle, both input variables have a positive effect on the target variable at the higher level of expression. However, they also appear to have a negative influence on each other. If the open access option is available, it does not make sense to offer the option of additional bookings, and vice versa. All other input parameter combinations have interactions that are less than 25 % in terms of amount. The interactions are therefore relatively small and are only expected to have a minor impact on the results of the simulation study. For this reason, they are not considered individually here.

In general, it is noticeable that there are stronger interactions between the input variables than between the flexibility options (see Table 3). It can be assumed that this is related to the higher effects of these input variables that have already been identified. Furthermore, negative interactions are more common with these input variables. The input variables therefore rarely complement each other at the same levels. In the case of flexibility options, there are roughly equal numbers of positive and negative interactions. This may be due to the fact that, in the case of input variables, a higher level is not always a better option, whereas in the case of flexibility options, the higher level always corresponds to the use of the option.

Table 3: Evaluation in factors based on their effect and interaction

Factors	Category	Effect	Interaction
<i>Parameters</i>			
Opening hours	Input nodes	→	→
TAS characteristics	Input nodes	↑	↗
No. drivers/shift	Input nodes	↗	↑
Traffic	Input nodes	↑	↑
<i>Strategies</i>			
Swapping	Flex. opt. truck	→	↗
Adding	Flex. opt. truck	→	↗
Rebooking	Flex. opt. truck	→	→
Overbooking	Flex. opt. truck	→	↗
Open access	Flex. opt. truck	→	↗

Rebooking has the lowest interactions with other input variables in terms of amount. Although the effect of this input variable is rather small, it is still significantly greater than that of other input variables that have higher interactions. It therefore appears to be a flexibility option that is largely independent of the other input variables. Adjusting opening hours and the open access approach are the input variables with the next highest interactions in terms of amount. They are significantly lower than rebooking. In the case of open access, the low effect may be the reason for the low interactions. Opening hours also show that this input variable is relatively independent of the others. The input variables with the highest interactions are traffic, the number of drivers per shift and the design of the TAS.

Based on the results, four of the nine parameters considered could be excluded from a subsequent scenario study. Of the parameters to be further considered, the design of the TAS, especially the length of the time slots, and the number of drivers per shift and the number of shifts have a particularly high influence. The flexibility options, which have a lesser influence on the overall system, nevertheless prove to be advantageous and recommendable for the majority of the scenarios examined. Based on these findings, recommendations are formulated that include fundamental design principles for TAS depending on the structure of the trucking companies in the port. These recommendations aim to improve the efficiency of container transport and to enable better adaptation of the systems to operational requirements.

5 Results and Outlook

Seaports and inland ports around the world are facing ever greater demands, many of which can only be met through more transparent process design and advancing digitalisation. One of these challenges is frequent congestion in port areas. This is caused, among other things, by long queues at logistics hubs and affects all traffic in the port as well as the processes at the hubs themselves. Reasons for the increasing congestion include the ongoing increase in ship sizes and the higher demands placed on transport service providers in terms of fast and punctual deliveries. Strategies proposed in practice to make TAS in seaports more flexible include rebooking, swapping and adding time slots for transport orders. However, these have only been scientifically investigated to a limited extent. Furthermore, solutions from other industries can also be transferred to ports. The possibilities of overbooking and the open access approach are especially interesting in this context.

In a factor screening using an event-discrete simulation model, the effects of nine input variables on the number of completed orders and the interactions between the various input variables were evaluated. The results showed that the design of the TAS, the number of drivers and shifts, the flexibility options of swapping and adding, and the option of overbooking are particularly relevant to the problem. These values should be examined in a detailed scenario analysis based on this, with additional levels of variation in each case. For further research, the booking of time slots for individual storage blocks at CTs, also in combination with longer time slots, the consideration of ship arrivals when allocating time slots, and the investigation of electrified trucks offer exciting potential. To generalise the findings, it would be useful to apply the model to other ports.

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