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DESIGN OPTIONS TO INCREASE THE EFFICIENCY OF INTRA-PORT CONTAINER TRANSPORTS

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ABSTRACT

High volumes, short buffer times and many other players influence the maritime transport chain and intra-port container transport. Congestion at logistics hubs leads to inefficient processes, increased waiting times, costs and emissions. Truck appointment systems are designed to reduce congestion by offering trucking companies time slots for delivering or collecting containers. However, these systems lack flexibility, which limits utilization and reduces efficiency. The study aims to develop strategies to evaluate and improve these systems in a simulation study. The results show that medium-length time slots improve the situation for transparent processes, or long time slots for limited transparency. Overbooking and open access are mutually exclusive, but offer slight advantages individually. Adjustments to opening hours of other nodes show little benefit. Overall, flexibility options positively influence the ratio of load trips and waiting times.

1 INTRODUCTION

Today's globalized world is based on running trade flows. Especially in times of international crises, such as climate change, the coronavirus pandemic, political unrest and war, trade offers stability through the supply of food, energy and other necessary commodities. At the same time, trade flows face the challenge of dealing with increasing uncertainty. Seaports represent the interfaces of global trade flows by handling goods between transshipment traffic while interacting with the hinterland. Thereby, seaports face increasing demands in terms of efficiency. An integrated analysis of different methods can leverage the existing optimization potential (Heilig et al. 2017a; Kastner et al. 2024; Raeesi et al. 2023). One process that can be optimized is truck handling at the terminal gate and on the terminal site. Many trucks arriving at the same time, partly with incomplete information and transport documents, can lead to congestion. This reduces the efficiency of the terminal and trucking companies, and significantly increases emissions. Other stakeholder groups, such as residents of port cities and their commercial companies and municipalities, are also affected by congestion and emissions from the port area (Abdelmagid et al. 2022; Morais and Lord 2006).

Truck Appointment Systems (TAS) have been increasingly used in the last decade as a digitalization strategy to avoid congestion. These booking systems allow trucking companies to reserve time slots at container terminals in advance. To register, they often have to provide detailed information. By indicating a target arrival time and further information, the terminal can plan the transhipment more accurately and thus reduce the handling time. Limiting the number of trucks arriving per time slot prevents congestion in front of or on the terminal which then reduces the waiting time for trucks. If truck drivers do not comply with the booked time slot or, if applicable, its buffer times, handling is usually refused and a new time slot must be booked (Abdelmagid et al. 2022; Parmaksizoglou et al. 2024). Such a system significantly influences intra-port transports, where trucks mainly move between logistics nodes within the port area. In that case, the same trucks call at logistical nodes that participate in a port's TAS several times in one day. While intra-port transports represent a small percentage of the total transport distances, they are a significant factor for a port due to the frequency of truck calls. Due to their special characteristics (e.g.

short distances, high volumes), intra-port transports should be considered separately from long-distance transports (Heilig et al. 2017b; Rose et al. 2022).

While numerous studies on TAS were conducted in the past, there are still considerable challenges in practical terms. This includes trucking companies in particular, but also logistics nodes such as packing stations or empty container depots, which, for example criticize a lack of flexibility or non-transparent processes at the terminals. Furthermore, industrial implementation and scientific studies of TAS usually only focus on terminals or trucking companies (Lange et al. 2023). Fixed time slots and a focus on a single partner often significantly reduce flexibility and thus efficiency of other partners. Often highly simplified systems that are considered do not adequately reflect the complexity of intra-port transportation with TAS at terminals.

Thus, the purpose of this analysis is to evaluate adaptation strategies in an integrated approach, enabling the players in intra-port container transportation to react to TAS impacts. The port system with TAS at the container terminals is examined with a simulation study, particularly with regard to three different options for more flexible arrivals (so-called flexibility options): swapping, adding, and overbooking time slots. If the swapping option is possible, the program examines whether an transport order can be more efficiently carried out using the time slot of another order. The adding option means that a time slot is already booked for either the drop-off or pick-up of a container can also be used for the other process step. This saves time for both the trucking company and the node, as registration at the gate is only carried out once for the two orders. Overbooking implies that additional bookings are permitted for a time slot whose capacity is fully utilized. This allows short-term unused capacity to be balanced out by no-shows in highly frequented time slots. These options enable both trucking companies and terminals to handle the booking of time slots and the transportation process more flexibly. The assumption is that the flexibility options can improve the performance of all parties involved in transportation. Dependencies between the number and size of shifts of the trucking companies, the configuration of the TAS, and the flexibility options are also examined in order to identify suitable strategies for the respective situation.

In the following, a short literature review on TAS is presented to derive the research question (Section 2). In Section 3, the research approach is discussed in detail. Section 4 presents the results of the detailed analysis. In Section 5, a short conclusion and an outlook to further research opportunities are given.

2 STATE OF RESEARCH

In literature, intra-port container transportation with TAS at the terminals is a complex field of research with a large number of sub-problems (Adi et al. 2021; Fan et al. 2019). The complexity arises as several trucking companies have to transport containers between different origins and destinations, each of which is subject to different time restrictions (e.g. time slots or opening hours). According to industry experts and scientific publications, container transports between storing and handling companies (logistical nodes) account for a large proportion of all transports in the port with a limited number of arrival addresses (Duinkerken et al. 2006; Heilig et al. 2017b; Schepler et al. 2017). Thus, it is the focus of further analysis. To address the broad scope of questions, different methods are used, resources are deployed and individual players, mostly container terminals or trucking companies, are examined in detail. The overall port system with its various stakeholder groups has been studied only to a limited extent due to the related complexity. Apart from the two main players other stakeholders, such as empty container depots, packing stations or rail terminals, have only been marginally considered. (Gracia et al. 2025; Torkjazi et al. 2022) In particular, the effects of TAS on operational processes of other stakeholders and their efficiency have hardly been investigated. Due to increasing detailing of the research subject in recent years and rising computational capacities, the methods used focused more and more on mathematical optimization (for example Huang et al. (2024), Wasesa et al. (2024)). However, even with increased use of heuristics, it is usually not possible to model complex dependencies or solve larger problems. This is another reason why the focus shifted to specific sub-problems (Lange et al. 2022). Publications often refer to North American or Asian ports. Due to regional differences in the equipment used and the associated terminal and port processes, a specific study for European ports is necessary (Schwientek et al. 2020). Based on the topics and contexts mentioned, the following research questions are derived:

How does a TAS at container terminals affect the players involved in intra-port container transports and what strategies can these players use to reduce the negative effects? 1. Which characteristics of a TAS at container terminals positively influence the efficiency of both trucking companies and nodes? 2. How do the flexibility options adding and swapping influence the productivity of nodes and trucking companies?

3 METHODOLOGY

Simulation is used to solve a large variety of strategic, tactical and operational problems in traffic and transportation logistics (Baudach et al. 2013; Gutenschwager et al. 2017). With regard to container terminals, one particular focus is on the analysis of real-time rule-based processes that improve the allocation of containers in the terminal yard, equipment scheduling and processes at and in front of the terminal gate (Gharehgozli et al. 2019). In the presented study, an event-based tour planning is applied, focusing both on vehicle scheduling for intra-port container transports and on landside processes at the terminals and logistical nodes. As this area of application, like many logistics systems, can be represented by events, processes and activities, discrete event simulation is particularly suitable (Wenzel 2018, p. 11). It is used here to describe the processes of transport operations and handling at the nodes and to test possible methods.

The processes' dynamics and stochasticity are considered in the presented questions, as the tour plan is adapted during the simulation depending on the flexibility options. Both transportation times (e.g. due to varying traffic densities, roadworks, waiting times at the gates) and handling times at the container terminals and other logistics nodes (e.g. due to weather conditions, varying skill levels of equipment operators, equipment breakdowns) are subject to stochastic influences. Solving this problem using analytical methods is not possible with reasonable computing time due to complex interdependencies. Even small problem instances with few constraints are already NP-hard (Aufderheide 2010; Kourounioti and Polydoropoulou 2018). This is also a complex problem for simulation. Therefore, in Lange et al. (2025), the input variables for the simulation were pre-checked with factor screening in an integrating approach to examine the complex overall port system.

3.1 Simulation Study Design

This study uses the Tecnomatix® Plant Simulation environment, which is widely used in science and in practice. The central control elements in this study are time slot booking and tour planning for transport orders (see Fig. 1). The simulation runs are performed on a workstation with an Intel(R) Core(TM) i7-6950X CPU @ 3.00GHz processor and 128GB RAM. The operating system used is Microsoft Windows 10 Pro. The simulation runs are performed with Tecnomatix Plant Simulation Version 16.0.3.2087 and Microsoft Office 2019 Version 1808. The runtime of the simulation runs depends significantly on the characteristics of the input variables (average 17 to 50 seconds per run). Each simulation covers 24 hours, starting with the first shift. A warm-up period is not required, as in reality truck orders are always planned day by day.

Both elements of control are considered separately and explained below. Based on the selected input parameters, an order list is generated for each simulation run, in which, among others, pick-up and drop-off addresses and opening hours are specified. The distribution of pick-up addresses bases on data from a Hamburg-based trucking company. If time slot booking is required for the respective nodes, time slots for the nodes are booked in a random order, considering the number of shifts of the trucking company, to prevent certain nodes from being prioritized. To simulate competition from other trucking companies, the available capacity of individual time slots is restricted. The higher the demand for a particular time slot in the real data, the lower is the probability of a successful booking in the simulation model. If there is no free capacity for a time slot during the booking attempt, an attempt can be made to book the time slot from the overbooking reserve if this flexibility option is selected. If both regular booking and overbooking fail, the booking process restarts with a new random number. A maximum of 500 booking attempts are made

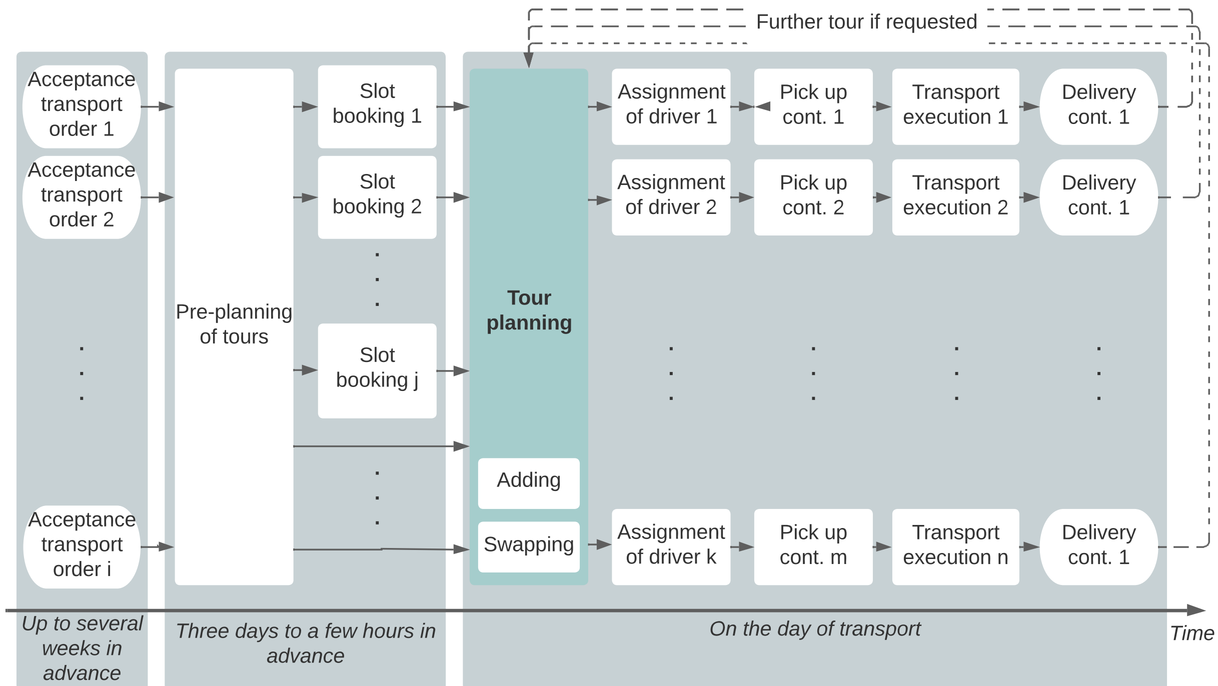

Figure 1: Processes in intra-port container transportation from the perspective of a trucking company.

per order and time slot before the transport order is canceled. Apart from slot booking before the start of the simulation model, new time slots may be booked during the simulation run. This is always the case when swapping or adding is used in tour planning. Furthermore, the possibility of overbooking influences the procedure of new time slot bookings.

Tour planning is initiated by vehicle events. A new order is assigned if a shift starts, after a rest from driving or a waiting period after an unsuccessful order assignment, or if an order has been successfully completed or canceled. In each case, the system first checks the compliance with the rest and shift times of the truck drivers in the event of a direct assignment. Next, the best open, executable order for the respective truck is assigned and execution starts. The control of tour planning, i.e. searching for the best open, executable order, is carried out using rule-based heuristics in the simulation. The priority rules search for the most suitable follow-up order for the initiating truck. For this purpose, all open orders in the order list are evaluated according to two criteria: urgency and required trip duration. Urgency is determined by opening times or booked time slots of the source and sink of the order in relation to the current simulation time. If there are several executable orders with identical urgency, the travel time to the source based on current traffic information is decisive for assigning an order. During the assignment process, the system checks whether it is still possible to execute the order based on forecast arrival times and conditions at the nodes.

The flexibility options swapping and adding extend the opportunities for assigning orders and are used directly by the trucking companies. The overbooking option is offered by the terminals. All three flexibility options are assumed to influence the success of the transportation process. Once the truck has been assigned a time slot for an order, it attempts to meet the time slot in the simulation model, as this is anticipated to have the shortest possible waiting time. If the flexibility option of swapping time slots is activated, the selected order is initially only marked as provisional. The system then checks whether the truck's empty runs can be minimized by swapping time slots. For each alternative order, the system checks if an efficient swap can be carried out from the orders that have not yet been completed or are reserved as (follow-up) orders and marked as swappable. In the simplest case, only time slots of bookings for the source of the order are swapped. This is the case if the sinks (of the original and alternative order) do not require a time slot and can be reached within the opening hours. If a sink requires a time slot booking, then another transport order (with only one booking at the relevant terminal) must be included in the swap process. A swap is only done if all orders involved in the swap can be carried out afterwards, i.e. the time conditions of the source and sink match. The planning horizon for swapping comprises a maximum of two orders to limit the calculation effort. If no efficient swap can be executed, the originally selected order is carried out. If it appears during the execution of a transport that a time slot cannot be met, an attempt is made to book another time slot, taking into account the available flexibility options. First, a check is made to see if it is permitted and possible to add to the current resp. future order. This requires the sink of the current order and the source of the subsequent order to match. If this is not the case, an overbooking attempt is made, if permitted. To simplify matters, it was assumed that an overbooking is successful with a probability of 20%. In the simulation model, an unlimited overbooking capacity is assumed, since the volatile situation at the terminals with continuous cancellations and new bookings by many trucking companies is difficult to map. However, as overbooking capacity is expected to be used by other trucks, the calculated overbooking probability was reduced to half. In a positive case, the new time slot is noted in the order list.

To increase the likelihood of an error-free model, various verification and validation techniques were combined. These include animation, limit value testing, desk testing and structured walkthroughs.

3.2 Definition of Input Parameters

Below, values for the input variables of terminals and other logistics nodes are shown. The Port of Hamburg serves as use case for the simulation. Thus, the input variables correspond to the parameters of the Port of Hamburg. These data were collected in numerous interviews with representatives of all types of players in the port and base on real data provided by companies. Additionally, data from the TAS website and the Google API was compared with the companies' real data (Lange et al. 2019; Beck et al. 2020). Based on data of a trucking company specialized in intra-port container transports in Hamburg, 22 relevant nodes are chosen according to their transport volumes: four container terminals, six empty container depots, six packing stations and six other logistics nodes. All terminals and nodes have a defined geographical location. The processing times for container pick-up or drop-off are derived from surveys of port companies and are modeled stochastically using normal distributions and depending on the node utilization (see Table 1).

Table 1: Processing times of the analyzed nodes [seconds].

	μ	σ	**Lower boundary**	**Upper boundary**
Container terminals	2400	900	900	6600
Other logistics nodes	1800	600	900	4200

The opening hours of nodes in the Port of Hamburg differ significantly. Terminals are open around the clock on working days, while empty container depots and other nodes frequently operate a two-shift system. Container packing stations often only handle trucks in single-shift operation. The opening hours selected are closely based on real opening hours of selected nodes in Hamburg. Preliminary studies showed that the opening hours strongly influence the distribution of truck arrivals over the course of the day and accordingly, the load peaks of the nodes.

The distribution of truck arrivals can be smoothed with varying degrees of efficiency by using a TAS. Since TAS at the terminals are also used by long-distance transports competing with the port's internal trucking companies for available time slots, the free TAS capacity must also be taken into account. Trucking companies differ in their size. This is described by the number of truck drivers per shift and the number of completed orders per day. Trucking companies with one shift are referenced by numbers 1 (small company with 12 drivers per shift), 2 (medium sized company with 36 drivers per shift) and 3 (large company with

60 drivers per shift). This system is applied for companies with two (numbers 4 to 6) and three shifts (numbers 7 to 9). The amount of drivers per shifts for small, medium and large companies stays the same. The composition of transport orders according to pick-up and drop-off locations also characterizes the trucking companies. The infrastructure parameters relate to the travel times between the nodes, which vary during the day due to different traffic conditions.

3.3 Design of Experiments

The factor screening carried out in Lange et al. (2025) identified six parameters that significantly influence the efficiency of intra-port transportation with TAS (see Table 2).

Table 2: Specification levels of the selected input parameters in the simulation study.

Input parameter	**Specification levels**			
TAS configuration	1 h±30 min	2 h±60 min	3 h±90 min	
No. of drivers	12	36	60	
No. of shifts	1	2	3	
Swapping	no	yes		
Adding	no	yes		
Overbooking	0 %	20 %	30 %	40 %

Combining all input parameter values leads to a total of 432 simulation runs in the experiment plan. Each simulation run is carried out with 50 replications. Table 3 shows an extract of the experiment plan.

Table 3: Extract from the experiment plan.

Nodes		**Trucking companies**		**Flexibility options**			
TAS configuration [h±mm]	**Overbooking**	**No. of shifts**	**No. of drivers**	**None**	**Only adding**	**Only swapping**	**Adding & swapping**
1 ± 30	none	1	12	1	109	217	325
1 ± 30	none	1	36	2	110	218	326
1 ± 30	none	1	60	3	111	219	327
1 ± 30	none	2	12	4	112	220	328
1 ± 30	none	2	36	5	113	221	329
⋮							
3 ± 90	40 %	2	36	104	212	320	428
3 ± 90	40 %	2	60	105	213	321	429
3 ± 90	40 %	3	12	106	214	322	430
3 ± 90	40 %	3	36	107	215	323	431
3 ± 90	40 %	3	60	108	216	324	432

In this experiment plan, input parameters are sorted according to the respective players for a better overview. The numbers of the simulation runs are listed in the last four columns. After an initial global consideration of the results of all simulation runs, selected runs with particular significance for answering the research questions are compared below and examined in more detail.

4 RESEARCH RESULTS

The analysis of the simulation results is structured according to the research questions. It focuses primarily on the number of completed orders as output parameter. In principle, all simulation runs are considered to analyze the results without and with mutual influence of the input parameters. Based on a preselection, selected runs are analyzed in more detail to answer the research questions. In each case, suitable output parameters are selected in addition to the number of completed orders for this analysis. Not every analysis takes the same output parameters into account.

4.1 Influence of TAS Configuration and Overbooking

There are some general trends with regard to the TAS configuration. For example, the longer the time slots, the more orders are completed per driver and shift. Regardless of other input parameters, longer time slots positively influence the number of completed orders. At the same time, the trucking company size also has an influence, with the time slot length affecting trucking companies operating two shifts (numbers 4, 5 and 6) the least. This means that long time slots are less important for two-shift trucking companies than for one- or three-shift trucking companies. There is often no difference between two-hour and three-hour time slots for single-shift trucking companies, but there is a difference for three-shift trucking companies.

Using overbooking only leads to slightly better values, thus, the rest of this section will focus on the options of no and 20 % overbooking. Furthermore, hardly any positive interdependency can be seen in the use of flexibility options and the TAS configuration. Thus, the rest of this section will only consider runs without flexibility options. Since the results for medium-sized and large companies are very similar, only small and medium-sized trucking companies (trucking company size 1, 2, 4, 5, 7 and 8) are considered. There remain 36 runs, which are examined in more detail in Figure 2 with a view to the TAS configuration.

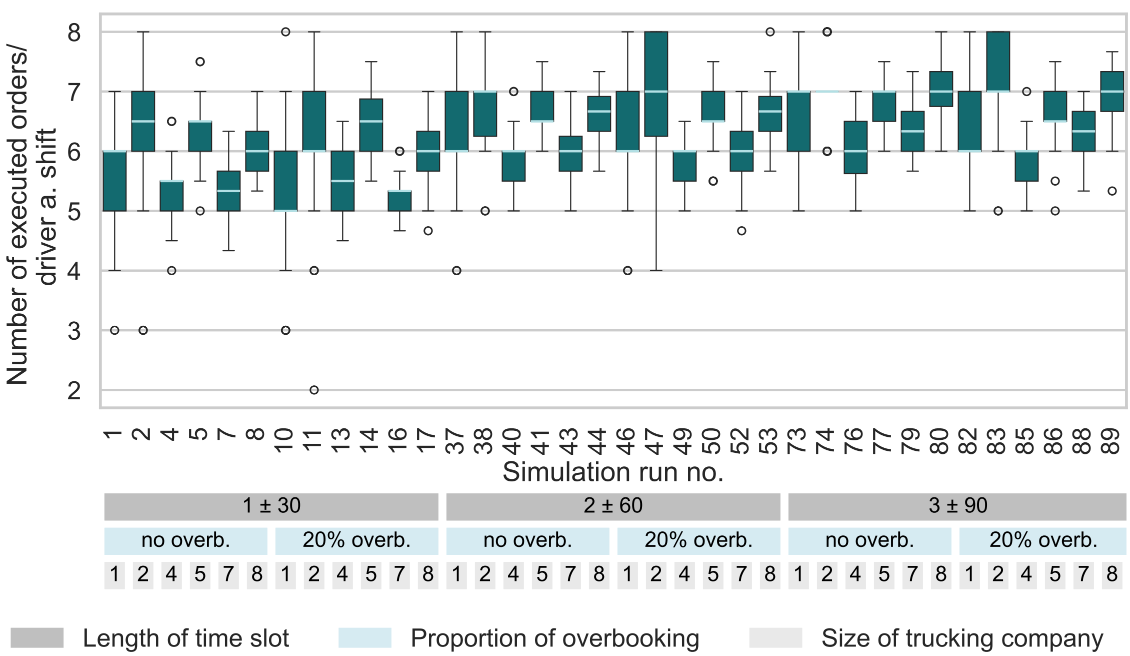

Figure 2: Number of completed orders for selected runs to determine the influence of the TAS configuration.

Figure 2 shows that, in principle, the most orders per driver and shift are completed in the runs with a time slot of three hours (right third in the figure). For example, the median of the results for this time slot length is between six and seven completed orders for the considered runs, and the upper quartile exceeds seven orders several times. Runs with a time slot length of two hours (middle third) are located in the midfield in terms of completed orders. For runs with a time slot of just one hour, the median number of completed orders is below six in some cases. The assumption that the number of completed orders increases with the length of the time slot is thus supported by the results considered here. This can be explained by the fact that longer time slots lead to increased flexibility for trucking companies, allowing them to carry out their planning more efficiently. In addition, traffic-related delays have less impact in the case of longer time slots. Despite the positive results, time slots longer than three hours are not advisable in practice, as truck's arrival times are more difficult to forecast, congestion situations can occur more frequently and the terminal cannot prepare sufficiently for transhipment due to the low accuracy of the information.

With the number of shifts remaining the same, a higher number of drivers always results in the same number or more completed orders per driver and shift. It is not recognizable that small or medium-sized companies require a different TAS configuration. Thus, the general recommendation remains that longer time slots lead to a higher number of completed orders. It is interesting to note that for almost all pairs of runs with one and two shifts, the interquartile range of the results is reduced when the number of shifts increases (e.g. runs 1 and 4, 2 and 5, 10 and 13). This can be explained by the fact that transport orders in the second or third shift are subject to less traffic. AS a result, the estimated transport times are adhered to more reliably and less rescheduling is necessary at short notice.

The results of the first research question are quite clear. Increasing the time slot length significantly influences the number of completed orders. This may be because orders can still be booked and completed in longer time slots that are canceled or not placed at all in shorter time slots. Based on this finding, a further study could investigate why orders are canceled and how their execution can be ensured without increasing the time slots to three hours. This could be achieved by better coordination with the other logistics nodes or a slight adjustment of opening hours. At the same time, time slots of three hours increase the uncertainty in planning for container terminals, making pre-stowage more difficult. When looking at the overbooking option, which is another TAS configuration feature, it emerges that the overbooking options neither have no recognizable effect with longer time slots. The answer to the first research question is, that time slots with a length of two hours should be favored if transparent real-time information is possible between the port players involved. If this is not possible, time slots with a length of three hours should be selected.

4.2 Influence of the Flexibility Options of Adding and Swapping on Nodes and Trucking Companies

In the simulation results, no dependency of the flexibility options, being the adding and swapping on the overbooking option can be seen. Thus, in the following section, only runs in which no overbooking is possible are considered. There is also a higher variance in the results for short time slots than for long time slots. In contrast, long time slots generally provide better results. Therefore, the following section considers short and long time slots. In addition, in case of short time slots, companies operating a single shift have a clear advantage over those operating a two-shift system, which in turn have a clear advantage over those operating a three-shift system. This tendency disappears with longer time slots. To illustrate this difference, only trucking companies operating a single shift and a three-shift system will be considered in the following. Medium-sized and large trucking companies often have similar results. Therefore, only simulation runs with small and large trucking companies are considered. The 32 simulation runs selected are shown as box plots in relation to the number of completed orders in Figure 3.

The first eight runs are those without a flexibility option. For the next eight runs, the option of adding can be used, and for the following eight, the option of swapping can be used. For the last eight selected simulation runs, both flexibility options are possible. Four of the selected runs always have short time slots and the subsequent four runs have long time slots. In each of these sets of four, the drivers work one shift in the first two runs and then three shifts in the following two runs. This initially involves a small and then a large trucking company. This composition is repeated for all selected runs. Many points stand out in the figure that are already described in the previous section. These dependencies and their causes are not discussed again. Apart from that, the median hardly changes at all with one or two flexibility options.

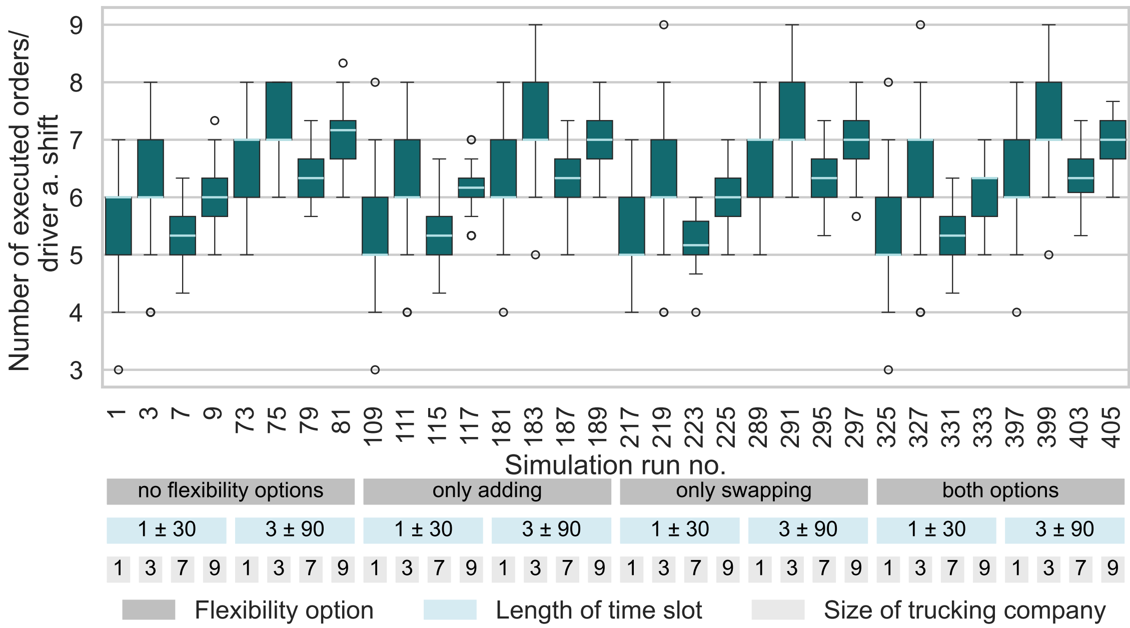

Figure 3: Number of completed orders for selected runs to determine the impact of the flexibility options.

One reason for this is again the relatively small number of orders for which a flexibility option was used compared to the total number of orders. When looking at the upper quartile boundary, more pronounced effects become visible. It shifts slightly upwards due to the presence of one or more flexibility options. This means that few orders that could no longer have been processed without a flexibility option are still completed with it. Otherwise, no dependencies of the other influencing variables and the flexibility options can be identified.

In addition to the analysis of the number of completed orders, the waiting time of the trucks in front of the nodes is shown as a box plot in Figure 4 for the same selected simulation runs. The values of the input variables are described in the same way as in Figure 3.

Here, the results are similar to those already presented in the previous sections. Apart from that, some interesting additional observations arise when considering the effects of the flexibility options. In seven of the eight runs in which only adding is possible, the upper quartile limit drops significantly. This means that these runs experience significantly fewer long waiting times than the runs without the flexibility option. It can be concluded that the option of adding is useful to reduce the waiting time of the trucks. Run 187 is an exception, as it has a significantly higher upper quartile limit than the comparable run without the flexibility option. This may indicate that the option of adding has fewer advantages for long time slots than for short time slots. When considering the eight runs in which swapping is possible, it is noticeable that the upper quartile boundary is also reduced compared to the runs without the flexibility option. This is even more pronounced than in the cases where only adding is possible. This flexibility option is also suitable for reducing waiting times at the node. A particular point of interest are the eight runs in which both flexibility options are possible. In these runs, both the median and the upper quartile limit are higher than in all the other runs considered. The only positive factor to be seen is that there are significantly fewer outliers than in the other runs. This behavior indicates that the two flexibility options negatively influence each other and thus lead to higher waiting times. It contradicts the general expected positive interaction between the flexibility options of adding and swapping. This apparent contradiction is due to the fact that the number of orders completed is not directly dependent on the waiting times. It is therefore, once again, clear that more orders can still be completed even with longer waiting times. For example, the bookings fall within more suitable time slots and can be better scheduled by the trucking companies.

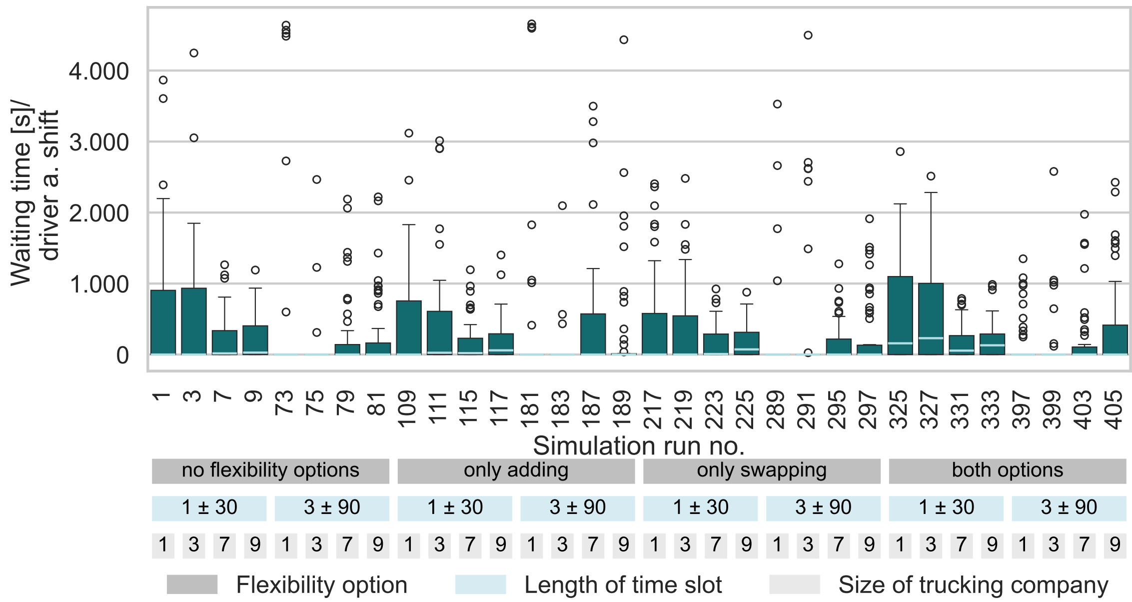

Figure 4: Cumulative waiting time of a truck in front of a node for selected simulation runs to determine the impact of the flexibility options.

The second research question can be answered as follows: the flexibility options have a slightly positive effect on the number of completed orders, but they are also comparatively complex to manage and, in particular, to implement in the IT system. The flexibility options have a more significant effect on waiting times at terminal gates. However, due to the small number of affected orders compared to the total number of completed orders, this has no noticeable effect. Nevertheless, as the trucks spend less time waiting with the engine running at the gates, a positive effect on emissions can be expected. The waiting time that arises is shifted to the allocation of a new order, which is usually spent in truck parks with the engine switched off. Furthermore, the flexibility options give trucking companies a sense of greater flexibility and co-determination. This can contribute to greater satisfaction within the system and thus better cooperation. Due to the cost connected with the implementation and management of the flexibility options, every terminal needs to carefully consider the connected benefits. Especially, if the truckers tend to be unhappy with the current system, the invest in flexibility option might be beneficial. Further flexibility of time slots, for example, through collaborative time slot booking systems, is likely to make sense in the long term and should be investigated in follow-up studies.

5 CONCLUSIONS AND OUTLOOK

Seaports and inland ports worldwide are facing ever greater demands, which in many cases can only be met by a more transparent process design and progressive digitalization. One of these challenges is frequent congestion in the port area. In particular, TAS have proven to be a comparatively simple way to reduce congestion in the port and increase the efficiency of logistics nodes. Since existing TAS often still cause significant cuts in flexibility for trucking companies and logistics nodes, the following research question was examined: What impact does a TAS at container terminals have on the stakeholders in intra-port container transport? What strategies can these stakeholders use to reduce the negative impacts?

The parameters considered in the study are the design of the TAS, the number of drivers and shifts, and the flexibility options swapping, adding and overbooking. The following findings can be derived from the simulation study. In response to the first research question, it can be concluded that when designing a TAS at container terminals, longer time slots are more useful than shorter ones. If the terminal exchanges data transparently with the other players in the port, time slots of two hours are desirable, as this allows for good planning of the terminal processes as well as the transport and transshipment at the other logistics nodes. If from time to time problems arise due to missing data at the terminal or if there are ongoing discussions with other actors in the port about data transparency, a slot length of three hours should be chosen. This gives the trucking companies the greatest possible flexibility without making arrivals at the terminal too imprecise for internal processes. The flexibility options of adding and swapping, which are the focus of the second research question, do not have a major effect on the number of completed orders, but they do have a significant impact on the waiting time of trucks at the nodes. Accordingly, they also have a positive effect on the emissions and operating costs of the trucks. There are no negative interactions between the flexibility options, so in principle both can be offered at the same time. Thus, if the implementation of these principles in the associated IT systems is possible with reasonable effort, it is recommended to enable trucking companies to use the flexibility options swapping and adding.

Due to the chosen scope, there are limitations in terms of content. In this form of TAS, only the total number of truck arrivals is usually considered when calculating the terminal capacity. This can lead to individual storage blocks or transfer positions being heavily used in a time slot, while others are almost empty. It would therefore make sense to move away from a purely temporal consideration and expand it to a temporal and spatial consideration. In particular, the combination of longer time slots with a restriction to a specific storage block or a specific transfer position is promising. In the case of longer time slots, information systems could also be used to determine the length of the queue at the gate to maintain flexibility and at the same time reduce possible congestion situations by providing up-to-the-minute information to trucking companies. Furthermore, it is possible and conceivable to add to these, as only a selection of strategies and measures has been examined. These include, for example, linking vessel-dependent time windows with classic TAS to improve coordination between ship arrivals and truck arrivals. In addition, the strategies and measures examined were only applied to one exemplary use case. It certainly makes sense and would be profitable to try them out in other applications of different sizes and configurations and to check their effects. It also makes sense to further investigate the effects of the input variables that were not the focus of this study. In particular, they can also be analyzed for their influence on other output values. By streamlining the processes at the terminals, the processing time could be further reduced. One possibility for achieving this is to use uninterrupted transport directly to the quayside, which would significantly reduce handling and storage times.

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