ROBUST PERIODIC BERTH PLANNING OF CONTAINER VESSELS

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ABSTRACT

We consider a container operator, who serves a number of shipping lines by discharging and loading their periodically arriving container vessels. Disruptions on vessels' travel times lead to stochastic arrivals in the port. To cope with these disturbances, the operator and each vessel line agree on two types of arrivals: arrivals i) within, and ii) out of a so-called arrival window. If a vessel arrives within its window, the operator guarantees a maximal process time. If not, the operator is not bound to any guaranteed process time. The problem is to construct a periodic window-based i) arrival, ii) departure and iii) time-variant crane capacity plan to minimize the maximal crane capacity reservation. In this paper, we propose a mixed integer linear program (MILP) that minimizes the maximal crane capacity reservation while window agreements are satisfied for all scenarios in which vessels arrive within their windows. Results of a case study suggest that with slight modifications to an existing plan, significant reductions in the maximal crane capacity reservation can be achieved. As a particular case, the MILP determines the conventional optimal window-ignoring plan. Results suggest that although the window-ignoring plan on itself requires less crane capacity than the window-based plan, it is much more sensitive to the arrival window agreements.

Key Words: Periodic Berth Planning, Robustness, Linear Programming

1. INTRODUCTION

The last few decades, air, road, rail and sea transportation of people and goods has grown tremendously. Since the expansion of these systems is commonly very expensive and sometimes impossible, the existing infrastructure has to be operated very efficiently to cope with the enlarged utilization. Time tables become more dense and with that more vulnerable to stochastic disturbances. In badly constructed timetables, the delay of a single transportation object might propagate through the entire schedule making it very difficult or even impossible to recover. To deal with stochastic disturbances in dense transportation schedules, two (complementary) approaches can be applied (Clausen 2007):

i) disruption management, which is concerned with operational recovery after a disruption, and ii) pro-active robustness, i.e. buffer times and other characteristics are built into strategic or tactical timetables to prevent delay propagation through a schedule.

The research in this paper focusses on incorporating pro-active robustness in a tactical periodic berth plan for container vessels. We consider a set of shipping lines, which run a regular service on their ports to be discharged and loaded. According to a fixed route and schedule along ports over the world, each line vessel has a preferred arrival time in each port. The current policy of a terminal operator is to construct a deterministic periodic timetable, which satisfies these preferences as good as possible. However, due to all kinds of events during travel (e.g. tailwind, storm, break-down), container vessels might arrive earlier or later than their scheduled arrival time. To cope with these disturbances, the terminal operator and each of the vessel lines agree on an arrival window positioned around the scheduled arrival time. The arrival window concept distinguishes between two kinds of arrivals: arrivals within and out of the predetermined window. If a vessel arrives within its window, the terminal operator has to guarantee a maximal process time. If not, the terminal operator is not bound to any process time, however aims to return to the schedule as soon as possible. A plan constructed from the current policy together with an unfavorable arrival scenario, might not yield a feasible operational plan for lack of quay meters or might require a large amount of crane capacity to fulfill the window agreements. We are therefore interested in robustness improvements when a berth plan, constructed from the current policy, is slightly changed. In our definition, a berth plan is robust with respect to a given set of arrival scenarios if a feasible solution exists for each arrival scenario within the windows and only a restricted amount of additional crane capacity reservation is required in the worst case scenario. The problem is then to construct a window-based berth i) arrival, ii) departure and iii) time-variant crane capacity plan with minimally required crane capacity that still satisfies the agreements for all scenarios in which vessels arrive anywhere within their windows.

We propose a mixed integer linear program, which constructs a window-based plan (WB-plan for the rest of this paper) taking the agreements for arriving within the windows into account. Besides the arrival and departure times of vessels being decision variables, the model also considers time-variant crane capacity reservations per vessel as decision variables. The model thus incorporates two flexibilities: i) shifting the berth plan of vessels in time and ii) reserving a time variant crane capacity for each vessel. In addition to satisfying the window agreements. These two flexibilities enable to better balance the workload over time and hence minimize the maximal crane capacity reservation.

This research is supported by the terminal operator PSA HNN in Antwerp, Belgium, which supplied us with typical berth plan data. Experimental results suggest that with only small changes to this berth plan already significant improvements on the robustness can be achieved. As a comparison we construct a window-ignoring plan (WI-plan for the rest of this paper), which ignores the arrival window agreements and constructs a berth plan with minimally required crane capacity. Results suggest the following: although the WI-plan finds a berth plan, which on itself requires less crane capacity than the WB-plan, the WI-plan can be very sensitive to different arrival scenarios within the windows. On the contrary, the WB-plan is by construction robust to all considered arrival scenarios. Results suggest that the WB-plan requires significantly less crane capacity than the WI-plan in the worst case scenario.

Although it is guaranteed that the terminal length capacity is never exceeded no matter what arrival scenario happens, the actual position allocation of the vessels in the terminal is still to be determined at an operational level. Similarly, the integer-valued quay crane allocation with non-crossing constraints is still to be determined. In this paper we solve a one-dimensional capacitated packing problem under disturbances within the arrival windows. In (Hendriks *et al.* 2008), a joint vessel position and container stacking problem and the integer-valued crane allocation are addressed. Current experiments suggest that for the typical utilization in today's ports a constructed plan on the tactical level is always feasible on the operational level. In (Hendriks *et al.* 2008),, we propose a rolling horizon to recover from i) all stochastic arrivals, i.e. arrivals within but also out of the arrival windows, ii) crane break-downs, iii) disturbances on vessels' load compositions. Consecutively, the position and integer valued crane allocations are constructed for each iteration step of the rolling horizon approach.

So far, most studies on disruption management are conducted for airline operations. However, over the last years, this approach is gaining more and more attention in railway applications as well. An overview of disruption management approaches for airline operations and the way these approaches now enter railway applications is given in (Clausen 2007).

A few studies on pro-active robustness in airline scheduling can be found. The authors in (Clausen 2007) and (Ball *et al.* 2007) address a number of robustness ideas. Of particular interest is the approach of adding slack between connected flights in (Lan *et al.* 2006). Flight schedules are often that tight that in case of a small plane delay, passengers might miss their connecting flight. Adding more slack between the flights is beneficial for the passengers, however reduces the productivity of the airline fleet. The authors propose an MILP in which both a flight's arrival time and the departure time of its connecting flight(s) can be scheduled somewhere within a window. Each possible arc between a time slot in the arrival window and a time slot in the departure window is called a copy. Each copy implies a connecting time and as determined from historical data induces a probability of passengers missing their connected flight (if the travel exceeds the connecting time). The objective is to select exactly one copy for each pair of connected flights such that the expected total number of delayed passengers is minimized.

With respect to pro-active robustness in railway applications, a few approaches can be found (Caimi *et al.* 2007), (Vromans *et al.* 2007). The study in (Caimi *et al.* 2007) presents a two-level approach: On the macro level pro-active robustness is embedded in the train timetable by allocating time windows for arrival and departures rather than single arrival and departure times. Minimal travel time is weighted against maximal flexibility at this level. This flexible scheduling approach increases the probability of finding a feasible solution (exact train routing at switch regions) at the micro level. A case study on instances of the Swiss Federal Railways 2007 demonstrates the advantages of this flexibility expansion, while the solution time increases only moderately in most cases. The authors in (Vromans *et al.* 2007) consider a stochastic optimization model for the macro-level for building in time buffers between connecting trips based on arrival and departure distributions for each train. They propose a model, which allocates a restricted amount of time supplement to a number of trips to minimize the expected total amount of delay. Experimental results suggest that applying slight modifications to an existing timetable can reduce the average passenger delay substantially.

In this paper on container vessel planning, we also built in buffers by reserving quay and crane capacities to satisfy the agreements in each arrival scenario within the windows. Our results also suggest that slight modifications to a representative plan yield significant improvements. A major difference with airline and rail operations however is the following:

passengers can enter a plane or train by themselves, but cranes are required for discharging and loading vessels. Besides satisfying the window agreements, an additional goal for container operators is therefore to reduce the maximal amount of crane capacity ever required. Our model constructs a berth plan that minimizes the maximal crane capacity reservation and still satisfies the agreements for all arrival scenarios within the windows.

To the best of our knowledge, only one study (Moorthy & Teo 2006) addresses the problem of pro-active robustness in the berth allocation problem. Arrival times of an existing plan are given and cannot be changed. The authors derive an expression for the expected delay for each vessel based on arrival distributions. Given these expected values and a desired berthing position for each vessel, suitable time buffers and suitable berth positions are allocated to each vessel. Conflicting objectives are to minimize total expected delay, the number of overlaps of vessels and the deviations from preferred berth locations. Once a periodic berth allocation is determined, simulations with stochastic arrivals are performed. Simulations compare the performance of a model neglecting disturbances and the model that incorporates disturbances. Results suggest that taking disturbances into consideration yields a reduction in total delay on the operational level. One of the recommendations of the authors is to incorporate crane allocations while constructing a robust berth plan.

In this paper, we as well aim for embedding robustness in an existing berth plan. In contrast to the study in (Moorthy & Teo 2006), the model in this paper does incorporate the crane allocation problem. Dependent on the arrival scenario, an appropriate time variant crane capacity allocation has to be decided on. Additionally, our model does have the flexibility to modify the scheduled arrival and departure times and takes the agreements for arriving within the window around the arrival time into consideration. With this WB-plan tool, the arrival and departure times are chosen such that with an intelligent crane capacity allocation the maximal crane capacity reservation is minimized and agreements are still satisfied. As a particular case, the model constructs a conventional WI-plan by simply reducing the arrival window to zero, hence the problem of allocating single arrival and departure times remains. It is interesting to compare i) the crane capacity required in the WB-plan and in the WI-plan, and ii) the sensitivity of both plans to the window agreements.

The outline of this paper is as follows: In Section 2, the problem is formally phrased. Then, an MILP is proposed to construct a WB-plan with minimally required crane capacity in the worst case scenario. In Section 3, results of a case study suggest that with only small modifications to an existing plan already significant improvements can be achieved. In a second experiment, the performances of the WB-plan and a WI-plan are compared. We end with conclusions and future work in Section 4.

2. MODEL

In this section, an MILP is proposed to construct a WB-plan with minimal crane crane capacity in the worst of arrival scenarios, where vessels arrive anywhere within their windows.

2.1. System description

For all of this paper the following holds, unless stated differently: $v \in \{1, 2, \ldots, V\}$, the set of vessels, and $k \in \{1, 2, \ldots, K\}$, the set of discrete time slots. We consider a terminal with quay length L and a set of V container vessels, where vessel v has length M_v. Each vessel is assumed to be discharged and loaded at this terminal exactly once a week. We define C_v to be the total amount of containers that has to be discharged from and loaded onto vessel v and assume this amount to be the same each week.

Parameter	Definition
V	Number of vessels in the set
K	Number of discrete time slots in the periodic plan
L	Terminal quay length [m]
M_v	Length of vessel v [m]
C_v	Nr. containers to be discharged from and loaded onto vessel v
S_v	Maximal nr. quay cranes that can process vessel v simultaneously
$\bar{\lambda}$	Mean crane rate [containers/time slot]
η_v	Crane efficiency on vessel v
W_v	Width of arrival window for vessel v
$P_v^{\min}$	Minimal process time of vessel v
$P_v^{\max}$	Maximal process time of vessel v
α_v	Fraction between $P_v^{\max}$ and $P_v^{\min}$

Table 1: Model parameters

Dependent on the length M_v of vessel v, a maximum number S_v of quay cranes can process vessel v simultaneously. In practice, quay cranes with different processing rates are present in the terminal. We do not take the specific allocation of quay cranes to vessels into account yet, but consider an average processing rate $\bar{\lambda} \in \mathbb{N}$ for all quay cranes. The efficiency $\eta_v \in [0, 1]$ of cranes on vessel v, depends on the length M_v of vessel v, the smaller the length, the lower the efficiency. Then the minimal handling time of vessel v in terminal t depends on i) the mean processing rate $\bar{\lambda}$ in terminal t, ii) the efficiency η_v of quay cranes operating vessel v, iii) the maximal number of quay cranes that can proces vessel v simultaneously, and iv) the total number of containers C_v to be discharged from and loaded onto vessel v. The processing time of vessel v is assumed to be inversely proportional to the first three of these items and proportional to the latter. The minimal integer number of time slots P_v^{min} required to process vessel v can thus be determined as follows:

$$P_v^{\min} = \left\lceil \frac{C_v}{\eta_v S_v \bar{\lambda}} \right\rceil. \tag{1}$$

As mentioned before, the terminal operator has to guarantee a maximal process time only if a vessel arrives within its arrival window. We assume the width W_v of the arrival window for vessel v to be equal to an integer number of time slots. In practice, the maximal process time agreed upon by the vessel line of vessel v and terminal operator after arriving within this window is a factor α_v larger than the minimal proces time. This we approximate by

$$P_v^{\max} = \left\lceil \alpha_v P_v^{\min} \right\rceil, \tag{2}$$

where $P_v^{\max}$ is the maximal number of time slots in which vessel v has to be processed only if it arrives within its arrival window, and $\alpha_v \geq 1$. Commonly, the value of α_v is significantly larger than 1, which implies that vessel v not has to be processed with the maximal number of cranes S_v permanently while berthing. Hence, for each possible arrival scenario an appropriate time variant crane capacity allocation can be decided on. The model parameters are summarized in Table 2.1..

The problem is to construct a periodic berth plan that is robust to the arrival scenarios where vessels arrive anywhere within their window. Robustness of this berth plan in our definition is twofold: i) the arrival agreements have to be satisfied for each of the arrival scenarios within the windows around arrivals in the plan and ii) the required amount of quay crane capacity in the worst case arrival scenario has to be minimal. In the next subsection, we propose an MILP with incorporates both these conditions.

2.2. MILP

Decision variables

a_v	=	First time slot that quay length and cranes are reserved for vessel v
d_v	=	Last time slot that quay length and cranes are reserved for vessel v
l_v	=	Left end of agreement window of vessel v
$q_v(k)$	=	Amount of crane capacity reserved for vessel v during time slot $[k, k+1\rangle$

Auxiliary variables

$$b_v(k) = \begin{cases} 1 & \text{if vessel } v \text{ can possibly berth during time slot } [k, k+1\rangle, \\ 0 & \text{otherwise.} \end{cases}$$

$$e_v = \begin{cases} 1 & \text{if } a_v > d_v, \\ 0 & \text{if } a_v \leq d_v. \end{cases}$$

r_v = Right end of agreement window of vessel v.

$$w_v(k) = \begin{cases} 1 & \text{if time slot } [k, k+1\rangle \text{ lies within the arrival window of vessel } v, \\ 0 & \text{otherwise.} \end{cases}$$

$$e_v^w = \begin{cases} 1 & \text{if } l_v > r_v, \\ 0 & \text{if } l_v \leq r_v. \end{cases}$$

$m_v(k)$ = Nr. quay meters reserved for vessel v during time slot $[k, k+1\rangle$.

Q = At least the amount of crane capacity required in the worst case scenario.

Constraints and objective

For each vessel v, the earliest possible arrival and latest possible departure time (a_v and d_v, respectively) have to be decided on. In between its earliest possible arrival time and its latest possible departure time, a vessel can possibly berth. Before its earliest possible arrival time and after its latest possible departure time, a vessel cannot berth at all (Hendriks *et al.* 2007):

$$1 - a_v \leq k \cdot \big(b_v(k) - e_v\big) \leq d_v - 1 \qquad \forall v, k, \tag{3}$$

$$r_v - K \leq \big(K - k\big) \cdot \big(b_v(k) - e_v\big) \leq K - a_v \qquad \forall v, k, \tag{4}$$

$$\sum_{k=1}^{K} \big(b_v(k) - e_v\big) = d_v - a_v \qquad \forall v. \tag{5}$$

If time slot $[k, k+1\rangle$ is a possible berthing time slot of vessel v, M_v quay meters have to be reserved during that time slot:

$$m_v(k) = M_v \cdot b_v(k) \qquad \forall v, k. \tag{6}$$

The sum of lengths of all vessels possibly berthing during time slot $[k, k+1\rangle$ should never exceed the terminal length L:

$$\sum_{v=1}^{V} m_v(k) \leq L \qquad \forall k. \tag{7}$$

If time slot $[k, k+1\rangle$ is reserved for vessel v, a capacitated amount of crane capacity can be reserved for vessel v during that time slot:

$$q_v(k) \leq S_v \cdot b_v(k) \qquad \forall v, k. \tag{8}$$

Considering the arrival agreements, an arrival window has to be allocated for each vessel v. This can be formulated in a similar way as the berthing window reservation in 5 through 7:

$$1 - l_v \leq k \cdot \big(w_v(k) - e_v^w\big) \leq r_v - 1 \qquad \forall v, k, \tag{9}$$

$$r_v - K \leq \big(K - k\big) \cdot \big(w_v(k) - e_v^w\big) \leq K - l_v \qquad \forall v, k, \tag{10}$$

$$\sum_{k=1}^{K} \big(w_v(k) - e_v^w\big) = r_v - l_v \qquad \forall v. \tag{11}$$

Additionally, the width of the arrival window for vessel v is fixed to W_v:

$$\sum_{k=1}^{K} w_v(k) = W_v + 1 \qquad \forall v. \tag{12}$$

We now have to guarantee that the window agreements for vessel v are satisfied. The agreements state that if vessel v arrives within its window, it should be processed within the maximal process time. Hence, for each range of time slots that starts from a time slot within the window of vessel v and ends $P_v^{\max} - 1$ time slots later, the sum of reserved crane capacities should be sufficient to process at least C_v containers. Since the position of the window of vessel v is a decision variable on itself, we have to explicitly consider the sum of crane reservations for each possible range of time slots of width $P_v^{\max}$. Only if the first time slot of such a range lies within the window of vessel v, sufficient crane reservations for vessel v during these time slots are required to process at least C_v containers. To model this we make use of the fact that for these cases $C_v \cdot w_v(k) = C_v$,

$$\sum_{i=k}^{k+P_v^{\max}-1} \eta_v \bar{\lambda} q_v(k) \geq C_v \cdot w_v(k) \qquad \forall v, k. \tag{13}$$

The sum of reserved crane capacities of all vessels during time slot $[k, k+1\rangle$ should never exceed the maximal crane capacity reservation:

$$\sum_{v=1}^{V} q_v(k) \leq Q \qquad \forall k. \tag{14}$$

The objective is to minimize the maximal crane capacity reservation:

$$\min_{a_v, d_v, l_v, q_v(k)} Q \tag{15}$$

3. CASE STUDY

The MILP proposed in the previous section determines a WB-plan with minimal crane capacity reservations in the worst case arrival scenario where vessels still arrive within their windows. The model thus incorporates the arrival window agreements and hence finds a plan robust to these agreements. In this section, we perform two experiments on a representative berth plan constructed by PSA HNN. This tactical plan considers one terminal and 15 vessels ($V = 15$), which call once each week. We set the arrival width of vessel v to eight hours, so $W_v = 8$, $\forall v$, which is a typical window width in real-life container operations. This implies that if a vessel arrives up to four hours earlier or four hours later than its planned arrival, it still has to be processed within its maximal process time. The values for the other vessel parameters as given in Table 2.1. are given as well. We assume $\alpha_v = 1.4$, $\forall v$. A time slot width of one hour is chosen, so $K = 168$.

In the first experiment, the WB-plan tool is applied to this berth plan for different extents of modifications. Results suggest that with small modifications, significant reductions in the maximal crane capacity reservation can already be achieved. As a particular case, the WI-plan is constructed by simply reducing the arrival windows width to zero ($W_v = 0$) in the model. Optimizing the MILP then results in an optimal periodic plan with minimal crane capacity. In the second experiment, the performance of both the WB-plan and the WI-plan are compared. Results suggest that although the WI-plan on itself requires less crane capacity reservations than the WB-plan, the WI-plan is much more sensitive to the arrival window agreements.

3.1. Benefit of plan modification

As mentioned before, vessels have fixed routes and a preferred arrival time in each port they call on. Negotiations have to point out whether vessel lines are willing to slightly modify their scheduled arrival times. Thus, an existing berth plan cannot completely be mixed up, but only small modifications (of a couple of vessels) may be possible. We thus aim for large crane capacity reductions with relatively small modifications to the existing plan. To obtain some more insight in the improvements that can be made dependent on the extent of modification, a sequence of 4 experiments is performed. In experiment i, $i \in \{1, 2, 3, 4\}$, a vessel subset $\mathcal{V}_i$ is selected from the dense part of the representative data set of PSA HNN, where $|\mathcal{V}_1| = 2$, $|\mathcal{V}_2| = 4$, $|\mathcal{V}_3| = 7$, $|\mathcal{V}_4| = 15$, and $V_i \subset V_{i+1}$, $\forall i \in \{1, 2, 3\}$. For each of the vessels in the subset $\mathcal{V}_i$ of experiment i, we allow a maximal modification of G_v time slots with respect to the existing plan, by introducing appropriate upper and lower bounds on the arrival window position l_v. For each experiment $i \in \{1, 2, 3, 4\}$, the WB-plan MILP with $W_v = 8$, $\forall v$ is optimized consecutively for $G_v \in \{0, 1, 2, ..., 8\}$.

Results are presented in Figure 1. The (scaled) maximal crane capacity reservation is plotted versus the maximally allowed plan modification for each of the four chosen vessel subsets. Each curve in this plot depicts the outcome of one experiment i. It can be noticed that all lines are monotonically decreasing. This makes sense, since increasing the extent of maximal possible time modification (G_v) can never yield a higher amount of required crane capacity. Along the same line, we can explain that the curve of experiment $i + 1$ never exceeds the curve of experiment i. Namely, if the plan of more vessels can be modified, a higher amount of maximal crane capacity reservation can never be determined by the model. An interesting result in this figure is that with allowing the modification of the plan of seven vessels, the same improvements can be achieved as by allowing the modification of the plan of all fifteen vessels. Moreover, by allowing a modification of only four vessels, at least 95% of these improvements can already be obtained. These results suggest that by modifying the plan of four out of fifteen vessels maximally 3 hours, a reduction of about 7.5% in the maximal crane capacity reservation can be achieved.

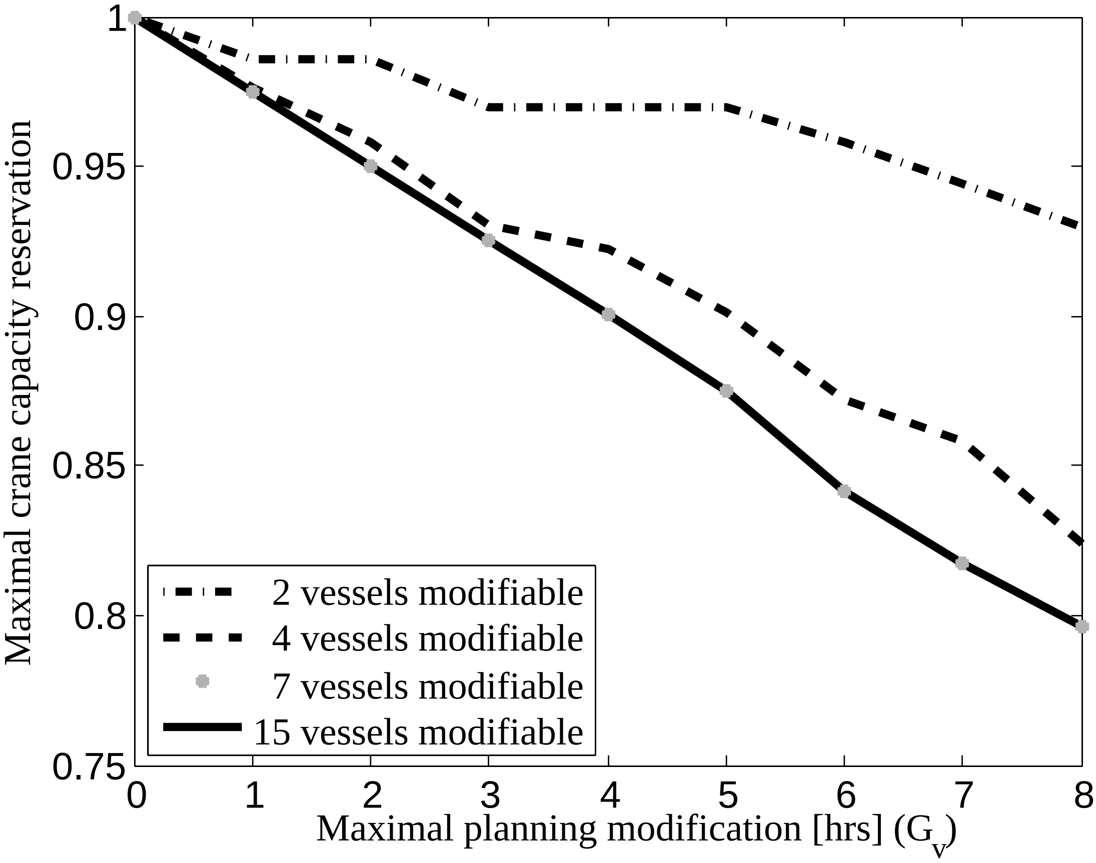

Figure 1: Benefit of modification.

3.2. WB-plan vs. WI-plan

Another approach to construct a tactical berth plan is to simply ignore the arrival window agreements and determine the optimal deterministic berth plan. Such a WI-plan can be determined by reducing the window width W_v to zero $\forall v$ in the MILP as proposed in Section 2. We are interested in the performance of the WB-plan and the WI-plan for bounded arrivals. We define the width between the arrival bounds to be U_v, where $0 \leq U_v \leq W_v$, $\forall v$. The performance of the constructed WB-plan and the WI-plan can now be determined as a function of U_v. In this paper, we only present the results of the performance for both extreme values, i.e $U_v = 0$, $\forall v$ and $U_v = W_v$, $\forall v$. The performance of the WB-plan and the WI-plan for intermediate values of U_v is discussed in a subsequent paper.

In this experiment, we only allow a modification of the vessels in the subset $\mathcal{V}_2$ of the previous experiment and hence $|\mathcal{V}_2| = 4$. For each of the values of G_v, $G_v \in \{0, 1, 2, ..., 22\}$, and $v \in \mathcal{V}_2$, the following procedures are applied to determine the performance of the WB-plan and WI-plan for $U_v = 0$, $\forall v$ and $U_v = W_v$, $\forall v$:

Procedure WB-planning:
1. a WB-plan is determined by optimizing the MILP with a window width $W_v = 8$,

2. the optimal value Q_8^{WB} is recorded,
3. the optimal values of the left end of the arrival window l_v^* are substituted into the l_v variables in the MILP and fixed,
4. optimization is done with a window width $W_v = 0$, $\forall v$,
5. the optimal value Q_0^{WB} is recorded.

Procedure WI-planning:
1. a WI-plan is determined by optimizing the MILP with a window width $W_v = 0$,
2. the optimal value Q_0^{WI} is recorded,
3. the optimal values of the left end of the arrival window l_v^* are substituted into the l_v variables in the MILP and fixed,
4. optimization is done with a window width $W_v = 8$, $\forall v$,
5. the optimal value Q_8^{WB} is recorded.

Figure 2 depicts Q_0^{WB}, Q_8^{WB}, Q_0^{WI}, and Q_0^{WI} as a function of $G_v \in \{0, 1, 2, ..., 22\}$ for $v \in \mathcal{V}_2$.

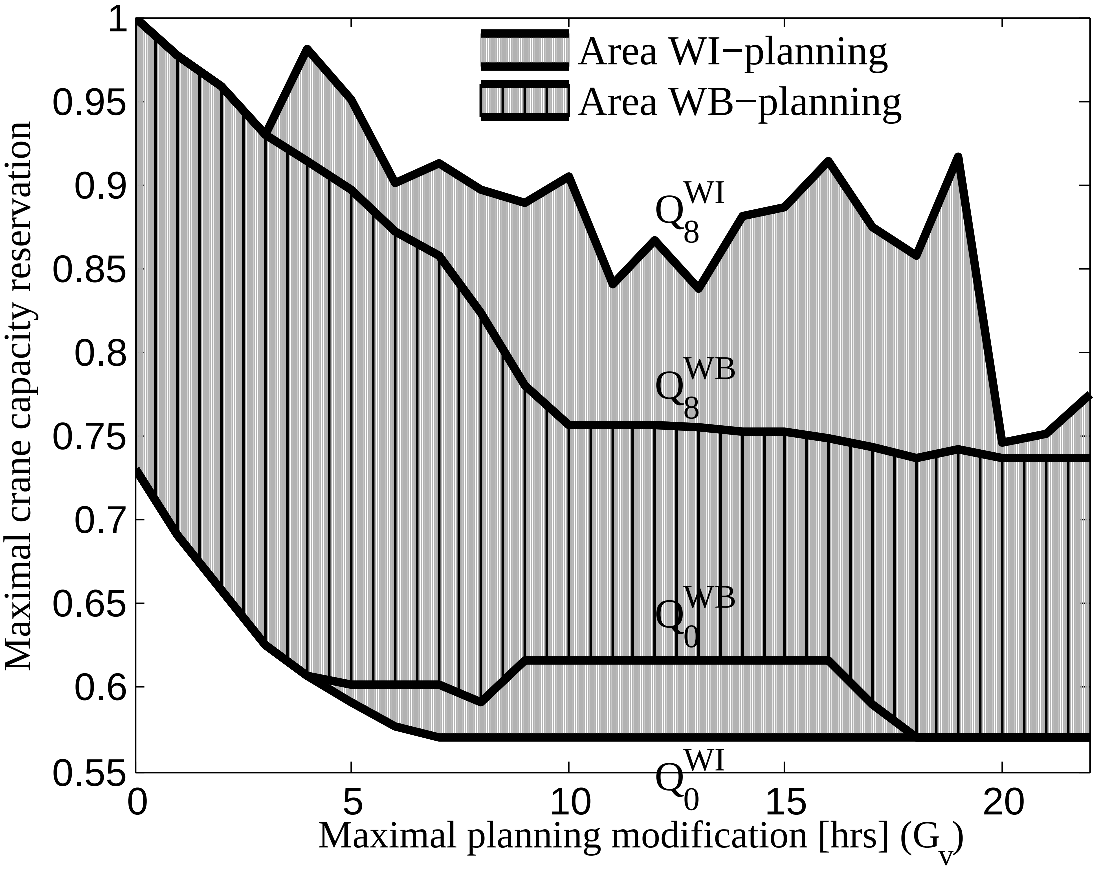

Figure 2: Window-Based plan (WB) vs. Window-Ignoring plan (WI).

In this figure we can notice the following:

- The grey area represents the range of maximal crane capacity reservations for all arrival scenarios within the windows ($W_v = 8$, $\forall v$) for the WI-plan. The shaded area represents the range of required crane capacities for all arrival scenarios within the windows ($W_v = 8$, $\forall v$) for the WB-plan. It can be noticed that the shaded area in total lies within the grey area. Apparently, the WI-plan outperforms the WB-plan if zero disturbances on arrivals are present, but is much more sensitive to stochastic arrivals. It is interesting to study the dependency of the WI-plan and the WB-plan on different stochastic arrivals within the assumed window size of 8 hours. This study is addressed in a subsequent paper.

- The curves for Q_0^{WI} and Q_0^{WB} are monotonically decreasing. This is to be expected, since these lines result from the first step optimizations (step 1 in both procedures). Hence, if the maximal plan modification increases, the maximal crane capacity reservation will never increase.

- The curves for Q_0^{WI} and Q_0^{WB} however, are not monotonically decreasing. If we have another look at the procedures, we notice that these are determined in a second optimization (step 4 in both procedures) in which the values from the first optimization are already fixed. Regarding this it makes sense, since the decisions made in the first optimization (step 1) do not necessarily have to be optimal in the second optimization (step 4), and might result in a higher crane capacity in the second optimization even when the maximal plan modification increases.

- The curve for Q_0^{WI} never exceeds the curve for Q_8^{WI}. This is to be expected, since the computation of Q_0^{WI} is constructed from the same plan as Q_8^{WI}, however assuming zero stochasticity instead of a distribution width of 8 hours. The incorporation of disturbances on the arrivals will always yield at least the same amount of crane capacity. The same reasoning can be applied for the observation that Q_0^{WB} never exceeds Q_8^{WB}.

- The curve for Q_0^{WI} never exceeds the curve for Q_0^{WB}. This is to be expected since Q_0^{WI} is determined in a first optimization (step 1) and Q_0^{WB} in the second optimization (step 4). Q_0^{WI} ignores the arrival window agreements and hence is the optimal plan if no arrival disturbances are present. Q_0^{WB} is constructed from a WB-plan, which incorporates the window agreements during optimization. The satisfaction of these agreements may lead to a plan which is not optimal when zero arrival disturbances are present.

- The curve for Q_8^{WB} never exceeds the curve for Q_8^{WI}. This is to be expected since Q_8^{WB} is determined in a first optimization (step 1) and Q_8^{WI} in the second optimization (step 4). Q_8^{WB} incorporates the arrival window agreements and hence is a robust plan if arrival disturbances are present. Q_8^{WI} is constructed from a WI-plan, which ignores the window agreements during optimization. Ignoring these agreements may lead to a plan which is not robust to arrival disturbances.

- The initial values of Q_0^{WI} and Q_0^{WB} are equal. This is to be expected since in this case $G_v = 0$, $\forall v \in \mathcal{V}_2$ and hence no modifications in the time plan can be made (l_v is fixed). An intelligent time-variant crane capacity allocation for the given plan results in the same amount of maximal crane capacity reservation when arrivals are assumed to be deterministic. The same reasoning can be applied for the observation that the initial values of Q_8^{WI} and Q_8^{WB} are equal.

- The initial values of Q_0^{WI} and Q_0^{WB} on one hand, and Q_8^{WI} and Q_8^{WB} on the other are not (necessarily) equal, although they are all based on the same berth plan (namely

l_v is fixed). Still, this observation makes sense, since in the former two cases (Q_0^{WI} and Q_0^{WB}) deterministic arrivals are assumed and in the latter two cases (Q_8^{WI} and Q_8^{WB}) stochastic arrivals (within the windows) are assumed. Disturbances on the arrivals will result in at least the same amount of crane capacity than in the case without disturbances.

4. CONCLUSIONS

We considered a set of container vessel that has to be discharged and loaded in a container port by a terminal operator on a periodic basis. Disturbances on travel times lead to stochastic arrivals in the port. To cope with these disturbances, the terminal operator agrees on a so-called arrival window for each vessel rather than a single arrival time. Only if a vessel arrives within its window, the terminal operator has to guarantee a maximal process time. If not, the terminal operator is not bound to any maximal process time.

We proposed an MILP to construct a window-based periodic berth plan (WB-plan) with minimally required crane capacity in the worst case arrival scenario, i.e. an MILP that minimizes the required crane capacity while the agreement for all scenarios where vessels arrive within their windows are still satisfied. Experiments on a representative plan obtained from the terminal operator PSA HNN in Antwerp, Belgium, suggested that with small modifications to the representative plan, already significant reductions in the required crane capacity can be achieved.

As a particular case, the MILP constructs a window-ignoring periodic berth plan (WI-plan) by reducing the agreement window width to zero. We investigated the performance of the WB-plan and the WI-plan for deterministic arrivals and stochastic arrivals within the windows. Results suggested that although the WI-plan requires less crane capacity than the WB-plan, it is much more sensitive to stochastic arrivals.

It is interesting to further investigate the performance of the WB-plan and the WI-plan as a function of the width of the arrival distributions. This study is addressed in a subsequent paper. Actually, the proposed MILP determines an upper bound on the maximal crane capacity reservation. Namely, it does not explicitly minimize the crane capacity for each individual arrival scenario permutation and then determines the maximum among all the objectives. It rather reserves sufficient crane capacity during a number of time slots for each vessel such that the window agreements are always met. This approximation significantly reduces the number of scenarios to be evaluated. A recent study investigates for small instances the deviation between our determined upper bound and the optimal value.

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