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Designing robust liner shipping schedules: Optimizing recovery actions and buffer times

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Abstract

Liner shipping schedules often cover longer periods of time during which significant delays can occur that increase costs. To avoid unanticipated increases in costs, robust schedules are required. Designing robust schedules requires optimal allocation of buffer time and planning of recovery actions to be taken when facing delay.

In this thesis this problem has been addressed by using both a mixed integer programming problem formulation and a heuristic approach. In addition, this thesis discusses possible extensions of the problem, including an approach for taking into account the effect of tides. The results of the methods discussed in this thesis were compared to a schedule with fixed buffer time and maximum speed on every sea leg. This revealed that a cost reduction of 9.6% can be achieved.

Contents

1 Introduction

Liner shipping represents one of the most important modes of transport for goods around the world. Liner ships operate according to fixed routes at a specified frequency, mostly weekly. The ships carry containerized cargo that needs to be transported from one port to another within a certain time window. The schedules of these liner ships specify the ports visited and corresponding arrival and departure times. Ports can be visited multiple times on one route (Kjeldsen et al., 2011). During the operation of these routes, delays can occur due to various reasons, as explained by Notteboom (2006). These reasons include terminal operations delay, port access delay, maritime passage delay and chance.

Disruptions can have large economic consequences for both shipping lines and customers (Kjeldsen et al., 2011). The liner shipping company faces increased bunker costs, additional port fees due to additional port calls and possibly extra costs because additional transportation of cargo between ports is required. Furthermore, the company will face a loss of reliability leading to a possible loss of customers. In addition, Kjeldsen et al. (2011) explained the economic consequences for the customers, which incur costs for every day their cargo on the ship is delayed.

The aim of this research is to find robust shipping line schedules by determining buffer time allocation and a recovery policy in order to minimize costs associated with delays and recovery actions. The methods used for this purpose are proposed by Mulder and Dekker (2016).

1.1 Literature review

Among others, Notteboom (2006) and Kjeldsen et al. (2011) discuss the effects of delays and disruptions in liner shipping schedules on the associated costs for the shipping company and its customers. One important measure to overcome delays is to increase sailing speed. However, this comes at the cost of increasing bunker costs, since fuel consumption increases proportional to the sailing speed cubed (Wang and Meng, 2015). Still, recovering delay by increasing speed is common. Wang and Meng (2012a) discuss the problem of designing shipping schedules considering uncertainties in both port and sailing times. They also overcome delays by increasing speed, but take into account the trade-off between higher bunker consumption and overall costs. Qi and Song (2012) aim to minimize fuel consumption while taking into account uncertainty in port handling times. By imposing a penalty on late arrivals they introduce a trade-off between increase in costs due to extra bunker consumption and due to late arrival.

Other studies have considered different strategies for recovering from disruptions. In addition to adjusting speed, Brouer et al. (2013) allow for recovering delays by swapping the order of port visits or by omitting certain ports. Furthermore, they introduce a finite time horizon after which delay has to be recovered. Similar to increasing speed, omitting and swapping ports can lead to increased costs for instance due to additional transport between ports. Brouer et al. (2013) evaluate disruption scenarios and aim to select recovery actions that balance the trade off between the costs of increasing speed and thus bunker consumption and those of delayed arrival of cargo, including missed connections and decreased service levels.

Similar to Brouer et al. (2013), Li et al. (2015a) allow for delay to propagate to following sea legs, but they do not have a fixed time after which delay has to be recovered. Li et al. (2015a) introduce a penalty for late arrivals and make a trade-off between these penalties and increased bunker consumption. Especially when travel time between two ports is short this can be less costly than recovering full delay on the current sea leg.

Li et al. (2015b) also focus on the real-time recovery after disruptions, but they distinguish between two types of disruptions. The first type concerns recurring and regular uncertainties, including port congestion and unexpected waiting times. The other type refers to one-off events such as labour strikes. According to Li et al. (2015b) the first type of disruptions could be buffered against in tactical planning by using probabilistic models. The second type is difficult to incorporate in tactical planning. Therefore, different strategies are proposed.

Wang and Meng (2012b) and Fischer et al. (2016) focus on this tactical level and discuss the problem of designing robust schedules for liner shipping, in order to minimize the effect of disruptions. Furthermore, Fischer et al. (2016) study recovery strategies once a disruption has occurred and the current schedule is no longer optimal. However, their study mostly focuses on roll-on roll-off shipping, which considers cargo that can be rolled onto and off vessels such as cars. Fischer et al. (2016) increase robustness of strategies by adding buffer time, rewarding early arrivals and penalizing risky characteristics, such as start times close to the end of time windows.

Liner shipping is not the only area that faces delay that results in additional costs to the company and its customers. Brouer et al. (2013) make a comparison between the recovery of disruptions in liner shipping and airline industry, since airlines can face delays due to reasons similar to the ones for liner shipping. Designing robust schedules for the airline industry was studied among others by Wu (2006). Wu (2006) uses sequential optimisation techniques to overcome the propagation of delays in airline schedules by considering allocation of buffer times in the process of aircraft rotation. However, Brouer et al. (2013) mention important differences between delay propagation in the liner shipping and airline industries. Delays in flights will often only exist for a limited number of consecutive trips, since the time planned in between trips exceeds the time required for the aircraft to be prepared for the next flight. In addition, a significant part of aircraft is idle over night. Another measure to overcome delays in the airline industry is by swapping aircraft, which is possible since an aircraft is emptied completely after each flight. Both of these measures are more difficult to use in liner shipping, since liner ships operate continuously for several weeks. On the other hand, in liner shipping there is more flexibility to overcome delay by varying speed.

1.2 Contribution and plan of approach

Even though the subject of delay recovery in liner shipping has been studied increasingly, little research has been performed on simultaneous development of robust schedules and recovery policies. Current literature mostly focuses on recovery after delay or disruptions have occurred, taking buffer time allocation constant. The effect of buffer time allocation on total delay and recovery costs has not been studied yet. In addition, savings could be realised by adjusting buffer time allocation and recovery policy to one another.

In this paper a model will be discussed that optimizes buffer time allocation and recovery simultaneously. First of all a mixed integer programming formulation (MIP) will be proposed, which results in the optimal allocation of buffer time on different sea legs and the optimal recovery policy. However, solving this problem to optimality will require significant computation time. In reality faster methods with possibly sub-optimal results could be more valuable. For this reason, a heuristic approach will be considered. In this value iteration heuristic (VIH) the savings of reallocating buffer time are estimated instead of calculated exactly, which decreases computation times significantly.

2 Problem definition

In the ship delay recovery problem we have a vessel that needs to visit a list of ports in a given order. For each port required handling time and distance to the next port are known. However, during the execution of port activities or covering sea legs delays may occur. In order to overcome propagation of delays through the entire schedule, actions need to be taken. However, such recovery actions cause additional costs. Hence, the goal is to implement recovery actions while keeping additional costs as low as possible.

As mentioned earlier, the aim of this research is to simultaneously determine the optimal recovery policy and buffer allocation. Therefore, we build on the original ship delay recovery problem and incorporate the allocation of buffer time. Based on the information given about the ports visited, the distances between them and the required handling times in ports, we obtain the minimum required time to execute the route. However, given the weekly frequency of the service and thus integer number of weeks to cover the route, some additional time will be available. This time can be used as buffer, such that delay does not propagate through the entire schedule when delays occur during a transition between ports or activities in a port. Buffer time should be allocated in advance in such a way that costs associated with delays and recovery actions are minimized. For each position of the ship, we want to determine how many additional time units are allocated.

3 Methodology

3.1 Mixed Integer Programming Problem

The ship delay recovery problem is formulated as a Markov decision process. The states of the Markov process are defined by the position of the ship, which includes the current port and whether the ship is arriving or departing, and the amount of delay. In order to obtain a finite number of states for the Markov process, all times are discretized and a maximum number of time units is set for delay, d^{max}. In addition, time units of four hours are used, reducing the number of states of the Markov process and thus leading to shorter computation times. As a consequence of modelling the problem by means of a Markov process, it is assumed that additional delay incurred in a state is only dependent on the current state, i.e. current position and delay, and the action chosen.

3.1.1 Ship delay recovery problem with fixed buffer times

First, we start by studying the ship delay recovery problem in which buffer time allocation is fixed. The first step in formulating the ship delay recovery problem as a linear programming problem is introducing the required sets.

P	set of possible port positions (port name and arriving/departing);
D	set of possible units of delay;
I	set of possible states of Markov process, where each state consists of a port position and number of units delay, $I = P \times D$;
K	set of possible actions;
$K(i)$	set of possible actions that can be performed when in state $i = (p, d)$.

Next, we need to determine the transition probabilities between states. The probability of a transition from state $i = (p, d)$ to state $j = (p', d')$ when action $k \in K(i)$ is chosen is denoted by p_{ijk}. Denote the probability of $\bar{d}$ additional units of delay occurring when the process is in state $i = (p, d)$ by $\bar{p}_{i\bar{d}}$. Let g_k and b_p be the number of time units gained by performing action k and the number of time units buffer available in port p respectively. A transition from state $i = (p, d)$ to $j = (p', d')$ can only occur if port p' is visited directly after port p and $d' = d + \bar{d} - g_k - b_p$. If $d' > 0$, the probability of transitioning from state i to state j is equal to the probability of incurring $\bar{d}$ additional units of delay, where $\bar{d} = d' - \min\{d, d^{\max}\} + g_k + b_p$. If $d' = 0$, the probability of transitioning from state i to j is the sum of the probabilities of incurring $\bar{d}$ additional units of delay such that $d + \bar{d} - g_k - b_p \leq 0$. Hence, p_{ijk} is given by Equation (1).

$$p_{ijk} = \begin{cases} \bar{p}_{i\bar{d}} & \text{with } \bar{d} = d' - \min\{d, d^{\max}\} + g_k + b_p \quad \text{if } d' > 0 \\ \sum_{\bar{d} \in D} \bar{p}_{i\bar{d}} & \text{with } D = \{\bar{d} | d + \bar{d} - g_k - b_p \leq 0\} \quad \text{if } d' = 0 \end{cases} \tag{1}$$

The decision variables in the linear programming formulation are π_{ik}, which denote the probability of being in state i and choosing action k. The resulting formulation of the ship delay recovery problem is given below.

$$\min \quad \sum_{i \in I} \sum_{k \in K(i)} C_{ik} \pi_{ik} \tag{2}$$

$$\text{s.t.} \quad \sum_{i \in I} \sum_{k \in K(i)} \pi_{ik} = 1 \tag{3}$$

$$\sum_{k \in K(j)} \pi_{jk} - \sum_{i \in I} \sum_{k \in K(i)} \pi_{ik} p_{ijk} = 0 \quad j \in I \tag{4}$$

$$\pi_{ik} \geq 0 \quad i \in I,\ k \in K(i) \tag{5}$$

The objective function (2) formalizes the aim of the model, which is minimizing costs. Constraint (3) ensures that the probabilities sum up to 1, while Constraints (4) guarantee the transition from one state to another. Constraints (5) restrict the probabilities to be non-negative.

3.1.2 Ship delay recovery problem with buffer time allocation

The standard ship delay recovery problem is extended to incorporate buffer time allocation. Several constraints are added to the formulation concerning the allocation of buffer times. This requires the introduction of some additional sets.

B	set of possible values of buffer time per ship position;
A	set of possible actions in the new Markov decision problem, $A = K \times B$.

The total buffer time available is denoted by M and B_b denotes the value in time units of buffer $b \in B$. Since transition probabilities between states do not only depend on the chosen action, but also on the assigned buffer time, p_{ija} is used instead of p_{ijk}, where a is specified by an action k and buffer time b. These probabilities are calculated in the same way as p_{ijk} in Equation (1), using action k and buffer time b that characterize action a instead of fixed buffer time. Furthermore, binary decision variable y_{bp} is introduced, where y_{bp} takes value 1 if buffer time $b \in B$ is allocated to ship position $p \in P$ and 0 otherwise.

The formulation of the ship delay recovery problem with buffer time allocation is as follows:

$$\min \quad \sum_{i \in I} \sum_{a \in A} C_{ia} \pi_{ia} \tag{6}$$

$$\text{s.t.} \quad \sum_{i \in I} \sum_{a \in A} \pi_{ia} = 1 \tag{7}$$

$$\sum_{a \in A} \pi_{ja} - \sum_{i \in I} \sum_{a \in A} \pi_{ia} p_{ija} = 0 \qquad j \in I \tag{8}$$

$$\sum_{p \in P} \sum_{b \in B} B_b y_{pb} = M \tag{9}$$

$$\sum_{b \in B} y_{pb} = 1 \qquad p \in P \tag{10}$$

$$\sum_{d \in D} \sum_{k \in K(pd)} \pi_{(pd),(kb)} \leq y_{pb} \qquad p \in P,\ b \in B \tag{11}$$

$$\pi_{ia} \geq 0 \qquad i \in I,\ a \in A \tag{12}$$

$$y_{pb} \in \{0,1\} \quad p \in P,\ b \in B \tag{13}$$

As in the simpler case without buffer time allocation, the objective (6) is cost minimisation. Constraints (7) and (8) have the same function as in the previous formulation. Constraint (9) ensures that total allocated buffer time equals total available buffer time. Constraints (10) are required to guarantee that only one possible buffer time is allocated to each ship position. Without this constraint multiple buffer times could be allocated to a ship position for different values of delay. Constraints (11) ensure that action $a \in K \times B$ can only be taken in state $i = (p, d) \in I$ if buffer time b is allocated to ship position p, i.e. if $y_{pb} = 1$. Constraints (12) and (13) restrict the domains of the decision variables.

3.2 Value Iteration Heuristic

The mixed integer programming problem can be used to solve the problem to optimality. However, as the size of the problem increases, computation time increases significantly. Therefore, a heuristic approach to the ship delay recovery problem with buffer time allocation is considered.

The Value Iteration Heuristic (VIH) starts from a feasible buffer time allocation. In every step of the heuristic savings are estimated of exchanging one unit of buffer time for each pair of port positions. It is assumed that the optimal recovery policy changes only slightly, when the assigned buffer time is increased or decreased by one unit. The costs of the slightly adjusted recovery policy is calculated using the value function. The value function denotes for each state the expected costs when following the current recovery policy. The heuristic continues until a cycle is detected. The best found solution is then returned.

When the number of units buffer time assigned to port position p increases by one, two options can be chosen. First, it would be possible to reduce the action by one unit, in which case the delay in the next port position remains the same. For state i, with $p \in i$, let $k'(i)$ be the recovery action in case the action is reduced by one unit. Then $k'(i) = k^*(i) - 1$, where $k^*(i)$ is the current optimal recovery action. The costs of this option are estimated by the first part of Equation (14). Second, the action could remain the same, leading to a one unit decrease in delay in the next port position. The costs of this option are estimated in the second part of Equation (14). Costs of performing action k when in state i are set to infinity when action k cannot be performed in state i. Hence, $C_{ik} = \infty$ for all $k \notin K(i)$. Furthermore, $v_{p,-1} = v_{p,0}$ for all $p \in P$, since negative delays are not possible. In Equation (14), $v_{i-1} = v_{p,d-1}$ with $i = (p, d)$.

$$v_i^+ = \min\{C_{ik'(i)} + \sum_{j\in I} p_{ijk^*(i)} v_j,\; C_{ik^*(i)} + \sum_{j\in I} p_{ijk^*(i)} v_{j-1}\} \tag{14}$$

In case buffer time in port position p is reduced by one unit, there are again two possibilities. Either the action can be increased by one unit, in which case delay in the next port position remains the same, or action can remain the same, resulting in an additional unit of delay in the next port position. In this case, we denote a one unit increase in action by $k'(i) = k^*(i) + 1$. In case we do not increase action and the maximum level of delay is already reached in the next port position, a penalty C_p is charged. Hence, $v_{p,d^{max}+1} = v_{p,d^{max}} + C_p$. The value function of reducing buffer time by one unit in state i is given by Equation (15), where $v_{i+1} = v_{p,d+1}$ with $i = (p, d)$.

$$v_i^- = \min\{C_{ik'(i)} + \sum_{j\in I} p_{ijk^*(i)} v_j,\; C_{ik^*(i)} + \sum_{j\in I} p_{ijk^*(i)} v_{j+1}\} \tag{15}$$

The expected gain of adding an additional unit of buffer to port p is calculated by taking an average over the estimated gains for all states i with port p, weighted by the probability of being in state i and performing current optimal action $k^*(i)$. The expected costs of removing one unit of buffer from port p' are computed as the weighted average of the expected costs for states i with port p'. Hence the expected benefits of increasing buffer time in port p by one unit, while reducing buffer time in port p' by one unit is given by Equation (16).

$$\sum_{i\in I|p\in i} \pi_{ik^*(i)}(v_i - v_i^+) - \sum_{i\in I|p'\in i} \pi_{ik^*(i)}(v_i^- - v_i) \tag{16}$$

The VIH is described in Algorithm 1. In case no profitable exchange is possible, the least costly exchange is made, but the current best solution remains stored.

Algorithm 1 Value Iteration Heuristic

1: Initialization: begin with feasible buffer allocation
2: **while** no cycle detected **do**
3: *Estimate savings:* For each combination $p, p' \in P$ determine savings of exchanging one unit of buffer time from p' to p (using Equation (16))
4: *Buffer exchange:* Make most profitable exchange
5: *Evaluate:* Determine costs of new buffer allocation, store cost and allocation when its better than current allocation
6: **end while**

3.3 Extensions

3.3.1 Recovery actions in ports

In the standard formulation, we assume that recovery actions can only take place during sea legs by adjusting speed. However, in some ports it may be possible to decrease port time by hiring additional workers or machine capacity. This means that delay cannot only be recovered on sea, but also in ports. This can be incorporated by expanding $K(i)$ with $i = (p, d)$, where p concerns the arrival in the port. Multiple actions indicate multiple possibilities for port handling times, where actions associated with shorter than regular port handling times bring along additional costs.

Different scenarios are considered with respect to the number of ports in which it is possible to hire additional capacity and the costs associated. In all scenarios considered, it is assumed that reduction in the number of time units required during a port visit is limited to one time unit. The set of ports in which handling times can be reduced is chosen to be either the complete set of ports or a subset containing two specific ports. This method can be easily extended to other subsets of ports. Different levels of cost associated with hiring extra capacity are applied. It is investigated at which cost levels and for which lengths of delay this option is advantageous.

3.3.2 Deepwater and non-deepwater ports

In the standard formulation, it is assumed that all ports are deepwater ports. Deepwater ports are ports that can be accessed by large vessels independent of the tide (Tierney, 2015). However, some of the ports visited on a shipping line may be non-deepwater ports. Tides pose a challenge for such ports, since time windows in which a vessel can arrive or depart are limited by the tides (Tierney, 2015).

The standard formulation can be adjusted in such a way that non-deepwater ports can be accessed only within certain time windows. This is done by adjusting the transition probabilities p_{ija} to states j, where the corresponding port is a non-deepwater port p'. For every given action a at state i with corresponding recovery action k and buffer time b, the delay at non-deepwater port p' is calculated as $d' = \bar{d} + \min\{d, d^{max}\} - g_k - b$. Using total port time, sailing time and buffer time until the non-deepwater port and the delay with which the vessel arrives in this port, the arrival time is calculated. When this arrival time corresponds to a time period of low-tide, the vessel will have to wait until it can enter the port during high-tide. This means arrival delay d' is increased with the number of time periods it has to wait until high-tide. Using the resulting transition probabilities, the schedule can be optimized in order to take into account tides and corresponding additional delays.

Since the number of units buffer time in the previous ports should be known in order to calculate the arrival time in a certain port, this extension is only implemented using the VIH. The MIP approach cannot be used, because total buffer time in previous ports is not yet known when calculation of transition probabilities takes place.

In this extension of the original problem, tides are taken into account. This implies that waiting times and hence costs can change depending on the time at which the vessel starts its trip. Therefore, the schedule can be further optimized by selecting the start time. This problem requires the introduction of additional binary decision variables z_t, for every possible start time $t \in T$. These variables indicate whether the vessel starts its route in the given time period or not. Constraint (17) needs to be added to the problem to make sure only one start time for the route is selected.

$$\sum_{t \in T} z_t = 1 \tag{17}$$

Furthermore, transition probabilities are now dependent not only on the current state, next state and chosen action, but also on the start time of the route. Therefore p_{ijk} becomes p_{ijkt} in the standard ship delay recovery problem, where t indicates the start time. Constraints (4) of the standard problem are replaced by Constraints (18). In these constraints the transition probabilities corresponding to the selected start time are used, because all transition probabilities are multiplied by the binary decision variable.

$$\sum_{k \in K(j)} \pi_{jk} - \sum_{i \in I} \sum_{k \in K(i)} \sum_{t \in T} \pi_{ik} p_{ijkt} z_t \; = \; 0 \;\; \forall j \in I \tag{18}$$

However, Constraints (18) are a non-linear constraints, since they contain the multiplication of non-integer decision variables π_{ijkt} with binary decision variables z_t. Here we run into a technical limitation, since this type of problem cannot be solved using CPLEX (IBM, 2016). Since the problem under consideration uses time units of four hours, only six starting times for the route are possible. Hence, as an alternative, the optimal starting time can be found by testing all possibilities, while still using limited computational resources.

4 Data

Data used consists of characteristics of the route and distributions of delay encountered during port stays and on sea legs.

Port	Port time (hr)	Distance (nmi)	Scheduled sailing time (hr)	Sailing time at v=23 (hr)	Buffer time (hr)
Jebel Ali	31	1329	72	60	12
Jawaharlal Nehru	33	443	24	20	4
Mudra	16	1122	56	52	4
Salalah	14	1553	68	68	0
Jeddah	11	778	36	36	0
Suez Canal	16	2283	100	100	0
Algeciras	18	1476	88	68	20
Felixstowe	24	156	16	8	8
Antwerp	16	366	32	16	16
Bremerhaven	24	283	24	16	8
Rotterdam	20	3829	192	168	24
Suez Canal	22	395	20	20	0
Aqaba	20	656	40	32	8
Jeddah	19	2648	124	116	8

Table 1: Characteristics of route

The characteristics of the route are adapted from the ME1 route of the Maersk Line network in September 2012 (see Table 1). The first column gives the ports visited and the rows the order in which they are visited. The second column shows the time required for each port visit. The third column gives the distance (in nautical miles) from the current port to the next. Distances are obtained from SeaRates (2015). The fourth column shows the scheduled sailing time between ports. The fifth column indicates the required sailing time when maintaining a speed of 23 knots, where 1 knot = 1 nmi/hr = 1.825 km/hr. The final column shows the current buffer time, which is the difference between the scheduled sailing time and the required time at an assumed speed of 23 knots. Total available buffer time is equal to 112 hours or 28 time units. Sailing times and current buffer allocation are rounded to multiples of four hours, consistent with Section 3.1.

Possible recovery actions concern increase and decrease of speed. Speed can be adjusted between a minimum and maximum value, which are taken to be 12 and 23 knots respectively, leading to an integer number of time units to cover the sea leg. Fuel cost per day in US dollars when sailing at a speed v (knots) is given by Equation (19).

$$C_f(v) = \tilde{f} \cdot p_{bunker} \left(\frac{v}{\tilde{v}}\right)^3 \tag{19}$$

In this equation $\tilde{f}$ represents fuel consumption in tons per day when design speed $\tilde{v}$ is maintained. Bunker price in US dollars per ton is given by p_{bunker}. In this paper a design speed of 16.5 knots, a bunker price 600 USD and a fuel consumption of 82.2 ton per day are used.

We can adjust these cost calculations to determine the fuel costs per sea leg following state i when action a is chosen, where a denotes the number of time units used to cover the sea leg (see Equation (20)). Here d_i denotes the distance to be covered on sea leg i and t_i the time required in time units when sailing at maximum speed. Multiplication by 4 transforms time units back to hours. Cost per time unit delay is assumed to be 10,000 USD.

$$C_f^i(a) = \tilde{f} \cdot p_{bunker} \left(\frac{d_i}{a \cdot 4 \cdot \tilde{v}}\right)^3 \cdot \frac{t_i \cdot 4}{24} \tag{20}$$

To obtain the results given in Section 5.1, discrete uniform distributions are used to determine delay for both sea legs and port stays. Delays for port stays are assumed to be distributed as $\bar{d} \sim U(0,2)$ and delays for sea legs as $\bar{d} \sim U(0, \lfloor 1 + \frac{d_p}{1{,}600} \rfloor)$, where d_p denotes the distance from port p to the next port. Maximum delay is set to one week, which corresponds to 42 time units.

To be able to compare the performance of the MIP to the VIH in Section 5.2, fifty test instances are generated, where delay is uniformly distributed between a lower and an upper bound. The lower bound is equal to 0 time units for both port stays and sea legs. The upperbound for port stays is a random integer number of time units between 1 and 4. For sea legs the upper bound is given by $x + \frac{d_p}{y}$, where x and y are discrete numbers, chosen uniformly from the intervals $[1, 3]$ and $[800, 3000]$, respectively.

Port	Buffer time (hr)	Max speed Average delay (hr)	Max speed On time prob (hr)	Max speed Avg fuel cons (ton)	Opt speed Average delay (hr)	Opt speed On time prob (hr)	Opt speed Avg fuel cons (ton)
Jebel Ali	12	1.59	0.33	497	7.93	0.17	443
Jawaharlal Nehru	4	0.77	0.63	166	3.81	0.54	166
Mudra	4	1.37	0.34	398	6.17	0.31	398
Salalah	0	1.93	0.22	618	8.37	0.20	618
Jeddah	0	3.43	0.04	277	14.37	0.03	277
Suez Canal	0	4.93	0.01	907	20.37	0.01	878
Algeciras	20	6.93	0.00	530	28.94	0.00	484
Felixstowe	8	3.52	0.13	45	16.13	0.00	41
Antwerp	16	3.12	0.18	146	14.22	0.06	84
Bremerhaven	8	1.39	0.52	68	6.56	0.38	52
Rotterdam	24	1.26	0.52	1517	5.72	0.45	1254
Suez Canal	0	0.27	0.88	117	2.00	0.68	117
Aqaba	8	1.77	0.15	210	8.00	0.11	202
Jeddah	8	1.42	0.33	1052	6.48	0.28	969

Table 2: Statistics current schedule

5 Results

5.1 Results optimized buffer time allocation

The expected costs incurred during a round tour in the original situation, when sailing at maximum speed (23 knots), are equal to 4.34 million USD. When recovery actions are optimized under the current buffer time allocation, using the ship delay recovery problem described in Section 3.1.1, the expected total costs are 4.11 million USD, which is a reduction of 5.3%. The average delay of arrival per port, the probability of on time arrival and the average fuel consumption for the following sea leg are given in Table 2 for the current buffer time allocation for both sailing at maximum speed and the optimized recovery actions. When the buffer allocation and recovery policy are optimized simultaneously, using the formulation from Section 3.1.2, the expected costs can be further reduced to 3.92 million USD. This is a reduction of 9.6% compared to the current schedule. Table 3 reports the statistics for the schedule with optimized buffer allocation and recovery actions.

In the original schedule, some ports were assigned large buffer times, up to 6 time units for Rotterdam, while other ports did not have any buffer time assigned. In the optimized buffer time allocation total buffer time is spread more equally across all ports, with at least one unit and at most four units assigned to every port.

Table 4 shows the optimal recovery policy corresponding to the optimal buffer time allocation. The numbers in the table represent the number of time units used to cover the sea leg from one port to the next. For every port the sailing time is reduced as delay increases. For example, when leaving Salalah without delay, 19 time units are used to travel to Jeddah. If there is one unit delay, sailing time decreases to 18 time units. If the vessel leaves Salalah with more delay, the sailing time decreases further to 17 time units, which corresponds to the maximum speed of 23 knots. Hence, this is the minimum required sailing time.

Port	Buffer time (hr)	Average delay (hr)	On time prob (hr)	Avg fuel cons (ton)
Jebel Ali	8	5.69	0.33	415
Jawaharlal Nehru	8	5.37	0.29	140
Mudra	4	4.41	0.47	358
Salalah	8	7.03	0.20	544
Jeddah	4	6.27	0.25	255
Suez Canal	16	8.60	0.14	772
Algeciras	8	4.60	0.40	470
Felixstowe	4	4.33	0.40	45
Antwerp	8	6.59	0.26	101
Bremerhaven	4	5.81	0.30	68
Rotterdam	16	8.01	0.20	1382
Suez Canal	4	5.56	0.36	95
Aqaba	8	8.05	0.16	178
Jeddah	12	6.97	0.24	952

Table 3: Statistics optimized schedule

	Delay (time units)							Minimum
Port	0	1	2	3	4	5	6	sailing time
Jebel Ali	17	16	15	15	15	15	15	15
Jawaharlal Nehru	6	5	5	5	5	5	5	5
Mudra	14	13	13	13	13	13	13	13
Salalah	19	18	17	17	17	17	17	17
Jeddah	10	9	9	9	9	9	9	9
Suez Canal	28	27	26	26	25	25	25	25
Algeciras	18	18	17	17	17	17	17	17
Felixstowe	2	2	2	2	2	2	2	2
Antwerp	5	5	4	4	4	4	4	4
Bremerhaven	4	4	4	4	4	4	4	4
Rotterdam	45	44	43	42	42	42	42	42
Suez Canal	6	5	5	5	5	5	5	5
Aqaba	9	9	8	8	8	8	8	8
Jeddah	31	30	30	29	29	29	29	29

Table 4: Recovery actions under optimized buffer allocation

5.2 Comparison MIP and VIH

In this section the results obtained from the two different methods are compared. As described in Section 4, fifty test instances with different delay distributions were created as input for both methods. For each of these instances different performance measures are calculated to compare the performance of the solution methods. The gap with the best bound, given in percentage, is calculated using Equation (21).

$$gap\,with\,bound = \frac{solution\,from\,method\ -\ lower\,bound\,MIP}{solution\,from\,method} * 100 \tag{21}$$

In order to reduce the time required by the MIP to reach a good solution some adaptations were made. To reduce the number of variables the maximum number of buffer time units allocated to a port is limited to the maximum delay incurred (sum of the upper bounds of delay in the port and on the following sea leg). Furthermore, the running time of the MIP problem is limited to 3,600 seconds.

Performance measure	VIH	MIP
Number of proven optimal solutions	0	7
Average gap with bound (%)	51.73	49.08
Maximum gap with bound (%)	100.00	100.00
Average difference with MIP solution (%)	0.80	-
Maximum difference with MIP solution (%)	7.43	-
Number of times better than MIP solution	0	-
Number of times worse than MIP solution	50	-
Average computational time (s)	199.46	3112.90
Number of times fastest	50	0

Table 5: Characteristics of the solutions

As shown in Table 5, the MIP does not always return the optimal solution, due to the restricted running time. Consequently, in only seven cases the results of both methods could be compared effectively. In these seven cases the VIH did not yield an optimal solution, but the smallest difference with the optimal solution from the MIP was 0.01%. The average difference between the objective values of both methods is equal to 0.80%. Given the fact that average computation time of the VIH is considerably lower than that of the MIP, the VIH computes good solutions.

5.3 Results extensions

5.3.1 Recovery actions in ports

A number of experiments was performed involving recovery actions in ports. First, it was analysed for the states associated with both visits to Suez Canal how the costs of reducing port times affect usefulness of port recovery actions. Second, the same approach was used when it is allowed to reduce port times in all ports on the route.

In case reducing port times is only allowed in Suez Canal and the costs associated with reducing port handling times by one time unit are up to 25,000 USD, the option is used independent of the current delay. Hence, the first time Suez Canal is visited, the handling time will be 3 time units instead of 4 and during the second visit 5 instead of 6. Average total costs in this case reduce by 2.29% compared to the optimal schedule to 3.835 million USD.

When the costs increase to 30,000 USD, regular port handling times are used during the second visit to Suez Canal in case there is no delay. In all other states the possibility to reduce port handling time is used. If the costs increases further to 40,000 USD, during both visits handling times are only reduced if there is a positive delay.

As costs increase further, the number of states for which the regular port time is used increases. When the costs are 75,000 USD the option of reducing port handling time is selected for all states which have 3 or more time units delay. The average costs in this case are 3.902 million USD, which is 0.59% lower than the costs of the optimal schedule. The option to reduce port handling times remains being selected as long as the cost stays below 200,000 USD.

In case the possibility to reduce port handling times exists in all ports a similar pattern is followed. The possibility of reducing port times is used in all states when the costs are 20,000 USD. In case costs are 25,000 USD, this possibility is still employed in nearly all states. Only when the port of Antwerp is reached without delay regular port time is used. When the costs increase to 50,000 USD, regular port times are used in all states in which no delay exists and several states with only one unit delay. Similar to the case in which reducing port time is only allowed in Suez Canal, the option is used when its cost is below 200,000 USD.

As an example, Table 6 gives the selected port handling times in the optimized schedule when the costs of reducing port time by one unit in a certain port are 100,000 USD. It can be observed that the option to reduce port times is used when a certain number of time units delay has been reached. In Salalah regular port handling time of 4 time units is used when the port is reached with up to 2 time units delay. When 3 or more time units delay are encountered upon arrival port handling time is reduced to 3 time units. The total costs in this situation are 3.899 million USD, giving a 0.66% reduction compared to the optimized schedule with regular port times.

Port	Delay (time units)							Regular
	0	1	2	3	4	5	6	port time
Jebel Ali	8	8	8	8	7	7	7	8
Jawaharlal Nehru	9	9	9	9	8	8	8	9
Mudra	4	4	4	4	3	3	3	4
Salalah	4	4	4	3	3	3	3	4
Jeddah	3	3	3	2	2	2	2	3
Suez Canal	4	4	4	4	3	3	3	4
Algeciras	5	5	5	4	4	4	4	5
Felixstowe	6	6	6	5	5	5	5	6
Antwerp	4	4	4	4	3	3	3	4
Bremerhaven	6	6	6	6	5	5	5	6
Rotterdam	5	5	5	5	5	5	4	5
Suez Canal	6	6	6	6	5	5	5	6
Aqaba	5	5	5	5	4	4	4	5
Jeddah	5	5	5	5	5	4	4	5

Table 6: Port times in time units at 100,000 USD port recovery action cost

5.3.2 Deepwater and non-deepwater ports

This section describes the results obtained when considering both deepwater and non-deepwater ports. It is assumed that there are four non-deepwater ports on the current route, which are Mundra, Salalah, Bremerhaven and Aqaba. Information on high- and low-tides is obtained from The United Kingdom Hydrographic Office (2016). Using the time periods indicated in Table 7, the periods in which the ports cannot be accessed are given in Table 8. The periods of low-tide are determined by transferring all times to UTC.

Period	Time (UTC)
1	00:00 - 03:59
2	04:00 - 07:59
3	08:00 - 11:59
4	12:00 - 15:59
5	16:00 - 29:59
6	20:00 - 23:59

Table 7: Time periods

Port	Not accessible (time period)
Mundra	1,4
Salalah	6
Bremerhaven	2,5
Aqaba	3,6

Table 8: Time periods low-tides

The starting time of the route is not fixed yet and can be equal to any of the 6 time periods, hence $T = \{1, 2, 3, 4, 5, 6\}$. Since this problem has only 6 possible starting times, the optimal solution is calculated for each of these separately. The results are displayed in table 9. As can be observed, different start times lead to small differences in average costs. The difference in average costs between the most and least advantageous start times is around 10,000 USD.

Start period	Costs (mln USD)
1	4.136
2	4.139
3	4.142
4	4.134
5	4.135
6	4.132

Table 9: Costs in million USD of optimal solution with different start times

The optimal start time is period 6, which gives average costs of 4.132 million USD, leading to a 5.4% increase compared to the optimized schedule when all ports are assumed to be deepwater ports. Such increase seems logical because delay will increase in case the vessel has to wait to enter a port. The buffer time allocation, average delay, on time probability and average fuel consumption are given in Table 10. As can be observed the average delays are higher than in the optimized schedule when not taking into account non-deepwater ports.

Port	Buffer time (hr)	Average delay (hr)	On time prob (hr)	Avg fuel cons (ton)
Jebel Ali	2	11.41	0.15	466
Jawaharlal Nehru	0	10.14	0.19	145
Mudra	2	17.76	0.03	392
Salalah	1	16.39	0.05	519
Jeddah	6	21.14	0.00	209
Suez Canal	2	5.73	0.43	796
Algeciras	3	7.79	0.21	471
Felixstowe	1	3.94	0.59	45
Antwerp	3	6.33	0.32	78
Bremerhaven	0	3.54	0.67	68
Rotterdam	3	9.54	0.11	1467
Suez Canal	1	8.68	0.24	117
Aqaba	2	12.17	0.15	199
Jeddah	2	10.58	0.19	1013

Table 10: Statistics optimized schedule when considering non-deepwater ports

6 Conclusion

During the execution of their routes liner ships face delay due to various reasons. In case no recovery actions are taken, this delay will propagate through the entire route, with significant consequences for the shipping company and its customers.

This thesis addressed this problem as a Markov decision problem. The states of the problem are defined by the position of the ship and corresponding delay. The resulting recovery policy describes for every state which action (i.e. adjusting sailing speed on the next sea leg) should be taken. In case buffer time is fixed, the problem was solved by means of a linear programming model. Buffer time allocation and recovery policy can be determined simultaneously using the mixed inter programming (MIP) model. In order to obtain solutions within limited time, also a heuristic approach (VIH) was proposed for solving this problem.

Data used in the experiments concern a shipping route that includes fourteen port visits. Additional delay could occur during both port visits and sea legs. For these delays uniform probability distributions were used. The upper bound of additional delay on a sea leg depends on the distance travelled. Recovery actions consists of either increasing or decreasing sailing speed, within a minimum and maximum speed. Additional costs are calculated based on fuel consumption and bunker costs.

Optimizing recovery actions for the given buffer time allocation reduces average costs by 5.3%. The schedule in which both buffer time allocation and recovery actions are optimized leads to a 9.6% decrease in costs compared to the current schedule. In addition, buffer time is spread more equally over the different sea legs. Therefore, average delay upon arrival is spread more evenly across the different ports.

Fifty test instances were used to compare the performance of the MIP with the VIH. The running time of the MIP was limited to one hour. Therefore, the optimal solution was found in only part of the instances. The average gap between the given solution and the lower bound was rather large. This is partly due to the fact that for some delay distributions no solution exists, since delay that exceeds the maximum allowed delay will be faced, giving a 100% gap with the lower bound. The average gap with the lower bound could be reduced by increasing the maximum running time, allowing for better solutions.

For the VIH, the difference with the lower bound is also large. However, the solution given by the heuristic is often close to the solution of the MIP. On average the difference between the two solutions is 0.80%. The VIH was not able to give an optimal solution to any of the instances, but the smallest difference with an optimal solution given by the mixed integer problem was only 0.01%.

Hence, the MIP requires longer computation times in order to give (closer to) optimal solutions. However, this makes practical implementation of the method more difficult. The VIH performs slightly worse than the MIP. However, computation times are much shorter and in case the mixed integer problem finds the optimal solution, the difference between the two methods is rather small. Hence, the VIH gives a quite good approximation. In addition the solutions obtained from the VIH reduce costs compared to the current situation. Therefore, implementation of the VIH is beneficial to the liner shipping company.

The original problem can be extended in multiple ways. Options include prioritizing between ports by differentiating between the costs of late arrival at different ports; selecting delay distributions based on weather conditions; including recovery actions in ports; and distinguishing between deepwater and non-deepwater ports. The latter two extensions were explored in more detail.

First, the possibility of taking recovery actions during port stays instead of only during sea legs was added. The possibility to reduce port time by one time unit was added either in all ports or only during both visits to Suez Canal. In both cases the option was chosen in any state, independent of position and current delay, when the costs of reducing port time by one unit were below 25,000 USD. As costs increased, regular port times were used in states without delay or with small delay, while the option to reduce port time remained being chosen when delay was larger. When costs increased to 200,000 USD regular port times were used in all states.

Second, a distinction was made between deepwater and non-deepwater ports. Non-deepwater ports can only be reached during high tide, which can lead to additional waiting times. An experiment was run in which Mundra, Salalah, Bremerhaven and Aqaba were considered to be non-deepwater ports. The average costs per round tour have increased by 5.4% compared to the situation in which all ports are deepwater ports. Since waiting times are dependent on the tides, the start time of the route can influence average costs. It was shown that for the given route the effect of the start time was relatively small.

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