1 Introduction

The Kiel Canal connects the North and Baltic seas and is ranked among the world's three major canals. In fact, in terms of traffic, it is the busiest artificial waterway worldwide. In a billion Euro project, the German Federal Waterways and Shipping Administration plans to enlarge the canal during the coming years. This project is about contributing to well-founded advises on how the enlargement can be optimally done. In order to evaluate various construction possibilities and enlargement strategies it is indispensable to first provide an accurate model for the ship traffic and designing an algorithm which (ideally optimally) controls it.

The problem very roughly is as follows. There is bi-directional ship traffic on the canal; there are several locks at both ends. Ships are classified in different size categories. Passing and overtaking is allowed only if the sizes of the two ships do not exceed a given threshold which depends on the meeting point. If otherwise a conflict occurs, ships have to wait at designated, capacitated places, the sidings. The objective is to minimize the total passage time, including lock and siding waiting times. The overall scheduling is currently done by teams of experienced planners, for the locks and for the sidings. In this abstract we concentrate on the latter problem, but both are treated in an integrated way during the project.

2 Ship Traffic Control

We are given an interval $C \subset \mathbb{R}$ as canal partitioned into a set of intervals $\mathcal{E} = (e_i)_{i=1,\ldots,m}$ with $\bigcup_{i=1}^{m} e_i = C$ as segments where some special segments $\mathcal{T} \subset \mathcal{E}$ are called sidings. Furthermore, a set of requests $R = \{(v_i, r_i, s_i, t_i, w_i, \ell_i, b_i, B_i) \mid i \in S\}$ is given that corresponds to ships $S = \{1, \ldots, n\}$ with maximum velocity $v_i$, release date $r_i$, start and target positions $s_i \neq t_i \in C$ somewhere in the canal, ship dimensions like width $w_i$ and length $\ell_i$ and finally waiting bounds per siding $b_i$ and in total $B_i$. Ship $i \in S$ is called updirected when $t_i > s_i$ and downdirected otherwise. The specified velocity of a ship $i \in S$ and the given length of a segment $e \in \mathcal{E}$ define the transit time $\tau_e$ of
ship $i$ along segment $e$ assuming constant full speed along each segment like the manual planners do.

For each segment $e \in \mathcal{E}$ we are given a set $C_e \subseteq S \times S$ of ship pairs having a conflict on segment $e$. These are at the one hand side those ships with opposite travel directions that are not allowed to pass each other on that segment. Therefore, a decision on who is passing this segment first must be made. But also for all ships traveling in the same directions an order must be decided. Thus, all same directed ships have a conflict.

To define a solution we need to determine feasible departure times $d_{ie}$ specifying when each ship $i \in S$ is leaving a segment $e \in \mathcal{E}$. Due to space limitations feasibility will be defined exactly only for a relaxed problem by the following conditions:

$$d_{i,e-} + \tau_e = d_{i,e} \quad \forall i \in S, e \in \mathcal{E} \setminus \mathcal{T}$$  \hspace{2cm} (1)

$$d_{i,t-} + \tau_{i,t} + w_{i,t} = d_{i,t} \quad \forall i \in S, t \in \mathcal{T}$$  \hspace{2cm} (2)

$$z_{i,j,e} = 1 \Rightarrow d_{i,e} + \Delta(i,j,e) \leq d_{j,e} \quad \forall e \in \mathcal{E} \setminus \mathcal{T}, (i,j) \in C_e$$  \hspace{2cm} (3)

$$z_{i,j,e} = 0 \Rightarrow d_{j,e} + \Delta(j,i,e) \leq d_{i,e} \quad \forall e \in \mathcal{E} \setminus \mathcal{T}, (i,j) \in C_e$$  \hspace{2cm} (4)

$$d_{i,e} \leq \overline{d}_{i,e} \leq d_{i,e} \quad \forall i \in S, e \in \mathcal{E}$$  \hspace{2cm} (5)

$$w_{i,t} \geq 0 \quad \forall i \in S, t \in \mathcal{T}$$  \hspace{2cm} (6)

$$z_{i,j,e} \in \{0,1\} \quad \forall e \in \mathcal{E} \setminus \mathcal{T}, (i,j) \in C_e$$  \hspace{2cm} (7)

All conditions concerning passing of and waiting in sidings are missing here. Equations (1) and (2) guarantee that departure times can be traveled with the given velocities and that waiting, represented by non-negative variables $w_{i,t}$ in (6), only occurs in sidings. Segment $e_{-i}$ is the segment that must be passed before $e$ when traveling in direction of ship $i \in S$. Each departure time variable is bounded from below by $d_{i,e}$ and from above by $\overline{d}_{i,e}$ that are defined by the release dates, the waiting bounds and the travel times (5). The binary variables $z_{i,j,e}$ of (7) decide how to deal with two conflicting ships on a segment. Depending on this decision one of the two conditions (3) and (4) must be respected. The used delta $\Delta(i,j,e)$ depends on the ship dimensions, the maximum allowed speed, the travel directions and the start and target positions of the two conflicting ships as well as the special safety distance regulations. It is not necessarily symmetric and can be a negative value.

The goal is to minimize the total waiting time $\sum_{i \in S, t \in \mathcal{T}} w_{i,t}$. This problem is shown to be NP-hard. Solutions are visualized in exactly the same way the planners are used to see them, in a distance-time diagram of the canal, see Figure 1.

Figure 1: Example of a distance-time diagram showing one of our solutions.
3 Challenges in Scheduling

The mentioned binary variables of the above model define a “sequence” for the conflicting ships on each segment. In this sense, we are talking here about scheduling decisions that must be made for each segment and form the hard part of this model (forgetting about the difficulties arising within the sidings). There are two main differences to classical scheduling which cause problems for the known standard techniques. First, the relation of having a conflict is not transitive and hence, the resulting “sequence” is no total order. Second, there is no designated “processing time.” The time period, for which a segment is blocked by a ship for another one really depends on the properties of both and even is not symmetric.

Even when restricting to special cases where these difficulties do not occur we get interesting scheduling problems. Consider the case of one segment surrounded by to sidings where all ships have a conflict on that segment and same velocity. Then the main task is to decide when to change the currently active travel direction on this segment, because every switch of travel direction induces lots of waiting time. The ships must be grouped into batches with setup costs. Hence, this problem can be interpreted as a two family batch scheduling problem with release dates, [1] and [3]. Under further restrictions inducing identical “processing times” this can be solved by dynamic programming in polynomial time. Considering more than one segment yields problems of job shop scheduling character.

It is also worth mentioning that there are certain similarities to train scheduling on a single track line [2], but also here the big problem of non conflicting ships occurs.

4 An Algorithm

The main goal of the project was to develop a software that can do simulations in lots of distinct settings to answer questions arising in the enlargement process. Therefore, our algorithm must cover all important real world conditions. This is implemented by an elaborate procedure for dynamic routing with time windows extending the techniques of [4]. Once these feasible and realistic solutions can be produced, it was embedded in a local search procedure that considers the scheduling decisions on the segments to improve solutions. To respect the online character this is done in a rolling horizon manner. Since the officers in charge of the enlargement were satisfied and impressed by the produced solutions, our software is a perfect tool for simulations.

References


