On- and Offline Scheduling of Bidirectional Traffic

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Abstract This work summarizes insights related to bidirectional traffic on a stretch containing bottleneck segments. On a bottleneck segment, concurrent traveling of vehicles in opposite direction is restricted. The considerations are motivated by the ship traffic at the Kiel Canal which connects the North and Baltic Seas and is operated bidirectionally. Since ships register their travel requests only on short notice, we investigate the Canal's ship traffic additionally in the online setting.

1 Introduction

We consider bidirectional traffic where bottleneck segments restrict concurrent traveling of vehicles in opposite direction. Single tracks in railway planning are an example for such bottlenecks. This work summarizes results of [8] that considers the example of ship traffic at the Kiel Canal.

Situated in the north of Germany, the Kiel Canal connects the North and Baltic Seas. With more passages than the Panama and Suez Canals together, it is the world's busiest artificial waterway. Compared to the way around Denmark, the canal saves an average of 250 nautical miles (460 km). The Kiel Canal, as the more ecological and safer route, became the basis for the trade between the countries of the baltic area with the rest of the world [7].

Since offshore vessels are not primarily designed for inland navigation, the passing of two ships with large dimensions is not possible at arbitrary positions. To facilitate bidirectional operation of the Kiel Canal, wider areas within the canal called sidings are needed that allow for passing and waiting, see Fig. 1. This yields a sequence of bottleneck segments and decisions must be made about who is waiting for whom, where, and for how long. Responsible for these decisions is the Waterways and Shipping Board (WSV/WSA) with a team of nautically experienced expert navigators.

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They try to keep the necessary waiting times in sidings on average over all ships as small as possible.

In expectation of a tremendous continuing growth of traffic demand an enlargement of the canal was planned. There are a bunch of possible construction options such as extending or creating sidings or to allow more flexible passing of ships by deepening and/or widening crucial parts of the canal. In order to assess the cost and benefit of these options their combined effects under predicted ship traffic needed to be reliably estimated. To that end, we developed an optimization tool for the "Planungsgruppe für den Ausbau des Nordostseekanals" of the WSV that emulates the current ship traffic control. This tool was used to evaluate the various construction options with the aim of selecting a most adequate combination.

In addition to the developed ship traffic control tool, insights being relevant beyond the concrete scope of the Kiel Canal are provided. These investigations concentrate on two characteristic properties of this ship traffic control. First, its *bidirectional* component is investigated in further detail. Second, we account for the fact that decisions must be adapted *online* since ships register their requests only shortly before their arrival.

2 Bidirectional Scheduling

For the theoretical investigations, we discuss the problem's natural relation to classical machine scheduling and analyze similarities and differences. This analysis concentrates on the following characteristic property being common for all kinds of bidirectional traffic on bottleneck segments: vehicles moving in the same direction can enter a tight lane sequentially with relatively little headway while vehicles in opposite direction must wait until the whole lane is empty again, cf. Fig. 1. With a compact scheduling model that accurately accounts for this specialty, a detailed analysis of the problem's off- and online complexity is accomplished. It facilitates the development of algorithms with provable performance bounds on the one hand and the identification of hardness inducing properties on the other hand.

Having flow shop scheduling in mind, we generalize rectangle jobs, that are passing through a sequence of machines in the given order, to parallelograms to be arranged on a sequence of segments in the given or opposite order, cf. Fig. 2. By that, a job is represented by two values on the time-axis: the time spent for entering

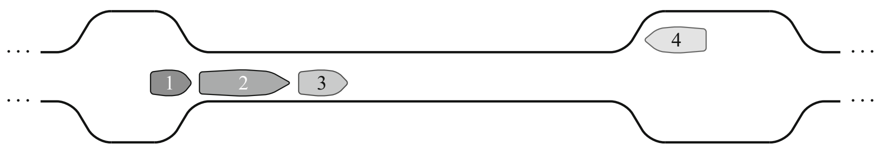

Fig. 1 Bidirectional ship traffic at the Kiel Canal. Ship 4 must wait in a siding until ships 1, 2 and 3 have left the bottleneck segment

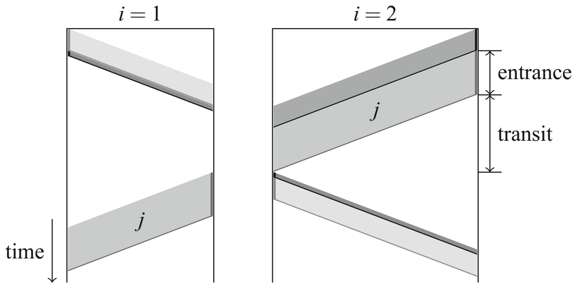

Fig. 2 Example of the compact bidirectional scheduling model with parallelograms representing movement of vehicles from *left* to *right* and *right* to *left*

the segment (the time between the first entrance of the prow and the moment the stern has accessed the segment) and the additional time needed to traverse the segment after the entering is finished. While the former prevents the segment from being used by any other job (running in *either* direction), the latter only blocks the segment from being used by jobs running in *opposite* direction. An intersection-free arrangement of parallelograms with appropriate orientation then ensures a feasible (collision-free) movement of vehicles where those with equal travel-direction can use a segment concurrently. Therefore, packing parallelograms relaxes the restriction that a resource can only be used by one job at a time since it is extended by a second dimension corresponding to positions.

With rectangles being special parallelograms, hardness results from scheduling carry over to the bidirectional case. From the application point of view the time for transit is dominating the time for entrance. Hence, we are especially interested in difficulties that additionally arise from delays induced by orientation-switches of the parallelograms instead of varying entrance times. To that end, we fix these entrance times in our considerations. By this we get insights according to complexity in dependence of the number of considered segments. Furthermore, the bidirectional traffic at the Kiel Canal is distinguished by the specialty that exceptions for the passing of ships with smaller dimensions exist. Thus, we consider parallelograms with opposite orientation that are *compatible* and hence, are allowed to overlap. In our investigations, we complement NP-hardness for general compatibilities with a classification of compatibilities that admit efficient exact algorithms. In the case of entrance times that are not fixed, the techniques of [1] can be extended to prove the existence of a polynomial time approximation scheme (PTAS) for bidirectional scheduling on a single segment. For further details on the complexity results we refer to [2].

In the online setting, we are interested in the increase of the costs due to the circumstance that vehicles register their transit requests only on short notice. In an online instance of bidirectional scheduling, jobs are not known in advance but appear by their release date. Once, an online algorithm has started a job on a segment it is not possible to revert the decision since it corresponds to the movement of the corresponding vehicle. In our considerations, we apply the common technique of competitive analysis where the results of an online algorithm over all instances are compared to the optimum an offline algorithm can achieve. This comparison is quantified by the *competitive ratio* and finding the best possible one yields a meaningful measurement of the loss caused by the online restriction. For bidirectional scheduling in general, we can bound the best possible competitive ratio from below by 2 and from above by 4, compare [5, 6]. For special cases, we can provide polynomial running time and decrease the gap between lower and upper bounds on the best possible competitive ratio. However, as in many online optimization problems we are not able to close this gap.

3 Competitive-Ratio Approximation Schemes

The concept of competitive-ratio approximation schemes is an alternative approach to deal with such open gaps in online scheduling [4]. Such schemes compute online algorithms with a competitive ratio arbitrarily close to the best possible competitive ratio. To that end, a new way of designing online algorithms is presented for the example of parallel machine scheduling with preemptive and non-preemptive jobs to minimize the weighted sum of completion times. The approach can furthermore be extended to bidirectional scheduling for a single segment.

In addition to structuring and simplifying input instances as in [1], an abstract description of online scheduling algorithms is used to reduce the infinite-size set of all online algorithms to a relevant set of finite cardinality. In addition, the competitive ratio of these algorithms can be approximated with $1 + \varepsilon$ precision. This combination is the key for eventually allowing an enumeration scheme that finds an online algorithm with a competitive ratio arbitrarily close to the optimal one and that approximates the corresponding value up to a $1 + \varepsilon$ factor. This implies a respective estimate for the optimal competitive ratio.

The approach differs strongly from those where (matching) upper and lower bounds on the competitive ratio of a particular and of all online algorithms were derived manually. Instead, the search for the best possible competitive ratio for the considered problems can be tackled by executing a finite algorithm.

4 The Ship Traffic Control Problem

For the original problem of ship traffic control at the Kiel Canal [9] more complex feasibility constraints for instance in the sidings must be respected. To that end, we combine the scheduling perspective with a dynamic routing approach and therefore integrate algorithmic ideas from two important related applications, train scheduling on a single-track network [11] and collision-free routing of automated guided vehicles [3]. The idea is roughly, to embed a sequential (local) routing method which considers only one ship at a time, in a simultaneous (global) scheduling method to optimize the complete fleet. In addition, we embed the algorithm into a rolling horizon approach. It is implemented such that after new request-information is incorporated, all parts of the solution that are not fix by that point in time is reconsidered again.

The sketched algorithmic combination yields a fast heuristic with an average running time of less than 2 min for historic instances covering a time horizon of 24 h each. The achieved objective function values significantly improve upon manual plans. Results of smaller instances are compared with instance-dependent lower bounds. The calculated solutions have been presented to the expert planners by animated ship-movements and as interactive distance-time diagram, see Fig. 3. The latter is based on the diagram that is used by the planners on site who approved the presented solutions. Most importantly, the practical context is modeled in such a high level of detail that the resulting tool perfectly reflects the effects of enlargement options at the Kiel Canal. This enabled the officials to evaluate the different options under ship traffic predicted for the year 2025, and to base their decisions on the simulation results.

Even though it was not intended by the study, the heuristic complies with important requirements for computer aided traffic control. In fact, the planning in rolling horizons is able to deal with the present online character. It perfectly integrates with a further heuristic [10] that schedules the locking process at each boundary of the Kiel Canal since entering, passing, and exiting the canal are interdependent. The overall system may support the expert planners during several potentially difficult years of construction work. Moreover, it was considered to use the tool for deciding

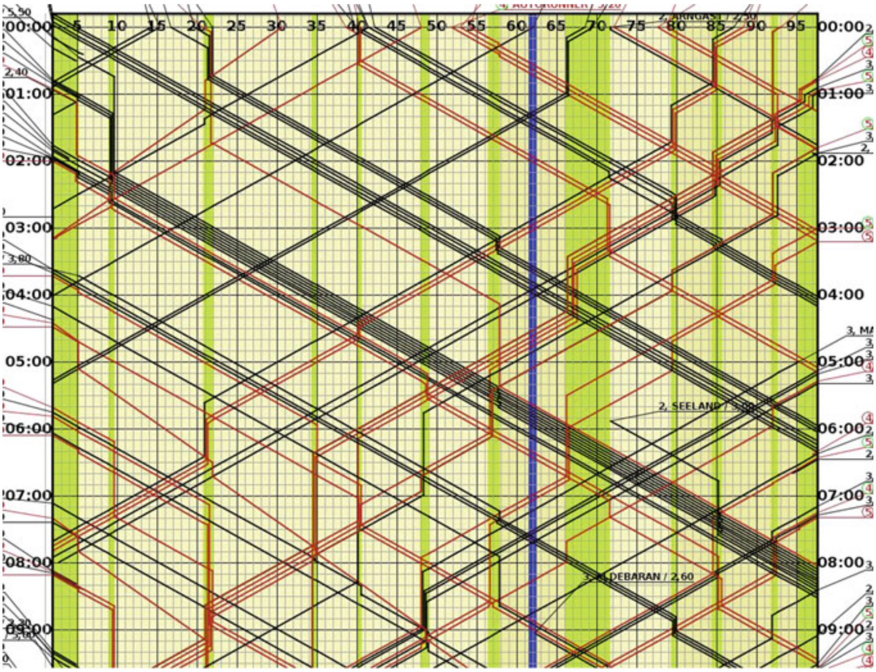

Fig. 3 A distance-time diagram presenting a solution of a complex ship traffic control instance that was calculated by the developed heuristic

about the schedule of the construction work itself: Different orders of construction and the selection of different excavating machines (several of which significantly hinder regular traffic) directly influence the traffic flow under scarce resources.

5 Summary

To summarize, we implemented a solution of high practical value that is able to tackle bidirectional traffic (1) as offline heuristic solving many instances of reasonable size fast and sufficiently detailed for meaningful study-results and (2) as online tool which is applicable as suggestion tool for the daily planning. In addition, we provide a compact model that admits theoretical insights on the nature of bidirectional traffic. It emphasizes the challenges occurring at bottleneck segments where bidirectional operation is necessary since they are origins of large delays. The investigations are accomplished in the offline and the online case. Finally, we present a new approximation concept for competitive analysis in online scheduling.

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