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Optimized load planning for motorail transportation

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ABSTRACT

This paper studies a real-world problem arising in the area of motorail transportation. The considered problem deals with the loading of cars and motorcycles onto motorail wagons under realistic technical and legal constraints. The load planning problem, introduced as motorail transportation problem (MTP), occurs during the booking process and afterwards during the loading process at motorail terminals. Optimization based decision support is highly valuable due to the combinatorial nature of these problems. In practical applications, the fast generation of good solutions is essential. Previous model formulations in literature reveal considerable optimality gaps in real-world instances. Hence, we propose and evaluate two novel integer linear programming formulations of the MTP. The first formulation is a simplified reformulation of the original problem, uses less variables and provides a tighter LP relaxation. The second model is a column-generation formulation of the reformulated model which is solved using branch-and-price. Both novel model formulations are compared and evaluated on the basis of real-world data sets and considerably outperform previous approaches in terms of solution quality and speed.

1. Introduction

Motorail service providers offer long distance transportation of cars and passengers on separate wagons. While passengers are carried in so-called sleeping cars, their vehicles are transported on motorail wagons. Due to long traveling distances, most journeys are carried out overnight, which allows a rested arrival at the destination for passengers in general and families in particular. Motorail transportation gained international popularity at the beginning of the 1950s. Today, motorail transportation services are globally offered by national as well as private rail transport companies. The densest network is provided in Europe, where motorail services are available in 13 countries. Further large networks exist in Australia, Chile and the United States. Due to increased capacity requirements by vehicles over the past 50 years – as a consequence of increasing vehicle lengths and widths, growing requests for optional equipment or the current popularity of large and heavy sports utility vehicles (SUV) – the present capacities of car transportation wagons become a critical issue.

We consider the problem of loading vehicles onto motorail wagons – in the following called motorail transportation problem (MTP) – which decides on which wagon, loading deck and position each particular vehicle should be loaded. Given a set of vehicles the objective is either to find a feasible allocation of all vehicles to transportation wagons or to maximize the number of vehicles loaded on a particular loading deck such that all other vehicles can be loaded as well. Integer programming formulations for the MTP as well as a variant of the MTP for order acceptance decision support, called motorail capacity problem (MCP), have been introduced by Lutter and Werners [1]. Practical applications of these models arise at motorail terminals (MTP) as well as during the booking process (MCP). In both cases fast solution times are essential.

At motorail terminals, vehicles consecutively arrive at the terminal. The goal is to select subsets of these vehicles to be loaded together, while assuring that all other vehicles can be loaded as well. Optimization based decision support aims at speeding up the entire loading process while guaranteeing the feasibility of the proposed loading plan at all times. Real-world decision support mainly relies on the computational performance of the optimization model. As the previous formulation of the MTP is hard to solve to optimality, this paper introduces two novel model formulations.

The MCP enables motorail companies to manage the order acceptance process when the exact vehicle weight is only known as an interval before acceptance of the order. Again, the computational performance plays a major role in real-world applications. Because the solution time of the original formulation of the MCP is slowed down by further binary and continuous variables, we propose a MTP-based formulation of the MCP. The novel formulation has the advantage that no additional variables are needed and it shows clearly superior computational performance. Both models have been successfully implemented at Deutsche Bahn Fernverkehr AG, a subcompany of Deutsche Bahn the largest

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German railway company, in order to optimize the order acceptance process and to improve the loading process at motorail terminals.

The contributions of this paper are as follows: Two novel integer linear programming formulations of the MTP and the MCP are introduced and evaluated. The first reformulation is derived from the four-index formulation of the MTP (see [1]) by reformulating height constraints in a combined height and capacity constraint which allows the use of three-fold indexed variables. It is shown that the three-index formulation provides stronger LP relaxations than the original four-index formulation. Second, on the basis of the three-index formulation an extended formulation is introduced, which provides the best LP relaxation but uses more variables than the other formulations. A customized branch-and-price approach is developed to solve the extended formulation. Third, it is shown that the reformulations of the MTP can be used to solve the motorail capacity problem as well. In contrast to previous work on these problems, we prove that both problems can be represented by the same set of decision variables. Extensive computational experiments with real-world data indicate that the novel formulations significantly outperform previous formulations of both problems and enable the real-world use in a decision support system.

The paper is organized as follows. In Section 2 related research is discussed. Two integer linear programming formulations for the MTP as well as the corresponding reformulations of the MCP are stated in Section 3. Computational results for all model formulations are provided in Section 4, while Section 5 concludes with some final remarks and perspectives for further research.

2. Literature review

Optimization models for motorail transportation have been introduced by Lutter and Werners [1,2]. The authors present an integer linear optimization model to assign vehicles to transporation wagons, which is called MTP. The model is extended to deal with order acceptance decisions when vehicle weights are only known within an interval. An extensive computational study for the order acceptance model which includes all MTP constraints is conducted using the commercial solver FICO Xpress. In total, 35 out of 82 tested instances were solved to optimality within a time limit of 1500 s. In the test set of large instances containing seven wagons and 59 up to 96 vehicles, only six out of 36 instances were solved to optimality. Many unsolved instances reveal considerable optimality gaps. These results show that solving the problem is far from being trivial. For real-world use large optimality gaps or run times are impractical and need to be reduced.

To the best of our knowledge, no further literature on motorail optimization exist. Related problems arise in the field of auto-carrier transportation and container loading. The auto-carrier transportation problem (ACT) deals with simultaneous loading and routing of auto-carriers. The problem is motivated by the real-world problem of delivering new cars to car dealers on demand. Auto-carrier loading comprises the selection and allocation of vehicles to parking positions on car transporters while routing decisions affect the itinerary planning of auto-carriers. The goal is to minimize the sum of transportation costs as well as penalty costs which occur when cars are not delivered by due date. The problem was introduced by Agbegha et al. [3] and further developed by Tadei et al. [4]. Both publications only consider a simplified version of the loading constraints. In a recent publication, Dell'Amico et al. [5] present a variant of the problem that incorporates the loading constraints in a more detailed fashion than the previous authors. Due to its computational complexity, the problem is commonly tackled heuristically. Tadei et al. [4] propose a decomposition of routing and load planning decisions and solve the sub-problems as integer programs with a standard commercial solver. Dell'Amico et al. [5] develop an iterated local search algorithm to solve the problem. In contrast to auto-carrier loading, motorail transportation requires different loading constraints due to significant technical differences in the used transportation technology and differing legal requirements.

Another related problem deals with the loading of containers onto freight trains. Container loading problems are characterized by a detailed treatment of physical loading requirements. In analogy to the motorail transportation problem, timetabling and routing decisions are not part of the optimization problem. Many papers on container loading aim at providing real-world decision support for container terminals [6–9]. While some containers are stored at container terminals before the beginning of the loading process, others arrive just-in-time. Thus, loading plans need to be revised during the loading process. Additionally, run-times are of high importance when focusing on real-world decision support. The same holds true for optimization at motorail terminals. Despite these commonalities, motorail transportation is distinctively different from container loading regarding physical loading constraints and the handling of transportation goods at motorail terminals. In the following, related literature with emphasis on real-world applications at container terminals is reviewed.

Corry and Kozan [6,7] first introduced an integer programming formulation for container loading at a realistic level of detail. The authors propose a dynamic load planning model to optimize the load planning of trains at intermodal terminals. Different types of containers are modeled with a finite set of different load patterns for every wagon. Local search as well as simulated annealing heuristics are proposed, since real-world instances of the original problem cannot be solved by exact methods in adequate time. Three different integer linear programming formulations for the container loading problem which vary regarding the consideration of length and weight constraints were considered by Bruns and Knust [8]. Their approach is related to what is considered in this paper in the sense that different model formulations of the same problem are provided and tested. In contrast to Corry and Kozan, they solve their problems with commercial and non-commercial solvers. In a subsequent paper [9], previous results are extended regarding the integration of data uncertainty. Novel formulations to hedge against different cases of uncertainties regarding container weight, container overhang as well as wagon failure are introduced. Again commercial solvers are used to solve their model formulations. More recently, a mathematical model for the train loading problem arising at automated terminals with an innovative transfer system for loading and unloading containers was introduced by Anghinolfi et al. [10]. To solve the model heuristically a Greedy Randomized Adaptive Search heuristic is developed which is able to generate good quality solutions in short time.

This study presents two new models to solve the MTP as well as the MCP and thus provides a significant extension to the developments made in the previous studies by Lutter and Werners [1,2]. While most approaches in the literature concerning auto-carrier loading and container load planning propose various heuristics to solve their problems, this paper focuses on exact solution methods.

3. Improved formulations of the motorail transportation problem

This section describes the problem of loading vehicles onto motorail wagons. The first subsection discusses relevant technical