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Economies of scale in recoverable robust maintenance location routing for rolling stock

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ABSTRACT

We consider the problem of locating maintenance facilities in a railway setting. Different facility sizes can be chosen for each candidate location and for each size there is an associated annual facility costs that can capture economies of scale in facility size. Because of the strategic nature of facility location, the opened facilities should be able to handle the current maintenance demand, but also the demand for any of the scenarios that can occur in the future. These scenarios capture changes such as changes to the line plan and the introduction of new rolling stock types. We allow recovery in the form of opening additional facilities, closing facilities, and increasing the facility size for each scenario. We provide a two-stage robust programming formulation. In the first-stage, we decide where to open what size of facility. In the second-stage, we solve a NP-hard maintenance location routing problem. We reformulate the problem as a mixed integer program that can be used to make an efficient column-and-constraint generation algorithm. To show that our algorithm works on practical sized instances, and to gain managerial insights, we perform a case study with instances from the Netherlands Railways. A counter intuitive insight is that economies of scale only play a limited role and that it is more important to reduce the transportation cost by building many small facilities, rather than a few large ones to profit from economies of scale.

1. Introduction

A *line plan* consists of a set of train lines, where each line is a path in the railway network that is operated with a certain frequency by one rolling stock type. The line plan within a railway network changes annually to accommodate changing travel demands. These changes include how lines run, up and down-scaling of service frequencies on any given line, the rolling stock types assigned to the lines, and the introduction of new rolling stock types. We capture these changes with a discrete set of scenarios. A *maintenance facility* is a facility that is responsible for the planned and unplanned maintenance of train units. Because maintenance facilities are used for a long period, any maintenance facility plan should take a wide range of scenarios into account. The size of the opened locations should satisfy the maintenance requirements of the current situation, but recovery against a price is possible for each scenario. Recovery consists of opening additional facilities, closing facilities, and upgrading the size of the existing facilities. Decreasing the size of existing facilities is not allowed. The reason

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for this is that shrinking the size of an existing maintenance facility is difficult, may not yield any revenue, and can even be costly.

The stations at the two end points of a train line are called *end stations*. When multiple train units of the same rolling stock type are located at the same end station their destinations can be *interchanged*. Whether such an interchange is possible depends on the shunting infrastructure of the end station and the time horizon between arrival and departure of the train units. The favored way for train units to enter a maintenance facility is to interchange from one train line to another until a maintenance facility is reached. In case a maintenance facility cannot be reached by such interchanges, an empty train drive is used to reach a maintenance facility. *Unplanned maintenance* occurs when a failure in the field occurs and in that case the maintenance facility can only be reached by an empty train drive. The routing of the train units to the maintenance facilities is called *maintenance routing* and the problem of finding the most efficient routes in combination with facility location decisions is called the maintenance location routing problem.

In the recoverable robust maintenance location routing problem for rolling stock (RRMLRP), we seek the optimal locations and sizes of maintenance facilities for rolling stock in a railway network. The objective consists of minimizing the annual cost of the facilities and the worst-case annual transportation and recovery costs, given a discrete set of scenarios. The annual cost of a facility depends on its location and size. The size of a facility must be chosen from a discrete set for each location. This discrete set allows us to model economies of scale: a facility which is twice as large costs less than twice as much. As a consequence, it is possible to open a few large facilities to profit from economies of scale or to open multiple smaller facilities to limit the transportation cost.

The recoveries, the inclusion of unplanned maintenance, and the multiple facility sizes that include economies of scale are new compared to the literature. Unplanned maintenance is generally not considered in the maintenance (location) routing literature. With our case study in Section 7, we show that it is important to include unplanned maintenance, as it has a large influence on the number and location of the maintenance facilities but also on the cost. Furthermore, we demonstrate with our case study that the number and location of the opened facilities depends heavily on the allowed facility sizes and the associated cost. Although facility location problems that consider different sizes exist (see the references in Melo et al. (2009)), they are often not considered in the facility location literature. In addition, we could only find one paper that mentions economies of scale in facility size (Melo et al., 2006). As a consequence, including multiple facility sizes that include economies of scale can potentially play an important role in many other settings. We also investigate the trade-off between large facilities with economies of scale versus many smaller facilities to reduce the transportation cost. Our case study demonstrates that even with increased economies of scale, economies of scale only play a limited role, and that it is more important to reduce transportation cost by building many small facilities. Economies of scale were thought to be more important and as a consequence this result may change the maintenance location strategy of the Netherlands Railways (NS).

We formulate the RRMLRP as a recoverable robust optimization problem, a two-stage robust optimization problem where the first-stage decisions can be modified in a limited way. The first-stage decision for the RRMLRP is to open facilities with a certain size, given candidate locations, and a discrete set of sizes for each candidate location and the associated facility costs. The first-stage decision has to be feasible for the current workload; the opened facilities have to be large enough to handle all maintenance visits occurring in the current situation. The second-stage problem is a maintenance location routing problem where, for each scenario, we can recover the first-stage decision and have to find the optimal routing to the maintenance facilities for the rolling stock. This second-stage problem is NP-hard.

We show that the two-stage model of the RRMLRP can be reformulated to a mixed integer programming model and we use this mixed integer programming formulation (MIP) to develop a column-and-constraint algorithm called scenario addition (SA). SA adds the constraints and variables associated with the scenario with the highest second-stage cost iteratively to the MIP until an optimal solution is found. SA has been applied successfully to a two-stage robust maintenance location routing problem (RMLRP) (Tönissen et al., In press), a problem similar to the RRMLRP that does not include the aforementioned recovery of location decisions, unplanned maintenance, and multiple facility sizes. In Tönissen et al. (In press) SA improved the solution time with two orders of magnitude compared to Benders decomposition.

SA finds the scenario with the highest solution value by solving the second-stage problem for each scenario. The RMLRP has a polynomial second-stage problem, while the second-stage problem is NP-hard for the RRMLRP, increasing the solution time of SA significantly. However, the scenario with the highest solution value can be found by solving the NP-hard second-stage problem for a limited number of scenarios. Many scenarios can be eliminated by a procedure that is similar to the pruning of nodes in branch-and-bound algorithms. This procedure uses an upper bound for each scenario and one lower bound. The upper bound can be found by a heuristic and the lower bound is equal to the highest exact second-stage solution value found so far. A scenario can now be eliminated when its upper bound is lower than the current lower bound. When a scenario cannot be eliminated, the second-stage problem for this scenario is solved to optimality, and the lower bound is updated if necessary. This procedure is described in detail in Section 5.2. Computational experiments show that this works very efficiently and that the NP-hard second-stage problem has to be solved only for a few scenarios.

The main contributions of this paper are:

1. We develop an SA algorithm that deals efficiently with the NP-hard second-stage problem by only solving the NP-hard problem for a limited number of scenarios. As a consequence this algorithm significantly reduces the solution time for the RRMLRP. Moreover, our SA algorithm can potentially reduce the solution time of many other recoverable robust optimization problems.