Reduced (winter) timetable in the Netherlands:

Process, Mathematical Models and Algorithms

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Abstract

In the winters of 2009-2012, severe weather conditions drove the Dutch railway network out-of-control a couple of times: Operations came to a full standstill and hardly any passenger information was provided. To prevent these situations, a reduced timetable is operated on days with severe weather conditions. The reduced timetable with about 20% less trains is prepared one day before the actual operation based on the latest weather forecast. The reduced timetable, as well as the corresponding rolling stock and crew schedules, are prepared within 16 hours. This paper discusses the process of generating a reduced timetable, and the algorithms (based on the mathematical models) to construct the adjusted rolling stock and crew schedule. These algorithms are implemented in TAM software for rolling stock scheduling and CREWS for crew scheduling. Since 2012, this process has been applied for about 20 times.

Keywords: severe weather conditions, reduced timetable, rolling stock rescheduling, crew rescheduling

1. Introduction

During several days in the years 2009-2012, the Dutch railway passenger had to suffer of a very poor performance of the Dutch railway system. This mainly happened on days with heavy snowfall. An analysis of the main railway operator, NS, the railway infrastructure manager, ProRail, and the Dutch minister of Transport showed that the Dutch railway system went out-of-control on some of these days. In such a situation, no trains are operated anymore although all resources (infrastructure, rolling stock, crew) are still available. Moreover, passenger information is inaccurate in such situations.

To prevent these out-of-control situations, NS and ProRail, have started a long-term improvement program. In addition, the minister, NS and ProRail decided to operate a reduced timetable when severe weather conditions are predicted for the next day. The reduced timetable is prepared one day before the actual operation based on the latest weather forecast. It adjusts the normal timetable by preventively cancelling train services on routes with high frequencies, e.g. a frequency of four times an hour is reduced to twice an hour. Nationwide about 20% less trains are operated. Since 2012, this timetable has been operated about 20 times.

In this paper, we describe the process of constructing such a reduced timetable and the related resource schedules (rolling stock and crew). To construct the adjusted rolling stock and crew schedules in a few hours, we use advanced Operations Research models and algorithms.

The remainder of this paper is set up as follows. In section 2, we give a detailed description of the current process of constructing a reduced timetable. We present a mathematical model and describe the outline of the algorithms to adjust the rolling stock and crew schedules in Section 3 and 4, respectively. Finally, we conclude the paper in Section 5.

2. Process

Figure 1 gives an overview of the timeline. The decision-making process starts with a decision to start the preparation of a new timetable at 10:30. Based on the weather forecast for the next day, the decision is taken whether or not the process will be started. Then the timetable will be specified in detail, i.e. it is checked whether the pre-defined reduced timetable fits on the specific day or not and if not, the pre-defined timetable will be adjusted. Afterwards, the rolling stock is rescheduled (see Section 3). The team that reschedules the rolling stock has about 6 hours to come up with an adjusted rolling stock schedule that fits with the changed timetable. In the meantime, at 15:30, board members of ProRail and NS, have a meeting about the final decision. Ultimately at 16:00, the decision has to be taken which timetable will be operated on the next day, i.e. the regular one or the adjusted timetable. From that moment on, either the rescheduling process is stopped and the regular timetable will be operated or the adjusted timetable will be operated. There is no way back anymore!

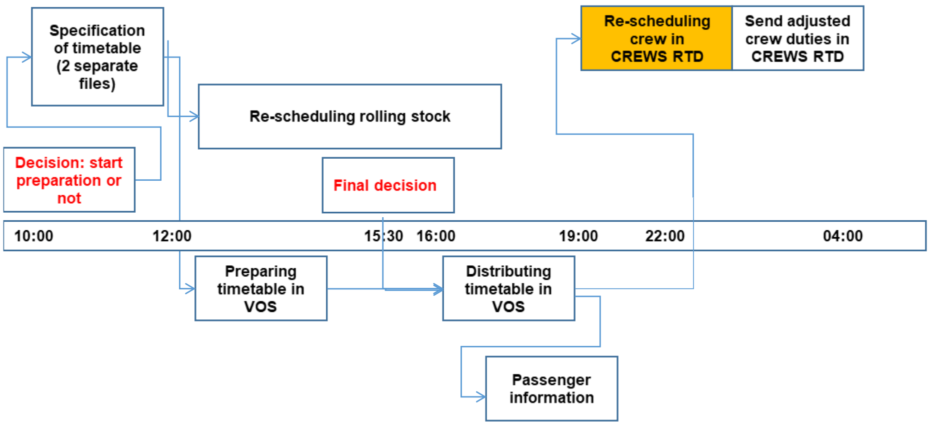

Fig. 1: Timeline of constructing the reduced timetable

In the latter case, the process continues with importing the new timetable in the VOS system by ProRail. This system is directly connected to the passenger information systems. Moreover, messages are broadcasted about the adjusted timetable via several channels, including the main television news programs and of course in the trains and at the stations.

Finally, the crew duties are adjusted (see Section 4). This process starts around 19:00 and needs to be finished before midnight. After the duties are changed, they are automatically sent to the smart phones of drivers and guards such that they can check their modified duty. Note that due to the moment of these changes, the duties can only start at the originally planned time or later. For social reasons, the duties are also not allowed to finish later than originally scheduled.

3. Mathematical model and algorithm for Rolling stock rescheduling

Rolling stock is one of the key resources of the train operations. NS operates an optimized tactical rolling stock schedule which aims at balancing service quality and operational costs. A good service quality is indicated by providing a sufficient seat capacity for the timetable services, while operational costs are commonly measured by the carriage-kilometers. NS uses about 700 electric multiple units of 9 different types; train units of the same type can be coupled one to another in order to form a longer composition. Rolling stock scheduling amounts to deciding both on the assigned type and on the length of the composition.

In tactical planning, the combination of a high service quality and low operational costs relies on adjusting the train lengths during the day by shunting operations at major stations: train units can be coupled or uncoupled between the arrival of an in-bound train and the subsequent departure of an out-bound train. For example, the compositions are reduced after the morning peak hours, and extended again right before the evening peak hours.

The reduced timetable requires adjusted rolling stock schedules. The problem setting differs from tactical planning in several aspects:

- The train cancellations of the reduced timetable lead to an elevated passenger demand on the remaining services.
- The adjusted rolling stock plan must assume that the rolling stock units are available in the morning at the location where they ended up the evening before. Indeed, the sharp time-line of the process does not admit any dead-heading movements before starting the operations of the reduced timetable.
- The severe weather conditions necessitate a simple use of the infrastructure: key switches are locked. Therefore shunting movements are impossible, except short windows in the early morning and late evening hours.
- The adjusted rolling stock plan for the entire network must be found within 6 hours.

The adjusted rolling stock schedules need to be designed from scratch because the tactical rolling stock schedule cannot be easily modified due to several reasons. First, the structure of the adjusted timetable differs from that of the tactical timetable, thus the pre-set rolling stock relations between in-bound and out-bound services cannot be maintained. Second, the tighter limitations on shunting make the tactical plans impossible to be carried out. Third, the availability of the rolling stock in the morning may not match the needs of the reduced timetable. In extreme situations, all starting services of a station can be canceled, and then the rolling stock stored at that station for the night cannot be used at all in in the adjusted rolling stock plan.

The adjusted rolling stock schedules are computed by TAM, an in-house developed decision support tool of NS. The very core of TAM is the mixed integer linear programming model of [2]. This model has proven to be flexible and powerful in tactical planning, and minor modifications allow us to use it for the reduced timetable, as well. The main decision variables are $X_{t,p} \in \{0;1\}$ to express that composition p is assigned to service t, and $Z_{t,p,p'} \in \{0;1\}$ to express the simultaneous assignment of compositions p and p' to an in-bound service t and its subsequent out-bound service, respectively. In addition, the non-negative integer decision variables $I_{s,m}^{0}$ and $I_{s,m}^{\infty}$ represent the number of rolling stock units of type m at station s in the beginning and at the end of the planning horizon. Then the model's main structure reads as follows (for further details we refer to [2]).

$$\min \quad \sum_{t,p} c_{t,p} X_{t,p} + \sum_{s,m} c_{s,m}^{0} \left| I_{s,m}^{0} - i_{s,m}^{0} \right| + \sum_{s,m} c_{s,m}^{\infty} \left| I_{s,m}^{\infty} - i_{s,m}^{\infty} \right| \tag{1}$$

$$\text{s.t.} \quad \sum_{p} X_{t,p} = 1 \qquad \forall t \tag{2}$$

$$X_{t,p} = \sum_{p'} Z_{t,p,p'} \qquad \forall t,p \tag{3}$$

$$X_{\varphi(t),p'} = \sum_{p} Z_{t,p,p'} \qquad \forall t,p' \tag{4}$$

$$i_{s,m}^{0} + \sum_{t} \alpha_{\tau,s,m,t,p,p'} Z_{t,p,p'} \geq 0 \qquad \forall s,m,\tau \tag{5}$$

$$I_{s,m}^{\infty} = i_{s,m}^{0} + \sum_{t} \beta_{s,m,t,p,p'} Z_{t,p,p'} \qquad \forall s,m \tag{6}$$

The objective function (1) minimizes the penalties for not covering the demand and for deviating from the desired beginning-of-day and end-of-day rolling stock balance $i_{s,m}^{0}$ and $i_{s,m}^{\infty}$; note that the objective can easily be linearized. By constraints (2), exactly one composition is assigned to each trip. Constraints (3)-(4) express the shunting possibilities by linking the X variables to the Z variables. Constraints (5) state that no station has a negative amount of the rolling stock at any time instant τ.

Finally, constraints (6) define the end-of-day rolling stock balance.

In the preparation of the adjusted rolling stock schedules, we divide the network into two sub-problems: one for the Intercity services, and one for the Sprinter (all-station) services. The sub-problems are solved by the commercial MIP software CPLEX.

In a typical optimization run for the adjusted winter timetable, CPLEX displays a feasible solution of (1) – (6) with an optimality gap of less than 5% within 2-3 minutes. In some cases, however, no feasible solution is found in 40 minutes of CPU time; such solution times are unacceptable in our rescheduling application. Therefore we implement a heuristic search for reasonably good solutions. We first solve the linear relaxation of (1) – (6), and we define an increasing sequence of neighborhoods around this fractional optimum. Then we solve (1) – (6) as a mixed integer program restricted to these neighborhoods. This procedure finds feasible solutions within 3 minutes of CPU time, although their optimality gap can in some cases be in excess of 20%. Finally, we resume to solving the actual model (1) – (6), using the heuristic solutions as hot start. Our approach enables planners under high time pressure to terminate the solution process, and to go on with the best available solution, even if the desired optimality gap has not been reached yet.

When applying our methodology, the resulting solutions often provide an unsatisfactory service quality even if the solution is near-optimal. This is due to too strict restrictions in the initial problem specification. However, some of the restrictions can be relaxed. For example, TAM's initial settings admit shunting at a service only if it was explicitly approved in the tactical planning phase. The rolling stock planners may create further shunting possibilities if it helps sending additional rolling stock to overcrowded services. The quick computation times allow us to solve gradually more refined problem instances several times in the allotted time frame.

4. Mathematical model and algorithm for Crew rescheduling

As mentioned before, the final step is adjusting the duties of train drivers and guards so that they adhere to the new timetable and rolling stock schedule. This is done in CREWS RTD (see [3]), the disruption management module of CREWS, which is a decision support tool developed by SISCOG for scheduling and rescheduling crew operations. This module incorporates algorithmic support to perform this final step, i.e. to solve the crew rescheduling problem (CRP), which we define now. Given an original crew schedule (i.e. a set of original duties, some of them containing tasks performed on cancelled trains), we want to obtain an adjusted crew schedule (i.e. a set of feasible duties, called final duties, that replace the original ones) that: (i) covers as much tasks as possible, (ii) uses as few reserves as possible and (iii) maximizes the number of final duties identical to the original ones. A feasible final duty is a duty: (i) with sign-in (sign-out) time greater or equal (less or equal) than the corresponding original duty, (ii) that has room for a meal break and (iii) that complies with several other labor rules.

More formally, we model the CRP as a set covering problem with additional constraints, using the notation adopted in [1]. We denote S as the set of original duties. For every original duty $s \in S$, we consider the set J_s containing the possible final duties that can replace the original duty s. To each duty j that can replace the original duty s we associate a cost c_{sj} that measures how undesirable it is to replace s by j. Finally, let T be the set of tasks that need to be covered. For each task $t \in T$ we define d_t as the cost of leaving t uncovered. We define a 0/1 parameter a_{sjt} that indicates whether the duty performs task t or not. Furthermore, we introduce binary decisions variables x_{sj} that indicate whether a duty is selected or not to be part of the solution. We also introduce binary decisions variables (a.k.a slack variables) y_t that indicate whether a task is left uncovered or not in the solution. The CRP is then given by:

$$\min \sum_{s \in S} \sum_{j \in J_s} c_{sj} x_{sj} + \sum_{t \in T} d_t y_t \tag{7}$$

$s.t.$

$$\sum_{s \in S} \sum_{j \in J_s} a_{sjt} x_{sj} + y_t \geq 1 \qquad \forall t \in T \tag{8}$$

$$\sum_{j \in J_s} x_{sj} = 1 \qquad \forall s \in S \tag{9}$$

$$x_{sj} \in \{0, 1\} \qquad \forall s \in S, j \in J_s \tag{10}$$

$$y_t \in \{0, 1\} \qquad \forall t \in T \tag{11}$$

The objective (7) is to minimize the total cost of the duties and of the tasks left uncovered. Constraints (8) ensure that a task t is either performed or y_t.is set to 1. Constraints (9) ensure that each original duty is replaced by one and only one final duty.

The costs c_{sj} and d_t are defined as follows with respect to a basic cost.. When s is a reserve duty and j a duty covering one or more tasks, than the cost c_{sj} is one order of magnitude larger than the basic cost. When j is equal to (different from) the original s, then the cost c_{sj} is equal to (50% larger than) the basic cost. Cost d_t is two orders of magnitude larger than the basic cost.

We solve the problem (7)-(11) with an heuristic based on the one described in [1], in the sense that it incorporates adjustments that aim at: (i) speeding up the solving process, (ii) enforcing heuristically the satisfaction of constraints (9), and (iii) handling slack variables y_t.

The heuristic described in [1] runs an initial procedure where an initial set of columns is generated (during the execution of a simple loop) and then runs the main procedure where solutions are obtained during the execution of two embedded loops. In each iteration of each loop Lagrangian multipliers are obtained by solving the Lagrangian dual with the subgradient optimization method and columns (representing duties) with negative reduced cost (computed with the Lagrangian multipliers) are generated with a dynamic programming procedure. In the outer and inner loops of the main procedure columns with lowest reduced cost are fixed as a way of intensifying the exploration of the search space. In the inner loop of the main procedure primal solutions are obtained with a greedy heuristic that selects columns starting with the ones with less reduced cost. The dynamic programming procedure computes shortest paths and variations along them in a graph where: (i) distances measure reduced costs, (ii) nodes are tasks and sign in/out activities and (iii) arcs connect tasks or activities that can be performed one after each other in the same duty. Paths with non-negative reduced cost or not complying with the labor rules are not included in the set of generated columns. All loops have upper bounds on the number of overall iterations and on the number of iterations without improvement.

We introduced the following modifications in the heuristic presented in [1]:

- the dynamic programming procedure computes shortest paths and variations along them between sign in and sign out activities of every original duty in S;
- the number of variations of the shortest-path produced in the dynamic programming procedure was reduced considerably in order to reduce the number of columns in the restricted master problem and therefore speed up the problem solving process;
- a procedure was introduced to repair and improve primal solutions obtained by the greedy heuristic; for the original duties that have more than two final duties, it keeps one and sets each task covered by the other duties as uncovered (by generating the corresponding slack variables); after that, it runs a steepest descent hill climbing search where neighbors are alternative ways of planning uncovered tasks (i.e. instantiating the corresponding slack variables with value 0), which can be: (i) inserting it in a normal duty, (ii) inserting it in a reserve

duty or (iii) replacing it with another task (overcovered or not); at each iteration the cheapest neighbor, according to cost function (1), is chosen; the process runs until it reaches a point where no neighbors are found.

Figure 1 shows a graph on solution quality with respect to crew rescheduling for drivers on a real life dataset with almost 8,000 tasks to be scheduled. It can be seen that the model is able to find a good enough solution after about 2 hours, with a very sharp increase in quality shortly after finding the first solution. After that only minor improvements can be reached, however it is usually not worthwhile to wait for this small improved compared to the good solution after 2 hours in the tightly time constrained process.

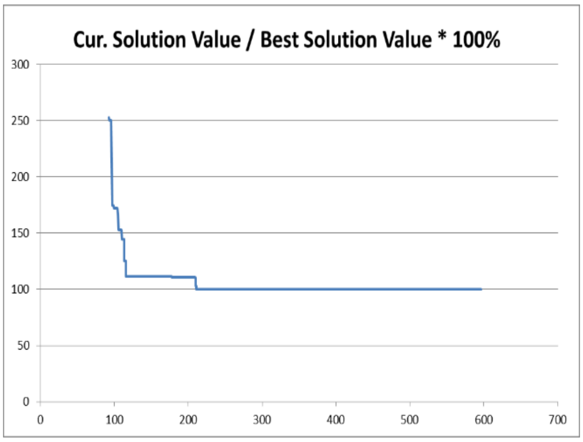

Figure 1: performance crew scheduling algorithm with on the horizontal axis the iterations of the algorithm and on the vertical axis the best solution value

5. Practical impact and Conclusions

The reduced timetable cancels about 20% of all train services in the Netherlands. This roughly means NS operates a frequency of 2 trains on all parts of the network, cancelling all trains that normally lead to a higher frequency. In this paper, we explained the process and algorithms to construct a reduced timetable on days where severe weather conditions are predicted. These sophisticated algorithms make it possible to construct such a timetable within 16 hours.

For rolling stock and crew duties this means that about two thirds of all duties have to be adjusted. For example, when the reduced timetable was implemented on Wednesday February 14th, 2013 the rolling stock schedule had 430 (68%) changed duties. Furthermore, almost half of the trains that still run in the reduced timetable were extended with respect to normal operations. As a result, with the optimized adjusted rolling stock plan is now able to offer around 90% of passengers a seat while running only 80% of train services. On a normal day around 95% of passengers has a seat. On February 14th, 2013 there were 1343 (64%) changed duties for drivers and guards. This included around 160 (7%) duties that became empty. These empty duties can be used as additional reserve duties and thus contribute to a more robust plan.

Between 2013 and 2019, the reduced timetable was implemented 20 times. On days that the adjusted timetable was implemented smooth operation has sometimes been a challenge. However, real chaos as was seen in the years before has not occurred anymore. In that sense, the adjusted timetable has been a great success. However, a reduced service on these days is not the ultimate goal of the Dutch railway sector. In the long run, the operations control process should be improved in such a way that operating a reduced timetable is not necessary anymore.

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