Reinventing Crew Scheduling at Netherlands Railways

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In 2001, the 6,500+ drivers and conductors of the Dutch railway operator NS Reizigers were very dissatisfied with the structure of their duties, which led to nationwide strikes. However, the successful application of an operations research model supported the development of an alternative set of scheduling rules. This alternative set of rules, called Sharing-Sweet-and-Sour, satisfied the drivers’ and conductors’ requests for more variety in their duties and improved the railway operator’s punctuality and efficiency. The application of the operations research model cut personnel costs by about $4.8 million (1.2 percent) per year. Moreover, we showed that the railway operator could even reduce personnel costs by over $7 million per year.

Key words: transportation: scheduling; government: services.
relied on the experience and craftsmanship of the planners.

**History**

On June 10, 2001, NS Reizigers introduced the set of scheduling rules, popularly called Circling-the-Church (in Dutch: Rondjes-om-de-Kerk), to schedule the duties of its drivers and conductors. The management wanted to improve their trains’ punctuality: according to this set of rules, train drivers and conductors would work on fewer different lines, and in principle, they would transfer from one line to another only during their meal breaks. In this way, management hoped to reduce the usual snowball effect of delays of trains. Management also expected that these rules would improve NS Reizigers’ passenger service, because crews would be more familiar with local conditions.

The unions and the works council had been involved in developing the Circling-the-Church rules and had approved their introduction. However, the drivers and conductors were quite unhappy when the details of the rules became apparent. They went on strike for several days in an attempt to prevent their introduction. For a country as densely populated as the Netherlands that is highly dependent on its public transport infrastructure, strikes in the railway system have a dramatic social and economic impact. As a consequence, the Dutch media paid a lot of attention to the problems within NS Reizigers.

After various mediation attempts had failed, the works council, the unions, and management finally came to an agreement on April 23, 2001. This agreement described a path towards normalized working relations. The railway operator would introduce the Circling-the-Church rules as planned on June 10, 2001. However, at the same time, the works council would have the opportunity to develop an alternative set of scheduling rules. This opportunity was not opened-ended: if management would not accept the council’s alternative, then the decision would be subject to binding arbitrage. If management would accept the council’s alternative, then it would go into effect in 2003.

Why were the drivers and conductors so unhappy with the Circling-the-Church rules? Because drivers and conductors would work on fewer different lines, they complained that they would have almost no variety in their duties: the resulting monotony would decrease the quality of their working conditions.

Moreover, the work on several lines of NS Reizigers (mainly in the Randstad in the western part of the country) is less attractive because of the relatively high level of passenger aggression on these lines. With the Circling-the-Church rules, the personnel from only a few crew depots would confront this passenger aggression. The drivers and conductors from these crew depots considered it unfair that they would get a large share of this unattractive part of the workload. Besides these direct issues, the crews also feared that management wanted to establish the Circling-the-Church rules because it had a secret agenda including privatization of the unprofitable lines. All these reasons contributed to a strong opposition against the Circling-the-Church rules.

**The Development of the Alternative Rules**

The April 23, 2001, agreement gave the works council the opportunity to develop an alternative to the Circling-the-Church rules. Besides that, the agreement specified that the works council could hire external experts to help it to develop this alternative set of rules. The works council finally asked the combination of Basis-en-Beleid (a consulting company with experience in social and political conflicts) and ORTEC (a consulting company with expertise in logistics) for support. The consulting companies’ assignment focused on avoiding arbitrage, because in the case of arbitrage, all parties would be losers. So, the consultants were to look for a compromise that would be acceptable to all parties.

However, there were many conflicting points of view. The differences between personnel and management were obvious, but the personnel also had many opinions, depending on function, age, and crew depot. In addition, the various unions held different points of view, and the relationship between the personnel and the works council was weak. Moreover, management positions turned out to be unstable: in the first few days of 2002, the complete board of the company and two top managers left the stage.
In other words, success was not guaranteed at all. But all involved parties agreed that they had to create a solid basis for the alternative set of scheduling rules.

The Participative Approach

ORTEC and NS Reizigers’ department of logistics could provide the needed expertise in logistics. But, on the other hand, it was clear that any plan developed by experts was doomed to fail. Therefore, Basis-en-Beleid and ORTEC opted for a participative approach: they developed the alternative set of scheduling rules in cooperation with the drivers and conductors. They therefore called the project Je-Bent-Er-Bij (You’re-Part-of-It). Openness and transparency were the central concepts. Everyone could follow the whole process at the project’s Web site, and all employees received dedicated newsletters.

In the first months of the project, the consultants conducted discussions with 700 people from all crew depots. One could fill a book by listing all the bottlenecks mentioned, but the central theme in all discussions was the demand for more variety in the duties. The consultants randomly selected 300 people to support the further development of the alternative set of scheduling rules. Four groups of 75 people met several times in two-day working conferences. As a result, the project came to life, and several alternative solutions saw the light. The working conferences informed the works council about these alternatives.

Finally, the works council chose the alternative Sharing-Sweet-and-Sour, which seemed to have the most solid approval among the drivers and conductors. After several lengthy negotiations about the details of the alternative set of rules, NS Reizigers’ management also accepted it. The Dutch media followed the whole process and the negotiations avidly, because the duties of the drivers and conductors had long been a hot issue.

The Role of Operations Research

Where did the alternative set of scheduling rules come from? Parallel to the participative process, experts from ORTEC and NS Reizigers’ department of logistics developed and evaluated several alternatives, which was easier said than done. A timetable consists of thousands of train movements. More than 6,500 crew members have to be assigned to the corresponding tasks. Moreover, in scheduling the crew members, a railway operator must satisfy the many rules prescribed by law and by the collective labor agreements. For example, each crew member has to work on average about eight hours per day and needs a meal break at an appropriate time and location. As a consequence, the crew of a train must be exchanged regularly. The transfer times between successive trips of the same crew cannot be too short. Moreover, each driver has a license for only a limited number of rolling stock types and a limited number of lines. The alternative set of scheduling rules had to produce efficient crew schedules, improve punctuality, and increase variety in the duties. Altogether, it was an enormous challenge.

To generate duties that complied with all these objectives, we used the planning support system TURNI. NS Reizigers’ department of logistics has been using TURNI to produce the basic structure of the duties for drivers and conductors since 2000. In particular, it used TURNI also to produce the duties in line with the Circling-the-Church rules. The kernel of TURNI is a set-covering model that is solved by a combination of dynamic column-generation techniques, Lagrangean relaxation, and heuristic-search methods. TURNI generates all the duties for drivers or conductors for a single workday in one single run.

We carried out the computations in parallel with the working conferences. The working conferences defined preferences that we translated into parameters for the model. We then informed the participants of the working conferences about the model results. The model results were also the basis for further choices. Due to the many different potential alternative sets of scheduling rules, we needed hundreds of runs with the model. Especially during the first phase of the process, we studied many scenarios at the same time with TURNI, keeping several PCs running continuously to solve them.

Initially, we used only a small number of key performance indicators to evaluate the many scenarios and to compare them with each other and with the reference scenarios (the Circling-the-Church scenario and a green-field scenario). The indicators that we used were the total number of duties (efficiency), the total number of transfers from one train...
to another (punctuality), and the total number of lines and rolling-stock types per crew depot (variety). After we eliminated a number of potential alternatives, we evaluated the scenarios in far more depth. In this process, we had to update and to customize TURNI several times to facilitate the evaluation of alternative sets of scheduling rules that were not yet included.

The participative approach and the development and evaluation of the different scenarios using TURNI were not separate activities. The quantitative results streamlined the discussions at the working conferences. They made the discussions more objective, because TURNI made the consequences of various alternative sets of rules transparent, guiding participants to discuss the real choices to be made. In this interplay between the working conferences and the quantitative analyses carried out by TURNI, the many alternatives gradually fell into a set of five main alternatives. From these five alternatives, the works council chose the alternative Sharing-Sweet-and-Sour on May 22, 2002.

In the subsequent negotiations with NS Reizigers’ management to set the details of several parameters of the rules, we used TURNI to evaluate the impact of different settings. The objectivity of the quantitative results provided by TURNI allowed NS Reizigers’ management to accept the alternative set of scheduling rules in the end. The symbiosis between the participative approach and the quantitative analyses was the basis for this final success.

Sharing-Sweet-and-Sour

As the name Sharing-Sweet-and-Sour reveals, this set of rules aims at a fair allocation of the sweet and sour workloads among the 29 crew depots. Sweet represents the variety in routes and lines as well as work on intercity trains, and Sour mainly represents work on lines with a lot of anticipated passenger aggression and work on old rolling stock.

The alternative set of scheduling rules describes quantitative norms for dividing the sweet and sour workloads among the crew depots. For example, there is a lower bound for the number of lines per crew depot, and there is an upper bound for the percentage of work per crew depot on lines with a lot of anticipated passenger aggression. To represent the requested fair allocation of the workload among the crew depots, the rules also contain upper bounds for the standard deviations over these percentages. Altogether, all rules are based on norms that can be checked objectively.

The norms for the standard deviations in the set of rules indicate that it is impossible to realize a 100-percent-fair allocation of the sweet and sour workloads. For example, when NS Reizigers was using the Circling-the-Church rules, crew depot Den Haag carried out all the work on the line through Zoetermeer, which is notorious for its passenger aggression. However, the Sweet-and-Sour rules allocate this work to other crew depots as well. Crew depot Den Haag is still responsible for most of the work on the line through Zoetermeer, but its crews consider it a major leap forward that other crew depots also contribute to this work. Of course, the downside is that these other crew depots also meet with passenger aggression on this line. Similarly, dividing the sweet workload fairly means that several crew depots have less sweet work than they had earlier. This is inherent to a fair allocation of the sweet and sour workloads. Thus, the alternative set of rules appeals to the solidarity among the crew depots.

The alternative set of rules also prescribes a sufficiently high variety in duties. To accomplish this variety, we introduced the concept of repetition-in-duty (RID). We divided the railway network into a number of routes, and, based on this division, we defined the RID_d of duty d as follows:

$$\text{RID}_d = \frac{\# \text{routes in duty } d}{\# \text{different routes in duty } d}.$$  

The associated rule specifies that the overall average RID over all duties should be less than 2.7. For each crew depot, the average RID should be less than 3.0. In other words, on average each duty should contain a certain route at most three times. The application of such concepts as the RID, leading to complex constraints both at the duty level and at the depot level, implies that the whole project was highly demanding from a mathematical point of view.

TURNI

The crew-scheduling system TURNI uses mathematical-programming techniques coming from operations research. These techniques are based on
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Figure 1: Seven duties for drivers from the crew depots Eindhoven (ehv), Den Haag (gvc), Heerlen (hrl), and Venlo (vl) covering part of the work on the line through Zoetermeer (ztmd). This line is subject to a lot of passenger aggression. The gray bars indicate the trips of the duties. For example, the last duty starts at 17:04 with a trip on intercity train 1962 from Venlo to Den Haag. After two trips from Den Haag up and down to Zoetermeer, a trip from Den Haag to Eindhoven on intercity train 1985, and a trip on regional train 6587 from Eindhoven to Venlo, the duty ends in Venlo at 1:12 on the next day.

set-covering models with a number of additional constraints. Most operations research textbooks include the mathematical description of such set-covering models.

The airline industry has used such models to solve crew-scheduling problems for many years (Barnhart et al. 1998, Desrosiers et al. 1995, Hoffmann and Padberg 1993, and Wedelin 1995). However, in the railway industry the sizes of the crew-scheduling instances are, in general, a magnitude larger than in the airline industry. Their size has made the application of these models in the railway industry prohibitive until recently. Developments in hardware and software enable the railway industry to use these models nowadays as well (Caprara et al. 1997, 1999a; Kohl 2003; Kroon and Fischetti 2001; Kwan et al. 1999).

A typical crew-scheduling instance at NS Reizigers related to a single duty type (driver or conductor) on a single workday requires assigning about 14,000 time-tabled trips to 1,000+ duties in 29 crew depots. This produces set-covering instances that are much larger than those addressed in the literature so far, and they have many additional nasty crew-depot constraints. Furthermore, these figures also imply that each duty covers about 14 trips on average, which is a higher number than airlines usually encounter.

**Model Description**

Using the notation \( t = 1, \ldots, T \) for the trips to be covered, \( d = 1, \ldots, D \) for the potential duties, and \( c = 1, \ldots, C \) for the additional constraints to be satisfied, the set-covering model with additional constraints can be formulated as follows:

\[
\min \sum_{d=1}^{D} \text{cost}_d x_d \tag{1}
\]

subject to

\[
\sum_{d=1}^{D} a_{t,d} x_d \geq 1 \quad \forall t = 1, \ldots, T, \tag{2}
\]

\[
\sum_{d=1}^{D} b_{c,d} x_d \leq u_c \quad \forall c = 1, \ldots, C, \tag{3}
\]

\[
x_d \in \{0,1\} \quad \forall d = 1, \ldots, D. \tag{4}
\]
Here the meaning of the binary decision variables is as follows:

\[ x_d = \begin{cases} 
1 & \text{if duty } d \text{ is selected in the final solution}, \\
0 & \text{otherwise}. 
\end{cases} \]

In the 0-1 matrix \( a_{t,d} \) each row represents a trip, each column represents a feasible duty, and \( a_{t,d} = 1 \) if and only if trip \( t \) is covered by duty \( d \).

Besides the regular trips that must be covered, TURNI also allows one to include a number of suggested or inadvisable trips in the model. These trips may be covered by a duty, but they need not be covered. Adding such trips to an instance may be helpful for finding a feasible schedule or for improving the overall efficiency of the schedule. There is no constraint (2) corresponding to the inadvisable trips, which are considered only within the duty-generation module. For each suggested trip \( t \), we have a dummy duty that covers trip \( t \) only and has a cost equal to the user-defined penalty for leaving trip \( t \) uncovered.

The additional constraint (3) is not related to the individual duties (such constraints are handled at the duty-generation level) but to certain forbidden combinations of duties. These are constraints at the so-called depot level. In these constraints, one can see \( u_k \) as the availability of a certain resource and \( b_{t,d} \) as a parameter describing the amount of this resource that is used by duty \( d \). These additional constraints may be related to the alternative set of scheduling rules aiming at a fair allocation of sweet and sour workloads or at appropriate values for the RID. However, they may also be related to more traditional issues, such as the number of duties per crew depot, the percentage of night duties per depot, or the average length of the duties per crew depot.

For example, if \( k_d \) and \( l_d \) denote the crew depot and the length of duty \( d \), respectively, and \( L \) denotes the maximum average length of the duties of each crew depot (say, eight hours), then the following constraints guarantee that the maximum average duty length for each crew depot \( k \) is respected:

\[
\sum_{d} (l_d - L)x_d \leq 0 \quad \forall k = 1, \ldots, K. \tag{5}
\]

The cost coefficients \( \text{cost}_d \) in (1) represent the fact that the main objective is to minimize the number of duties required to cover all trips. However, these coefficients also handle additional penalties for discouraging undesirable characteristics of the duties, such as an unfair allocation of the sweet and sour workloads, uncovered suggested trips, covered inadvisable trips, or positioning trips. In particular, we can use a penalty term for each unit of slack in constraint (2) to reduce (or even forbid) positioning trips (on a positioning trip, a driver or conductor is traveling as a passenger to the start of his next trip).

### Solution Method

In a set-covering model, the solution process usually consists of a duty-generation module and a duty-selection module. The algorithm first generates a large set of potential duties that satisfy all the rules at the duty level. Thereafter, the duty-selection module aims at selecting a subset of these potential duties to cover each of the trips with at least one of the selected duties, to satisfy the additional constraints at the depot level, and to minimize the total costs. In other words, the algorithm solves the model (1)–(4) with the generated set of potential duties as input.

In more detail, TURNI solves the set-covering model by applying dynamic column generation, Lagrangean relaxation, and several heuristics. Dynamic column generation means that the duties are not generated a priori, but on the fly during the solution process. We must use this dynamic approach for generating the duties, because the set of feasible duties is extremely large. Hence, enumerating all possible duties a priori is not feasible.

The solution process is organized in a sequence of passes, in each of which the algorithm tries to obtain better and better solutions. Within each pass, the algorithm iterates between the duty-generation module and the duty-selection module. The duty-generation module produces new prospective feasible duties based on a number of dynamic programming heuristics. In other applications of dynamic column generation, it is usual that such algorithms evaluate the effectiveness of a feasible duty based on dual information related to the linear-programming relaxation of the underlying model. However, TURNI uses Lagrangean relaxation and subgradient optimization instead of linear programming to calculate the required dual information.
The algorithm deletes feasible duties that were generated in earlier stages and whose effectiveness turns out to be low during later stages of the process. The latter is done to keep the number of active duties manageable. The duty-selection module heuristically looks for a solution for the overall model based on the currently available set of feasible duties. The applied heuristic is also driven by the Lagrangian dual information. That is, the heuristic evaluates and selects duties from the set of active duties based on the Lagrangian dual information (Caprara et al. 1999b).

Within each pass, the algorithm applies the generation and selection modules cyclically for a certain number of iterations in an attempt to update the best solution found. Thereafter, it activates a fixing procedure to select some duties that appear to be particularly efficient and to fix them as belonging to the final solution. Then, the algorithm repeats the overall process on the trips not covered by the fixed duties: it iterates the duty-generation and duty-selection phases for a while on the subproblem resulting from fixing, fixes new duties, and so on. In this way, the algorithm typically evaluates several million potential duties in the duty-generation phase, and it constructs and evaluates thousands of alternative solutions during the selection phase. It also applies a heuristic refinement procedure from time to time in an attempt to improve the best solution by locally exchanging trips among duties (Figure 2).

**Efficiency Improvement**

After NS Reizigers adopted TURNI in 2000, it used it in several projects to study the effects of different sets of rules to be applied in its crew-scheduling process. Examples are the Circling-the-Church rules and the Sharing-Sweet-and-Sour rules. The railway operator also used TURNI in a bidding process, which helped it to win a long-term concession to operate trains in the neighborhood of Liverpool (United Kingdom).

Although NS Reizigers operated its trains quite efficiently already before adopting TURNI, it estimates that using TURNI saves up to two percent per year
on its crew costs. In particular, NS Reizigers used TURNI to schedule the duties for the drivers and conductors for the 2004 timetable. For this timetable, the total workload increased by about 3.2 percent in comparison with the 2003 timetable. This increase resulted from NS Reizigers increasing the number of trains to provide better service. However, supported by TURNI, the planners generated a set of duties that satisfied all the new rules but required only 1.2 percent more duties than in 2003. In other words, the operator realized initial savings of about two percent. For a total of 6,500+ crews, this amounts to savings of over $7 million per year. In practice, NS Reizigers estimates the savings to be $4.8 million per year, since management gave away part of the initial savings to further increase the drivers’ and conductors’ acceptance of the crew schedules. The final savings of 1.2 percent were still well above the target of 1.0 percent that management initially set. These estimates of the savings are quite conservative, in particular because generating the crew schedules would have been impossible without the support of TURNI.

The target for the crew schedules for 2005 is a further cost reduction of about 2.5 percent per year. NS Reizigers is achieving this by maintaining the same basic efficiency as in 2004 and by relaxing some of the constraints. In particular, punctuality analyses have shown that reducing the time allowed for drivers and conductors to transfer from one train to another from 25 minutes to 20 minutes has only a minor negative effect on punctuality but has a positive effect on the efficiency of the crew schedules. With a system like TURNI, changing the transfer time from 25 minutes to 20 minutes is easy, whereas it would be very complex and time consuming to handle the change manually.

Final Remarks
At the start of this project, the working relations between the various parties at NS Reizigers were so strained that nobody believed that a solution to the conflicts existed. However, a well-directed combination of a participative approach to build personnel involvement and expertise in operations research for quantitative support was successful. Operations research revealed its power by facilitating the analysis of the complex scenarios. Moreover, in emotional discussions, quantitative results helped people to evaluate arguments objectively. These quantitative and objective results enabled the management of NS Reizigers to accept the Sharing-Sweet-and-Sour rules in the end.

The railway operator’s experience with the alternative set of rules is quite positive so far. After the drivers had expanded their knowledge of the routes, the introduction of the alternative set of scheduling rules on December 15, 2002, took place quite smoothly. Since then, the average punctuality has increased gradually from about 80 percent to about 86 percent. Punctuality of 86 percent means that 86 percent of the trains arrive with a delay of three minutes or less. Obviously, this increase in punctuality is caused only partially by the alternative set of rules: several other developments have improved the punctuality as well, for example, the introduction of new, more dependable rolling stock and the intensified maintenance of the railway infrastructure.

The only negative comments about the alternative set of scheduling rules come from the traffic-control organization. Because the complexity of the structure of the drivers’ and conductors’ duties increased with the Sharing-Sweet-and-Sour rules, in real time, reconstructing the duties in case of severe disruption of the railway services is more difficult than it was under the Circling-the-Church rules. However, these negative comments are outweighed by the fact that the alternative set of rules improved the motivation of the drivers and conductors, which certainly had a positive effect on the trains’ punctuality.

To the best of our knowledge, this is the first time that a European railway company has used operations research techniques successfully to support its crew-scheduling process in practice. Until recently, the size and complexity of railway crew-scheduling problems prohibited the application of such techniques.

NS Reizigers’ application of TURNI led to operational savings of about $4.8 million per year. The railway expects to save over $30 million over the next five years. A further advantage is that the railway operator became less dependent on the experience and craftsmanship of the planners. Moreover, the application reduces the throughput time of the logistic planning processes, which increases the organization’s flexibility and allows it to react quickly
to requests for modifications or to changes in the environment.

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