Algorithmic Support for Railway Disruption Management

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Abstract

Disruptions of a railway system are responsible for longer travel times and much discomfort for the passengers. Since disruptions are inevitable, the railway system should be prepared to deal with them effectively. This paper explains that, in case of a disruption, rescheduling the timetable, the rolling stock circulation, and the crew duties is so complex that solving them manually is too time consuming in a time critical situation where every minute counts. Therefore, algorithmic support is badly needed. To that end, we describe models and algorithms for real-time rolling stock rescheduling and real-time crew rescheduling that are currently being developed and that are to be used as the kernel of decision support tools for disruption management. Furthermore, this paper argues that a stronger passenger orientation, facilitated by powerful algorithmic support, will allow to mitigate the adverse effects of the disruptions for the passengers. The latter will contribute to an increased service quality provided by the railway system. This will be instrumental in increasing the market share of the public transport system in the mobility market.

1 Introduction

Increasing the market share of public transport is considered as one of the solutions for the mobility problems in the Netherlands. Moreover, public transport is seen as a *green* mode of transportation. Thus for achieving sustainable mobility, travellers will have to be seduced to use the public transport system instead of their own cars. In order to make the public transport system more attractive, an increase in its service quality is needed. This is especially true for railway systems. Indeed, one of the weak points of railway systems is that disruptions seem to be more or less inevitable, leading to much discomfort.

In the Netherlands, relatively large disruptions occur on average about three times per day, each time leading to a temporary and local unavailability of the railway system. A disruption and the involved uncertainty often lead to much more discomfort for the passengers than the few minutes of delay with which they are confronted regularly, see Brons (2006). In a disrupted situation, also the lack or incorrectness of travel information may lead to a lot of discomfort. For many people these issues are disqualifiers to use public transport.

In case of a disrupted situation, the disruption management process should quickly provide a modified timetable, rolling stock circulation, and duties for the crews, so that as much as possible of the service for the passengers can be upheld. However, one of the bottle-necks in the current disruption management process is that it is carried out completely manually, and that a large number of parties are involved, see Jespersen-Groth et al. (2007). This leads to slow response times and to solutions that are far from optimal. For example, several trains may be canceled since no appropriate drivers could be found.

Faster response times and better solutions can be expected by the application of *algorithmic support*. That is, the modified timetable, rolling stock circulation, and duties for the crews are generated *automatically* based on appropriate mathematical models and on algorithms for solving these models.

In March 2009 the advantages of using algorithmic support for rescheduling the crew duties of Netherlands Railways (in Dutch: Nederlandse Spoorwegen, NS) in case of a disruption were clearly demonstrated by the application of an automated crew rescheduling tool after a freight train derailed near station Vleuten. This derailment damaged the railway infrastructure over 5 kilometers, which required the timetable, the rolling stock circulation, and the crew duties to be rescheduled during nearly 7 days. A comparison between the automated rescheduling process for the driver duties with the manual rescheduling process for the conductor duties revealed the advantages of the automated rescheduling process: it lead to better solutions in less time.

Algorithmic support will be needed especially if the plans underlying the railway system are tight. That is, there is just a small amount of slack in the system. This will be the case if the utilization of the railway infrastructure is increased in the near future by higher frequencies and traffic volumes. For example, there are plans to introduce a system with 6 intercity trains and 6 regional trains per direction and per hour on several Dutch corridors.

Conversely, the application of algorithmic support will also allow to increase the efficiency of the railway system. This is relevant since the railway world is becoming more and more competitive. In particular, currently several buffers (e.g. in the form of relatively large numbers of stand-by crew members) are present in the system as a safety net in case of disruptions. However, part of these buffers will become redundant at the moment that effective algorithmic support is applied, thereby increasing the system's efficiency.

A scientific challenge that needs to be solved for the application of algorithmic support for disruption management is the development of the appropriate models and sufficiently powerful algorithms for quickly solving these models. Indeed, in order to be effective in real-time, the computation times of these algorithms need to be short: an algorithm that needs hours to compute a decision that is required more or less instantaneously is useless. Also dealing in

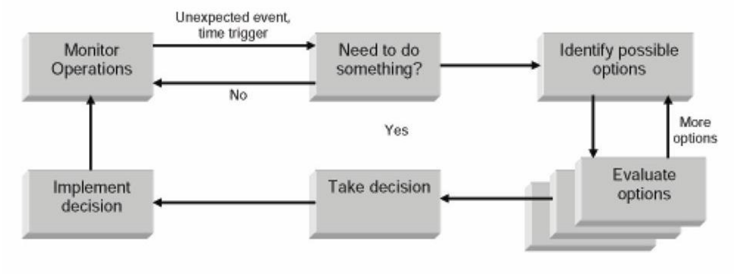

Figure 1: A high level view of disruption management, see Kohl et al. (2007)

an adequate way with the uncertainty and volatility that are inherent to the disruption management process is still a scientific challenge.

This paper describes the challenges and the potential benefits of the application of algorithmic support for the quality of the railway system. Section 2 starts with a general description of disruption management. Section 3 describes how the timetable is modified in case of a disruption. Then Section 4 gives a description of models and algorithms for rolling stock rescheduling that are currently developed. Section 5 proceeds with models and algorithms for crew rescheduling. This section also describes the Vleuten case mentioned above. Passenger oriented disruption management is described in Section 6. Section 7 presents final remarks and subjects for further research.

2 Railway disruption management

Figure 1 from Kohl et al. (2007) gives a high level view of disruption management. Disruption management is an ongoing process that focuses both on the question whether a situation is disrupted or not and on the measures to correct a disrupted situation. For evaluating whether a situation is disrupted, and for reacting effectively in case of a disruption it is essential to have real-time information on the positions of train units and crews. Furthermore, for upholding as much as possible service for the passengers, it is necessary to have real-time information on the locations and destinations of the passengers. Modern information technology allows this kind of information to be more and more available, although real-time passenger information is still scarce.

A disruption of the railway system is often caused by a blockade of part of the railway infrastructure. Such a blockade may be complete or partial. In the first case no railway traffic is possible at all on the blocked infrastructure, e.g. due to malfunctioning power supply. If only part of the available parallel tracks is blocked, as in the case of a broken-down train unit, then some railway traffic remains possible, but usually a number of trains have to be canceled.

The modifications in the timetable usually make the rolling stock circulation and the crew duties infeasible as well. Indeed, if some trains are canceled, then certain train units and crews cannot follow their planned duties. Thus rescheduling the rolling stock circulation and the crew duties is required. The railway operators are responsible for carrying out this rescheduling process.

A complicating issue in a disrupted situation is the fact that the duration of the disruption is usually not known exactly. As time proceeds, the initial estimate of the duration of the disruption may turn out to be incorrect. As a consequence, the rescheduling process must be carried out several times then. Furthermore, all process times (running times, dwell times, etc.) are stochastic. Thus future arrival and departure times of trains are not known with certainty, but can only be estimated. d'Ariano et al. (2007) describe models that can be used to deal with uncertain process times.

An important difference between scheduling in the planning process and rescheduling in the real-time operations is the dynamic environment in which the rescheduling process has to take place. That is, while the rescheduling process is carried out, the status of the railway system is changing at the same time. Thus apart from the fact that the rescheduled plans are needed as soon as possible, this is another reason for the need for short rescheduling times. Since the rescheduling problems that have to be solved are large and complex, the realization of sufficiently short computation times of the rescheduling algorithms is still a large scientific challenge.

A further difference between planning and operations is the fact that in the operations the existing plans have to be taken into account. This holds in particular when rescheduling the crew duties: the end times of the rescheduled duties should not differ too much from the end times of the original duties. Similarly, the shunting processes related to the rolling stock circulation must not be changed too much, since the feasibility of modified shunting processes is hard to check. For further differences between planning and operations, see Grötschel et al. (2001) and Séguin et al. (1997).

Note that disruption management is different from online scheduling, where events occur completely *unexpectedly*. Conversely, in the real-time operations permanently monitoring the railway processes provides a lot of information about upcoming events. Each event has at least an *expected* event time. Based on this information, one may forecast whether there will be conflicts in the near future due to the timetable, the rolling stock circulation, or the crew duties.

3 Timetable rescheduling

In case of a disruption of the railway system, usually a number of trains cannot be operated. Thus the timetable is modified by canceling a number of trips. In the Netherlands, these modifications are usually based on a *disruption scenario*. The disruption scenarios have been prepared by the traffic control organization of the infrastructure manager in cooperation with the railway operators. They describe e.g. which trips in the timetable have to be canceled, which trips have to be rerouted, and in which stations short returns of trains have to be introduced.

The selection of the disruption scenario to be used in case of an actual disruption may require a lot of -time consuming- communication between the infrastructure manager and the railway operators. Moreover, although there may be several hundreds of disruption scenarios, there is usually no scenario that fits exactly with the disrupted situation. Therefore, some fine-tuning of the selected scenario will be needed. For automatically solving this kind of problems, algorithmic support has not been developed yet.

Figure 3 shows how the timetable of the 3000 intercity line of NS may be modified if temporarily no railway traffic is possible between Amsterdam and

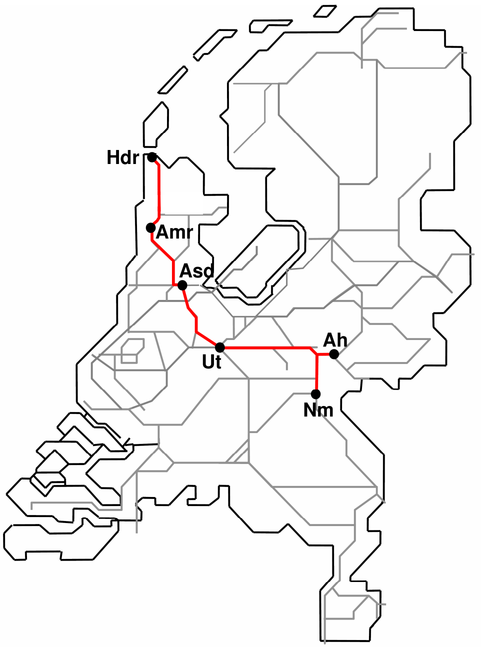

Figure 2: The 3000 line runs twice per hour in each direction between Den Helder (Hdr) and Nijmegen (Nm)

Utrecht due to malfunctioning railway infrastructure. The 3000 line provides twice per hour an intercity connection from Den Helder (Hdr) to Nijmegen (Nm) and vice versa, via Alkmaar (Amr), Amsterdam (Asd), Utrecht (Ut), and Arnhem (Ah), see also Figure 2. The timetable of the 3000 line is cyclic with a cycle length of 30 minutes.

The disruption between Amsterdam and Utrecht starts at 8:40 am, and has an estimated duration of 2.5 hours. A usual scenario for modifying the timetable is to cancel the disrupted trips between Amsterdam and Utrecht, and to introduce short returns of the trains in Amsterdam and Utrecht. That is, a train arriving in Amsterdam from Alkmaar returns in the timetable of the 3000 line to Alkmaar. Similarly, a train arriving in Utrecht from Arnhem returns to Arnhem. Note that this requires that the routes of these trains in Amsterdam and Utrecht must be modified.

As can be seen in Figure 3, only the first disrupted trains in Amsterdam and Utrecht are put aside at the shunt yards there. After the end of the disruption, these trains are put into operation again. These trains belong to the *grey area* between the regular undisrupted situation and the "regular" disrupted situation.

As was mentioned earlier, the initial estimate of the duration of the disruption often turns out to be wrong. If this is indeed the case, then the timetable, the rolling stock circulation, and the crew duties must be rescheduled again at the moment that the difference becomes clear.

Due to the described disruption scenario, the services on the 3000 line outside

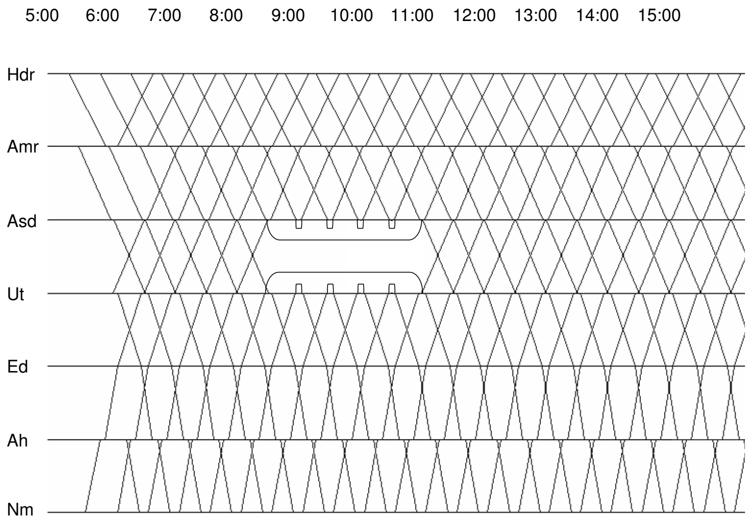

Figure 3: A disruption of the railway traffic between Amsterdam (Asd) and Utrecht (Ut) starting at 8:40 am with an estimated duration of 2.5 hours

the disrupted area remain as much as possible the same as usual. In order to compensate for the canceled trains between Amsterdam and Utrecht, buses may be operated on the disrupted route. Note that also several other train lines operate on the indicated infrastructure. However, in order to keep the figure simple, these have not been shown.

4 Rolling stock rescheduling

4.1 Introduction

The rolling stock circulation strongly influences the service of the railway system, and rolling stock costs are a large part of the operational costs of a railway operator. Rolling stock planning aims at allocating an appropriate amount of rolling stock to each train in the given timetable. A rolling stock circulation can be expressed in terms of the rolling stock compositions of the trains, but it can also be expressed in terms of the rolling stock duties. Here a rolling stock duty is a sequence of tasks to be carried out by a single train unit on a single day. A task for a train unit is a trip in a train from one station to another at a certain time instant in combination with a position in the train.

Relevant papers on rolling stock scheduling and rescheduling are Caprara et al. (2007), Alfieri et al. (2006), Fioole et al. (2006), Peeters and Kroon (2008), Jespersen-Groth et al. (2006), Budai et al. (2007), Cacchiani et al. (2009), and Nielsen et al. (2009). In Section 4.2 we provide some details of the latter paper.

Figure 3 illustrates the need for rescheduling the rolling stock circulation in case of a disruption. Indeed, since the compositions of the trains depend on the expected numbers of passengers -which strongly vary over the day and per direction- it is highly improbable that, after a short return of a train in Amsterdam or in Utrecht, its actual composition is exactly the same as its planned one. This difference will propagate to other trains and will lead to mismatches between demand for and supply of seats later on. Furthermore, it will lead to off-balances by the end of the day, i.e. train units ending at the wrong locations. Thus the rolling stock circulation must be rescheduled.

4.2 A multi-commodity flow model

This section describes a model and an algorithm for rescheduling the rolling stock circulation in case of a disruption of the real-time operations. This description is based on Nielsen et al. (2009). The model is a multi-commodity flow model, but it has several additional features.

4.2.1 Problem description

Nielsen et al. (2009) describe a model and an algorithm for the real-time Rolling Rolling Stock Rescheduling Problem (RSRP). Here the timetable and the available rolling stock may change several times in case of a disruption. Real-time RSRP is the problem of updating the current assignment of train units to trips in the timetable whenever the timetable or the rolling stock availability is changed. Formally, an instance of real-time RSRP contains the following elements:

- The original timetable T_0.
- The original rolling stock M_0.
- The original rolling stock circulation C_0.
- A finite list of changes to the timetable and the rolling stock availability,

$$< t_1, T_1, M_1 >, < t_2, T_2, M_2 >, \ldots, < t_n, T_n, M_n > .$$

Here an element in the list is a triple consisting of a time instant t_i, an updated timetable T_i, and an updated rolling stock availability M_i. The time instants are assumed to be distinct and sorted such that $t_1 < t_2 < \ldots < t_n$. Each element in the list represents a time instant where a new situation appears, which renders the current rolling stock circulation infeasible. At any point in time t, the changes in the timetable and the rolling stock availability that will appear after time t are not known yet.

The problem is then to reschedule at time t_i the rolling stock circulation C_{i-1} to serve timetable T_i with rolling stock M_i. The resulting rolling stock circulation is called C_i. At time t_i the rolling stock assigned to trips in T_i departing before time t_i is fixed. The objective of real-time RSRP measures several aspects of the intermediate and the final rolling stock circulations. These aspects are described in Section 4.2.2.

Note that the foregoing implies a "Wait-and-See" approach to the rolling stock rescheduling problem, see Wets (2002). That is, one waits until there is a certain need to update the rolling stock circulation, since the existing rolling stock circulation has become infeasible. Otherwise, when rescheduling the rolling stock circulation, one might anticipate already on future changes in the timetable or the rolling stock availability. Also in practice it is quite usual to apply a “Wait-and-See” approach.

4.2.2 Objective function

The first objective in real-time RSRP is the feasibility of the new circulation where the limitations on the lengths of the trains are the most challenging ones. In addition, there are several other objectives to be taken into account in the rescheduling process. The following lists several perspectives of real-time rescheduling and the objectives associated with them.

- **The service perspective.** The inconvenience for the passengers should be minimized, which means that canceling trips due to lack of rolling stock (in addition to the trips that are directly canceled due to the disruption) should be minimized. Similarly, assigning too little capacity related to the expected number of passengers should be avoided. A complicating issue here is that in a disrupted situation it is hard to forecast the passenger behavior and hence the passenger demand.
- **The process perspective.** Deviations from the original rolling stock circulation should be communicated to the involved parties. In particular, the feasibility of the modifications of the shunting plans may be hard to check in detail at short notice. Therefore the number of such modifications should be minimized.
- **The robustness perspective.** The propagation of the effects of the disruption should be kept local. In particular, the number of off-balances by the end of the day should be minimized, since otherwise the effects of the disruption propagate to the next day.
- **The efficiency perspective.** The number of carriage kilometers driven is closely related to the operational costs of the rolling stock circulation. Unnecessary carriage kilometers should be avoided. Similarly, deadheading trips for solving rolling stock off-balances should be avoided as well.

4.2.3 Solution method

Nielsen et al. (2009) use a model for rolling stock rescheduling that is deduced from the models of Alfieri et al. (2006) and Fioole et al. (2006). The latter models are multi-commodity flow models which also consider the order of the train units in the trains. The concept of a transition graph is used to deal with this aspect. This concept is based on the assumption that for each trip a successor trip is known. The transition graph describes for each allowed combination of a trip and a train composition the feasible train compositions on the successor trip. Then the problem is an integer multi-commodity flow problem, where at the same time for each train a feasible path in the associated transition graph is to be found, and the objective function is optimized.

Nielsen et al. (2009) adapt this planning model to the rescheduling context by adding a number of features. First of all, the original rolling stock circulation has to be taken into account. The original timetable is T_0 and the original rolling stock M_0 is assigned to the timetable as described by the original rolling stock circulation C_0. The train compositions prior to the start of the disruption are fixed. The model is also extended with the possibility to assign an empty composition to a trip, i.e. the trip is canceled.

The model of Nielsen et al. (2009) is applied on a rolling horizon in order to speed up the solution process. That is, rescheduling the rolling stock is only carried out for a fixed time period ahead. This is done whenever the rescheduling horizon has elapsed or at the moment that new information has become available about updates of the timetable or the rolling stock availability. In order to guide the rolling stock inventories such that the off-balances by the end of the day will be low, the model aims at minimizing the off-balances by the end of each planning horizon. The therefore required intermediate target inventories are deduced from the inventories in the original rolling stock circulation. The weights of the intermediate off-balances increase as time proceeds.

To analyze the rolling horizon solution heuristic, Nielsen et al. (2009) tested it on a set of instances of NS involving a disruption on the so-called Noord-Oost lines. These form the most challenging cases for rolling stock scheduling at NS. The disruption in the described instances occurs between Utrecht and Amersfoort, implying that no trains can run between these two stations then. The actual length of the disruption is not known initially, but only an estimated length is available. In these experiments it turned out that the rescheduling method is able to quickly reschedule the rolling stock circulation.

5 Crew rescheduling

5.1 Introduction

Each train needs a train driver and one or more conductors. For both types of crew members, a task is related to a trip on a train between two stations where the crew possibly can be changed. A crew *duty* is the set of tasks to be carried out by a single crew member on a single day. Thus there are duties for drivers and duties for conductors. Initially, the duties are anonymous, i.e. they have not been assigned to real crew members yet. This assignment of duties to crew members is specified by the crew *rosters*.

Crew *scheduling* is the problem of a priori generating the crew duties. In real-time crew *rescheduling* the duties obviously have been assigned to real crew members already. Thus one must take into account the existing duties as well as the individual competencies of the assigned crew members then.

Since crew scheduling is a complex and yet generic problem, a lot of research on models and solution techniques for solving this problem in off-line planning processes has been carried out. Abbink et al. (2005), Fores et al. (2001), Kohl (2003), and Kroon and Fischetti (2001) describe a number of successful applications of these models within railway companies.

Research on models and solution techniques for crew rescheduling in railway systems is still scarce, see Huisman (2007), Rezanova and Ryan (2009), Walker et al. (2005), Abbink et al. (2009) and Potthoff et al. (2008). In Section 5.2 we present some details of the latter paper. Crew rescheduling for airline systems has received more attention, see Song et al. (1998), Stoiković et al. (1998), Lettovský et al. (2000), Yu et al. (2003), Clausen et al. (2005), Medard and Sawhney (2006), Nissen and Haase (2006), and Kohl et al. (2007).

Figure 3 shows the need for rescheduling the duties in case of the earlier mentioned disruption between Amsterdam and Utrecht. In this example, it is usual that there are planned duties for drivers covering the three tasks Amr-Asd, Asd-Ut, and Ut-Ah on one of the disrupted trains. Since the trip Asd-Ut in such a duty is canceled, the involved driver will not be able to carry out the task Ut-Ah in his duty. So this task must be assigned to another driver. Conversely, it is usual that the driver follows the train in the short return in Amsterdam. Thereby he is moving into another direction than prescribed in his duty. Thus this duty must be rescheduled to get this driver in time back in his home depot, while at the same time carrying out as much as possible tasks.

Although the crew rescheduling process is mainly an internal process, it is one of the recognized bottle-necks in the disruption management process, since it is impossible to manually reschedule tens of duties in just a couple of minutes. One of the reasons is that for rescheduling the timetable and the rolling stock circulation dispatchers heavily use the fact that (the basic structures of) these plans are cyclic. Unfortunately, the crew schedule is by definition non-cyclic, for instance because a crew member needs to reach his home depot after a certain amount of time. Moreover, crew rescheduling has to take into account many complex labor constraints. And finally, an important feature is that crews can refuse certain changes in their duties. Currently this happens in practice mainly because crew members are not informed about their completely rescheduled duties, but only about their next tasks. Therefore, they do not know if they will arrive in their home depot at a reasonable time.

As a consequence, manually rescheduling one disrupted duty usually requires 5 to 10 minutes. Given the fact that it is not unusual that 50 to 100 duties are hindered by a disruption, it requires a lot of time to reschedule all the crew duties. This may have a very negative impact on the quality of the railway system. Especially in this process, advanced algorithmic support is badly needed: a train that cannot be provided with an appropriate crew will have to be canceled with all the negative consequences for the passengers.

5.2 A Set Covering based model

This section describes a model and an algorithm for rescheduling crew duties in case of a disruption of the real-time operations of NS. This description is based on Potthoff et al. (2008). The model is a set covering model, but it has some additional features which allow it to deal with the existing duties.

5.2.1 Model description

It is assumed that the disruption takes place at a certain location, starts at time t_0, and lasts until t_1. The duties that are unfinished at time t_0 are represented by the set Δ. In addition, N is the set of tasks which have not started at the time of rescheduling, and K^δ is the set of all feasible completions for original duty $\delta \in \Delta$. A feasible completion is a sequence of tasks after time t_0 by which the tasks in the original duty are replaced such that the duty still fulfills all constraints at the duty level and ends in the right crew depot at an appropriate time. For every duty $\delta \in \Delta$ and every feasible completion $k \in K^\delta$ we have:

- c_k^δ: the cost of feasible completion k for original duty δ. The cost of a feasible completion is zero if the duty is not modified. Otherwise, the cost is the sum of the cost for changing a duty, the cost for taxis, and the penalties for short connection times and overtime.

- a^{δ}_{ik}: a binary parameter indicating if task i is covered by feasible completion k for original duty δ or not.

Finally, we define f_i as the cost of canceling task i. Potthoff et al. (2008) now formulate the crew rescheduling problem using binary variables x^{δ}_k corresponding to the feasible completions of duty δ. That is, x^{δ}_k is 1 if and only if feasible completion $k \in K^{\delta}$ is used to complete duty $\delta \in \Delta$. Furthermore, binary variables y_i indicate if task i is canceled (1) or not (0).

$$\min \sum_{\delta\in\Delta}\sum_{k\in K^{\delta}} c^{\delta}_k x^{\delta}_k + \sum_{i\in N} f_i y_i \tag{1}$$

$$\text{s.t.} \quad \sum_{\delta\in\Delta}\sum_{k\in K^{\delta}} a^{\delta}_{ik} x^{\delta}_k + y_i \geq 1 \quad \forall i \in N \tag{2}$$

$$\sum_{k\in K^{\delta}} x^{\delta}_k = 1 \quad \forall \delta \in \Delta \tag{3}$$

$$x^{\delta}_k, y_i \in \{0,1\} \quad \forall \delta \in \Delta, \forall k \in K^{\delta}, \forall i \in N. \tag{4}$$

The objective function (1) takes into account several aspects, such as the number of uncovered tasks, the number of modified duties, the number of used stand-by duties, and the differences between the durations of the original duties and the rescheduled duties. Constraints (2) guarantee that every task is either covered by a feasible completion or is canceled. Moreover, constraints (3) ensure that every original duty is assigned to exactly one feasible completion.

5.2.2 Solution method

The crew rescheduling method in Potthoff et al. (2008) uses an algorithm that is based on large neighborhood search in combination with a column generation heuristic. It can be summarized as follows:

- **Step 1.** Define an initial core problem based on a set of duties to be rescheduled. The set of tasks that is considered is the set consisting of the directly disrupted tasks and some other tasks either on the same route or around the same time on adjacent routes.

- **Step 2.** Compute an initial solution using a Column Generation heuristic. This heuristic is very similar to the method described by Huisman (2007). It uses Lagrangian dual values to construct new columns by solving resource-constrained shortest path problems. Constructive heuristics are used for generating feasible solutions from these columns.

- **Step 3.** Check whether there are still uncovered tasks. If all tasks have been covered, then stop.

- **Step 4.** Define a neighborhood by extending the set of duties to be rescheduled. The additional duties are selected based on the fact (*i*) that they cover tasks in the neighborhood of an uncovered task, and (*ii*) that the involved drivers are able to carry out these uncovered tasks. Finally,

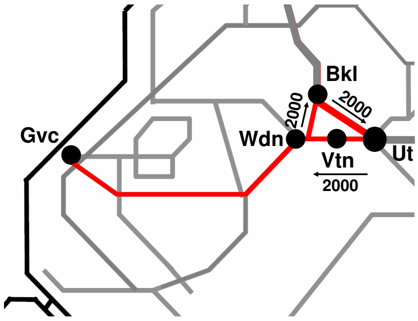

Figure 4: The disruption took place near station Vleuten (Vtn) between Utrecht (Ut) and Woerden(Wdn). The trains of the 2000 line from The Hague (Gvc) to Utrecht made a detour via Breukelen (Bkl).

also a number of additional duties are selected based on their similarity to the duties selected according to (*i*) and (*ii*).

- **Step 5.** Explore the neighborhood by a Column Generation heuristic. Here the same comments apply as in Step 2.
- **Step 6.** Goto Step 3.

Computational results based on realistic instances of NS are reported in Potthoff et al. (2008). These results show that the described rescheduling method usually finds acceptable solutions in a short computation time on a regular pc. Especially in the case that a number of stand-by crews are available, usually no trains have to be canceled due to lack of a driver or conductor.

5.3 Practical application

The method described in Section 5.2 was applied by NS for rescheduling the duties of the drivers during a major disruption. As was mentioned in Section 1, a freight train derailed near station Vleuten (Vtn) on Monday, March 23, 2009. Due to this accident, the railway infrastructure was damaged over 5 kilometers, which blocked the route between Utrecht (Ut) and Woerden (Wdn) for nearly a week, see Figures 4 and 2. Initially, this route was blocked completely.

On Tuesday, March 24, one track could be opened again, so that limited railway traffic was possible. Therefore, it was decided that the 2000 line (The Hague (Gvc) - Utrecht) would be operated again on Wednesday. However, in one direction (The Hague - Utrecht) it would use another route, namely via Breukelen (Bkl), where it could turn in the direction of Utrecht. This alternative route was selected to have only trains in the direction Utrecht - The Hague on the disrupted route. As a consequence, the timetable of other trains had to be modified as well. This situation lasted until the evening of Sunday, March 29.

On Monday and Tuesday of this week, the crew duties were rescheduled completely manually. However, the driver duties for Wednesday and Thursday were rescheduled by the method of Potthoff et al. (2008). In fact, only the first three steps had to be carried out: all trips were covered then. In total, on each day 260 driver duties were directly affected by the disruption and had to be rescheduled. The algorithm found a good feasible solution in about 1 hour of computation time.

Unfortunately, the output of the algorithm could not be imported directly into the computer system of the Operations Control Centers of NS. Thus two dispatchers typed in all Wednesday's duties during the night before. The same happened during the next night for the Thursday's duties.

The duties for the conductors were still modified manually by the dispatchers. Therefore, we could make a comparison between the algorithmic approach and the current manual process. During the night, four dispatchers could reschedule the tasks in the conductor duties that started until 13:00 on the next day. The remaining part of the conductor duties had to be rescheduled during the day, resulting in many duties that did not finish at the regular time and in a lot of communication during the day.

For the driver duties, this was not necessary. Although the solution approach might have taken into account individual route and rolling stock knowledge of the drivers, this information was not available at NS in electronic format. Therefore, there were still some conflicts in the driver duties with the actual route and rolling stock knowledge. Fortunately, these problems could be solved relatively easily during the day.

For the last three days of the disruption (Friday until Sunday), the CREWS planning system was used to reschedule all the crew duties. This system contains the algorithm described in Huisman (2007) to reschedule the crew duties during planned track maintenance. Of course, such an algorithm also works for an unplanned disruption which is known some time in advance. The CREWS system could not be used for rescheduling the crew duties during the first days of the disruption, since the application of this system has a relatively long lead time. In particular, the process of rescheduling the crew duties for Friday with the CREWS system started on Wednesday already.

Although this Vleuten case does not yet provide an example of algorithmic support for *real-time* disruption management, this case is quite close to it. Anyway, it clearly demonstrates the advantages of algorithmic support for rescheduling the crew duties in the operations: it leads to better solutions in less time. Especially the latter aspect will be crucial and decisive when the algorithmic support is applied in a real-time environment.

6 Passenger oriented disruption management

The current disruption management process is mainly based on a standard set of disruption scenarios, which focus on isolating the disruption and on "keeping the system running". Service for the passengers is not considered as input, but is just a result of the taken decisions.

However, as can be seen from the Vleuten case described in the previous section, sometimes more attractive alternatives for the passengers exist. Examples of such alternatives are: temporarily operating another timetable (e.g. rerouted trains, or shuttle trains), and more or longer trains outside the disrupted area in order to facilitate the rerouting of passengers. Moreover, along the alternative routes transfers from one train to another with short transfer times should be facilitated. This may require trains to wait somewhat longer for each other than in the normal situation. Obviously, the passengers should be informed permanently in an adequate way about their alternative routes. Thus the railway network should be so flexible that its capacity can be adapted quickly to the modified situation during a disruption.

Although the methods in Sections 4 and 5 are initially developed to support the current disruption management process, they will be especially helpful when NS wants to offer alternative timetables in a disrupted situation. For instance, in the Vleuten case it would have been possible to assign more rolling stock to the trains that were still in operation during the disruption. Some of these trains had much more passengers than regularly, while on the other hand rolling stock was not needed for the trains that could not be operated.

Louwerse (2009) shows that by reassigning the rolling stock to the different trains in the morning peak the number of passengers not having a seat could almost be halved. Since longer trains require more conductors, such a reassignment would not only result in more changes in the rolling stock plan, but also in additional changes in the conductors' duties.

To summarize, a much better service to the passengers can be provided during disruptions, but this results in even more complex rescheduling problems than the current ones. Since it is currently already extremely difficult for dispatchers to reschedule the rolling stock and crew duties in case of a severe disruption, algorithmic support is obviously necessary if NS wants to focus on passenger oriented disruption management.

7 Conclusions and further research

In this paper we argued that the application of algorithmic support will be crucial in increasing the service level of the railway system for the passengers, which is required to increase its market share in the mobility market.

First, it will help to determine appropriate measures for adapting the timetable. Moreover, it will help to provide an appropriate capacity per train during and after the disruption, and to rebalance the rolling stock by the end of the day. Second, it will help to reduce the number of canceled trains due to missing crew. This is currently one of the bottle-necks in the disruption management process. The advantages of the application of algorithmic support for this purpose was clearly demonstrated by the Vleuten case described in Section 5.3. Further research into the direction of passenger oriented disruption management will increase the flexibility of the railway system, so that it will be able to adapt itself to the modified situation in case of a disruption.

Next, the application of algorithmic support will also help to increase the efficiency of the railway system. In particular, currently several buffers (e.g. in the form of relatively large numbers of stand-by crew members) are present in the system as a safeguard for disruptions. However, part of these buffers will become redundant at the moment that effective algorithmic support is applied, thereby increasing the system's efficiency.

Algorithmic support for rescheduling rolling stock and crews are currently being developed within NS. The status quo is that the available models and algorithms provide promising results in a laboratory environment: in relatively short computation times appropriate solutions can be generated for the rolling stock circulation and the crew duties. These results were discussed with and approved by the dispatchers in practice.

A further scientific challenge is to solve these resource rescheduling problems in a dynamic and uncertain environment, where the status quo of the system may be changing during the computation time of the algorithms. This also requires an appropriate model for forecasting the status of the system during the computation time. Another challenge is to solve the resource rescheduling problems in an integrated way. For example, preferably the rescheduling problems for the rolling stock and the drivers are solved together. Otherwise one may end up with a solution where one trip must be canceled due to missing rolling stock, and another trip must be canceled due to a missing driver. This solution is obviously infeasible in practice. Also the extension of the models towards passenger oriented disruption management requires a lot of further research. A final challenge is to test the algorithmic support methods also in a real-life environment. This is not only a challenge from an algorithmic point of view, but also from an information systems point of view.

The potential benefits of algorithmic support in the disruption management process are currently recognized by the board of NS through the successes of the application of such tools in the off-line planning processes. In 2008 the latter lead to winning the INFORMS Edelman Award for the application of algorithmic support for the development of the 2007 timetable of NS, see Kroon et al. (2009). Now there is a certain eagerness to apply such tools in the disruption management process as well. As a consequence, this is the right time for research in this area, and for getting the results implemented in practice.

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