Algorithmic Support for Disruption Management at Netherlands Railways

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Abstract

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. Faster response times and better solutions can be expected by the application of algorithmic support in the disruption management process. That is, the modified timetable, rolling stock circulation, and crew duties are generated automatically based on appropriate mathematical models and algorithms for solving these models. In this paper, we present such models and algorithms that were developed at Erasmus University Rotterdam and are being implemented at Netherlands Railways. Finally, we discuss challenges for research and implementation in practice.

1. Introduction

Netherlands Railways (or shortly NS: Nederlandse Spoorwegen) is the main operator of passenger trains in the Netherlands. During the last two decades NS has implemented several Operations Research (OR) models to support its planning processes. For example, the completely new timetable introduced in December 2006 was constructed to a large extent with advanced algorithmic optimization methods. These methods were developed by NS in cooperation with the scientific community (see Kroon et al., 2009). In addition, OR models and algorithms were developed for scheduling rolling stock and crew (see Abbink et al., 2005; Fioole et al., 2006). As reported by Kroon et al. (2009), the benefits of these methods can be quantified in annual savings and additional revenues of 70 million euro in 2007. In addition, the punctuality of the Dutch railway system has been improved to an all-time high level in 2007, and since then it remained constant at a level between 86.5% and 87% measured on a 3-minute basis.

Nevertheless, NS still faces many challenges, especially during severe disruptions. For instance, the last two winters (2009/2010 and 2010/2011) have shown the vulnerability of the railway system in the Netherlands: both the railway infrastructure and the rolling stock could not cope adequately with the bad weather conditions. This resulted in a nearly complete stand-still of the railway system in several parts of the country, leading to many frustrated passengers as well as to debates in the parliament and in the media. Also during other major disruptions occurring more or less daily and under more normal weather conditions, the performance of the railway system is often insufficient. The criticism does not only focus on the fact that many trains have to be cancelled in such situations, but also on the lack of dependable and consistent travel information for the passengers.

In this paper we focus on the application of algorithmic tools to support the real-time operational re-scheduling processes in case of a major disruption of the railway system. We expect that the application of algorithmic support tools in the Operations Control Centers will help NS to improve its service during disruptions in the future. This expectation is based on our experiences with the application of such tools to support the planning processes of NS, and on the first experiences that were obtained with the application of such tools in disrupted situations.

During the last years, NS and Erasmus University Rotterdam jointly carried out several research projects in the area of disruption management. In the PhD theses of Potthoff (2010) and Nielsen (2011), new models and algorithms have been developed for re-scheduling crew and rolling stock in real-time, respectively. In this paper, we summarize the developed models and methods. In addition, we discuss the results of the first experiments that were carried out at NS, and we provide some insight in the application of these methods in every day practice. We also describe some of the challenges NS has to face in order to make these algorithmic tools fully operational.

The remainder of this paper is set up as follows. In Section 2, we give a description of the disruption management process. Two important aspects are the re-scheduling of rolling stock and crew. Section 3 summarizes solution approaches for re-scheduling rolling stock, and Section 4 for crew. In Section 5, we report the results of the first experiments at NS. Finally, in Section 6, we discuss a number of challenges that must be solved before the algorithmic tools can be fully applied in the real time disruption management processes. We also sketch the potential impact of these developments to the actual railway operations in the Netherlands.

2. Railway disruption management

Figure 1 from Kohl et al. (2007) gives a high level view of the disruption management process. 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. Preferably, there is no need to do something, but if there is a disruption, then the disruption management process should act promptly and unambiguously. In that sense, the disruption management process is comparable with the process that is carried out in a fire brigade. Also in an undisrupted situation, 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 during a disruption, it is necessary to have real-time information on the locations and destinations of the passengers. Modern information technology (smart cards, cell phones, GPS, etc.) allows this kind of information to be more and more available.

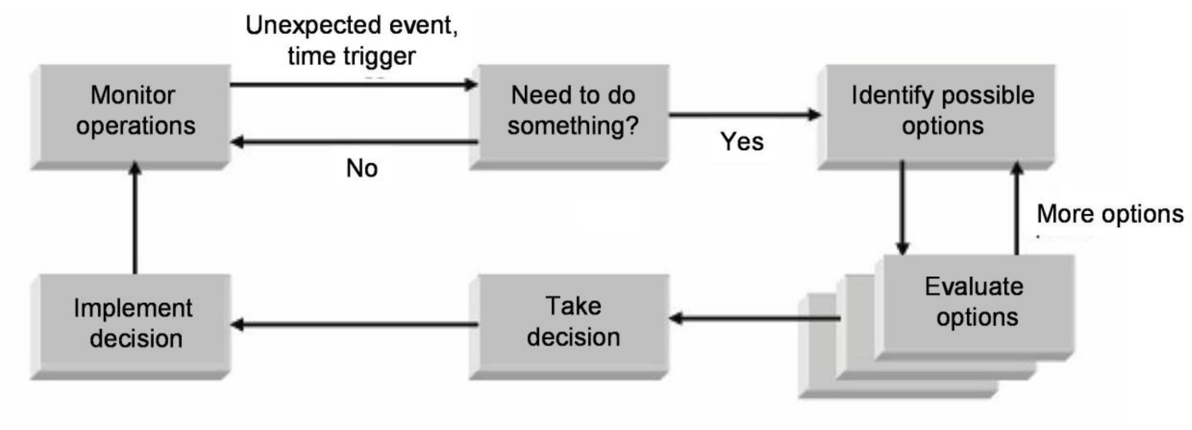

Figure 1: A high level view of the railway disruption management process (Kohl et al., 2007)

A disruption of the railway system is often caused by a blockade of part of the railway infrastructure (see Jespersen-Groth et al., 2009). 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 a malfunctioning safety system or 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. 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.

In case of a disrupted situation, the disruption management process should quickly provide a modified timetable, rolling stock circulation, and crew duties, so that as much as possible of the service for the passengers can still be upheld.

In the Netherlands, the modifications of the timetable are usually based on so-called disruption scenarios. These describe how the regular cyclic timetable is adapted into a new cyclic timetable that fits on the reduced capacity of the railway infrastructure. For example, if the tracks between two regional stations are blocked by a disruption, then the regional trains will return at these regional stations, and the intercity trains will return at the intercity stations nearest to the blocked route. For transporting passengers along the blocked route, buses may be operated temporarily.

Note that these disruption scenarios only describe a *modified steady state cyclic* timetable that can be operated on the reduced railway infrastructure. They do not describe the transition from the regular cyclic timetable to this modified timetable, nor do they describe how to return from the modified timetable back to the regular timetable once the disruption is over.

Especially the first transition is a complex process, where several decisions have to be taken quickly in highly uncertain circumstances. For example, an estimate of the remaining capacity of the railway infrastructure must be made, a disruption scenario must be selected, and decisions with respect to the trains (timetable, rolling stock and crews) in the direct environment of the disrupted area, which will queue up immediately after the start of a disruption, must be made quickly. Taking these decisions requires an enormous amount of experience of the dispatchers, in particular since there is a strong dependency between the timetabling decisions and the decisions for rolling stock and crews. Research for developing algorithmic tools for this kind of decisions has not started yet.

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. As a consequence, rolling stock and crews are not at the locations where they are assumed to be according to their planned duties. Thus re-scheduling the rolling stock circulation and the crew duties is required. This is a highly complex task, where for instance it is not uncommon that hundreds of duties have to be re-scheduled in a couple of minutes. It is clear that a manual dispatcher cannot perform this task in such a short amount of time.

Especially re-scheduling the crew duties is a highly complex task, since the duties have to satisfy certain strict conditions, for example related to the timing of a meal break and to the timing of the return of a crew member at his/her own crew base. Rolling stock is more flexible at this point: first, it is not required that by the end of the day each individual rolling stock units is at the location where it was planned to be: rolling stock units of the same type are basically interchangeable. Here the only requirement is that the total numbers of rolling stock units per location and per type roughly match with the planned numbers, so that the timetable of the next day can be carried out. Moreover, in re-scheduling the rolling stock, one may utilize the fact that the Dutch timetable and the basic structure of the rolling stock circulation are cyclic with a cycle time of one hour.

3. Rolling stock re-scheduling

The timetable of NS is mainly operated by train units. If several trains have been canceled, then the rolling stock circulation must be modified as well. Nielsen et al. (2009) and Nielsen (2011) describes a model that can be used for re-scheduling rolling stock units in a disrupted situation. The model is based on the rolling stock *planning* model of Fioole et al (2006). This model focuses on the situation of NS, where the capacities of the trains may be adapted several times during a day in order to cope with the different levels of passenger demand during peak and off-peak hours. Since the Dutch timetable is cyclic, the only way to accommodate the capacity of the railway system to varying levels of passenger demand is to change the capacities of the trains by coupling or uncoupling train units. Thus the related shunting processes that are required to couple or uncouple train units to trains are taken into account in the model of Fioole et al. (2006), be it at an aggregate level.

Relevant objectives in the rolling stock *planning* process are service to the passengers (in terms of the seating probability), efficiency (in terms of the number of carriage kilometers), and robustness (in terms of the number of shunting movements). Concerning the latter: coupling and uncoupling train units to a train are technical processes with a positive failure probability. Moreover, the related shunting movements increase the already high utilization of the railway infrastructure inside the railway stations. The latter are often the bottle-necks of a railway system. Therefore, too many shunting movements may de-stabilize the railway system, and must be avoided.

The model described by Fioole et al. (2006) and by Nielsen (2011) is a multi-commodity flow model with several extensions. The latter mainly take into account the characteristics of the shunting processes. Nielsen (2011) does *not* focus on efficiency, since in the disruption management process this is not really an issue. In the disruption management process, one should focus on service to the passengers, and it is even *undesirable* to modify the rolling stock circulation for efficiency purposes. Nielsen (2011) focuses both on the situation where the reaction to the passengers to the disruption is given, but he also develops a model in which the reaction of the passengers depends on the rolling stock re-scheduling process. For example, if insufficient capacity has been allocated to a certain train, then some of the passengers for that train will remain at the platform. The latter is then a trigger to allocate more capacity to that train in the next iteration of the algorithm, if available of course.

A relevant aspect that must be taken into account with respect to the rolling stock circulation after the disruption is over is the fact that several rolling stock units are on their way to a maintenance facility. That is, they have a certain *appointment* to appear in the maintenance facility at a certain time (see Maróti and Kroon, 2005; 2007). Due to the disruption, these rolling stock units may miss their appointment, so that a new plan must be created to get them still in time in maintenance. Note that re-scheduling the maintenance routes during the disruption is not useful, since the situation is too uncertain. Only when a new steady state after the disruption has started, it is useful to re-schedule the maintenance routes of these urgent train units.

The foregoing illustrates that, by adequately re-scheduling the rolling stock in a disrupted situation and thereby actively taking into account the modified passenger flows, one can *really make a difference for the passengers*. Since rolling stock re-scheduling is currently a difficult task already, actively taking into account the modified passenger flows will complicate this task even further. Therefore, the availability of algorithmic tools for supporting this process is badly needed. This will be even more true in the near future, when, due to increased efficiency targets of NS, the planned capacities of the trains will be better matching with the forecasted passenger flows than in the current situation. Currently, several trains still have some slack capacity, especially during the off-peak hours. It can be concluded that, the less slack is *planned* in the system, the higher the demand for an excellent operations control system, in particular for an excellent disruption management system.

4. Crew re-scheduling

Due to changes in the timetable and the rolling stock circulation, the crew duties usually become infeasible as well. In the operational crew re-scheduling problem, infeasible crew duties need to be repaired and additional train tasks have to be scheduled. In this optimization problem, the first goal is to minimize the number of tasks that cannot be served by a crew member, and the second goal is to minimize the number of changed duties and the amount of changes in the duties. The reason for the latter is that all changes in the crew duties must be communicated with the crews, which is a time consuming process. As was mentioned earlier, a rule that must be satisfied is that each crew member is back on his/her own crew base within a certain amount of time since the start of his/her duty.

The crew re-scheduling problem in the situation of planned maintenance of the railway infrastructure was studied by Huisman (2007). This algorithm is based on the formulation of the crew re-scheduling problem as a Set Covering model. This Set Covering model required several extensions, for example to deal with the constraints at the crew depot level. The algorithm of Huisman (2007) can also be used for dealing with disruptions that will last for several days or for dealing with a modified timetable on the next day. For those purposes, the algorithm has been implemented into the CREWS system. This system is used by NS in its regular planning process on a daily basis to generate the crew duties of the train drivers and the conductors. However, the computation time of this algorithm usually takes several hours. Thus it cannot be used in real-time on the day of operation.

In Potthoff et al. (2010) a new, innovative algorithm has been developed that can re-schedule up to 100 duties in a couple of minutes. This algorithm does not take into account all crew duties, but heuristically selects only those crew duties that can probably add to the solution of the conflicts in the disrupted crew duties. Furthermore, the algorithm uses advanced column generation techniques combined with a large neighborhood search algorithm. In Veelenturf et al. (2011), this method has been extended to allow for small changes in the timetable. That is, delaying certain trains with a couple of minutes. The thereby obtained increased flexibility allows more tasks to be covered. In this way, the number of trains that need to be cancelled because a driver is missing can be reduced.

The last couple of years, also other algorithms have been developed for solving operational crew re-scheduling problems. Rezanova and Ryan (2010) developed a similar algorithm using column generation techniques to re-schedule crew duties. Experiments with instances at DSB S-train in Copenhagen show that their algorithm provides good solutions in a reasonable amount of time. Abbink et al. (2009) developed an artificial intelligence (AI) method using agent technology and local search algorithms to re-schedule the crew duties. A comparison between the OR based techniques and the AI based techniques showed that for large instances the OR techniques performed significantly better, but for small instances the AI techniques gave sometimes better results.

5. Impact of algorithmic support

In March 2009, the advantages of using algorithmic support for re-scheduling the crew duties of NS in case of a disruption were for the first time clearly demonstrated by the application of an automated crew re-scheduling 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 re-scheduled during nearly 7 days.

In this case, the duties for the train drivers were re-scheduled with the support of algorithmic crew re-scheduling tools, partly by the algorithm developed in Potthoff (2010) and partly by the CREWS system using the algorithm of Huisman (2007). A comparison between the solutions of the automated re-scheduling process for the train driver duties and the solutions of the manual re-scheduling process for the conductor duties revealed the advantages of the automated re-scheduling process: it leads to better solutions in less time.

Similarly, in January 2010, the crew duties for a whole weekend for train drivers and conductors were re-scheduled because of anticipated bad weather conditions. For that purpose, the CREWS system was used again. This system could not yet be used for real-time re-scheduling purposes, but it has proven its value in such cases where the crew schedules have to be updated just before the operations start, in order to comply with modified circumstances.

After the winter problems of 2009/2010, NS decided to purchase the real-time dispatching module of the CREWS system. In addition, the algorithm developed in Potthoff et al. (2010) was implemented in this system. From January 2011, NS experiments with the new software in the Operations Control Center. The goal of the experiments is to fine-tune the parameters and to develop an implementation strategy such that it can be used in production by the end of the year 2011.

Similarly, the tool developed by Nielsen (2011) for supporting the rolling stock re-scheduling process was used in several situations to apply some last-minute changes to the rolling stock circulation. For example, in some cases where the capacity of the rolling stock re-scheduling department was insufficient to re-schedule the rolling stock circulation, the algorithmic tool was used to support the rolling stock re-scheduling process. The conclusions were comparable to the conclusions for the crew re-scheduling tool: it leads to solutions that are at least as good as the manually created ones, but in only a fraction of the required amount of time.

The potential benefits of algorithmic support for dealing with last-minute changes in the plans and with disruptions in real-time are currently recognized by the board of NS. The board's trust in the algorithmic tools increased both by the inability of the manual re-scheduling process to deal with such issues adequately, and by the successes of the application of algorithmic tools in the offline planning processes. As a consequence, there is a certain eagerness to apply such tools in the real-time disruption management process as well, although it is also recognized that there is still a long way to go until a complete implementation will be realized. Some of the challenges are described in the next section. Anyway, this is the right time for carrying out research in the area of railway disruption management, and for getting the results implemented in practice as soon as possible.

6. Further challenges and prospects

6.1 Internally

As was mentioned in the previous section already, the algorithmic tools that are currently available at NS have been used so far for planning purposes and for re-scheduling purposes in the *grey* area between the planning and the real-time operations. Thus a first major challenge to be solved by NS is the full implementation of the algorithmic tools into the real-time operations. This requires at least a continuous and real-time data connection between the information systems that monitor the status quo of the railway system with respect to the timetable, and the rolling stock and crew duties. Any delays of trains and any conflict in a rolling stock duty or a crew duty (either already existing or foreseen in the near future) must be observed, so that adequate actions can be planned and executed at appropriate instants. For conflicts that are foreseen but that are not immediately urgent, it may be better to wait for some time with the implementation of their resolution, since further disturbances may invalidate the initially found solutions otherwise.

It must be noted that implementing the algorithmic support tools into the real-time operational processes is not only a technical process: it also requires implementing different working protocols, both *within* the dispatching organization, and *between* the dispatching organization and the operational railway processes. Within the dispatching organization, the current decentralized dispatching process, which is split over 5 Operations Control Centers centers, must be organized more centrally. This is particularly true for the crew re-scheduling process, since crew duties currently often intersect with the areas of several crew re-scheduling centers. This requires a lot of communication between these centers. The decentralized dispatching process does not fit with the algorithmic approach, which assumes that the crew re-scheduling problem is solved as one centralized problem. In fact, that is exactly one of the advantages of the algorithmic approach.

Furthermore, the working protocols must be modified such that solutions obtained by the algorithmic tools can be communicated quickly and unambiguously to the people and organizations that have to take actions accordingly (for example, train drivers, conductors, shunting crew, etc.). This is in contrast with the current situation, where the manually obtained solutions sometimes have to be negotiated with these people and organizations. This negotiation process is not only time consuming, but there is also the risk that it invalidates the obtained solutions. This risk can be avoided by a priori clearly defining the characteristics of the acceptable solutions and the ones that are not. This will avoid time consuming negotiation processes in time-critical disrupted situations. Obviously, such modifications of the working protocols are managerial and outside the scope of Operations Research.

6.2 Externally

The current disruption management process is strongly focused on the railway system itself, instead of on servicing the passengers. That is, the process is focused on *keeping the trains running* as much as possible, given the reduced capacity due to the disruption. Obviously, the latter is a *conditio sine qua non,* but it is just not enough! The disruption management process currently focuses on isolating the disrupted area, and on keeping the railway system outside the disrupted area as much as possible the same as planned originally.

In particular, the system does not focus on providing additional train services or additional transport capacity along possible detour routes, although, in a disrupted situation, the passengers are usually advised to travel along these detour routes. Note that, especially in the Randstad area (the metropolitan area including large cities like Amsterdam, Utrecht, Rotterdam, and The Hague), the structure and the density of the railway system are such that there are often detour routes in case a certain route is disrupted. However, in the current situation, the passengers are assumed to *reroute themselves*, but they are not actively supported thereby.

Thus the next step in the development of the disruption management process is a *passenger oriented* focus, where the capacity of the railway system is adapted in a flexible way to a local disruption, so that the railway system can accommodate the modified passenger flows adequately. Initially, the capacities of the trains on the detour routes will be adapted to the modified passenger flows on these detour routes. However, in the ideal situation on the longer term, the trains are rerouted themselves along the detour routes, so that the passengers, apart from a somewhat longer travel time, will hardly notice the fact that there is a disruption.

As was mentioned before, this requires an excellent organization of the railway system, both of its planning processes, and of its operational and disruption management processes. The railway system should know its *regular* passenger flows, but it should also know how these passenger flows *react* in case of delays or disruptions. And based on this knowledge, the system must be so flexible that it can adapt itself quickly in order to accommodate the modified passenger flows as well as possible. Since these modifications will make the disruption management process even more complex than it currently is already, algorithmic tools for supporting the disruption management process will be indispensable then.

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