2 Innovation in Railway Planning Processes

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Abstract

On May 13, 2010 it was a shock to hear that Jo van Nunen suddenly passed away when he was visiting the POMS conference in Vancouver. It was a privilege for the authors of this contribution to the Liber Amicorum in memory of Jo van Nunen to have had the opportunity to cooperate so closely with him. During the last years, our main focus was on the development of planning support systems for improving the planning and the real-time operations of Netherlands Railways (NS). Jo especially stimulated the recent shift of the research focus from the planning to the real-time operations.

This contribution describes the innovation that resulted from the introduction of planning support systems within the Logistics Department of Netherlands Railways. This department is responsible for the operational planning of the timetable, the rolling stock circulation and the crew duties of NS. Traditionally, this was a manual planning process relying to a large extent on the experience and craftsmanship of its planners. The introduction of planning support systems lead to more efficiency in the resulting logistic plans and in more efficiency and shorter throughput times in the planning process itself. The paper describes practical issues and lessons learned during the innovation process. The underlying research was carried out in close cooperation of NS and Erasmus University Rotterdam (EUR), in particular with Jo van Nunen.

2.1 Operational railway planning process

The operational plans of a passenger railway operator are related to the timetable, the rolling stock circulation, and the train crews (train drivers and conductors). The related planning process is a continuous process, since the timetable has to be detailed for every calendar day due to maintenance of the railway infrastructure or due to special events attracting additional passengers. These timetable changes usually also influence the rolling stock circulation and the crew duties.

Obviously, also several other aspects have to be planned for operating a passenger railway system. Examples are the long-term capacity of rolling stock and crews. However, these strategic elements fall outside the operational scope of this paper. This paper necessarily describes several aspects only briefly. Further details can be found in Caprara et al. (2007) and in Huisman et al. (2005).

2.1.1 Cyclic timetable

As in several other European countries, the Dutch railway timetable is highly cyclic with a cycle time of one hour. That is, it is very much the same during different hours of the day, even during peak hours and weekends. This is easy to remember for the passengers, but it also has some drawbacks. For example, over the day it is hard to match the provided transport capacity with the passenger demand.

In case of a cyclic timetable, the operational planning process starts with the creation of the Hourly Timetable (HT) and the Hourly Platform Allocations (HPAs) of the trains in the stations. These describe the timetable for a single hour. The HT describes the departure and arrival times of the trains in the stations and at several other locations. The HPAs describe how the trains are allocated to the platforms in the stations, and how they are routed through the stations. Based on the HT and the HPAs only *estimates* of the required rolling stock and crew capacity can be made. Detailed schedules for rolling stock and crews are created only in a later stage, since these schedules are non-cyclic.
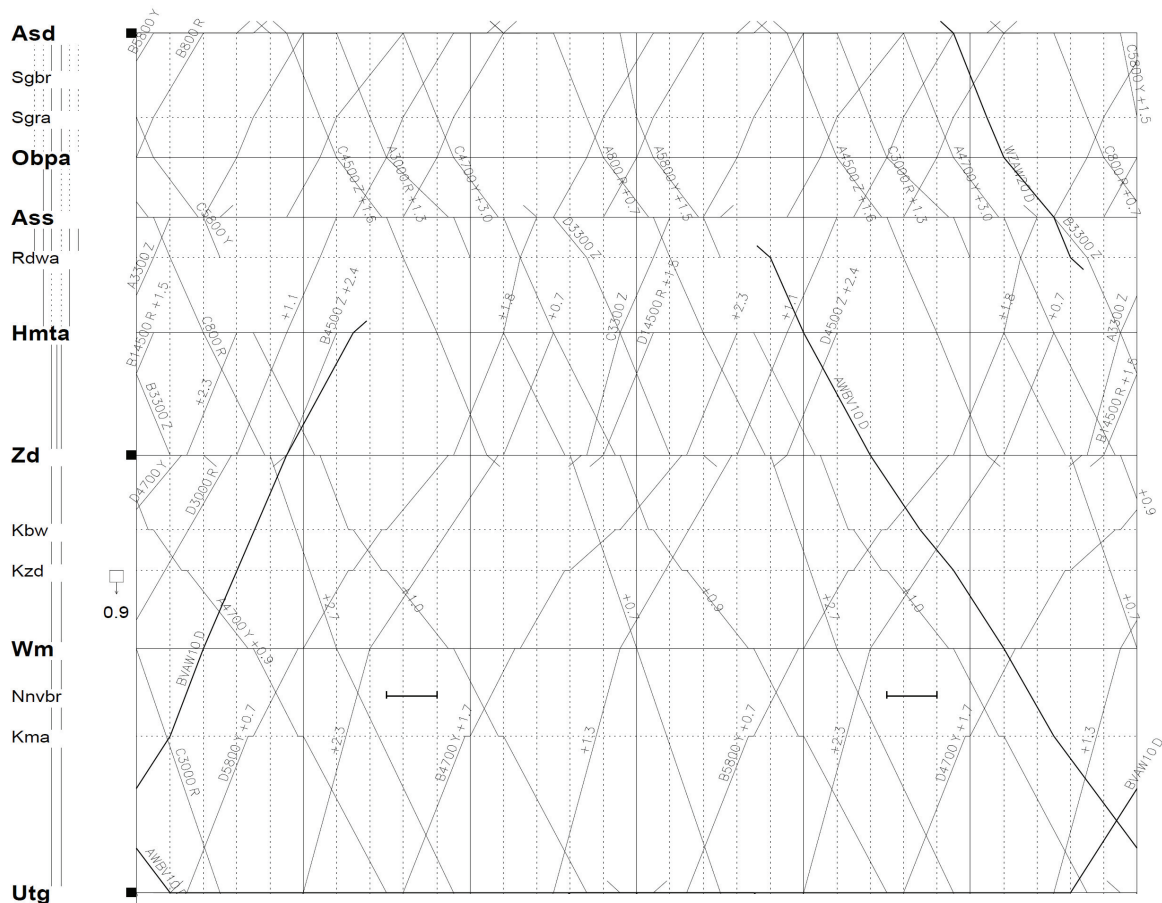
Figure 1: A time-space diagram of the 2009 HT of the line between Amsterdam (Asd) and Uitgeest (Utg). The horizontal axis represents time (one hour), the vertical axis represents space (viaAmsterdam Sloterdijk (Ass), Zaandam (Zd), Wormerveer (Wm) and several smaller locations).

2.1.2 Generic plans

The HT and the HPAs are used to create the plans for a generic week. These are the repeating plans for a general period from Monday to Sunday. The generic plans are usually valid for a period of 1 to 2 months. Therefore, it is worthwhile to spend quite some effort on optimizing these plans.

In this generic planning process, the HT and the HPAs are copied one after another as often as required for obtaining a timetable for a single day. Thereafter, the start and end of each day and the differences between peak and off-peak hours are generated separately. In the generic plans for the timetable also the generic maintenance of the infrastructure is taken into account already.

The rolling stock circulation is planned thereafter in terms of anonymous duties for the rolling stock units. Each task in a rolling stock duty represents a trip on a certain train and a position in that train. The days of the generic week fit after another: all rolling stock that is needed in the morning at a certain location for the start-up of the timetable ends its duty there on the previous evening already. Also the shunting plans are generated in this stage. These describe how the shunting processes inside the stations have to be carried out. Time, space, and shunting crew have to be allocated here.

Finally the crew duties and rosters for the train drivers and conductors on the trains are created. Each duty describes the consecutive tasks to be carried out by a single crew member on a single day. The rosters describe for each crew member the sequence of duties to be carried out on consecutive days. Usually, the rosters are valid over a longer period of time than the generic plans, possibly a year. Indeed, the crew members appreciate it to know already long time ahead on which days they will be working. Both duties and rosters have to satisfy many complex rules.

2.1.3 Plans for calendar days

The next step in the operational planning process is the creation of the plans for the calendar days. Calendar days are different from generic days due to maintenance of the infrastructure or due to special events, such as a soccer match, leading to locally increased numbers of passengers. In the first case, usually several trains are cancelled. In the second case, additional trains may be operated. In both cases this has consequences for the rolling stock circulation, the shunting plans, and the crew duties. These must be updated, but in doing so the original plans must be considered: the adapted plans should not differ too much from the original plans, since these have been checked for feasibility in an earlier stage. For example, the start and end times of the crew duties should not be changed too much, since otherwise the modified duties may not fit in the rosters anymore.

2.1.4 Real-time operations control

After the planning process has been completed, the plans are handed over to the real-time control organization for executing them. On one hand this is the traffic control organization of the infrastructure manager ProRail for dealing with real-time modifications of the timetable. On the other hand this is the operations control organization of NS. There the real-time modifications of the rolling stock circulation and the crew duties are handled. These real-time control organizations permanently monitor the real-time railway processes. If there are neither disturbances nor disruptions, then there is no need for them to act. However, if there are delays or disruptions, then they have to reschedule the timetable, and, if necessary, also the rolling stock circulation and the crew duties.

2.2 Shorter throughput time

The European railway industry is becoming more and more a competitive area. Therefore, there is more focus on service and efficiency nowadays. This requires taking into account the most recent information related to the passengers' demand and the availability of the resources (infrastructure, rolling stock, crews). Thus the plans must be updated more frequently. In order to accomplish this, it is desirable to have a throughput time of the planning process that is as short as possible.

On the other hand, the timetable must be published to the passengers. Moreover, it is the representation of the joint utilization of the scarce railway infrastructure by different train operators. From these points of view, it should be generated sufficiently long before the operations. In contrast, it is basically possible to generate the operational plans for the rolling stock and crews just before the operations. However, in practice the crews prefer to know their duties rather long time in advance. Thus there are certain conflicts in the time horizons of the planning processes for the timetable, the rolling stock and the crews.

Traditionally these conflicts were tackled by generating all plans long time in advance, leading to a lot of rescheduling between the initial conception of the plans and their execution, and leading to lost opportunities by not adapting the schedules to the most recent demand information. The early start of the generation of the plans was also caused by the fact that the planning process of NS used to be a manual process relying heavily on the experience and the craftsmanship of the involved planners. This necessarily leads to long throughput times of the planning process.

It can be concluded that operational planning support tools are needed for reducing the throughput time of the operational planning processes, in particular for scheduling and rescheduling the resources rolling stock and crews. In addition, capacity planning tools are needed for carrying out capacity checks on the availability of the required resources longer time in advance.

2.3 Planning support

Van Wezel et al. (2006) distinguish four levels of support provided by planning support systems. In increasing order of the provided support, these four levels are the following:

1. Editing and storing plans. The system can be used to store plans and to distribute them further into the process chain. The system may also provide (graphical) editing functions for modifying the plan. However, no intelligent support is provided at all.
2. Checking plans. The system checks whether certain constraints are satisfied by the plans. For example, the system may check whether the length of each train fits along the platforms.
3. Evaluating plans. The system can evaluate the plans along several dimensions. For example, the system may count the number of carriage kilometres, or the number of seat shortage kilometres in a rolling stock circulation. This allows making a well-founded trade-off.
4. Generating plans. In addition to the previous functions, the system is able to generate (parts of) plans automatically, thereby taking into account that no conflicts are generated, and in such a way that the results are (nearly) optimal according to the applied evaluation function.

The traditional planning support system used by NS (VPT, short for "Vervoer Per Trein" or "Transport By Train") consists of several database systems that are used for editing and storing plans. Thus VPT is of the first type in the above classification. In addition, a few functions are available for checking the plans. For example, the rolling stock balances by the end of the day can be checked.

VPT is currently still in operation, but a large project is being carried out to replace it by a modern planning support system, called Donna. The final version of Donna will be of the fourth category. That is, the system contains functions for generating (parts of) plans automatically. A lot of the research that was carried out over the last years aimed at providing the required generation functions for Donna. In addition to the generation functions, Donna will also contain extensive functions for graphically editing plans and for checking and editing plans. Another important feature of Donna is that the central planning (related to the movements of the trains *between* the stations) and the local planning (related to the movements of the trains *inside* the stations) are integrated.

2.4 Mathematical models

The kernel of the generation function of a planning support system consists of a mathematical optimization model and of solution techniques to generate (parts of) solutions automatically. The latter may be mathematical optimization techniques, but also other methods may be used. For an example of the latter, see Mobach et al. (2009), who use agent-based techniques to reconstruct the duties of train drivers that have been disrupted in the operations due to a number of train cancelations.

2.4.1 Cyclic timetable

Generating a cyclic timetable consists of two components, namely (*i*) generating the departure and arrival times of the trains in the stations, and (*ii*) routing the trains through the stations.

The problem of generating a cyclic timetable can be modelled as a Periodic Event Scheduling Problem (PESP). The PESP model was first introduced by Serafini and Ukovich (1989). It models one period of the timetable of length T in such a way that this period can be repeated as often as desired. The timetable is considered as a set of processes that have to be carried out. For example, a train must run from one station to another, dwell in the second station, and then run to a third station. These are three processes. Also passenger connections and headways can be seen as processes. For the duration of each process a lower bound L_p and an upper bound U_p are given. The timetabling problem is then to find for each process the start time S_p and the end time E_p. Or, similarly, to determine for each process the exact duration. All constraints are related to the start and end times, or to the process times. The constraint for process p has the following form:

$$L_p \leq E_p - S_p + Q_p \times T \leq U_p$$

Here the additional term $Q_p \times T$ involving the binary decision variable Q_p is introduced to model the cyclicity of the timetable. That is, $Q_p = 1$ if and only if process p ends in a next cycle than it started. The objective function may aim at minimizing the travel times of the passengers, or at maximizing the robustness of the timetable. Peeters (2003) and Liebchen (2006) also describe the stronger cycle-base

formulation of PESP. Kroon et al. (2008) describe a stochastic optimization extension of PESP for improving the robustness of a cyclic timetable by optimally allocating the time supplements in the timetable. The PESP model was used to generate the 2007 timetable of NS, see Kroon et al. (2009).

The problem of routing the trains through a station can be described by a set packing model with several additional constraints, see Zwaneveld et al. (2001). That is, for each train that passes a certain station, all feasible routes for that train are generated a priori. Each route has a certain preference. Next, for each pair of routes it is determined whether they are conflicting. Then the set packing model selects for each train a feasible route such that no pair of selected routes is conflicting, and such that the total cost of the selected routes is minimal. One may also aim at maximizing the robustness of the routing. Another model for solving the routing problem is presented by Caimi (2009). This approach starts with the railway infrastructure, resulting in a stronger Linear Programming relaxation.

2.4.2 Rolling stock circulation

The problem of generating a rolling stock circulation can be described by a multi-commodity flow model with several additional constraints. These additional constraints mainly have to guarantee that the obtained solutions are feasible with respect to the shunting processes in the stations. In particular, in most stations it is prescribed what kinds of shunting movements can be carried out to modify the composition of a train. For example, it may be specified that in a certain station train units may be uncoupled from a through going train, but only from the rear side of the train.

Constraints of this type can be handled by using a so-called transition graph. Such a graph describes the possible compositions of a train on a each trip, given the composition of the train on the previous trip. In this way, the problem is translated into the problem of finding a minimum cost, multi-commodity flow and at the same time for each train a feasible path in the associated transition graph. The objective function consists of elements related to efficiency (carriage kilometres), service for the passengers (seat shortage kilometres), and robustness (number of shunting movements). A description of the basic version of this model is given by Fioole et al. (2006).

2.4.3 Crew scheduling

The problem of generating the crew duties can be described by a set covering model with several additional constraints, see Abbink et al. (2005). A set covering model assumes the a priori existence of a large set of feasible crew duties. The optimization problem is then to select from this set of feasible duties an optimal subset in such a way that each trip is indeed covered by at least one of the selected duties and that the total cost of the selected duties is minimal. The feasible duties all satisfy the constraints at the duty level. Usually, also additional constraints at the depot level must be satisfied, for example dealing with the average duty time per depot or the number of duties per depot.

Since usually the number of potential duties is too large to be generated a priori, a technique that is often used for solving this kind of problems is dynamic column generation. That is, prospective feasible duties are generated on-the-fly during the execution of the algorithm. The generation process of the duties is modeled as a resource constrained shortest path problem. The algorithm iterates between a generation stage in which new prospective duties are generated and a selection stage, in which complete feasible solutions are generated based on the currently available set of prospective duties. A set covering model may generate the crew duties from scratch, but it may also generate the crew duties such that they deviate minimally from the original crew duties, see Huisman (2007).

2.5 Practical implications

The introduction of planning support systems has had significant implications for the planning processes within NS, and for its planning products. The following consequences can be mentioned:

1. The application of planning support systems lead to significant increases in the operational efficiency. Within NS it resulted in about 6% and 4% efficiency improvement in the rolling stock circulations and the crew duties, respectively, see Kroon (2009). Note that it is not easy

to determine such figures, since the circumstances may change over time. For example, the rules to be satisfied by the crew duties may change. However, by applying a planning support system to *old* instances under the *old* conditions, and by comparing the obtained results with the manually obtained solutions for these old instances, such figures can be determined.

2. By the application of planning support systems, one may easily determine a number of plans instead of just a single one. For example, one may determine the most efficient plan satisfying all service requirements, or one may determine the plan that provides maximum service within a certain budget. Such analyses provide insight into the cost of service. Then it is a managerial problem of selecting the most appropriate plan. Based on extensive a priori analyses, management can make better-founded decisions. This is in contrast with the manual way of planning: there one usually just does not have the time to generate multiple plans.

In this context, it can be mentioned that NS was the winner of the 2008 INFORMS Edelman Award for the application of its planning support systems to support the generation of its 2007 timetable, see Kroon (2009). This 2007 timetable was constructed completely from scratch, in contrast with earlier years, when the next timetable was always generated by modifying the previous timetable.

Next, the following consequences can be mentioned for the operational planning processes of NS:

1. A significant reduction in the throughput time of the planning processes has been obtained. In particular, planning a rolling stock circulation or a set of crew duties for the drivers or conductors can be accomplished in a couple of days now, whereas in the past at least several weeks were required.

2. An important issue is that all processes within a certain planning chain should be synchronized, so that in all parts of the chain the same speed-up is facilitated. This is still a bottle-neck within the rolling stock planning chain, in particular related to the planning of the local shunting processes at the railway stations.

3. Also a significant increase in the efficiency of the planning processes can be observed. For example, the number of planners needed for planning the crew duties was reduced by more than 60% since the introduction of the planning support systems. This reduction in the planning capacity was achieved over a period of several years without redundancies. The reduction followed the application of the planning support systems: the shorter throughput time allowed carrying out the planning process with a smaller number of planners.

2.6 Lessons learned

Currently, there is quite some interest within NS for the application of the (prototypes) of the planning support systems that were developed during the last years. This interest is caused by the following two developments, which can be characterized as *bottom-up* and *top-down*:

1. Bottom-up: The results of the planning support systems have been recognized by the planners as correct and reliable. They trust that the planning support systems provide solutions that are at least as good as the ones that they would have generated themselves. Once their enthusiasm had been raised, they started asking for the application of the systems themselves.

2. Top-down: Due to the need for a higher efficiency and passenger service in public transport, there is a request for more efficient plans and for more flexibility, agility, and shorter throughput times in the planning processes. As a consequence, also the management feels an urgency to replace the manual planning processes by tool-supported processes.

In order to stimulate the bottom-up trust of the planners, they were involved in the development of the planning support systems. During the development of these systems for NS, several experiments have been carried out together with the planners, in order to make them aware of the possibilities and the limitations of the planning support systems under construction. In addition, the planners themselves

may feel a certain urgency for the introduction of planning support systems. For example, only after the rules to be satisfied by the crew duties of NS had become so complicated that it was quite hard for the planners to generate the crew duties manually, automated planning support was welcomed.

Furthermore, the involvement of management is crucial. Management should recognize the advantages of the introduction of planning support systems, and should stimulate their development and introduction in the operational planning processes. It is helpful if management also feels a certain *urgency* for the introduction of planning support tools. For example, only after the capacity of some subdepartments of NS had become insufficient to continue its manual planning process, their management started to ask for automated planning support. Similarly, the large logistic railway problems in December 2009 due to bad weather conditions accelerated the development of automated planning support systems for the real-time crew rescheduling process significantly.

Another element that turns out to be crucial every now and then is the availability of a user-friendly interface to the planning support systems. For example, the system for supporting the crew scheduling process is the planning support system that is most widely used within NS. This is mainly due to the fact that it is a complete planning support system including all levels of support mentioned in Section 2.3, see Van Wezel et al. (2006). This system can be operated by the planners themselves. The fact that a user-friendly interface is still lacking for the rolling stock planning tool seems to be one of the main reasons that this tool is not yet as widely accepted. Therefore, currently such a user-interface is being developed, both for being used temporarily and as part of the earlier mentioned Donna system.

2.7 Further challenges

Currently, the majority of the models that were described in this paper is available in prototype form, and is used on a regular basis to support the operational planning processes of NS. At this moment also experiments are being carried out with the application of planning support systems for disruption management in the real-time operations. In case of a disruption, the timetable, the rolling stock circulation and the crew duties may become infeasible, for example by a temporary blockage of the railway infrastructure. In that case, they must be recovered by rescheduling as soon as possible. Especially quickly rescheduling the crew duties is quite a challenge, see Potthoff et al. (2008). Disruption management is a research area that is still rather unexplored due to its sheer complexity. Nevertheless, planning support systems are starting to be implemented in the real-time operations. In particular a planning support system for real-time crew rescheduling is being implemented by Netherlands Railways currently, since crew rescheduling is a main bottleneck in a disrupted situation.

A scientific challenge that needs to be solved for the application of planning support systems for disruption management is the development of sufficiently powerful algorithms for *quickly* solving these problems. 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 nearly instantaneously is rather useless. Also adequately dealing with the uncertainty and volatility that are inherent to the disruption management process is still a scientific challenge. For example, there is usually a high uncertainty about delays of trains and about the duration of a disruption.

A practical challenge when implementing a real-time planning support system is the development of an on-line information link between the real-world railway system and the planning support system. That is, the planning support system must be provided permanently with the most recent information on the status quo of the railway system (locations and delays of trains, locations of rolling stock and crews, etc.). Conversely, the solutions that have been computed by the real-time planning support system must be communicated to the real-world in an unambiguous way, so that they can be applied there. The existence of such an adequate information link is a *conditio sine qua non* for the real-time planning support system to be effective in practice. For a real-time environment, the development of such a link is much more a challenge than in a planning environment, which is less time-critical.

A final challenge in a disrupted situation is to focus on the passengers rather than on the railway system itself, possibly leading to an overall improvement in the service for the passengers. For

example, in a disrupted situation on a certain route, the current strategy is to keep the timetable and the rolling stock capacities on the other parts of the railway network as much as possible as planned originally. However, for the passengers it would be better if the capacities on the detour routes were increased. Based on the currently available high-tech data from smart cards and cell phones, passenger behaviour can be studied and taken into account nowadays much better than before.

2.8 Acknowledgements

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