Adjusting the Rolling Stock Allocation in Case of Disruptions

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Re-allocating the rolling stock on Wednesday 25th March 2009

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Abstract

A passenger railway operator has to deal with disruptions. In order to minimize the nuisance for the passengers, the crew and rolling stock schedules have to be adjusted as fast and efficient as possible. This thesis deals with the adjustment of the rolling stock schedule in case of disruptions. The first two steps of the disruption planning process are discussed; estimating the number of passengers for each train in the new timetable, and re-allocating the available units of rolling stock over the different train series. To perform the second step a mixed integer programming model is formulated that minimizes the number of seat-shortage kilometers and the differences of the new rolling stock allocation compared to the standard rolling stock allocation. This model is tested on the data of Wednesday 25th March 2009. Resulting from a derailment of a freight train on Monday 23th March, the tracks between Utrecht and Woerden were blocked for one week. Consequently, the trains on Wednesday 25th March could not be operated according to the standard timetable. Using the re-allocation model results in a decline in seat-shortage kilometers on this day.

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1. Introduction

1.1. Problem Introduction

The Dutch railway operator Netherlands Railways (Nederlandse Spoorwegen, NS) transports more than one million passengers every working day. Providing a high level of service to its passengers is of highest importance for NS. To reach this, high punctuality of trains and an adequate rolling stock capacity is needed.

Abbink et al. (2004) describes the problem of finding the most effective allocation of the train types, subtypes, and units of rolling stock to the train series so that as many passengers as possible can be transported with a seat, especially during rush hours. Given this allocation, the most efficient schedule for a set of units of rolling stock has to be determined.

A passenger railway operator faces situations in which the train traffic is disrupted by some unforeseen events. As a consequence of disruptions some tracks can be blocked for a certain period, so that no or less intensive traffic is possible on these tracks. Consequently, the timetable as well as the rolling stock and crew schedules have to be adjusted. In the paper of Jespersen-Groth et al. (2007) railway disruption management is defined as the process of finding a new timetable by rerouting, delaying or cancelling trains and rescheduling the resources such that the new timetable is compatible with the resources schedules. Three sequential steps have to be made. First, a new timetable has to be proposed based on the expected duration of the disruption. Second, the rolling stock has to be rescheduled. The third and final step is concerned with rescheduling the crew. In the past years NS has developed an algorithm to adapt the crew schedule automatically. As described in Huisman and Potthoff (2009) this makes it possible to anticipate faster to disruptions than before and to minimize the level of nuisance for the passengers. Reactions can be more efficient by developing an algorithm or model to appropriately adapt the rolling stock circulation.

This thesis focuses on the problems that are faced by a passenger railway operator when the rolling stock has to be re-scheduled due to disruptions. For this purpose a mixed integer programming model is formulated to re-allocate the rolling stock to all trains that run parallel at the busiest moment of the day.

1.2. Motivation

The motivation for the subject of this thesis is the derailment of a freight train on Monday 23th March 2009 at station Vleuten. As a consequence of the recovery work that had to be done, the tracks between Woerden and Utrecht were blocked for one week. Since these tracks belong to the most intensively used tracks of the Netherlands (usually 14 trains run every hour in each direction), ten thousands of passengers per day were affected by the derailment.

Due to the disruption, for one week it was only possible to operate the 2000 line between Woerden and Utrecht, which means that two trains travelled directly from Utrecht to The Hague each hour and two trains travelled from The Hague to Utrecht via Breukelen each hour. It has to be noted that the travel time of the trains from The Hague to Utrecht was about thirty minutes longer due to the detour these trains had to make. All other trains travelling between Utrecht and Woerden could not be operated. So most passengers had to be redirected. In this thesis, the focus will be on Wednesday 25th March 2009.

Though this thesis explicitly deals with the derailment in week 13 of 2009, this situation is not an exception. The Dutch railway network experiences on average three large disruptions per day, according to Pothoff et al. (2008). Because NS has hardly any influence on factors causing the disruptions, it is very important that their consequences are limited.

1.3. General Overview

The remainder of this thesis is organized as follows. The next chapter provides some background information on the rolling stock allocation problem. Chapter 3 describes the allocation problem more thoroughly. A literature overview is given in chapter 4. The process of estimating the number of passengers for each train in the new timetable is described in chapter 5. Chapter 6 provides the formulation of the re-allocation model, as well as the underlying assumptions and the notation. Chapter 7 presents the computational results. This thesis is finished in chapter 8 with conclusions and a subject for further research.

2. Background Information

This chapter provides some background information concerning the rolling stock problem of NS. Among others, it provides some information about the different train categories and rolling stock units used by NS.

2.1. Line System

NS uses two different train categories for passenger transport; regional trains stop at all intermediate stations along the route and intercity trains stop only at the main stations of the Dutch railway network. Therefore, intercity trains are the most suitable for passengers travelling long distances. Each train series, which connects an origin station to a destination station with a certain frequency and a certain stopping pattern, belongs to one of the two train categories. The line system contains all these train series. Figure 2.1 shows part of the train series in the Western and most congested part of the Netherlands.

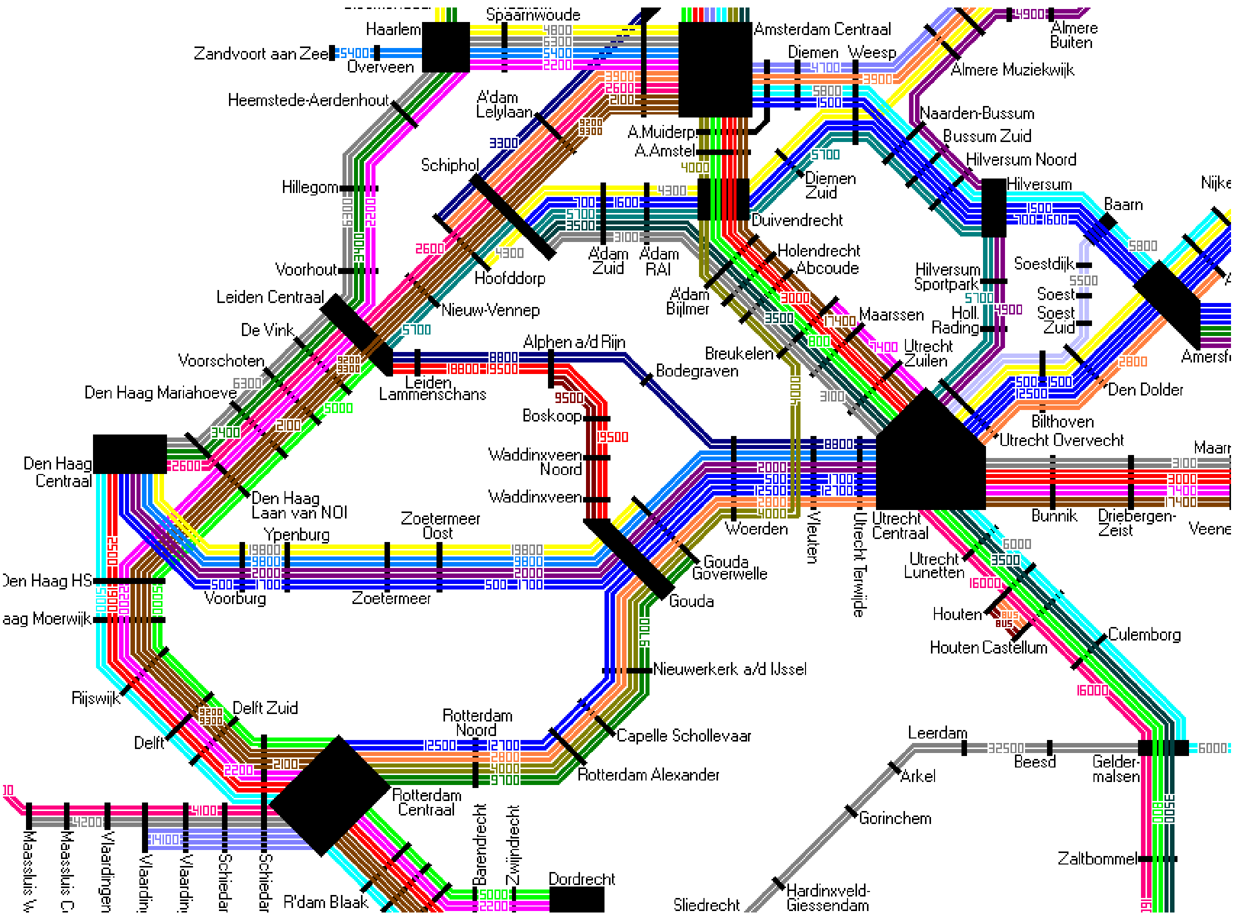

Figure 2.1 Part of the train series of NS in the Western part of the Netherlands.

2.2. Train Types

Different types of rolling stock units are operated by NS. Three main classes can be distinguished; power-driven equipment, diesel-driven equipment, and locomotive-hauled carriages. The latter class consists of units which can only move with a locomotive, while the former two classes contain units which can move individually. Each class includes different train types. The power-driven equipment class is the largest class and contains for instance Koplopers, used for intercity lines, and Mat'64, used for regional trains.

Each type can be distinguished further into a certain number of subtypes. Each subtype has a different length. For instance, Koplopers can be distinguished into two subtypes; Koploper units with three and four carriages. A graphical representation is shown in Figure 2.2.

Figure 2.2 Koploper train units with three and four carriages.

Train units of the same type (but possibly of different subtypes) can be put together to form longer trains. For each train, the upper bound on the number of carriages it can contain, is determined by the technical properties of the units used and by the length of the shortest platform along the route.

For each rolling stock type the first and second class capacity is specified. For the capacity in the second class there are three different standards. The first standard represents the number of seats. This standard is the most stringent and usually used for intercity lines to ensure that all passengers have a comfortable journey. The third standard is less severe and does not require that all passengers have a seat. This standard is used for shorter journeys with regional trains and during peak hours. It specifies the number of seats and the number of passengers who can stand in the train, using the criterion that four passengers can stand per square meter. The second standard is somewhere in between these two standards. Which standard to use is determined by the line under consideration and the time of the day the train travels. In the first class the capacity is calculated according to the first standard, as especially in this class it is important that every passenger has a seat.

NS composed an overview of preferred rolling stock types for each train series. Making this overview the train category of the train series, the technical and running time characteristics of the train types and subtypes, the required capacity per train, and the passengers' preferences were taken into account. For instance, concerning the train category of the train series comfortable rolling stock types are preferred for intercity trains, while types that can accelerate and decelerate quickly are preferred for regional lines. Since NS has only a limited number of rolling stock units of each type, it is not always possible to assign the most preferred type to a train series.

2.3. Passenger Demand

NS wants to provide good service quality to its passengers. This means among others that passengers, and especially first class passengers, need to have a seat during their journey. Therefore, an important goal in rolling stock allocation is to assign to each train series an appropriate amount of the appropriate rolling-stock type. The capacity of each train series should be sufficient to meet the expected number of passengers on these trains. On the other hand, if the capacity of a train exceeds the expected demand too much this results in an inefficient and therefore undesirable situation.

Important factors in this context are the total demand for passenger railway transportation, the number of first and second class passengers, and the difference between demand in peak and off-peak hours. Conductors make estimates for the number of passengers in the first and second class per train. A statistical procedure can translate the conductor estimates into a required capacity for each train. However, it has to be noted that the actual number of passengers is stochastic so that a seat for each passenger can never be guaranteed.

Not only the number of passengers without a seat is important but also the distance these passengers have to travel without a seat. It is reasonable to have a higher penalty on a certain amount of seat-shortages on a longer trip than the same amount of seat-shortages on a shorter trip. Therefore, a frequently used measure in this context is the number of seat-shortage kilometers. In Fioole et al. (2006) this is defined as the expected number of passengers without a seat multiplied by the length of the involved trip, and added up for all trips.

3. Problem Definition

This chapter describes the rolling stock re-allocation problem in detail. The concepts of disruptions and cross-sections are explained, followed by a description of the planning process.

3.1. Disruptions

In general, a disruption can be any variation from the normal or average situation. Jespersen-Groth et al. (2007) provides the following definition of a disruption in relation to railway operations: "An event or series of events that renders the planned schedules for rolling stock, crew, etc. infeasible." Examples of disruptions are infrastructure malfunctions, rolling stock break downs, weather conditions, and accidents. This thesis deals with any disruption with the consequence that no or fewer trains can be operated on some tracks. Disruptions can be caused by the operator or the infrastructure. They frequently result in trains that are delayed, passengers who have to travel via another route and, when passengers can travel via the same route, they face a longer travel time. The additional travel time and the duration of the disruption are the main determinants of the degree of nuisance for the passengers.

3.2. 8 o'clock Cross-Section

A cross-section indicates all trains that run parallel at one particular moment of the day. The first step in the rolling stock planning process is to determine the allocation of the rolling stock to the trains that operate around 8 o'clock in the morning. The required capacity during the morning peak is usually higher than the required capacity during the evening peak, because the evening peak lasts longer and it has a lower demand per unit of time. It is reasonable to assume that if an appropriate allocation of the rolling stock at 8 o'clock can be determined, this allocation will be suitable during the other hours of the day as well.

The number of trains of each train series in the cross-section depends on the frequency with which the trains are operated (one or two times every hour) and the duration of the trip. Notice that the trains in the 8 o'clock cross-section are not always the trains that run exactly at 8 o'clock. It can be that some trains finish just before 8 o'clock or that some trains start just after 8 o'clock. The reason that these trains are part of the cross-section is that the required capacity of these trains is much higher than the required capacity of their successor or predecessor trains respectively. This usually happens with trains running to and from the major cities. In the morning peak a lot of workers and students travel to these cities, while much fewer passengers travel from these cities.

3.3. Planning Process

When the rolling stock allocation is determined for the cross-section trains running at 8 o'clock, the next step is to determine an allocation for all other trains during the day. This allocation is done on a line-by-line basis to reduce the changeover effects of delays from one line to another. Next, the rolling stock circulation model is solved on a line-by-line basis and per day of the week. Some modifications are needed to ensure that the single day rolling stock circulation fit after each other.

3.4. Three Steps in the Disruption Planning Process

As stated before, this thesis deals with the adjustment of the rolling stock schedule in case of disruptions. Three steps are necessary to make this adjustment.

First the number of passengers for each train in the new timetable has to be estimated. As a consequence of the disruption no or fewer trains can be operated on some tracks. This means that all or a significant amount of passengers have to travel via another route. No scientific approach is available to predict along which route the passengers will travel. Therefore the estimates in chapter 5 of this thesis are based on past experiences and the alternative routes NS recommends to its passengers on her website and via the information panels at the railway stations.

In the second step the available units of rolling stock have to be re-allocated over the different train series. A mixed integer programming (MIP) model needs to be formulated to make a new 8 o'clock rolling stock allocation. The aim is again to make an allocation such that as many passengers as possible have a seat along their journey. Another objective is that the differences between the new 8 o'clock rolling stock allocation and the standard 8 o'clock rolling stock allocation have to be minimized. Some of the constraints used in Abbink et al. (2004) are taken into account in the model, for instance the constraints denoting that trains should not be longer than the shortest platform on its route. The major difference with the standard rolling stock allocation model is that the allocation does not start from scratch but that the rolling stock is allocated at a certain station at the moment the re-allocation process starts. For instance, looking at Wednesday 25th March 2009, the stations at which the rolling stock units are located on Tuesday evening 24th March 2009 are used as input in the model. Constraints have to be specified to take this into account.

The third and final step is the determination of a detailed rolling stock circulation plan for each type of train unit. This can be done using the model described in Nielsen (2009). This third step falls beyond the scope of this thesis.

4. Literature Overview

Most publications concerning railway rolling stock deal with the problem of routing and scheduling locomotives and freight trains, some of them deal with the rolling stock problem for passenger trains. A selection of papers of the last category is described below.

As already noted in the introduction of this thesis, Abbink et al. (2004) describes a model to find an optimal allocation of train types and subtypes to the lines. The objective function of the model focuses on minimizing the weighted total number of seat-shortages on the trains. The main constraints are concerned with the specification of a feasible allocation of the rolling stock units to the train series. To test the model they use the mixed integer solver CPLEX. Practical instances of NS can be solved in short time and the obtained solutions show a significant service improvement over the manually planned allocation.

In Fioole et al. (2006) an integer, multicommodity flow model for rolling stock circulation (ROSA) is described. Given the departure and arrival times, as well as the expected number of passengers on each train series, the available rolling stock has to be assigned to the timetable services. The model optimizes different objective criteria related to operational costs, service quality and robustness of the railway system.

Budai et al. (2007) addresses the rolling stock balancing problem (RSBP) that arises when rolling stock has to be re-scheduled due to changing circumstances. As input for the RSBP are given a timetable and a rolling stock schedule, where the adjusted rolling stock allocation does not fit to the allocation before and after the planning period. Correcting these off-balances results in a modified schedule that can be implemented in practice. Because the problem has to be solved quickly for practical usage, they use heuristic approaches.

Nielsen (2009) provides the mathematical formulation for a task based model for simultaneous rolling stock scheduling and rostering. It considers the position of each rolling stock unit in the timetabled trains under a number of constraints of the shunting possibilities at each station, and the minimum and maximum lengths of the compositions.

None of the above mentioned papers deals with the problem of reallocating the rolling stock as a consequence of disruptions. Abbink et al. (2004) is the only paper that deals with the rolling stock allocation problem, however their model seems to be too comprehensive for the re-allocation model. In the framework of this thesis, the paper of Fioole et al. (2006) shows some interesting and useful improvements with respect to the paper of Abbink et al. (2004). They specify beforehand the set of possible compositions for each trip. A binary decision variable indicates which composition of this set is used for the trip. This sounds promising for the re-allocation problem as well, because in this problem the exact order of the train units is of no importance.

5. Estimating Passenger Demand

The first step in the disruption planning process is the estimation of the number of passengers on all trains on Wednesday 25th March 2009. For this purpose, it has to be determined which train series cannot be operated anymore and which train series can be operated with a lower frequency or an adjusted timetable. As no passenger counts are available for this day, estimates have to be made about the percentage of passengers using other means of transport and the percentage of passengers using other lines. This will successively be described in the remainder of this chapter.

5.1. Adjusted Line Series

Due to the disruption at Vleuten on Monday 23th March 2009, most train series could not be operated between Woerden and Utrecht the next six days. In figure 5.1 these train series are denoted by dotted lines. As can be seen, the 2000 line between The Hague and Utrecht was the only direct connection between Gouda and Utrecht. As already noted in chapter 3, the trains on the 2000 line from The Hague to Utrecht had to travel via Breukelen which means a longer travel time. The trains in the other direction did not have to make this detour, but due to the recovery work they had to travel with lower speed.

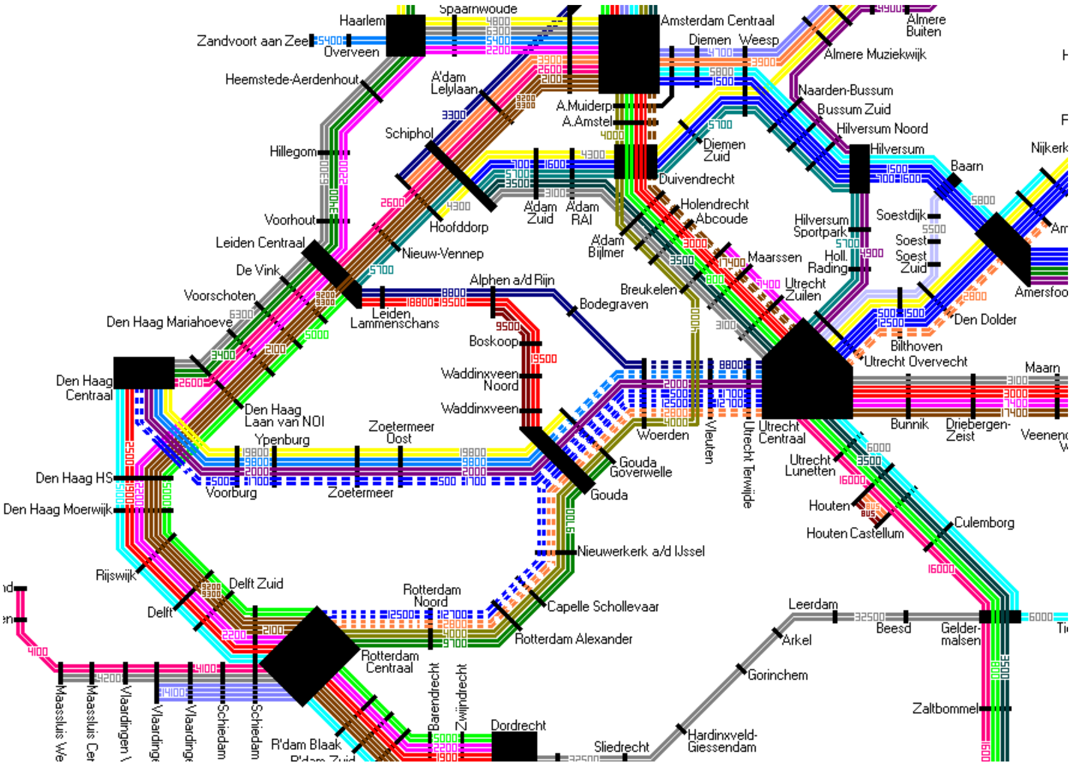

Figure 5.1 Train series in the western part of the Netherlands on Wednesday 25th March 2009.

Passengers travelling to and from the cities Rotterdam and The Hague had the possibility to travel with the regional trains to Gouda and to switch there to the 2000 line in the direction of Utrecht. Because the 2000 line made an additional stop in Woerden, also passengers travelling between Leiden and Utrecht could use this line.

5.2. Passenger Choices

Passengers hindered by the disruption had three different choices. First, since the disruption resulted in significantly longer travel times between The Hague and Utrecht, and Rotterdam and Utrecht, it was probably beneficial for part of the passengers usually travelling along these routes to use another means of transport like car or bus, or to work or study at home. Secondly, a percentage of passengers travelled by train but via another route. For instance passengers travelling between The Hague and Utrecht, and Leiden and Utrecht could travel via Schiphol, and passengers between Dordrecht and Utrecht via Geldermalsen. Finally, a significant amount of passengers used the regional trains to Gouda and Woerden and switched there to the 2000 line.

It is assumed that most passengers did not have the possibility to use another means of transport or to stay at home. This means that more capacity was needed on the trains between The Hague and Gouda and Rotterdam and Gouda and on the trains operated on the 2000 line, but also on the trains between Utrecht and Schiphol, Schiphol and The Hague, Schiphol and Rotterdam, Dordrecht and Geldermalsen, and Geldermalsen and Utrecht.

A few remarks have to be made. First, the trains between Dordrecht and Geldermalsen are not operated by NS, so the capacity of these trains cannot be changed. Besides, the needed capacity on the trains between Geldermalsen and Utrecht is relatively low. Therefore, these lines are not taken into account in the model. Finally, also the capacity of the trains between Amsterdam and Brussels (9200 line) and the Thalys between Amsterdam and Paris (9300 line) cannot be changed as these are international trains and use their own dedicated rolling stock.

5.3. Estimating Passenger Demand

A dataset is available that indicates for each train on each day of the week the number of expected passengers travelling in the first and second class, when the trains are operated under the normal timetable. There are no passenger counts available for past disruptions. Consequently, only rough estimates can be made for passenger demand on Wednesday 25th March 2009. Since the solutions of the model described in the next chapter depend on the passengers estimates, two different scenarios, based on different passenger estimates, will be developed in this thesis. The following two statements are assumed to hold in general, and specifically for both scenarios:

- In case of a disruption most passengers (between 80% and 90%) will still travel by train as another means of transport is not at their disposal. The exact percentage depends on the extent to which passengers are affected by the disruption, the additional travel time these passengers face, the travel time of alternative means of transport, and the duration of the disruption.
- First class passengers are easier inclined to use another means of transport than second class passengers. However, this assumption may be unimportant as on average the number of seats in the first class in relation to the number of seats in the second class is much higher than the number of first class passengers in relation to the number of second class passengers. Thus seat-shortages in the first class will have only a minor contribution to the total number of seat-shortages.

5.3.1. Scenario 1

Passenger estimates in the first scenario are based on the two statements made above and on the following two assumptions:

- About 40% of the passengers usually travelling with intercity trains between Leiden and Utrecht, and The Hague and Utrecht travelled with the intercity trains via Schiphol. Their travel time was somewhat longer but they expected their journey to be more comfortable because they expected these trains to be less congested. For the passengers travelling between Rotterdam and Utrecht this percentage was somewhat lower, about 25%, as their additional travel time was longer.
- Most passengers usually using a regional train from Rotterdam or The Hague to Gouda, and from there an intercity to Utrecht still used the regional trains and changed at Gouda to the 2000 line. The same holds for passengers using these trains in the opposite direction.

5.3.2. Scenario 2

The two general statements are also assumed to hold in the second scenario. Besides it is assumed that 60% of the passengers usually travelling between Leiden and Utrecht and The Hague and Utrecht travelled via Schiphol. Also the percentage of passengers usually travelling between Rotterdam and Utrecht is higher than in the first scenario, as it is around 45% now. Finally, as in the first scenario, most passengers usually using a regional train from Rotterdam or The Hague to Gouda, and from there an intercity to Utrecht still used the regional trains and changed at Gouda to the 2000 line. If they wanted to use the intercity trains via Schiphol these passengers originally had to travel to Rotterdam and The Hague respectively. Since this results in much longer travel times it was a very adverse alternative for them. The same holds for passengers using these trains in the opposite direction.

6. Model Formulation

A mixed integer programming (MIP) model is used to re-allocate the rolling stock units in case of disruptions. MIP is a technique used to optimize an objective function subject to a set of constraints for problems in which some of the decision variables are constrained to have only integer values. The following sections describe successively the assumptions, notation, objective function, and constraints of the model.

6.1. Assumptions

Some assumptions have to be made to model the rolling stock re-allocation problem. First of all, it is assumed that the timetable and the required capacity for each train are known so that the trains relevant for the 8 o'clock rolling stock can be determined.

The second assumption is that for each train series a list of allowed compositions is available, as well as the first and second class capacity of these compositions and the types and subtypes of train units used in the compositions. In the specification of the allowed compositions among others the length of the shortest platform along the route and the combining possibilities of the different subtypes of each train unit type are taken into account. Note that the compositions only provide information about the number of carriages of different subtypes and not about the order of the different carriages, as the order is not important in this model.

Next, a selection has to be made of train series to include in the model. Most important are the lines connected with the track(s) on which the disruption occurred. The lines can have a direct connection, in the sense that these lines cannot be operated anymore or can only be operated with a lower frequency, or an indirect connection, meaning that the passengers affected by the disruption will travel along these lines. Because it is likely that the composition of most train series without a direct or indirect connection with the disrupted trains series will not be altered in the optimal solution, the re-allocation problem will be applied only in the region in which the disruption occurs.

The initial inventory of each station, the number of units per type and subtype that start at the station at the beginning of the planning horizon, is known. The initial inventory is determined by the standard rolling stock allocation, with which the rolling stock allocation in a week without disruptions is meant. Thus it is determined by the places where the rolling stock units are at the moment the disruption occurs. In the model the inventories at the beginning of the day at the stations are used to determine the 8 o'clock rolling stock allocation. It is assumed that the trains running before 8 o'clock have the same composition as the trains of the same lines in the 8 o'clock cross-section. Because of the relatively small number of trains that are operated before the 8 o'clock cross-section trains, it is reasonable to assume that no coupling or uncoupling operations take place before 8 o'clock.

6.2. Notation

In the rolling stock re-allocation model the trains in the 8 o'clock cross-section are denoted by $t = 1, \dots, T$. The consecutive trips of train t are denoted by $g = 1, \dots, G_t$. Compositions $b = 1, \dots, B_t$ describe all allowed compositions for train t. First and second class are denoted by $c = 1, 2$. The stations where trains can start are denoted by $s = 1, \dots, S$. Finally, the different rolling stock subtypes are denoted by $q = 1, \dots, Q$. The following parameters are used in the model:

- $C_{b,c}$ indicates the capacity in class c of composition b.
- $P_{t,g,c}$ indicates the expected number of passengers in class c of consecutive trip g of train t.
- $O_{t,s}$ is (1/0) if train t (does/does not) gets it units from the inventory at station s.
- $N_{q,b}$ indicates how many units of subtype q are in composition b.
- $S_{q,s}$ indicates how many units of subtype q are in the inventory at the beginning of the day at station s.
- $D_{t,b}$ is 0 if composition b is the same as the standard composition of train t, is a_1 if composition b has a different number of units but the type of units is the same, and is a_2 if composition b uses a different type of train units. Here $0 \leq a_1 \leq a_2$, and the values of a_1 and a_2 can be used according the way differences in compositions need to be penalized.
- $L_{t,g}$ indicates the distance that consecutive trip g of train t travels.

Decision variables of the model:

$Y_{t.b}$ a binary decision variable indicating whether composition b is used for train t. Note that $b \in B_t$, with B_t the set of all compositions allowed for train t.

$X_{t,c}$ an integer decision variable denoting the number of seat-shortage kilometers in class c for train t.

6.3. Objective Function

The objective function of the rolling stock re-allocation model has two objectives. The function has the form:

$$\text{Min} \quad w_1 \sum_{t \in T} \sum_{c=1,2} X_{t,c} + \; w_2 \sum_{t \in T} \sum_{b \in B_t} D_{t,b} \, Y_{t,b} \tag{6.1}$$

The first objective is similar to the objective function described in Abbink et al. (2004), although they minimize the number of seat-shortages whereas in this thesis the first objective is to minimize the number of seat-shortage kilometers. The number of seat-shortages in class c of train t is calculated as all passengers in class c of train t that do not have a seat during part of their journey. To obtain the seat-shortage kilometers, this number is multiplied by the length of the trip of train t.

The second objective is to minimize the differences between the new rolling stock allocation and the standard rolling stock allocation. In this thesis, this means that the new allocation is compared with the rolling stock allocation on a Wednesday without disruptions. Using the definition of the parameter $D_{t,b}$ it is possible to have a higher penalty on the allocation of a different train unit type than on the allocation of a different number of units of the same type.

By changing the weights w_1 and w_2, the weights for the seat-shortage kilometers and the differences in composition respectively, the relative importance of the two objectives in the objective function can be changed. By setting either w_1 or w_2 at zero, it is possible to focus on only one of the two objectives.

6.4. Constraints

The constraints of the model can be described as follows:

$$X_{t,c} \geq \sum_{g \in G_t} L_{t,g} (P_{t,g,c} - \sum_{b \in B_t} C_{b,c} Y_{t,b}) \qquad \forall\, t \in T, c = 1,2 \tag{6.2}$$

$$X_{t,c} \geq 0 \qquad \forall\, t \in T, c = 1,2 \tag{6.3}$$

$$\sum_{b \in B_t} Y_{t,b} = 1 \qquad \forall\, t \in T \tag{6.4}$$

$$\sum_{t \in T} \sum_{b \in B_t} O_{t,s}\, N_{q,b} Y_{t,b} \leq S_{q,s} \qquad \forall\, q \in Q, s \in S \tag{6.5}$$

Constraints (6.2) describe that the seat-shortage kilometers in class c on a specific train are not less than the expected number of passengers in class c on that train minus the capacity in class c in the composition used for train t (the part in brackets), multiplied by the number of kilometers on that train. Because seat-shortages usually do not occur on the whole length of the route of a train, each train is split into a number of consecutive trips to get a good representation. These consecutive trips are denoted by g. Constraints (6.3) are necessary to require that the number of seat-shortage kilometers cannot be negative. In an optimal solution at least one of the constraints (6.2) and (6.3) is satisfied with equality for each $X_{t,c}$ given that the total number of seat-shortage kilometers has to be minimized.

Constraints (6.4) specify that exactly one allowed composition of train units has to be used for cross-section train t. Constraints (6.5) guarantee that the total units of subtype q used by all trains getting their units from the inventory at station s respect the inventory at station s.

6.5. Alternative Representation

Abbink et al. (2004) describes an alternative way of representing the first objective in the objective function. Instead of using the absolute number of seat-shortages, the seat-shortages as a percentage of the required capacity can be used by dividing the right side of constraints

(2) by $P_{t,g,c}$. In linear optimization models this relative seat-shortages can be handled more easily. However, a disadvantage is that a certain percentage of seat-shortages on a busy train is as bad as the same percentage of seat-shortages on a quiet train. In the next chapter both representations will be used to evaluate feasible solutions of the rolling stock re-allocation model.

7. Computational Results

The model as described in the previous chapter is implemented in AIMMS 3.8 and solved using CPLEX 10.1. The hardware applied was an Intel Pentium D CPU with 3.00GHz and 1.99GB RAM. The model is applied to the data of Wednesday 25th March 2009. We reallocate the rolling stock over 12 train series, with a total of 49 cross-section trains. This results in a model with 332 constraints and 1,361 variables (1,262 integer variables). The computation time of the model is less than one second. This chapter describes the assumptions made by the implementation of the model and analyzes the solutions of the model for both scenarios, as described in section 5.3.

7.1. Implementation

We made the following assumptions when implementing the model:

- Different subtypes of the same rolling stock type can be combined in any possible way to form compositions. Besides, there is a maximum number of twelve carriages in each composition, regardless of the train type used in the composition and the line on which the composition is used. Combining these two assumptions means that the set of possible compositions contains all possible combinations of rolling stock units of the same type with a total of twelve carriages or less.
- Originally, five different rolling stock types are operated on the lines under consideration, each type having two subtypes. Two of the rolling stock types are used for intercity trains, the remaining three types are used for regional trains. This division will be the same, in the sense that compositions containing these types will only be allowed on intercity and regional trains, respectively.
- Since all trains in the model are operated during peak hours, the third standard is used to determine the second class capacity of each composition (recall section 2.2).
- New compositions that use a different type of train unit compared to the standard composition have a penalty that is twice the value of a penalty related to a new composition that uses the same rolling stock type (possibly a different subtype) but has a different number of units. Thus in the specification of $D_{t,b}$ as described in section 6.2 it holds that $a_2 = 2a_1$.

7.2. Scenario 1

7.2.1. Standard Rolling Stock Allocation

To analyze the rolling stock re-allocation model the allocations computed by this model have to be compared with the standard rolling stock allocation. Table 7.1 shows some of the characteristics of this standard allocation. The first three columns show the number of trains with seat-shortages in the first class, in the second class, and the total number of trains with seat-shortages, respectively. The next three columns show the total number of seat-shortages in the first class, in the second class, and in total, respectively. The final column denotes the number of seat-shortage kilometers. The number of seat-shortages is large because more passengers are expected on these trains but the capacity allocated to the trains is the same as on a normal Wednesday. There are about twelve times more seat-shortages in the second class as in the first class.

Table 7.2 provides information about the utilization of the capacity in the standard rolling stock allocation. The utilization of a train is calculated as the ratio of the required and the allocated capacity. Because trains can be split up into a number of consecutive trips, this utilization is a weighted average of the utilizations of the different consecutive trips. As weights we use the length of the consecutive trips, divided by the total distance travelled by the train they belong to. Table 7.2 shows the minimum, mean, and maximum utilization in the first and second class, respectively. For the second class a distinction is made between seat-shortages, calculated using the first capacity standard, and shortages, calculated using the third capacity standard. This last standard is based on the statement that it is acceptable if there are four passengers per square meter. In reality however, though undesirable, a situation is possible in which more passengers can stand per square meter. In this thesis, we assume that an utilization of at most two is sufficient to transport all passengers. Without adjusting the standard rolling stock allocation, this cannot be reached for all trains.

# 1st class	# 2nd class	Total	1st class	2nd class	Total	SKM
28	22	32	2,417	28,229	30,646	9,897,510

Table 7.1 Seat-shortages, standard rolling stock allocation

	Minimum Utilization	Mean Utilization	Maximum Utilization
1st class seat-shortages	0.617	1.221	2.540
2nd class seat-shortages	0.748	1.775	3.363
2nd class shortages	0.355	1.065	2.246

Table 7.2 Utilization, standard rolling stock allocation.

7.2.2. Minimizing Seat-Shortage Kilometers

To focus on minimizing the number of seat-shortage kilometers, a relatively small positive value has to be assigned to the weight w_2 in the objective function. Assigning the value zero to this weight, it would not be possible to interpret the solutions in terms of differences in compositions.

As described in section 6.5, the absolute and relative number of seat-shortages can be used in constraints (2) in the model. The results obtained with these two objectives are shown in tables 7.3 and 7.4. Both representations give similar results. From table 7.3 it can be concluded that their solutions are almost identical in terms of seat-shortages and seat-shortage kilometers. Compared to the standard allocation, there is a decline of about 13 percent in both the number of seat-shortages and the seat-shortage kilometers.

Also calculations of the utilization in the first class give similar results for both representations. For the utilization in the second class calculations of the minimum and mean give comparable results, however the maximum utilization is higher when the absolute shortages are used. This can be explained by the fact that when focusing on the relative shortages the model has a stronger incentive to distribute the shortages as percentage of the total number of passengers expected on a train, equally over the different trains. Compared to the standard allocation, the utilization rates have all declined.

It can be seen that the alternative objective performs better in minimizing the maximum utilization but performs worse in minimizing seat-shortages. In the remainder of this chapter the focus will be on the absolute number of seat-shortages.

	# 1st class	# 2nd class	Total	1st class	2nd class	Total	SKM
Absolute	21	17	26	1,735	24,947	26,682	8,628,480
Relative	21	18	26	1,793	25,146	26,939	8,639,210

Table 7.3 Seat-shortages, minimizing the seat-shortages

		Minimum Utilization	Mean Utilization	Maximum Utilization
Absolute	1st class seat-shortages	0.500	1.050	2.381
	2nd class seat-shortages	0.633	1.553	3.363
	2nd class shortages	0.290	0.947	2.246
Relative	1st class seat-shortages	0.557	1.038	2.217
	2nd class seat-shortages	0.672	1.526	3.226
	2nd class shortages	0.289	0.937	1.563

Table 7.4 Utilization, minimizing the seat-shortages

Focusing on the absolute number of seat-shortages, 15 out of 49 cross-section trains have a different composition. For twelve trains another composition with units of the same or different subtypes is used, for three trains another rolling stock type is used. In particular most trains on the 2000 line and trains starting in Utrecht have another composition. For the former category this results from the large increase in the required capacity of these trains. For the latter category this can be explained by the fact that there is an excess inventory at station Utrecht at the beginning of the day as a significant amount of trains starting at the beginning of the day at this station have been cancelled due to the disruption.

7.2.3. Allowing all Rolling Stock Types

NS prefers to use some rolling stock types only for intercity trains, while other types are preferred to be used on regional lines. These preferences are taken into account in the model. It might be interesting to know if and to what extent seat-shortages can be decreased further if there are no restrictions on the type of rolling stock used for each trains series. Again, the focus is on minimizing the seat-shortage kilometers. The results can be found in tables 7.5 and 7.6. A decline in seat-shortages and seat-shortage kilometers of about twenty percent is visible compared to the standard allocation. Besides, there is a decline in the maximum utilization in both the first and second class. This indicates that the available units of rolling stock can be used more efficiently.

Analyzing the solution it turns out that in seven cases rolling stock types preferred for regional trains are used for intercity trains and vice versa. These seven trains do all belong to a different lines. Again, three of them start at station Utrecht. Although NS has to assess whether the obtained solution would be appropriate to be implemented in practice, the results give an indication of the impact the restrictions have on the solutions of the model.

# 1st class	# 2nd class	Total	1st class	2nd class	Total	SKM
23	12	27	1,727	23,072	24,799	7,889,210

Table 7.5 Seat-shortages, allowing all rolling stock types

	Minimum Utilization	Mean Utilization	Maximum Utilization
1st class seat-shortages	0.357	1.068	1.940
2nd class seat-shortages	0.877	1.502	3.226
2nd class shortages	0.521	0.924	1.563

Table 7.6 Utilization, allowing all rolling stock types

7.2.4. Weights in the Objective Function

In the previous sections of this chapter the focus was only on minimizing the seat-shortage kilometers. In this section, we also focus on minimizing the differences in compositions between the standard and the new rolling stock allocation. Because these two elements of the objective function are contradictory, a trade-off has to be made.

Figure 7.1 shows the relationship between the total number of shortage kilometers and the number of different compositions. The number of shortages is calculated as the number of seat-shortages in the first class added up with the number of shortages in the second class according to the third capacity standard. This third standard is used as it is not required in this situation, during peak hours and as a consequence of a disruption, that all passengers in the second class have a seat. The graph is obtained by varying the ratio of the weights w_1 and w_2 in the objective function. The trend line is mainly drawn for interpretational purpose. As the number of different compositions can only be integer values, most points on this line cannot be reached. The standard allocation is represented by the point where the graph coincides with the horizontal axes. Starting from the standard allocation, allowing more differences in compositions will result in a decrease in the number of shortage kilometers. Because the graph is convex, it follows that the decrease in shortage kilometers will be less as the number of differences in compositions is higher. Independent of the number of different compositions that are allowed, in this scenario the number of shortage kilometers cannot be decreased further than about 2,700,000.

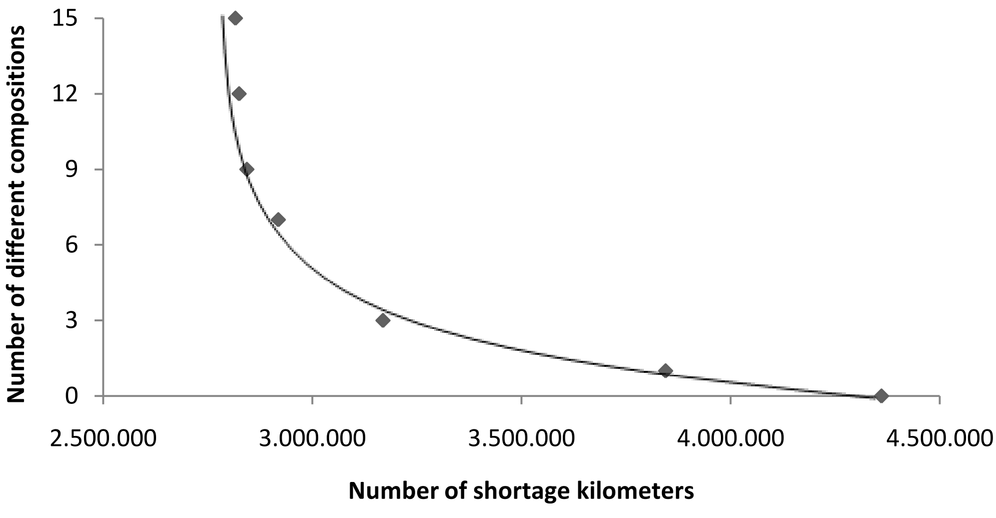

Figure 7.1 Relationship between shortage kilometers and differences in compositions

7.3. Scenario 2

7.3.1. Standard Rolling Stock Allocation

Comparing the standard rolling stock allocation in both scenarios, seat-shortages and seat-shortage kilometers are about 25 percent higher in scenario 2. There are sixteen times more seat-shortages in the second class as in the first class. Shortages occur on all trains of the 2000 line and on most intercity trains travelling from Rotterdam, The Hague and Utrecht to Schiphol, and vice versa.

The maximum utilization in both the first and the second class is higher than two, which means that at least for one train the allocated capacity is not sufficient to transport all passengers.

# 1st class	# 2nd class	Total	1st class	2nd class	Total	SKM
28	29	32	2,285	36,779	39,064	12,299,150

Table 7.7 Seat-shortages in the standard rolling stock allocation

	Minimum Utilization	Mean Utilization	Maximum Utilization
1st class seat-shortages	0.500	1.151	2.778
2nd class seat-shortages	0.641	1.776	4.240
2nd class shortages	0.284	1.091	2.832

Table 7.8 Utilization in the standard rolling stock allocation.

7.3.2. Minimizing Seat-Shortage Kilometers

Compared to the standard rolling stock allocation the seat-shortages and seat-shortage kilometers declined with eight percent and nine percent, respectively. For 15 cross-section trains another composition is used. Most of them are trains of the 2000 line and intercity trains travelling from The Hague, Rotterdam and Utrecht to Schiphol, and vice versa.

Analyzing the utilization of the capacity, it can be concluded that the minimum utilization is almost the same as in the standard rolling stock allocation but the mean and maximum utilization have decreased. According to rows one and three of table 7.10, on average the capacity of the trains is sufficient to meet passenger demand.

# 1st class	# 2nd class	Total	1st class	2nd class	Total	SKM
22	24	25	1,902	33,928	35,830	11,164,840

Table 7.9 Seat-shortages, minimizing seat-shortages

	Minimum Utilization	Mean Utilization	Maximum Utilization
1st class seat-shortages	0.500	1.028	1.902
2nd class seat-shortages	0.641	1.585	2.894
2nd class shortages	0.284	0.982	1.970

Table 7.10 Utilization, minimizing seat-shortages

7.3.3. Allowing all Rolling Stock Types

Allowing all rolling stock types on all cross-section trains, seat-shortages can be reduced by 16 percent in total. The solution provided has 23 cross-section trains with a different composition, this is almost 50 percent of the total number of cross-section trains. Out of these trains, four intercity trains use rolling stock units of a type preferred for regional trains and five regional trains use rolling stock units of a type preferred for intercity trains. Again, most of these trains are intercity trains travelling via Schiphol and trains starting at station Utrecht.

# 1st class	# 2nd class	Total	1st class	2nd class	Total	SKM
21	17	24	1,277	31,547	32,824	10,326,240

Table 7.11 Seat-shortages, allowing all rolling stock types

	Minimum Utilization	Mean Utilization	Maximum Utilization
1st class seat-shortages	0.409	0.988	1.937
2nd class seat-shortages	0.748	1.562	2.984
2nd class shortages	0.630	0.949	1.970

Table 7.12 Utilization, allowing all rolling stock types

7.3.4. Weights in the Objective Function

Figure 7.2 shows the relationship between the number of different compositions and the shortage kilometers. The number of shortages are calculated as described in section 7.2.4. The shape of the curve is the same as in figure 7.1. Again, starting from the standard rolling stock allocation, allowing more changes in compositions will result in a decrease in the number of shortage kilometers. However, this effect is transitory as in this scenario the number of shortage kilometers will always be above 3,600,000.

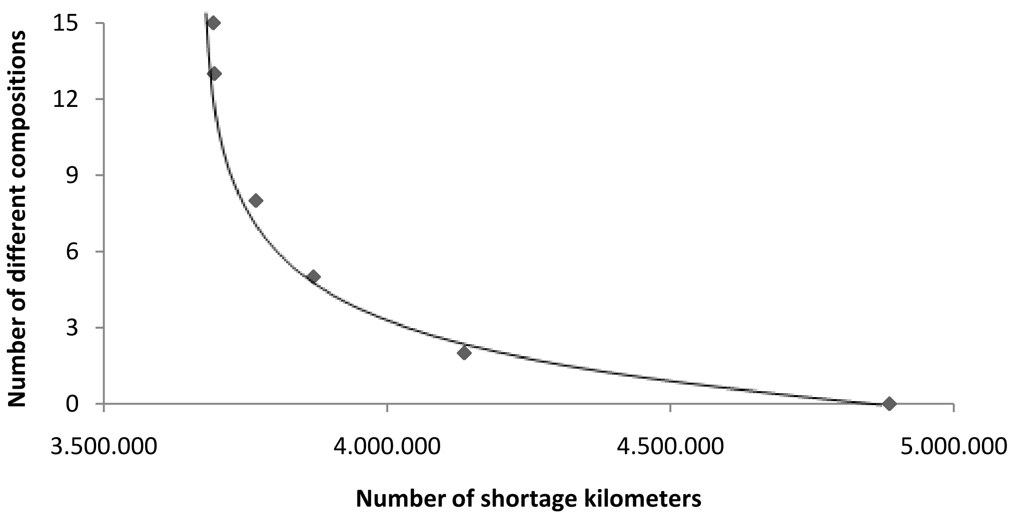

Figure 7.2 Relationship between shortage kilometers and differences in compositions

7.4. Some concluding remarks

Analyzing the results in the previous sections, it can be concluded that for these two scenarios:

- The number of seat-shortages is high using the standard rolling stock allocation. On some trains the capacity is not sufficient to satisfy passenger demand.
- In the standard rolling stock allocation as well as in the solutions provided by the model the number of seat-shortages in the first class is a small percentage of the total number of seat-shortages.
- Using the rolling stock re-allocation model the seat-shortages can be reduced by about ten percent.
- Using the rolling stock re-allocation model and allowing all rolling stock types to be allocated to all trains the seat-shortages can be reduced by almost twenty percent. For all trains, the allocated capacity is sufficient to satisfy passenger demand.
- The number of shortage kilometers can be decreased by allowing more changes in compositions, though this effect is transitory.

8. Conclusion

In case of disruptions the rolling stock has to be re-allocated as fast and efficient as possible to minimize the level of nuisance for the passengers. This thesis describes the first two steps in the rolling stock disruption planning process. The first step is the estimation of the number of passengers in the new timetable. In the second step, the available rolling stock units have to be re-allocated over the different train series. The main part of this thesis is concerned with a mixed integer programming model to re-allocate the available rolling stock units. The allowed compositions for each train are determined beforehand. The model assigns a composition to each train while minimizing the number of seat-shortage kilometers and the differences between the new and the standard rolling stock allocation.

The formulation of the rolling stock re-allocation model is very general. The model can be used for every disruption. To analyze the solutions provided by the model, this thesis focuses on Wednesday 25th March 2009. As a consequence of a train derailment, there was only very limited traffic possible between Utrecht and Woerden in week 13 of 2009. That means that a large number of passengers had to be redirected.

It turns out that using the standard rolling stock allocation on Wednesday 25th March 2009 would have resulted in a lot of seat-shortages. These seat-shortages occur mainly in the second class; the seat-shortages in the first class are only a small fraction of the total number of seat-shortages. The solutions provided by the model show re-allocations of the rolling stock for which the seat-shortage kilometers have declined by about ten percent. The seat-shortage kilometers can be decreased further by allowing all rolling stock types on all trains. However, it is questionable whether this solution is appropriate enough to be implemented in practice. Finally, this thesis has shown that allowing more changes in compositions will decrease the number of shortage kilometers, although this effect is transitory.

A topic of further research is the third and final step of the disruption planning process; the determination of a detailed rolling stock circulation plan for each type of train unit. This step falls beyond the scope of this thesis.

References

Abbink, E., Van den Berg, B., Kroon, L., and Salomon, M. (2004). Allocation of Railway Rolling Stock for Passenger Trains. *Transportation Science* **38**, 33-41.

Budai, G., Maróti, G., Dekker, R., Huisman, D., and Kroon, L. (2007). Re-scheduling in railways: the Rolling Stock Balancing Problem. *Econometric Institute report*, Report EI2007-27, Erasmus University Rotterdam.

Fioole, P.-J., Kroon, L., Maróti, G., and Schrijver, A. (2006). A rolling stock circulation model for combining and splitting of passenger trains. *European Journal of Operational Research* **174**, 1281-1297.

Huisman, D., Kroon, L., Lentink, R.M., and Vromans, M.J.C.M. (2005). Operations Research in passenger railway transportation. *Statistica Neerlandica* **59**, 467-497.

Huisman, D., and Potthoff, D. (2009). NS kan steeds sneller reageren op verstoringen. *EconomieOpinie.nl* April.

Jespersen-Groth, J., Potthof, D., Clausen, J., Huisman, D., Kroon, L., Maróti, G., and Nielsen, M.N. (2007). Disruption Management in Passenger Railway Transportation. *Econometric Institute*, Report EI2007-05, Erasmus University Rotterdam.

Kroon, L., Huisman, D., Abbink, E., Fioole, P.-J., Fischetti, M., Maróti, G., Schrijver, A., Steenbeek, A., and Ybema, R. (2009). The New Dutch Timetable: The OR Revolution. *Interfaces* **39**, 6-17.

Nielsen, L.K. (2009). A task based model for rolling stock scheduling. Draft paper, Arrival – TR-209, Erasmus University Rotterdam, The Netherlands.

Pothoff, D. Huisman, D., and Desaulniers, G. (2008). Column generation with dynamic duty selection for railway crew scheduling. *Econometric Institute*, Report EI2008-28, Erasmus University Rotterdam.