The Dutch Winter Timetable

Assessment of Alternative Line Systems for the Dutch Railway Network during Winter Weather

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Challenge the future

The Dutch Winter Timetable

Assessment of Alternative Line Systems for the Dutch Railway Network during Winter Weather

by

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Preface

This thesis is the result of my graduation research concerning the winter timetable on the Dutch railway network and concludes my studies in Transport, Infrastructure & Logistics at the Delft University of Technology. From the 1st of February till the 31st of July 2014, I worked on this thesis as an intern at the department of Process Quality and Innovation at Netherlands Railways (NS). Besides my graduation research, the internship at NS has given me a "sneak peek" of the corporate culture of this organization and led to my first job.

As is tradition, there are some people I would like to thank as they have been a great asset during my research. Since the start of this project, I have been steadfastly in my ambition to finish my work within the planned time frame: Six months. I am very glad I have been able to stick to this planning, but without my supervisors this would not have been possible. First and foremost, I thank Dennis Huisman and Rob Goverde for their intensive support and the detailed feedback on my work. Additional gratitude goes to Prof. Serge Hoogendoorn, Jan Anne Annema and Timo van de Walle for the feedback in their respective area of expertise and their trust in my work.

Another thanks goes to Peter Scheffel and Marc Hesseling, who introduced me to the subject and helped me in setting the first step towards an alternative timetable. I am extra grateful to Joël van't Wout for his support and his effort to adapt the line planning software to my needs. Without these adjustments, I would have had much more work.

Last but not least, I would like to thank my parents, my brother Wouter, my sister Nicoline and my girlfriend Joline for their everlasting love and support. They have always been there when I needed them, not only during my graduation project.

Enjoy reading!

Maarten Trap
July 2014

Executive Summary

The winters in 2009, 2010, 2011 and 2012 were some of the most extreme winters in The Netherlands in decades. The low temperatures led to heavy snow and frost, resulting in many disruptions in daily life. The Dutch railway network suffered from these extreme winter circumstances many times. Large disruptions on winter days are merely caused by malfunctioning infrastructure and broken rolling stock. If there are too many disruptions at the same time, coordination between control regions becomes impossible and the railway network runs out-of-control.

Since the first problematic winter of 2009/2010, Dutch railway operator Netherlands Railways (NS) and infrastructure manager ProRail have come up with a comprehensive winter programme to prevent out-of-control situations in the future. One aspect of this winter programme was a winter timetable, a special timetable for winter circumstances. This timetable facilitates better operational control during winter weather and has less interdependencies between infrastructure, rolling stock and crew. Over the years, the winter timetable evolved to a robust and stable plan which has proven able to prevent an out-of-control situation on the railway network.

The winter timetable of today, called the Landelijk Uitgedunde Dienstregeling (LUD), reduces the train services to a basic level, such that there is more slack time between trains and perspective for action in case of a disruption. In the economic area of the Randstad, this effectively results in cancellation of about 50% of the trains to reduce the frequency to a "basic" level, being 2 InterCity (IC) and 2 Sprinter (SPR) trains per hour. Due to this, the transport capacity during the LUD has proven to be insufficient.

The goal of this study is to explore the possibilities for a new winter timetable for the Dutch railway network. Such a timetable should at least be as robust as the LUD, but should provide more capacity to transport passengers. Robustness and transport capacity are closely related. Decreasing the number of trains yields a more robust network but decreases the transport capacity and the other way around. Since designing a complete timetable is an intensive and time-consuming process, we only focus at the *line system*. A line system describes all lines in the network and their frequencies. The objective is thus to study line systems where both robustness and transport capacity are acceptable. This goal is reflected in the research question of this thesis:

> *Which line system and corresponding rolling stock distribution can be applied on the Dutch railway network during extreme winter weather and provide enough transport capacity to limit crowded trains, while conserving robustness for controlling train operations?*

Formulation of design criteria

In order to design a robust line system, we first determined the characteristics of a robust network. Robustness is a very broad term and defined differently depending on the use. In general, a robust system is able to adapt itself to a range of possible futures. To what extent this is possible defines the degree of robustness. For railway networks, the robustness can be defined as a function of two aspects, being the absorption capacity and the controllability. The absorption capacity defines to what extent a system can adapt to external influences without the need for intervention by a

controller. It is therefore a proactive measure, often achieved by adding time slack (margins) to the process times in the timetable. The controllability defines the ability to control the network in case of large disruption. This comprises the effectiveness of the controller, but also the complexity of the network.

Based on findings from literature in multiple fields and interviews with planners, four criterion *groups* have been identified which define the robustness of a line system. Most of these groups relate to the controllability of the railway network. Every group consists of one or multiple *indicators*, which enable measurement of the robustness. The criterion groups are subsequently used as starting point to design new line systems. These groups are:

1. Line length. Longer lines are resulting in more interdependencies between stations in the network, since disruptions are likely to propagate through the network. The impact of disruptions can be restrained by operating shorter lines
2. Traffic intensity. A larger number of trains per track section per hour results in less time between trains and consequently less time to resolve problems before the next train arrives.
3. Control region attendance. Railway lines often run through multiple control regions. In case of a disruption, these regions need to coordinate back and forth to control the problem. The less regions a train attends, the less regions are concerned with controlling the disruption.
4. Disruption risk. Every train operation has a certain chance to cause a disruption, but some have a higher probability than others. The high-speed switches in the Netherlands are notorious for their failure rate and are very likely to cause a disruption during winter weather. Not operating these switches yields less risk on a disruption.

The transport capacity of a railway network is much easier to define than the robustness. The transport capacity of a line is defined by the number of passengers that line can transport per hour, which is depending on the capacity and thus length of the train and the frequency. Since frequency has influence on both the robustness and the transport capacity of a railway network, frequency is a very important factor. Moreover, a higher frequency and same average speed results in a higher transport capacity but less robustness and the other way around. This also implies a tight relationship between robustness and transport capacity.

Design methodology

Three alternative line systems have been designed, based on the above mentioned criterion groups. The line systems are thus merely designed from a robust perspective. Each alternative has a different underlying principle, which is translated into a *recipe* that is derived from one of the criterion groups. Every alternative line system thus aims to "optimize" the score of this criterion group. The following alternatives have been developed:

A1. Short lines: An alternative where a line may attend a maximum of 4 major stations.

A2. DVL regions: An alternative where a line may attend a maximum of 2 DVL control regions.

A3. Evading switches: An alternative where lines may only pass high-speed switches in one direction.

An alternative related to the traffic intensity has proven to be inefficient and is therefore discontinued. The characteristics of the line system enable computation of the values of all indicators for robustness. To determine the transport capacity, we need to compare the travel demand per train with the capacity of that train. The travel demand is estimated using a passenger allocation model called TRANS, which distributes all passengers over the lines and trains in the network. This yields the number of potential passengers per train, which is input for the assignment of rolling stock.

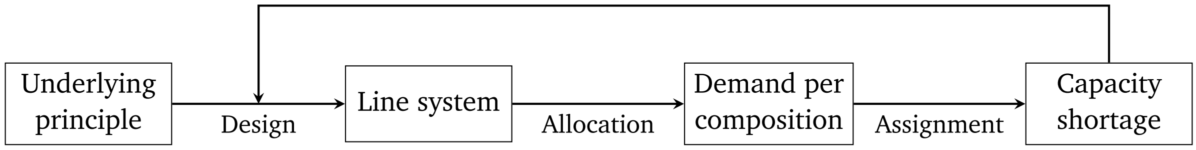

Figure 0-1: Methodology to design an alternative line system

The rolling stock is assigned using a linear integer assignment model with the objective to minimize the capacity shortage. Constraints regarding the fleet size, possible compositions and the maximum length of the trains are in effect. The result is the total capacity shortage, which should be as low as possible.

To create a robust line system with sufficient transport capacity, iterations are made. Each alternative is initially designed from a robust perspective, which yields large shortages in capacity. By increasing the frequency on the busy axes, the shortages will decrease. This also decreases the robustness of the line system, which makes that the indicator values must be recalculated. Using this iterative process, three robust line systems are created with a minimal capacity shortage. The complete methodology is shown in fig. 0-1.

Evaluation of alternatives

The three alternatives are evaluated with a Multi-Criteria Analysis (MCA) using the criteria regarding robustness and transport capacity. In this evaluation, the alternatives are compared to the LUD, which is therefore the zero-alternative (A0). A *robustness index* is created, which is a benchmark value indicating the robustness of the line system. The reference index is 100 and a lower value is better. This means that A0 has a robustness index of 100 and the alternatives are more robust than A0 if their index is < 100. To prioritize certain criterion groups and indicators over others, weights are determined using an Analytic Hierarchy Process (AHP). A sensitivity analysis on the weights shows that all alternatives are in any case more robust than A0. Figure 0-2 shows the range of the robustness index of all alternatives in relation to the capacity shortage.

Given the criteria for robustness, all alternatives are more robust than the LUD. The alternatives have less capacity shortage too. There are, however, several other important criteria that determine the usefulness of a line system. The feasibility, the comfort for passengers and the costs have been left out of scope so far. A second analysis therefore evaluates the more "commercial" effects of these line systems. This shows that all alternatives are resulting in more transfers and a larger average travel time. Additionally, changing the direction of trains at terminal stations will require more infrastructure.

Conclusions

The main research question can be answered as follows: There are alternative line systems which are theoretically more robust than the LUD and yield more transport capacity. Alternative A1 and A3 are two completely different line systems, but both perform better than the LUD. Both line systems have advantages and disadvantages, and should be further developed to assess their applicability and usability in practice.

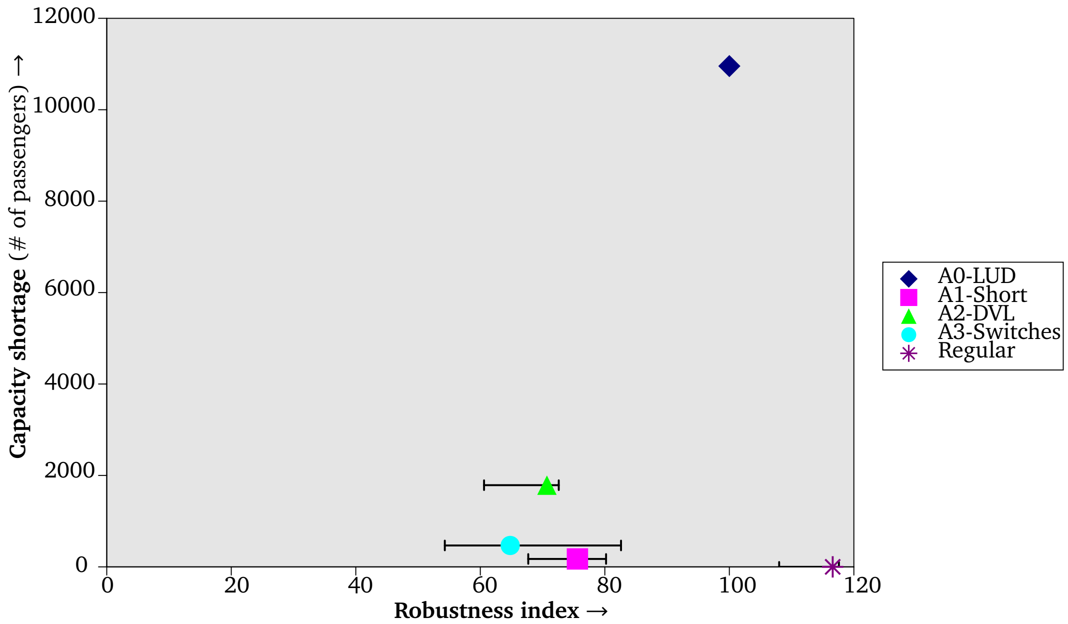

Figure 0-2: Ranges of the robustness index of all alternatives and their capacity shortage

Other important conclusions from this study include:

- Given the line system of the LUD, the capacity shortage is due to the reduced frequency. The rolling stock assignment model has proven that the LUD timetable is by far not able to transport all passengers, even if the assignment of rolling stock is optimal.
- A frequency of 2 trains/hour yields enough transport capacity on the large part of the Dutch railway network, but is insufficient in the Randstad. In order to transport all passengers, at least 3 trains/hour must run on the busy axes in the Randstad. These axes are:
  - Eindhoven - 's-Hertogenbosch - Utrecht Centraal - Amsterdam Centraal - Alkmaar
  - Amsterdam Centraal - Schiphol - Leiden Centraal - Den Haag HS - Rotterdam Centraal
  - Arnhem - Utrecht Centraal
  - Amersfoort - Utrecht Centraal
  - Utrecht Centraal - Gouda
- To prevent capacity problems due to platform constraints, outskirts of the country should be decoupled from lines in the Randstad. This makes that trains operating on the busy axes are not limited in length by short platforms.
- On average, the alternative line systems cause up to 2 minutes extra travel time and 0.15 extra transfers per passenger compared to the LUD. Increasing the robustness and transport capacity therefore has a negative effect on the passenger utility.
- High-speed switches on the network have proven to fail more often during winter weather. Evading high-speed switches is, theoretically, a way to decrease the risk on a disruption and should therefore be encouraged. The usefulness of the operational high-speed switches as indicator is, however, questionable.

Recommendations

There are alternative timetables which are more robust and yield more transport capacity. This conclusion is, however, based on a very theoretical approach. The alternatives in this study are more robust and yield more transport capacity than LUD, but are completely different from the regular timetable. This makes that passengers, crew and the operational controllers will have to abandon their daily routine and operate according a very different plan. Trains will consequently arrive at and depart from other platforms at different times than everyone is used to. Additional research is required to assess if it is at all possible and desirable to use such an alternative, because the alternatives are very different from the regular timetable. A few recommendations are made:

- At least one of the alternatives should be expanded into a more detailed timetable. Creating a Basic Hour Pattern (BHP) is required to check if a feasible timetable without conflicts is possible at all.
- Further investigation is required to assess the consequences of the alternative line systems on aspects other than the robustness and transport capacity. This includes the deviation from daily routine, changes in the preparation processes and the costs and benefits of a different plan over the LUD.
- The LUD can possibly improve if high-speed switches are locked into one direction, as many switches do not require changes in the line system. It should be examined if it possible to use other switches to prevent disruptions this way.

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1 Introduction

The winter of 2009/2010 was one of the most extreme winters in The Netherlands in decades. With a mean temperature of $1,1°C$, it was the coldest winter since 1996. Excessive snowfall caused the snow cover to break the record of 1979 multiple times (KNMI, 2010). The subsequent winters in 2011, 2012 and 2013 were similar, with more or less the same weather conditions. Low temperatures and heavy snow have had a major impact on daily life, especially on transport (NOS, 2009b).

During these winters, the Dutch railway network has been completely disordered for a few times. The extreme weather circumstances resulted in broken trains and malfunctioning infrastructure, often at the same time and at multiple locations. Recovery from these disruptions is very difficult due to the intensive use of the Dutch rail infrastructure. The interdependencies between routes, rolling stock and crew make that delays are easily propagating through the whole network. Since the first problems in 2009/2010, Netherlands Railways (NS) has been working on alternative timetable concepts to prevent winter related problems in the future.

1.1 History and context

The first real problems due to frost and heavy snowfall started in December 2009. Any winter-related problems before this moment are not worth mentioning or have not been structural. The 17th of December is therefore known to be the first real problematic day. A substantial amount (> 30 cm) of snow led to the first "out-of-control" situation in the history of the Dutch railway network (KNMI, 2010). In such a situation, the operational control organizations are no longer able to control the train traffic due to the many disruptions. Another snowfall on Sunday the 20th led to the same problem and a large amount of rolling stock broke down due to these weather conditions. Passengers were advised against travelling by train on the subsequent Monday and Tuesday as only very limited train traffic was possible (NOS, 2009a, 2009b).

Due to defects in the rolling stock and the on-going frost, several trains were cancelled in January 2010, resulting in criticism and complaints from both passengers and the government (NOS, 2010a, 2010b). NS and ProRail formed a team to come up with a plan for the next winter. One aspect of this plan was an alternative timetable called Alternatieve Dienstregeling Volgende Dag (ADVD). This timetable was largely based on shuttle services. By operating short lines between the larger stations, delays could not propagate further through the network. A successful test of the ADVD in October 2010 led to the idea that NS and ProRail were "well-prepared" for the next winter.

On December 4th and 17th 2010, extreme winter weather once more resulted in out-of-control situations on the Dutch railway network. Remarkable is that the ADVD timetable was not deployed on any of these days. To prevent more problems, a quickly drafted plan was made for the 18th and the days after, since it was too late to start preparations for the ADVD. This plan was called Snel Aangepast Plan (SAP). The SAP is an ad-hoc plan based on the regular timetable, but with less trains. It is essentially a *reduced timetable*, since the frequencies of the train services are downgraded to a basic level. To apply the SAP, the regular timetable has to be mutated which is a much easier process than applying a completely different plan like the ADVD.

Since the SAP required less preparation time and seemed effective in preventing an out-of-control (though not proven), the more elaborate Landelijk Uitgedunde Dienstregeling (LUD) was designed. The LUD is directly derived from the SAP and less complex than the ADVD. The main difference is the concept itself as the LUD describes the mutations from the *regular timetable*, while the ADVD is a completely *different plan*. The idea behind the LUD is to downgrade the regular timetable to a reduced timetable, where most frequencies in the Randstad are set back from four times/hour to twice/hour.

In the winter of 2011/2012, the LUD was the new solution to stay in control during extreme winter weather. This was proven on the 5th of February, where a successful deployment of the LUD has prevented an out-of-control situation. On the days before, nevertheless, the network went out-of-control twice. On both days, the LUD was not deployed. An internal investigation concluded that the decision making regarding the deployment of the LUD was unclear (NS, 2012a). Too many stakeholders were involved and there were no clear decision criteria. The decision process regarding the use of the LUD should thus be improved. As a result, a clear decision structure was arranged along with a list of conditions and criteria to start preparing the deployment of the LUD.

The winter of 2012/2013 was another heavy season for the Dutch railway network. The first snowfall was on the 30th of November, while the last snowfall was on the 24th of March. 27 days within this period were subject to LUD deployment regarding the criteria set in the preceding year. Of these, the LUD was in effect for 12 days. There was not a single out-of-control situation during this winter, but there have been many complaints about crowded trains and insufficient transport capacity. Additionally, there have been complaints about a too premature and cautious deployment of the LUD (NOS, 2013). An overview of all events from the first heavy winter in 2009 is shown in fig. A-1 in Appendix A.

1.2 A range of solutions in the Netherlands and abroad

The long term ambition on the Dutch Railway Network is to *provide reliable transport services and sufficient travel information under (almost) all circumstances* (NS, 2013c). Since extreme winters are compromising this ambition, special winter programmes have been set up to prevent winter-related disruptions and to enable the operational controllers to cope with these problems. Other countries are dealing with extreme winter weather as well. An international benchmark by LeighFischer (2012) concludes that countries like the United Kingdom, Switzerland, Sweden and Germany have had at least one winter with similar problems in the last five years. In all counties, these problems have led to increased awareness and arrangements to prevent problems in the future. Most of these solutions are ranging from switch heaters to snow-clearing trains and heated overhead wires, such that the accumulation of snow and ice is prevented (MTA, n.d.; Networkrail, n.d.).

The winter programme in The Netherlands is set up by NS and ProRail under the authority of the Ministry of Infrastructure & Environment and is aiming to reduce the impact of winter weather on the train service (NS, 2011, 2012c, 2013c). The winter programme improves every year and contains a comprehensive set of both proactive and reactive measures, ranging from the reliability of the rail assets to the care of passengers in case of a disruption. Next to switch heaters and anti-icing arrangements for rolling stock, the alternative winter timetable is an important aspect of the winter programme. This is different in other countries, as most of them only reduce speeds or arrange changes on local level. In Switzerland, where the traffic intensity is similar to the Netherlands, the regular plan already has up to 10% slack time in the timetable which makes a reduced timetable superfluous (LeighFischer, 2012).

Other differences between the Netherlands and other countries are related to the infrastructure and the different safety regulations. In all countries benchmarked by LeighFischer (2012), maintenance personnel is allowed to repair switches on single tracks such that train traffic in the opposite direction is still possible. Moreover, the train drivers in most of these countries are allowed to exit the cabin to inspect and clean a jammed switch themselves. In the Netherlands, the current safety regulations do not allow this (RailAlert, 2012). A switch failure therefore always requires a maintenance team to emerge to fix the switch, while in the mean time the train traffic is blocked in both directions. To prevent a large queue of trains, the Dutch railway network benefits from a reduced timetable.

1.3 Alternative timetable prevents out-of-control

The different alternative timetables are essentially aberrant in their *line system*, which states the origin, intermediate stops, destination and frequency of every line. The *timetable* is a detailed elaboration on the line system and specifies at what exact times the different trains arrive and depart. This is further explained in chapter 2. The LUD is largely based on the regular line system with some mutations in line length and frequency, while the arrival- and departure times (i.e. the timetable) are almost alike. This makes that the LUD can be deployed in a relative short time frame, as this only requires mutations in the regular plan. As a result, the LUD has more or less the same pattern of arrival and departure times which makes that passengers and crew is easily familiarized with the alternative plan. The line system of the ADVD is, on the contrary, a fully different line system with therefore a completely different timetable.

Since the first winter programme in 2010, the severity of winter-related problems has decreased and the preventive measures have converged to a stable solution. As of this moment, the LUD is successful in preventing out-of-control situations on the Dutch railway network. It is therefore considered as a *robust* solution during extreme winter weather. Decreasing the frequency of the train service yields extra margins and less delay propagation in case of a disruption, but limits the transport capacity. Spare rolling stock which is induced by cancelling trains is used to extend the operating trains, yet is not always satisfactory. Analysis shows that 50% of the trains in the winter of 2012/2013 has had a composition deviant to the alternative plan. Trains were either longer than planned, shorter than planned or cancelled (NS, 2013d).

Besides the differences in planning and execution, the theoretical transport capacity of the LUD is not sufficient. For numerous lines, the trains cannot be extended since their length is already at maximum. Lengthening trains to supply more capacity is thus a difficult process and not always possible. Reducing the nuisance caused by crowded trains is therefore one of the main objectives for the next winter (NS, 2013c).

1.4 Problem statement

The following conclusions can be drawn from the preceding sections:

- Alternative timetables are essentially different in their line system. The line system is the foundation of a timetable and can be changed to adapt the train service to different circumstances.
- The LUD alternative timetable is effective in preventing an out-of-control situation on the Dutch railway network in extreme winter weather. It is therefore seen as a robust solution.
- The similarities between the LUD and the regular timetable enable deployment within a short time frame and yields familiarity with passengers and crew.
- The reduced frequency of multiple lines in especially the Randstad yields extra margins, but limits the transport capacity to an insufficient value.
- Lengthening the operating trains with additional rolling stock is a complex process and is not always possible due to platform constraints.

The conclusions above make clear that the LUD is an unsatisfactory solution during winter weather regarding transport capacity and that extending the trains cannot sufficiently change this. Another alternative must be found to reduce crowding in the trains while the robustness is conserved. Since the regular timetable is the foundation of the LUD, it might be useful to use a different foundation.

1.4.1 Research objective

The objective of this study is to explore the possibility to reduce the nuisance of crowded trains while conserving robustness, such that train controllers can appropriately respond to disruptions. To achieve this, the regular timetable is disregarded. The aim is to explore what line systems can yield sufficient transport capacity and robustness during extreme winter weather, even if such a solution requires a completely different plan. Multiple alternative line systems, along with a corresponding distribution of rolling stock, will be designed and evaluated to assess their robustness and transport capacity. These line systems must contribute to the goal to *stay in control during multiple infrastructure- and rolling stock disruptions while limiting the consequences for passengers* (NS, 2013c). The line systems are therefore subject to be used during severe winter weather and possibly during other forms of extreme weather. They are not (directly) intended for daily use.

The *theoretical objective* of this study is to explore which factors affect the robustness of a railway network and what indicators can be used to measure this on the level of the line system. Another objective is to estimate the transport capacity of a network if only the line system is known.

The *practical objective* of this study is to reduce the impact of disruptions caused by winter weather on the Dutch railway network while supplying sufficient capacity to transport all passengers. This is done by evaluating the robustness and transport capacity of the proposed solutions.

1.4.2 Research questions

For this study, the following research question has been formulated:

> **Main research question:** *Which line system and corresponding rolling stock distribution can be applied to the Dutch railway network during extreme winter weather and*

provide enough transport capacity to limit crowded trains, while conserving robustness for controlling train operations?

To answer the main research question, several sub questions are formulated:

Sub question 1: *What are typical events during extreme winter weather on the Dutch railway network and how are they operationally controlled?*

Sub question 2: *What factors define the robustness and transport capacity of the Dutch railway network and how to measure these?*

Sub question 3: *What are possible approaches to design a robust line system with sufficient transport capacity and what alternatives do they yield?*

Sub question 4: *To what extent are the alternative line systems contributing to a robust solution with sufficient transport capacity?*

The terms used in the different questions are defined in section 1.5.

1.4.3 Scientific and societal relevance

The scientific relevance of this study lies within the development of a novel approach of designing a line system, often called the Line-Planning Problem (LPP). Many researchers have written about this problem, often proposing mathematical methods and models to optimize the line planning. Most models are aiming to minimize the costs while maximizing the utility for the passenger (see e.g. Bussieck, 1998; Claessens, Van Dijk, & Zwaneveld, 1998; Goossens, 2004). In this study, the cost factor is intentionally left out of scope, as the deployment of an alternative timetable is incidental and not intended to save costs. The LPP will therefore have a different approach in this study, where *robustness* (in terms of a controllable timetable) and *transport capacity* (in terms of available seats) are the key decision factors.

The societal relevance of this study is regarding both NS and the passengers on the Dutch railway network. For NS, this study provides insight into the trade-offs in designing a line system and the alternative, non-typical approaches to do so. Furthermore, the conclusions of this study can stimulate NS into an alternative way of thinking regarding robust line systems and corresponding timetables. The passenger benefits in an indirect way, as the findings of this study can help NS to deploy an alternative timetable during winter weather which is better than the current LUD in terms of robustness and transport capacity.

1.5 Scope

Because of limitations in time and available data, boundaries for this study have been set. This section defines the terms used in the research questions to avoid ambiguity and states the assumptions made to reduce the complexity of the subject matter. An overview of other terms and abbreviations can be found in the glossary in Appendix H and the acronym list in Appendix I.

The scope of this study is as follows:

- This thesis focuses on alternative *line systems* to be deployed in extreme winter weather.
  - In order to operate an alternative line system, a complete plan is required. Such a plan consists of (amongst others) a detailed timetable, a rolling stock schedule and a crew

plan. These succeeding steps in the planning process are further explained in chapter 2, but are not covered in this study.

  - All further occurrences of the term *alternative timetable* refer to the complete plan which is a result of the alternative line system. That is, an alternative timetable is the complete package of line system, timetable, rolling stock schedule and crew planning, based on the alternative line system.

- The Dutch railway network is defined as the main railway network tendered to NS.
  - The Dutch railway infrastructure is split up in multiple sub networks, of which the *main railway network* (in Dutch:"hoofdrailnet") is the largest. The concession to operate the main railway network is tendered to NS and is subject to have an alternative timetable. See the ProRail Network Statement (2013) for a detailed description of this network.
  - The High-Speed Train (HST) track between Amsterdam and Breda is included as a regular travel option, but the train service is fixed. The HST provides a complementary train service which is assumed to operate without supplement if an alternative timetable is in effect. It is, however, yet not possible to increase the frequency or train length on this line.
  - Other sub networks operated by NS (e.g. Zwolle-Kampen and Gouda-Alphen) are left out of the scope, because these lines are completely separated from the main railway network. Previous alternative timetables have not been affecting these lines either.
  - International lines on the main railway network (e.g. IC Amsterdam-Berlin) are left out of the scope, since these lines are not under full authority of NS. If these lines are operational during winter weather and subject to serve inland traffic, this is seen as a collateral benefit complementary to the domestic network.
  - A trip from station i to station j has a fixed price depending on the distance between these stations. If there are multiple ways to travel from i to j, all travel options have the same ticket price.
  - Freight transport is neither considered nor kept in mind, as NS is a passenger train operator.
- Winter weather is defined as weather conditions with either temperatures below $-10°$C or a snow cover of 1.5 cm or more (NS, 2013c). These conditions are derived from the criteria that define when preparations for an alternative timetable should start.

1.6 Thesis outline

Chapter 2 starts with an overview of the railway planning process, along with the interpretation of this process at NS. In chapter 3, robustness and transport capacity are defined based on recent literature and related studies. This chapter furthermore defines the criteria to assess the robustness and transport capacity of a line system.

In chapter 4, the methodology to design alternative line systems is presented. This chapter elaborates on the working method to create alternative line systems, determine the demand per train and presents a model to assign train compositions to the lines. Subsequent chapter 5 describes the alternatives in detail, along with their values for the different robustness indicators. A Multi-Criteria

Analysis is performed to calculate the robustness index of the alternatives, such that the relation between robustness and transport capacity can be determined.

Chapter 6 contains the conclusions of this study and discusses the implications of these conclusions. Furthermore, this chapter encloses recommendations for NS regarding an alternative timetable, as well as recommendations for further research.

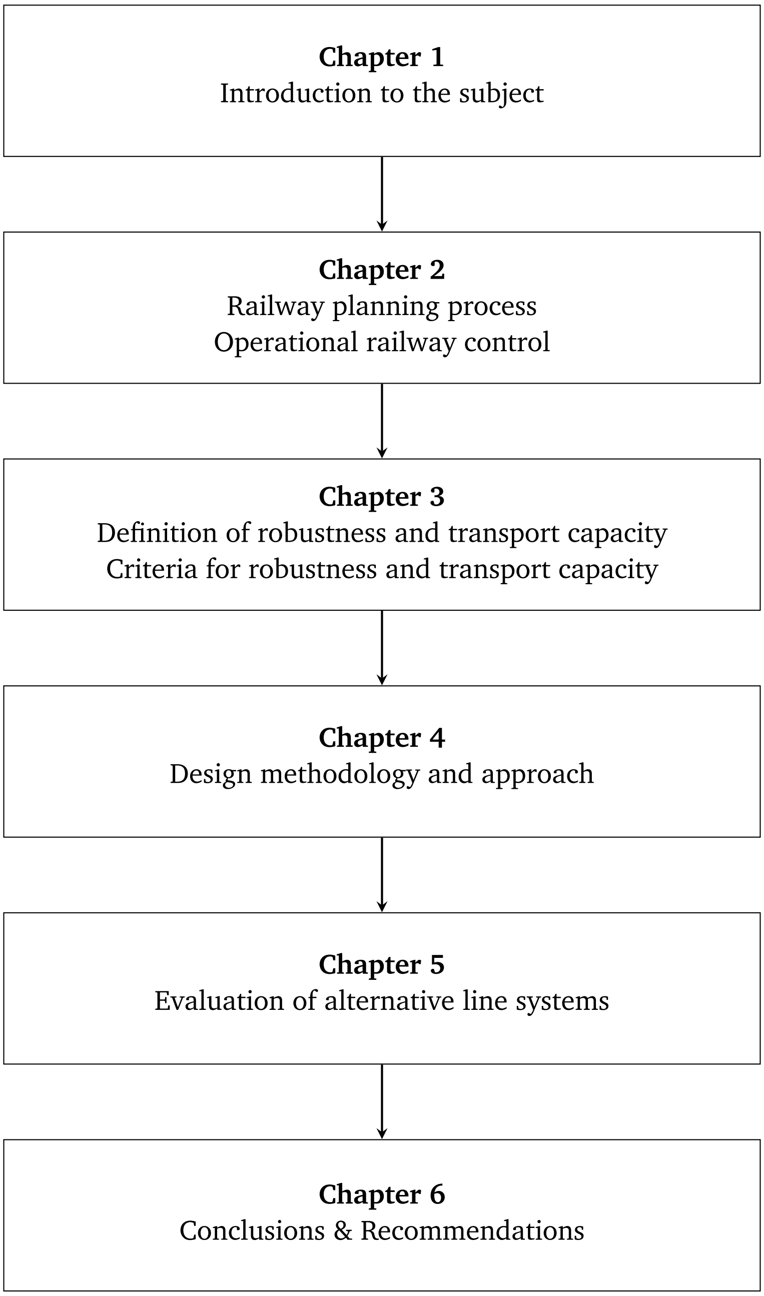

Figure 1-1: The outline of this thesis in a flowchart

2

Railway planning and operations

As for all different kinds of Public Transport (PT), a railway network requires a detailed specification of the services that are being operated on the network. For passengers using the network, these services are often specified in a timetable, indicating at what times which trains operate in which direction. Such a timetable is, however, only one component of a bigger and often complex planning process.

Ceder and Wilson (1986) were one of the first researchers to formulate five steps for the planning of PT networks. Although their focus was primarily on bus networks, these planning steps are in general applicable to all other forms of PT. Several other studies slightly adapted this framework to fit a specific modality, public transport operator or a combination of both (see e.g. Bussieck, 1998; Goossens, van Hoesel, & Kroon, 2004; Huisman, Kroon, Lentink, & Vromans, 2005).

The focus of this study is on the line planning phase, which is the process of creating a line system. In order to determine the transport capacity of this line system, a global assignment of rolling stock has to be made. This requires a few assumptions and calculations derived from the timetabling step. A generalized overview of the planning process is shown in fig. 2-1. The box indicates the focus of this thesis. This chapter elaborates on the different steps in the planning process and how they are executed at Netherlands Railways.

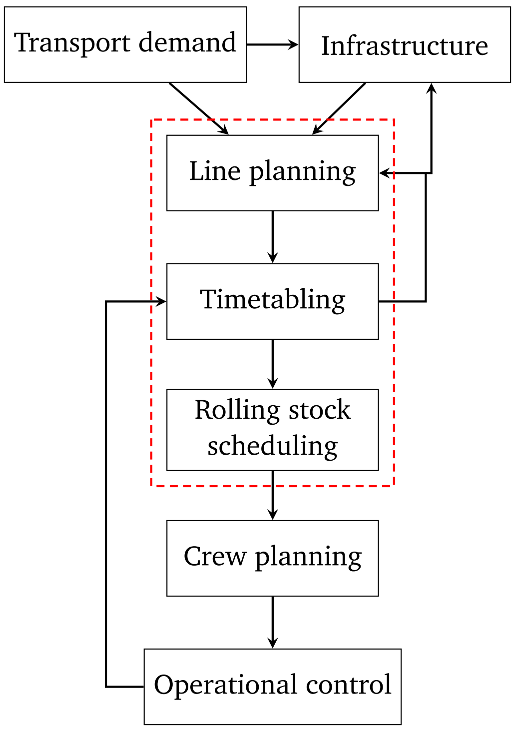

Figure 2-1: The railway planning process and the focus of this thesis

2.1 Estimation of travel demand

The very first step in the planning process is the estimation of the number of potential passengers, being the travel demand. This is usually presented in an Origin-Destination matrix (OD-matrix) $D = (D_{ij})$, indicating the travel demand between origin i and destination j. The purpose of an OD-matrix is often to *forecast* the travel demand and this is similar when planning a railway network: Once it is known how much passengers are willing to travel, the operator can adapt its transport supply to the demand. For the purpose of designing a railway network, there are generally two approaches to estimate the OD-matrix: Using the demand for the *respective mode* or using the demand for *travel in general*.

The first approach is relatively easy and is based on counts in the own network. The origins and destinations in the OD-matrix are all possible stations in the network. By calculating the load factor of the current rolling stock, it can be determined to what extent the supply is matching the demand. Recent developments like smart cards (i.e. the OV-Chipkaart in the Netherlands) are simplifying this process as they provide operators with accurate data about the origin and destination of their passengers (Munizaga & Palma, 2012). The main disadvantage of this approach is obvious, as it does not take origins and destinations other than the stations into account. Since stations are seldom the real origin and destination, there is no information about the access and egress trips from and to the stations.

The second approach for OD-matrix estimation is more complex as it takes multiple transportation modes into account. The estimation of the OD-matrix as such is the result of the first two steps in the four-step transportation model shown in fig. 2-2 (McNally, 2000). The origins and destinations can range from neighbourhood to postal code to province, depending on the size and purpose of the model. The trip generation step determines the number of trips that will originate in origin i, traditionally performed by regression methods using zonal data like the number of households, car ownership, income etc. The trips are subsequently distributed over the possible destinations j by using a gravity- or entropy-based model depending on the number of activities, the size and the distance (and travel costs) between i and j (Van Aerde, Rakha, & Paramahamsan, 2003). The resulting OD-matrix shows the travel demand regardless the transportation mode.

Using the four-step method, the resulting OD-matrix provides insight in the *potential* demand, as it contains O-D relations that are not depending on the layout of the different transport networks. This way, the demand can be used to plan for new rail tracks and stations to tap into new potential markets. This approach is more elaborate, but requires many assumptions and parameters. Today, new technologies like cellular network data can be used for OD-matrix estimation (Mellegard, Moritz, & Zahoor, 2011).

The above mentioned approaches to estimate the travel demand are simplified in several ways. In practice, the actual demand is to a large extent depending on the time of day and the day itself. In the morning and afternoon peaks, the demand for travel is considerably higher than between these peaks, and weekdays are generally busier than weekends. When also taking the preference for different transport modes into account (third step in fig. 2-2), there are even more uncertainties in estimating OD-matrices.

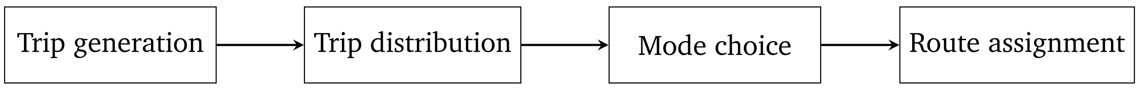

Figure 2-2: The four-step transportation model (McNally, 2000)

Demand estimation in practice

At NS , the travel demand is estimated by the MarketResearch and Advise (MOA) department. This department is responsible for gathering travel related data and estimating the demand for different time periods. The department is using a model called "De Kast" to forecast future demand. The input for this model ranges from data generated by the OV-Chipkaart to ticket sales and passenger counts. This yields a large matrix with the the demand from and to all railway stations in The Netherlands. To forecast future demand, the model takes multiple factors into account like ticket prices, demography, car travel costs and the economy. This yields OD-matrices for years ahead.

For this study, an OD-matrix for morning peak demand in 2014 is used which is assumed to present a realistic view of the travel demand. This is a 411×411 matrix, with demand data from and to all stations in The Netherlands. Although there are only 253 stations on the main railway network, passengers travelling from and to the other stations might use the main network. Therefore, demand data from all 411 stations is taken into account.

2.2 Infrastructure management

The second step in the planning process is an assessment of the available infrastructure. Especially for railway networks this is an important step, since trains are always bound to their dedicated infrastructure. Based on the demand estimation, it is possible to adapt the infrastructure and increase the capacity of the tracks and stations or expand the network into new areas (Goossens et al., 2004).

The available infrastructure can be expressed in terms of *links* and *nodes* as shown in fig. 2-3. Links are the railway tracks between two nodes. A node can be any point in the network where links start, branch, merge or end. On a macro level the nodes are often the larger stations, while on a micro level a node may depict a switch.

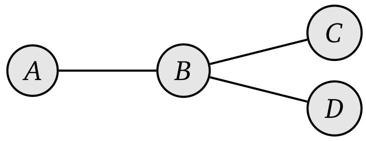

Figure 2-3: Example of a network with four nodes and three links

In combination with the demand, the infrastructure characteristics are the input for the line planning phase. The characteristics of the different infrastructure elements are important here. A double-track link usually yields four times more capacity than a single track and four tracks can increase the capacity of a double-track up to 50% (Abril et al., 2008). The allowed speed on a track limits the capacity too, as well does the actual planned speed of the train. A higher speed requires a longer braking distance and therefore more distance between two subsequent trains.

Another factor is the used safety system. The block size on the tracks determines the minimum distance between two trains (increased block size is more minimum distance). The size of a block is often such that the longest and heaviest train can safely stop within one block (Goossens, 2004). New safety systems like the European Train Control System (ETCS) use train-dependent braking curves which enables subsequent trains to run much closer together, increasing the capacity (Goverde, 2012). The infrastructure and its characteristics therefore play a major role in planning a railway network. The capacity of the infrastructure is further explained in section 3.2.1.

Intermezzo: Graph theory

In order to analyse, comprehend and evaluate complex networks, transit networks are often translated into *graphs*. The field of *graph theory* was amongst others developed by Berge (1962) and is essentially a formal mathematical method. Within graph theory, a (railway) network is transformed into an undirected graph $G = (V, E)$ where $V = \{s_1, s_2, \ldots, s_n\}$ is the set of vertices (nodes) and $E = \{e_1, e_2, \ldots, e_m\}$ is the set of edges (links) connecting the vertices (Bussieck, Kreuzer, & Zimmermann, 1997).

When modelling a railway network, two types of graphs are important to distinguish: An *infrastructure graph* is a graph that consists of all available infrastructure, where the nodes are stations and/or switches and the edges are *tracks*. For simplicity it is assumed that the number of railway tracks is an edge property. This means that there is only one edge between two vertices, regardless of the actual number of tracks.

The second type is the *network graph*. In this graph the vertices only represent stations, but multiple edges are possible. Since it is possible to have more than one line operating between two stations, every edge represents a train *line*. This makes a network graph a little more complex than the infrastructure graph. To simplify the network graph, the number of vertices can be reduced to only the stations where passengers can transfer lines and terminal stations (Derrible & Kennedy, 2010). Any intermediate stops without transfer possibility are not shown in the graph which reduces the graph to a conceptual map where the lines either start, end or meet each other.

Figure 2-4 shows both an infrastructure graph (left) and a network graph (right). In the network graph, only transfer- and terminal stations are shown which excludes station C. A different colour indicates a separate line.

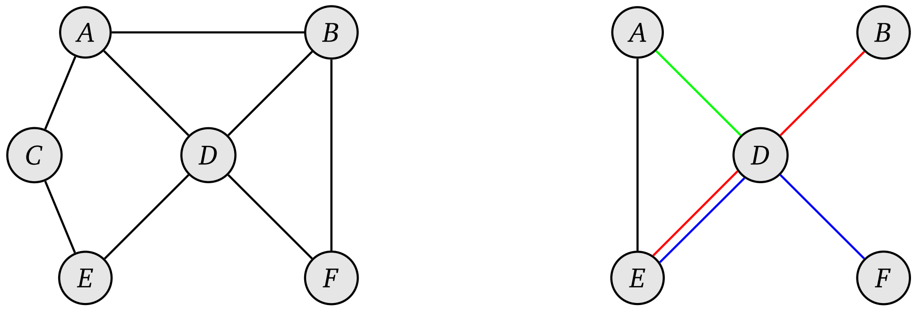

Figure 2-4: Example infrastructure graph (left) and network graph (right)

Infrastructure management in practice

In The Netherlands, ProRail is responsible for managing the rail infrastructure commissioned by the Ministry of Transport. Since NS is by far the largest operator on the Dutch railway network, NS and ProRail work closely together in many different fields. The rail infrastructure is continuously subject to expansion, especially on the busy axes in the Randstad.

At this moment, the main railway network can be seen as an infrastructure graph $G = (V, E)$ where $V = \{s_1, s_2, \dots, s_n\}$ is the set of vertices representing the stations and $E = \{e_1, e_2, \dots, e_m\}$ is the set of edges representing the tracks between the stations. The main railway network consists of $n = 253$ vertices and $m = 227$ edges.

2.3 Line planning

Based on the available infrastructure and the travel demand, a line plan can be made. There are many (mathematical) practices in literature to make a line planning for multiple types of PT networks. These practices are mostly referenced to as the LPP.

A *line* is a path in the railway network with a certain frequency. This path is defined by a sequence of nodes $s_0, s_1, \dots, s_k, k \geq 1$, where s_0 is the origin and s_k is the destination. In-between nodes $s_1, \dots, s_{k-1}$ are the intermediate stops on the line (Bussieck, 1998). The frequency $f_l \in \mathbb{Z}_+$ of line l tells how often the service is offered per time unit T, where T is mostly one hour. A *line system* $(\mathscr{L}, f)$ is the set of all lines $\mathscr{L}$ and their frequencies f_l for all $l \in \mathscr{L}$ (Goerigk, Schachtebeck, & Schöbel, 2013). In most cases, the line system also includes connections between train lines.

There are many different ways to solve the LPP. Most papers about line planning are constructing a line system by picking lines from a line-pool $\mathscr{L}^0$, which contains a large set of possible lines. The LPP then consists of finding a feasible set of lines (i.e. the line system), subject to different constraints while optimizing an objective. There are many different objectives and corresponding constraints. Common recurring approaches in literature are for instance to reduce cost (Claessens et al., 1998; Goerigk et al., 2013; Schöbel, 2012), lower the number of transfers (Bussieck, 1998; Bussieck et al., 1997; Kaspi & Raviv, 2013), improve service in general (De Keizer, Fioole, & Van't Wout, 2013; Van Oort & Van Nes, 2009b) or a combination of previous mentioned approaches (Goossens, Van Hoesel, & Kroon, 2006).

Since most rail networks are offering different *types* of train products, there are also different types of lines (Goossens, 2004). These types mostly include InterCity (IC) trains and Regional (R) trains. Every line $l \in \mathscr{L}$ is therefore either an InterCity (IC) or Regional (R) line, as is every station $s \in V$. In practice, IC trains only stop at IC type stations, while R trains stop at both R and IC stations. Some countries also know an InterRegional (IR) train, which is a type in-between the IC and R trains.

Line planning in practice

The line system for the main railway network is usually planned a long time in advance. Larger changes in the line planning require several other steps in the planning process (see fig. 2-1), which makes that changing the line system is a long-term strategic decision. Examples of changes in the line planning date from 2007 (increasing the frequency in the Randstad to 4 trains/hour) and 2013 (introduction of the Hanzelijn), resulting in radical changes in the line system. The next planned (radical) change is the introduction of a high-frequent line with a 6 trains/hour service from 2017.

In the Netherlands, the two train types IC and R are known. The regional train is called Sprinter (SPR) but has the same characteristics. Some lines in the current line system are a combination of an IC and SPR line. These are basically IC trains, but are performing a partial SPR service from a certain point on the line. These types of lines are neglected during the rest of this study and treated as regular IC lines.

When the line system is complete, every line gets its own number, often called the *train series*. This number is usually a multiple of 100, such that all trips during a day have their own *train number*. The odd and even numbers distinguish the direction. For example: Train series 3100 is the line from Nijmegen to Schiphol Airport with possible train numbers between 3100 and 3199. Odd train numbers indicate a trip from Schiphol to Nijmegen, while even numbers are assigned to a trip in the opposite direction.

2.4 Timetabling

Once a line system has been chosen, a schedule of arrival and departure times –the timetable– for all trains and stations will be constructed. In many countries the timetable is *cyclic*. This means that the pattern in the departure and arrival of the trains is repeating every time period, which is typically one hour (Peeters, 2003). A train departing at 9:14 will therefore also depart at 10:14, 11:14 and so on until the end of the day. The Periodic Event Scheduling Problem (PESP) described by Serafini and Ukovich (1989) is the corresponding mathematical problem with the objective to find a feasible cyclic timetable.

When constructing a timetable, multiple inputs are required. These include the route structure, frequency and the different *process times* which are explained in table 2-1. The running time between origin and destination is for instance depending on the characteristics of the rolling stock, speed limits and the dwelling time on the intermediate stations. These running times can be estimated theoretically, but also using simulation or historical data. A timetable is usually defined for longer time periods (e.g. a year).

One of the most pressing challenges in timetabling is the synchronization of different lines to enable fast transfers. Ideally, two trains arrive close to each other and on both sides of the same platform such that passengers can interchange trains with only minimum waiting time. This yields a so-called

Table 2-1: Different process times and their definition (based on Landex & Kaas, 2005)

Process time	Explanation
Running time	The theoretical travel time from A to B, based on the infrastructure and the characteristics of the rolling stock (e.g. acceleration and deceleration rate).
Dwelling time	The time a train stops at a station for alighting and boarding passengers. These times are often different per train type.
Minimum headway	The minimum required time between two consecutive train movements. This is determined using blocking times (see e.g. Hansen, 2009)
Actual headway	The actual time between two consecutive trains. This is depending on the frequency of a line and the minimum headway.
Buffer time	The difference between the minimum headway and the actual headway. If the delay of the first train exceeds the buffer time, it causes a knock-on delay.
Layover time	The time required to turn a train at a terminal station. This often includes a supplement in case the train arrives too late.
Travel time	The time a trip actually takes, being the sum of running times, dwelling times and a supplement.
Round-trip time	The time a train takes to make a round trip from origin to destination and back. This is the sum of the travel time and layover time.

cross-platform transfer. In larger networks, this challenge cannot be solved using an exact method (Desaulniers & Hickman, 2007). A second challenge is to determine the right amount of *allowance time* in the timetable, which is a little buffer added to the running time of a train. Adding allowance time makes that small disturbances can be absorbed and that the running time differences between different types of rolling stock can be resolved. However, a too large buffer results in an increased travel time and unnecessary long dwelling time if the train is on schedule.

Another aspect of the timetabling process is to assign tracks (and platforms) for all trains that pass or stop at the stations in the network. This for instance concerns the cross-platform transfer challenge described above. In general, routing trains trough a station can be a very complex problem, since there are many constraints regarding safety to take into account (Zwaneveld, Kroon, & Van Hoesel, 2001). Every movement within a station, like passing a switch after an other train or a crossing movement, requires a minimum headway to ensure safety.

Timetabling in practice

NS uses cyclic timetables which are created by a system called DONS. This system has two solvers called CADANS and STATIONS, which optimize towards a cyclic timetable and route trains through the stations respectively (Kroon et al., 2009). In fact, DONS is a system that aims to solve the PESP. The result is a Basic Hour Pattern (BHP), which contains arrival- and departure times of all train series. The BHP is the foundation of the timetable and is entered into a system called DONNA. From here, the timetable can be adjusted to its final form. A macro-level network simulator called SIMONE is used to assess the performance of the timetable.

The Dutch railway timetable changes every year on the second Sunday of December. This timetable is called the *annual plan* and is based on the BHP. All larger changes (if any) are introduced at this moment. If there are new developments regarding the line system and in the planning of crew or rolling stock, the changes are made here. Such changes are based on the BHP. If there are larger changes, like the introduction of the Hanzelijn, the BHP is adjusted too. Between annual plans, small adjustments are made to fit the plan to the actual demand and availability of the assets (Schaafsma, 2001). This results in incremental changes in the annual plan. Table 2-2 gives an overview of these different timetable "products".

Once every two months, a so-called *change sheet* is issued. This adapts the annual plan slightly, based on the experience of last months. If there are maintenance works at stations, some tracks might be out of service for a few months. Rolling stock may be taken out of service for maintenance or renovation in a similar way. Typical adjustments in the change sheet are therefore platform changes, minimal adjustment of arrival or departure times and changes in the distribution of rolling stock. The annual plan can be seen as a "big" change sheet with larger changes.

To adapt the train service to daily circumstances, a *day plan* is made. This operational plan is a direct derivative of the annual plan and change sheet and is used to incorporate the events of the day into the timetable. These events include football matches, concerts, fairs and other events that are likely to change the travel demand. Typical adjustments to the timetable include extra stops, longer trains and extra trains at the end of the day to transport everybody home. (Planned) maintenance works on railway tracks sometimes require a very different day plan because of unavailable tracks and detours. These day plans strongly deviate from the annual plan, but aim to maintain the pattern in departure times such that passengers and crew is still familiar with the timetable. Preparation of a strongly aberrant day plan can therefore take up to a few months.

Table 2-2: Long-term and short-term timetable products

Name	Frequency	Input
BHP	Irregular	Network structure Line system Process times
Annual plan	1x/year	BHP Rolling stock fleet Collective labour agreements
Change sheet	6x/year	Operations feedback Station building phases Rolling stock fleet
Day plan	Daily	Large events Planned track maintenance Rolling stock fleet

2.5 Rolling stock scheduling

When the timetable has been constructed, the trains can be scheduled to perform the specified operations. There are often different types and quantities of rolling stock which must be assigned with respect to the demand. A train is a *composition* of multiple *units*, which can consist of multiple coaches or *carriages*. Each unit has its own *stock number*, which is the number on the train unit itself. Figure 2-5 illustrates the different elements of a train. Rolling stock scheduling is the process of assigning a complete *train* to a *train number*.

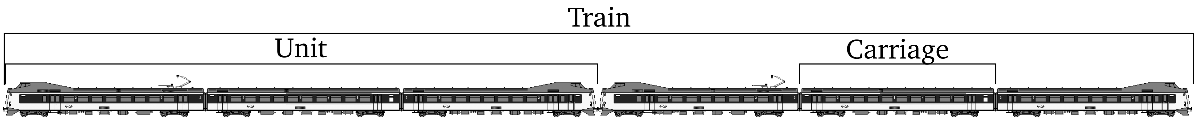

Figure 2-5: Composition of a train consisting of two units with three carriages each

Efficient scheduling of rolling stock is a very important issue for rail operators, since it is one of the largest cost sources for most rail operators (Goossens, 2004). The assignment often takes place in two phases. The first phase distributes the complete pool of rolling stock over the lines in the line system. This is often based on the required capacity during the busiest peak hour. If the allocation is appropriate during this peak hour, it will be appropriate after the peak as well (Abbink, Van Den Berg, Kroon, & Salomon, 2004).

The number of trains required per line is depending on the running time from origin to destination, the layover time and the frequency of the line. Dividing the time required for a complete round trip by the time between two consecutive trains yields the number of trains required to operate that line.

Consider a line as shown in fig. 2-6, with a running time of 60 minutes in both directions and a required minimum of 15 minutes layover time. The total round-trip time is therefore 150 minutes. If this line has a frequency of 1 train/hour and thus an actual headway H of 60 minutes, there are (at least) $\lceil 150/60 \rceil = 3$ trains required (with 30 minutes extra buffer). While operating the line two times per hour, H becomes 30 and the required number of trains is $\lceil 150/30 \rceil = 5$.

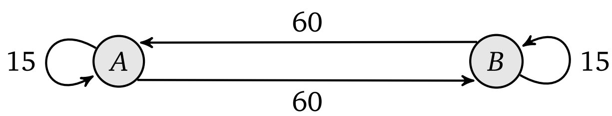

Figure 2-6: A line between nodes A and B with running- and layover times

The second phase is more detailed and assigns the number of carriages to the ride numbers. Because of possible fluctuations in the demand, for instance due to events, scheduling rolling stock is an operational task and planned a few weeks in advance. Trip 5510, for instance will be operated by a train consisting of units B2 and B4, resulting in a train with 6 carriages in total. The stock numbers associated with this train are often not planned on beforehand, but assigned on a daily basis. Abbink et al. (2004) make a difference between the peak hour planning and off-peak planning. During peak hours it is important to have an *effective* plan, which makes that the capacity is well-distributed and complies with the demand over the whole network. The planning of rolling stock for the rest of the day is an *efficiency* problem with the aim to minimize the carriage-kilometres.

Rolling stock scheduling in practice

In practice, rolling stock scheduling starts before constructing the timetable. Every train type has different characteristics, such that scheduling a different type of rolling stock can result in a different cycle time. Every train series is usually operated by the same train type. Before the actual timetable is constructed, the type of rolling stock is therefore mostly known. NS basically owns six train types operating on the main railway network. The maintenance planning and circulation of rolling stock results in a continuously changing number of train units that is actually deployable. Almost every train type knows two sub types with a different length[1] and capacity as shown in table 2-3. The length is expressed in the number of carriages, so is the length of station platforms.

Train units of the same type can be coupled to form a longer composition. The combination of ICM3+ICM3+ICM4 for instance has length 10 and a capacity of 955 passengers. The ICM and VIRM train types are deployed on IC lines, while the SGM, SLT and MAT64 train types are used for SPR services. The DDZ train type is used for both IC and SPR purposes at this moment.

Table 2-3: The operational NS train fleet on the main railway network by May 2014

Train type	Length	Fleet size	Capacity
ICM3	3	81	299
ICM4	4	46	357
VIRM4	4	92	478
VIRM6	6	69	722
DDZ4	4	24	449
DDZ6	6	18	763
SGM2	2	19	199
SGM3	3	51	345
SLT4	3	66	285
SLT6	4	55	437
MAT64	2	29	201

After constructing the timetable, the available units must be distributed over the different train series. The distribution depends on the demand and the capacity per train unit. To determine the demand, the *8 o'clock cross-section* is used. This is the number of passengers on a line at 8 o'clock in both directions, as it is assumed that the demand has its peak at this moment. If there is enough capacity at 8 o'clock, there will be enough capacity during the rest of the day.

The daily assignment of rolling stock (i.e. exact train length) is made to measure. Rolling stock is one of the largest cost drivers for railway operators like NS and custom-fitting the rolling stock assignment is an important way to save money. The exact assignment is therefore subject to change often. During normal operation, trains are often split and combined multiple times to fit the supply to the demand (Fioole, Kroon, Maróti, & Schrijver, 2006). It is assumed that this is not possible during winter weather as explained in section 1.5.

Figure 2-7 shows a diagram of the rolling stock assignment for train series 8800 between Utrecht and Leiden. Each line in the diagram indicates a train number (stock number not shown). The diagram indicates that after 8.00h all trains will be reduced from 3 to 2 units, and that these units will be used for other trains on the 8800 line later that day. These "spare" train units will be transferred to a shunting yard where they wait for their next duty.

[1]The SLT train type has smaller coaches than the other types, hence the difference in length.

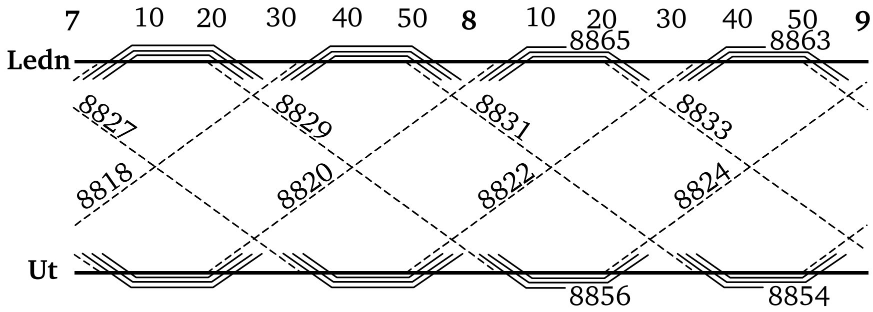

Figure 2-7: Part of the rolling stock assignment for train series 8800 (Abbink et al., 2004, p.36)

2.6 Crew planning

The last step in the planning process is the assignment of crew to all train movements on the network. Every train requires a driver and in most countries at least one guard (also called conductor). The required crew may also be depending on the train size as longer trains often have multiple guards. Every train trip is split into a sequence of *tasks*. These include all commercial trips for passengers, but also shunting movements and empty (dead-heading) train trips. One task must be performed by the same crew member (Goossens, 2004). Tasks start and end at crew bases and at so-called *relief points*, which are stations where crew is allowed to change trains (Potthoff, 2010). A sequence of tasks is called a crew *duty*.

The crew planning problem knows two phases. The first phase is the *scheduling* phase and defines all necessary crew duties such that they comply to a number of constraints. A duty has a maximum length, must start and end at the same crew base and should have a meal break if the duty takes longer than a certain threshold. These duties can be generated long time in advance. The second phase is the *rostering* phase, as it assigns the available crew to the different duties. There are again some constraints here, since the crew must amongst others be familiar with the train type. The train driver has another important constraint, as the driver must be licensed to drive on the route he is about to be assigned on (Potthoff, 2010). Crew rosters are typically made few weeks in advance, since they are depending on the exact rolling stock schedule and the availability of the crew (Shibghatullah, Eldabi, & Rzevski, 2006).

Crew planning in practice

At NS, the crew planning is divided in two phases as described above: Scheduling and rostering. The scheduling phase creates all duties necessary to operate the trains in the network. Generation of efficient and feasible duties is performed using the CREWS tool. There are constraints per duty and per crew depot, which are subject to change as a result of labour agreements. Every crew member should have enough variety in his or her duties and a duty may not be longer than 9 hours. The rostering phase assigns the available crew to the duties. This is done per crew depot with respect to holidays, full-time or part-time employment, absence and acquaintance with the rolling stock and route. NS has around 2,300 train drivers and guards on duty every day (NS, 2013a).

Figure 2-8 is a gantt chart of four duties belonging to three different crew depots (Abbink, Fischetti, Kroon, Timmer, & Vromans, 2005). The first duty starts in Eindhoven at 15:09 with a task to Den Haag, followed by a task to Zoetermeer and back. Since Zoetermeer is no relief point, the task consists of two rides. The third task is from Den Haag to Heerlen and the last task is ending at the crew depot in Eindhoven.

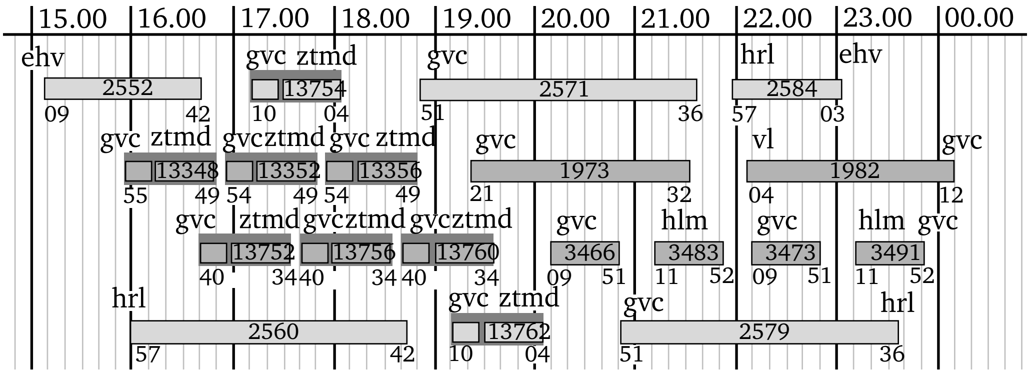

Figure 2-8: Part of a crew schedule with four duties (Abbink et al., 2005, p.397)

2.7 Operational railway control

Previous sections have described the *planning* process on railway networks. On the day of operations, there are often small events disturbing the *execution* of the plan. A robust plan requires no or little adjustments to cope with these disturbances. When the amount of these disturbances exceeds a certain threshold, however, adjustments to the plan are required. In this case, a controller interferes and adjusts the plan according to a predefined measure. This is the operational management of the railway network.

2.7.1 Controlling traffic and transport

It is important to distinguish two types of controllers: A *dispatcher* is in charge of the train traffic and intervenes when a train is running outside its planned path in the timetable. Dispatchers can for instance prioritize delayed trains to bring them back on their planned path or adjust the train path itself. The dispatchers are supported by *signallers*, who are controlling the traffic locally. Signallers are setting routes and performing small adjustments to the plan. All dispatchers and signallers are working for ProRail VerkeersLeiding (VL), controlling all passenger and freight traffic on the main railway network and all regional routes. They are also called traffic controllers.

A *transport controller* is monitoring the assets of the operator, being the rolling stock and the crew. Transport controllers make sure that the right trains and crew members are on the planned train path. They can for instance reschedule crew duties if a crew member calls in sick or has been delayed during a previous task. Transport controllers are working for NS Transportbesturing (TB) and are only controlling NS crew and rolling stock.

The different controllers have a number of "tools" to intervene in the railway operation. Schaafsma (2001) distinguishes three different traffic controlling measures:

- Adjusting: Adjustment of the traffic plan that doesn't affect the quality of the train service.
- Controlling: Modification of the traffic plan that does affect the quality of the train service, but is still based on the original plan.
- Rescheduling: A large modification that results in a new traffic plan with downgraded service.

Both types of controllers have different reasons to intervene, depending on the nature of the problem. Therefore, a distinction is made between two types of problems as described by Cacchiani et al. (2014): A *disturbance* is a relatively small perturbation of the railway system which is mostly handled by adjusting and/or controlling the train paths. This is typical work for a dispatcher, hence some trains might depart and arrive later than initially planned. A *disruption* is a relatively large incident which requires rescheduling. This commonly affects the train paths, but also the assignment of rolling stock and crew. Transport controllers are thus usually intervening in case of a larger disruption.

2.7.2 Control regions

Operational control of the train service is separated into multiple regions, such that the traffic and transport controllers have their own coverage area. The dispatchers and signallers are working from twelve traffic control centres (called Decentrale VerkeersLeiding (DVL)). Transport controllers are operating from five regional transport control centres (called Regionaal BijsturingsCentrum (RBC)). Both types of control centres have a different coverage area as shown in figs. B-1 and B-2 in Appendix B. The borders of both types of regions are partially shared, such that each transport control region has two or three traffic control regions within it.

Table 2-4 presents the five RBC regions and the DVL regions within them, along with their size in terms the stations they control (vertices) and the tracks between stations (edges). Note that the DVL is also responsible for traffic outside the main railway network of NS. It might look like DVL Groningen has a small coverage area, but that is not entirely true. There are multiple regional railway lines in the coverage area of Groningen that do not belong the the main railway network.

Table 2-4: The different traffic control regions within the transport control regions and their size

Transport region (RBC)	Traffic region (DVL)	Vertices	Edges
Randstad Noord	Alkmaar	39	40
	Amsterdam	28	35
Randstad Zuid	Den Haag	18	20
	Rotterdam	13	14
	Roosendaal	17	17
Utrecht	Utrecht	28	32
	Amersfoort	18	21
	Arnhem	18	18
Noord-Oost	Groningen	4	3
	Zwolle	33	35
Zuid	Eindhoven	19	21
	Maastricht	18	18
	Total	253	274

Besides the regional RBC and DVL control centres, there are also national equivalents. The Landelijk BijsturingsCentrum (LBC) is the national transport control centre and the Landelijke VerkeersLeiding (LVL) is the national traffic control centre. Both are located in the Operational Control Centre Rail (OCCR), which is the largest control centre in The Netherlands. From here, all train movements are monitored 24/7. The OCCR is especially useful in case of a larger disruption that affects multiple control regions, since both dispatchers and transport controllers are working closely together here. In case of a larger disruption, the OCCR can coordinate between the control centres such that recovery is faster.

2.7.3 Rescheduling in disrupted situations

In case of a larger disruption, the dispatchers must try to keep the nuisance to passengers to a minimum. Such a disruption is often a blocked track section, regardless of the cause. If the disruption is reported, the dispatchers will "downgrade" the train service according to a predefined plan called a *contingency plan*. Due to safety regulations, the train traffic is often cancelled in both directions (RailAlert, 2012). Once the track section is released, the full train service can be restored gradually. Between the blockage and full recovery of the train service, there are three phases (Berenschot, 2011):

1. Downgrading the train services according to the contingency plan
2. Running a reduced train service while fixing the problem
3. Restarting the full train service

The first phase is the most important since it is crucial to know the exact problem before the right contingency plan can be initiated. This makes time essential in the first phase. Once the problem is identified, the train service is downgraded and all affected track sections have been cleared from stranded trains, until a stable situation is achieved. This makes the first phase a crucial phase with many ad-hoc and pragmatic decisions. It is especially difficult to deal with multiple first phases at the same time.

During the second phase, the train service has been downgraded while the problem is being fixed. According to the estimated time required to restore the infrastructure, a start-up plan is made. This is a plan to restore the train service to the normal situation and starts as soon as the infrastructure is released (phase 3). Once the full train service has been restored, the caused delays will decrease gradually.

A typical way to downgrade the train service is to uncouple the affected lines (NS & ProRail, 2012). This means that trains are switching direction at a suitable station and return in opposite direction, called *short-turning*. A long line is uncoupled into two smaller lines, starting up- and downstream of the disruption. This way, most stations on the line are still served. The short-turn stations are also called *uncoupling points* and are included in the different contingency plans.

Consider the example in fig. 2-9: The tracks between stations B and C are unavailable due to an infrastructural failure. As part of the contingency plan, trains from A will short-turn in B and still provide a train service west of the disruption. The same happens in C for the eastern part of the line. Depending on the nature of the disruption and the estimated duration, buses may be deployed to transport passengers between B and C.

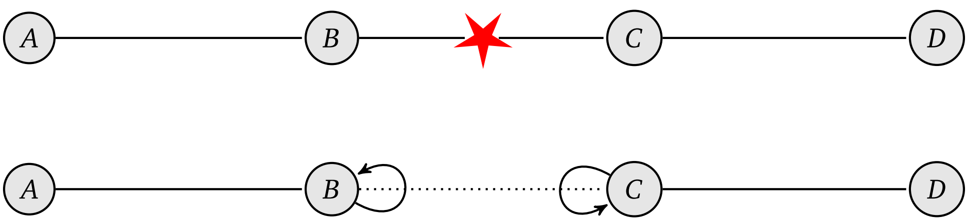

Figure 2-9: A line between nodes A and D and short-turning measure in case of a disruption

2.7.4 Typical disruptions during winter weather

Larger disruptions on the railway network are occurring on a daily basis. Such disruptions can be related to either the infrastructure or the rolling stock, but in both cases it affects the actual train service. Table 2-5 gives an overview of typical major disruptions on the Dutch railway network. During extreme winter weather, both disturbances and disruptions are occurring more often than on an average day. Conclusions from multiple winter evaluations by ProRail (2014) and NS (2011, 2012a) indicate the weaknesses of rolling stock and infrastructure when it comes to snow and frost. Yap (2014) provides an overview of major discrete events on the Dutch railway network from January 2011 to August 2013 and compared the data with the weather forecast. Yap concludes that three types of disruptions are occurring much more often during winter days with snow. It should be noted that the weather itself is often not considered as a disruption, as the weather is the *cause* for other disruptions like vehicle breakdowns, switch failures and signal failures. Figure 2-10 portrays the number of disruptions in January 2013. The spikes clearly indicate the days with snow.

Table 2-5: Major disruptions on the Dutch railway network

Infra	Rolling stock	Other
Signal error	Vehicle breakdown	Restrictions by emergency services
plaatsen Switch error	Collision	Crew lateness
Defect overhead wire	Derailment	Copper theft
Damaged bridge		Suicide
Power failure		Pedestrians near the tracks
Obstacle on track		

Vehicle breakdowns are occurring approximately twice as often as on a normal day (Yap, 2014). This has to do with damage caused by freezing parts of the train. Refreezing snow on the trains can result in failure during the day. Melting snow can also result in a short circuit. Some train types are not well in resisting frost at all and break down when they are not in operation (during the night). NS is currently experimenting with anti-icing solutions to prevent refreezing snow on the trains, although not all types of rolling stock can be treated with this substance (NS, 2013e).

Switch and signal failures are the main problem on winter days and occur up to 10 times more often (Yap, 2014). The main reason for these failures is that parts of switches are blocked by chunks of ice. When a train passes the switch, the resulting vibrations can cause detachment of ice on the underside of the train. If the ice falls between the switch blade (also called the switch's tongue), the switch jams and causes a failure. Additionally, a moving switch blade works like a shovel, accumulating snow between the moving parts of the switch. Most switches have a heating element to prevent frozen switch blades, but these heaters are not capable of melting large ice chunks. In other countries, the number of switch failures during the winter is around 20-30% higher compared to the other seasons. This clearly indicates that switches are critical infrastructure assets during the winter (LeighFischer, 2012).

A study by ProRail (2014) regarding switch failures between February 2012 and February 2013 shows that these failures are occurring up to 7 times more often on a winter day with snow. Where a "normal" day has on average 17 switch failures, the average on a day with snow is 114. During winter weather, ProRail therefore deploys mobile maintenance crews throughout the country to enable fast recovery. These are often positioned at strategic stations, since most switches are located at or close to these stations.

A more thorough analysis shows that the failure rate of switches is correlated with the *crossing angle*

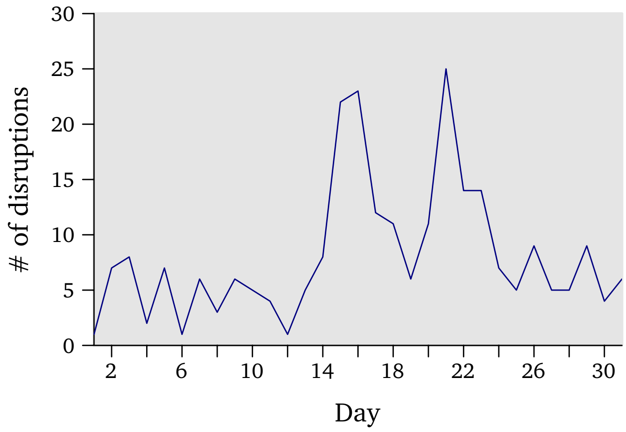

Figure 2-10: Disruptions in January 2013 (Rijdendetreinen, 2014)

of the switch. Switches with a greater crossing angle are considerably causing a failure more often. This merely concerns the switches with a crossing angle of 34.7 or 39.1, the so-called high-speed switches. These switches have a very long switch blade, such that they can be crossed at high speeds in both normal and reverse direction. On normal days, their failure rate is already higher than for other switches. Snowy days are causing even more failures, which is related to their long switch blade. There are around 100 high-speed switches in The Netherlands.

Another problem of high-speed switches is their location in the network. Logically, these switches are located on open tracks where the speed limit is up to 140 km/h. In case of a failure the maintenance crew needs to drive to this switch by car, which takes time. Especially during winter weather when the roads are snowy too. This makes that high-speed switches are poorly accessible for maintenance crews.

2.7.5 Operational management running out-of-control

The direct cause for a comprehensive winter programme are the out-of-control situations in the winters of 2009, 2010 and 2012. If this happens, one or more operational control instances on the railway network are not able to control the train traffic anymore. More specifically, the situation is out-of-control if one of the following conditions holds (NS, 2012a):

- At least one of the actors in the operational control of the railway network gives up, resulting in cancelled train traffic while necessary resources (infrastructure, rolling stock, personnel, ICT) are available.
- At least one of the actors in the operational control of the railway network does not know what happens in the operation or what other actors are doing.

If this happens, the controllers completely lose control of the train service meaning that no usable information can be provided. There are three main underlying causes resulting in an out-of-control situation (NS, 2012a):

1. The way of controlling and adjusting the daily train system (this becomes apparent in a disturbed situation).
2. Lack of a timely, clear, unambiguous and fully communicated decision by the right persons on all levels.

3. Undermining routine by introduction of new, complex operational (winter) measures and adjustments.

The report concludes that there is a daily train control problem, which is especially visible in case of extreme weather in the winter. The problem is tried to be solved with extra operational measures, leading to even more problems.

Further analysis shows that the way of controlling the Dutch train network has not really changed in the last 20-30 years. Train controllers are reordering, rerouteing and cancelling trains manually using computer systems that do not have any decision support (NS, 2012b). Moreover, the Dutch train network has become much busier since 1998 as the frequencies of almost all train services in the Randstad have doubled to 4 times/hour. Deploying a reduced timetable during winter weather gives the controllers more room to deal with the disturbances.

2.8 Summary of railway planning

Planning and controlling a railway network is very complex. The planning process knows strategic, tactical and operational decision processes and there are many ways to approach the problems in all phases of the process. Due to this, there are many interdependencies between the different phases of the process. Changing the line system, for instance, has its consequences on the timetable, the rolling stock assignment and the crew planning. Major changes are therefore occurring only once in many years.

External influences make that it is difficult to run operations exactly as planned. These influences range from small disturbances to large disruptions, respectively causing minor delays to completely cancelled train trips. The operational controllers of the network, separated in dispatchers, signallers and transport controllers, are intervening when needed to keep control of the operations and return to a stable situation as soon as possible.

On days with extreme winter weather, several types of disruptions are much more frequent. Snow and ice has its effects on both infrastructure and rolling stock, resulting in malfunctioning switches and broken trains. Such disruptions occur up to 10 times more often during days with snow. NS is experimenting with anti-icing to prevent the accumulation of ice on the trains, while ProRail deploys mobile maintenance crews to fix switch failures. High-speed switches are particularly notorious for their failure rate during winter weather, but are not easily accessible by maintenance crews because of the location of these switches. If there are too much disruptions at the same time, the network can run out-of-control.

Reducing the timetable to a basic service makes the network more robust as it yields more room for operational control. This way, an out-of-control can be prevented. In the next chapter, we will take a closer look at robustness and how robustness can be achieved in a railway network. Furthermore, the relationship between the robustness and the transport capacity of a railway network will be addressed.

3

Definition of robustness and transport capacity

The previous chapter has given an extensive overview of the planning process and operational management of a railway network. Since the objective of this study is to create a robust line system with enough transport capacity for winter circumstances, it is necessary to define what factors determine the robustness and transport capacity of a line system and how they relate to each other. Especially robustness is a very broad, ambiguous and non-consistently used term. This chapter elaborates on how robustness and transport capacity are used in literature, and defines criteria and corresponding indicators for further use in this study.

3.1 Defining network robustness

Robustness is a very broad term, which is subject to multiple different interpretations. Many authors have written about robustness and defined the term in such a way that is is applicable to their field of research. The general thought is that a robust system takes uncertainty into account by considering the ranges of possible values of parameters. The robustness of an initial decision is the degree of flexibility in the future. Rosenhead (2013, p.1346) defines robustness in a very formal way by *"the number of acceptable options at the planning horizon that are compatible with that [initial] commitment, as a ratio of the total number of acceptable options"*. Robustness therefore tells something about the possibility to deal with possible scenarios in the future. This section gives an overview of the aspects and characteristics of a robust network in different application fields.

3.1.1 Supply chain networks

Supply chains have been changing to fast, dynamic systems in the last years. Static, linear and simplified strategies have been replaced with more complex and dynamic variants to be able to respond to changes in supply and demand (Choi, Dooley, & Rungtusanatham, 2001). A literature review by Klibi, Martel, and Guitouni (2010) shows that there are many performance measures to value the possibility of a supply chain network to return to its stable condition. These measures include terms as flexibility, agility, reliability, robustness, responsiveness and resilience. Klibi et al. state that these terms have a considerable overlap and that the notions of *robustness, responsiveness* and *resilience* are sufficient.

Robustness has to do with the possibility to deal with sudden changes. Wieland and Wallenburg (2012, p. 890) define robustness by *"the ability of a supply chain to resist change without adapting its initial stable configuration"*, while Klibi et al. (2010) state that a robust supply chain remains effective for all plausible futures. This means that a robust supply chain is capable to return to a stable situation without the need for (human) intervention. Possible risks are mitigated on beforehand, which makes the supply chain insensitive to noise factors (Mo & Harrison, 2005).

The ability to cope with changes in a reactive manner is defined by the responsiveness and the resilience of a supply chain. Responsiveness is typically described as the possibility to respond to short-term variations in supply and demand (Klibi et al., 2010). Resilience is described as the ability to quickly recover from disruptions caused by unexpected events. Wieland and Wallenburg (2012, p. 890) summarize both responsiveness and resilience in the term *agility*, which is specified as *"the ability of a supply chain to rapidly respond to change by adapting its initial stable configuration"*. Increasing the responsiveness of a supply chain can amongst others be done by creating capacity buffers, overtime policies and flexible sourcing contracts. Resilience strategies are aiming to reduce risks and enable efficient implementation of responsiveness policies (Klibi et al., 2010).

Wieland and Wallenburg (2012) differentiate between *reactive* and *proactive* strategies. The difference between these two aspects is the need for intervention. A proactive strategy yields robustness, as it aims to return to a stable situation by resisting changes. A reactive strategy yields agility, as it aims to return to a stable situation by responding to changes. The difference between robustness and agility is thus the way a supply chain (or system in general) responds to changes. Whereas an agile system responds to changes, a robust system rather resists these changes (Husdal, 2010).

Lambrechts, Demeulemeester, and Herroelen (2011) introduce a proactive approach to deal with uncertainty. Proactive scheduling is a method using statistical knowledge of possible uncertainties to construct predictive schedules. By using extra resource capacity or extending the execution time of an activity (i.e. by introducing a buffer), the predicted uncertainty can be compensated without the (direct) need for rescheduling. A schedule is therefore considered robust if it is able to absorb the predicted disturbances without affecting other planned activities (O'Donovan, Uzsoy, & McKay, 1999).

3.1.2 Road networks

When it comes to road networks, many researchers have written about the ability to cope with disruptions during operations. The degree to which extent a road transport network is able to do so, is mostly referred to as the robustness of the network. A higher degree of robustness is achieved when a network is designed such that certain variations or failures of components are tolerated (Immers, Yperman, Stada, & Bleukx, 2004; Tahmasseby, 2009). Based on the findings of Immers et al. (2004), Snelder (2010) has defined five elements that contribute to making a road network more robust:

- Prevention: This can either relate to prevention of congestion due to disruptions, or the prevention of (larger) disruptions in itself.
- Redundancy: The redundancy relates to the spare capacity in the system. When disruptions occur, the spare capacity can be used to compensate for the unavailable infrastructure. A distinction is made between active and passive redundancy, where the first includes solutions that are in use like alternative routes, and the second includes back-up solutions like ferries in case of a bridge failure.

- Compartmentalization: This term defines to which degree congestion remains restricted to one part (i.e. link) of the network. Less interdependencies in the network will make sure that congestion cannot propagate further.
- Resilience: The capability of a transport system to recover from an overload
- Flexibility: The capability of a transport system to fulfil different functions than it has been designed for.

The opposite of robustness is called the *vulnerability* of a network (Tahmasseby, 2009). It is defined by the sensitivity of services to variations in transport supply caused by disruptions. High robustness indicates that a system is not vulnerable, while a highly vulnerable system implies that it is not very robust. To improve transport systems, Tahmasseby (2009) distinguishes two approaches. The first approach is the *prevention-oriented approach*, where the robustness is increased by reducing the vulnerability. The *coping-oriented approach* is focusing on eliminating or mitigating the impacts of disruptions. The prevention- and coping-oriented approach are therefore comparable with respectively the proactive and reactive strategies defined by Wieland and Wallenburg (2012).

3.1.3 Rail networks

Railway networks are similar to road networks when it comes to their function: Providing transport services. Railway networks are however different from road networks as they have a timetable and are usually not open to anyone at any time. Rail networks are also less flexible than road networks because trains are fixed to their dedicated infrastructure. In a road network, moreover, the users and the vehicles are the same entity, which is not the case in a rail network. The timetable of a rail network is basically an ordered list of tasks which should be performed at a designated time. Deviation from this timetable has influence on the succeeding tasks and should therefore be minimized. Especially in The Netherlands, where the same infrastructure is shared by different railway services, delays can easily propagate (Vromans, Dekker, & Kroon, 2006).

To prevent delay propagation, a timetable should be robust. A typical technique from scheduling theory to do so is by introducing time slacks (margins) to the execution of tasks (Davenport, Gefflot, & Beck, 2001; Kroon, Dekker, & Vromans, 2007). In railway scheduling, these margins are added to some of the process times mentioned in table 2-1 to prevent trains from running out of their schedule. The most effective margins are buffer times. These are slack times between two consecutive trains used to prevent knock-on delays, which means that the second train is delayed because the preceding train is behind schedule (Andersson, Peterson, & Törnquist Krasemann, 2013; Gestrelius, Aronsson, Forsgren, & Dahlberg, 2012). Another way to incorporate slack is to add time supplements to the running time of a train. Such a supplement will for instance allow trains to let a trip take longer than theoretically possible, such that a small delay can be compensated. Time supplements therefore enable the railway system to recover from a disturbance without intervention by a controller (Van Oort & Van Nes, 2009a). If the train is on time, these time supplements enable energy-efficient train operations as the train does not need to operate at full speed (see e.g. Scheepmaker, 2013).

Cacchiani et al. (2012) indicate that robustness in railway timetables can refer to either the *absorption capacity* or the *recoverability* of a schedule. The absorption capacity indicates the ability of a timetable to deal with relatively small disturbances without the need for structural changes. Recoverability expresses the ease to adjust the schedule in case of a larger disruption. According to Fischetti, Salvagnin, and Zanette (2007), a robust timetable favours delay compensation without intervention by the traffic controller. Either way, robustness is mainly necessary to reduce the *impact* and *propagation* of delays of any size through the network.

Goverde and Hansen (2013) distinguish the robustness, stability and resilience of a timetable. The robustness of a timetable is referred to as the ability to withstand changing operational conditions. Variations in travel times for different types of trains and the stochastic nature of process times require time slacks to *prevent* delays. Stability is the ability of a timetable to absorb disturbances, such that a stable timetable can automatically *engage* delays without the need for dispatching. Resilience is the flexibility of a timetable to reduce delays by *interventions* from dispatchers. Hence, robustness is concerned with delay prevention, stability with proactive delay absorption and resilience with reactive delay management.

Robustness is closely related to the reliability of a railway system. Reliability says something about the predictability of the (door-to-door) travel time, and is a major factor in deciding what transport mode to use (De-Los-Santos, Laporte, Mesa, & Perea, 2012; Vromans et al., 2006). The most used indicator to assess the reliability is punctuality, being the percentage of trains arriving or departing within a certain threshold (Schaafsma, 2001). In the end, the traveller wants to have a reliable travel time from origin to destination. A robust network leads to less variations in travel time due to disturbances and disruptions, and thus more reliability (Snelder, 2010).

3.1.4 Proactive and reactive aspects

Previous work by different researchers shows that robustness is a broad term without a clear and common definition. The concept of robustness is, however, the same: The tolerance for a certain degree of uncertainty (Policella, Oddi, Smith, & Cesta, 2004), the extent to which a network is able to maintain its function (Snelder, 2010) or the ability to resist imprecision (Salido, Barber, & Ingolotti, 2008). Robustness is thus the ability to endure (un)expected changes, based on statistical variations in the execution of a process. The degree of this ability defines the degree of robustness.

Most of the authors distinguish the difference between proactive and reactive methods to obtain robustness. Some authors state that both proactive and reactive methods are ways to achieve robustness (Cacchiani et al., 2012; Immers et al., 2004; Klibi et al., 2010), while others state that robustness refers to proactive methods only and that reactivity is achieved by having agility, responsiveness or resilience (Fischetti et al., 2007; Gestrelius et al., 2012; Salido et al., 2008; Wieland & Wallenburg, 2012). A concept by Liebchen, Lübbecke, Möhring, and Stiller (2009) is called *recoverable robustness*, which integrates both reactive and proactive prospects into one framework.

In short, proactive methods are precautionary measures like slack times and buffers to enable a system to absorb small changes. These methods are all aiming to *prevent* the system from becoming disrupted and *limit* the impact of disturbances. Reactive methods require *interventions* by agents, which could be a human train controller or controlling software, typically issuing rescheduling measures to recover from larger disruptions. More specifically, reactive methods are interventions as described in section 2.7.1. It is important to note that proactive control (like switching the order of two trains) is a reactive method, as it requires an action from the dispatcher.

From this point, robustness is defined as a collective term that indicates the ability to endure changes with both a proactive and a reactive component. Proactive methods are referred to as preventive techniques to reduce the impact of disturbances in a timetable, preventing small delays from propagating through the network. These techniques define the *potential to absorb* disturbances during operations. When the proactive methods are insufficient, for instance during larger disruptions, reactive methods are required. These comprise the *ability to control* the railway network. This makes that robustness has two components, being absorption capability and controllability as visualized in fig. 3-1. Recall the difference between a disturbance and a disruption, explained in section 2.7; Absorption capability relates to disturbances, whereas controllability relates to disruptions.

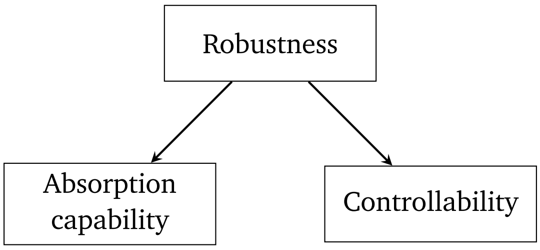

Figure 3-1: Visualization of the term robustness and its two components

Despite the separation, the absorption capability and the controllability of a timetable are nonetheless closely related. A timetable with a high absorption capability will be able to absorb disturbances while maintaining punctuality and without the need to cancel trains (Steenhuisen & Van Eeten, 2008). A too tight schedule requires more adjustments and possibly the cancellation of trains, for it has less absorption capability. Insufficient absorption capability will thus require earlier adjustment, which makes that small disturbances are being treated as larger disruptions.

Applied to the situation in The Netherlands, both components of robustness refer to different processes. The capability to absorb disruptions is preventive and thus something you can plan for. The absorption capability is consequently depending on the timetable, rolling stock schedule and crew planning. The controllability is depending on the competence, the effectiveness and the number of operational controllers on the railway network, being the dispatchers, signallers and transport controllers.

3.2 The transport capacity of a railway network

The transport capacity of a railway network, and in particular the capacity of a line, is much easier to define than the robustness. If the capacity is expressed in the number of passengers a line can transport from A to B within time period T, this is the product of the train capacity and the frequency. Hence a train with 200 seats and a frequency of 2 trains/hour can transport 400 passengers per hour (assumed it is not possible to transport standing passengers). Increasing the transport capacity is thus straightforward and can be done by increasing the capacity of the train and/or increasing the frequency. To maximize *both* the robustness and the transport capacity, trains should thus be as long as possible while the frequency is as low as possible.

3.2.1 Coherence of transport capacity and infrastructure

Both the length of a train and the frequency cannot be increased infinitely. The train length is often bound by the length of the platforms. Passengers need to board and alight trains from a platform, such that a train cannot be longer than the length of the platform. More specific, the length of the *shortest platform* a train attends determines the maximum length of the train. Other constraints can relate to the traction or energy a train requires. In the Netherlands, platform length is the most important constraint for train length. The longest trains on the Dutch railway network have a length of 12 carriages and require at least 325 metres of platform.

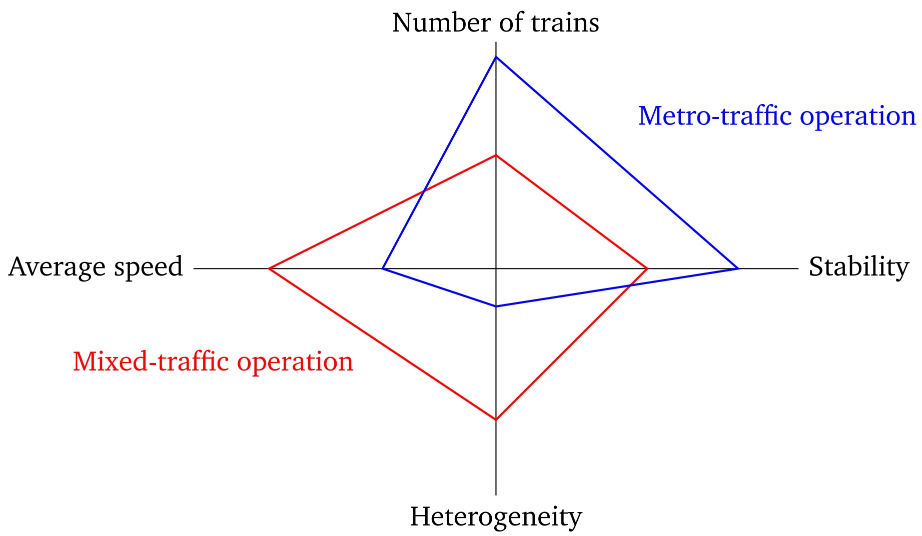

Figure 3-2: The railway capacity balance (UIC, 2004)

The maximum frequency of a line is depending on the capacity of the *infrastructure*. The UIC (2004) states that capacity as such does not exist and that the capacity of railway infrastructure is depending on the way it is used. This is often called the *infrastructure occupation*. The infrastructure occupation can be calculated using the timetable compression methods, which is explained by Goverde and Hansen (2013). On a given infrastructure, the infrastructure occupation is derived from several interdependent elements:

- The number of trains, being the sum of the frequency of all lines on the edges
- The heterogeneity, being the mix of different types of trains (SPR and IC, but also freight trains)
- The average speed, since a higher speed results in a longer braking distance
- The stability, being the different margins and buffers to absorb delays (hence, the absorption capability)

The way these four elements interrelate is shown in fig. 3-2, where the length of the chord indicates the *theoretical* capacity. The theoretical capacity is the maximum number of trains under ideal circumstances (UIC, 2004). A metro-traffic operation implies a high frequency and much stability, as the average speed is low and the traffic is very homogeneous. A mixed-traffic operation has a higher average speed and more heterogeneity, which is possible if the number of trains and/or the stability is reduced.

3.2.2 The trade-off between transport capacity and robustness

Salido et al. (2008) describe the coherence between absorption capability, optimality, transport capacity and heterogeneity. They state that the absorption capability is a function of the other three factors. By decreasing the values of these, the absorption capability will increase.

Optimality is decreased by introducing time supplements and buffer times at strategic points in the timetable. A journey with more supplements will take longer and thus decrease the optimality of the trip, but there is less sensitivity to delays. The optimality can be seen as an element of average speed as defined by the UIC, as more supplements will result in less average speed. There is, though, no consensus in literature on the location of these supplements (Gestrelius et al., 2012).

The aspect of heterogeneity corresponds with the capacity balance of the UIC. Heterogeneity is defined by the mix of train types, where the difference in train characteristics is decisive. Vromans (2005) presents measures to homogenize the train traffic by for instance equalization of the number of stops between IC and SPR trains and overtaking. This results in a larger buffer between two subsequent trains. The Sum of Shortest Headway Reciprocals introduced in Vromans (2005) and Vromans et al. (2006) shows that an even distribution of actual headways (hence, trains) yields less interdependencies between the trains and thus more absorption capability.

The third factor described by Salido et al. (2008) is capacity, but is a confusing term in this context. Salido et al. intend to indicate the number of trains in this case, which makes that they use the same measure as in the UIC capacity balance. Limiting the number of trains has more or less the same effect as homogenization. The average headway becomes larger. Therefore, decreasing the number of trains yields a higher absorption capability too (Abril et al., 2008).

As a consequence of the above, it can be concluded that an even distribution of trains over a time period yields the largest average headway and thus the most stable operation. Hence, the absorption capability is maximized. Increasing the buffer can be done by homogenizing the traffic, decreasing the number of trains and/or decreasing the average speed. Figure 3-2 clearly shows these trade-offs. Moreover, it shows the direct relation between frequency and absorption capability. If the frequency is increased while the average speed and heterogeneity are fixed, there is less capacity left to absorb small disturbances and vice versa. Decreasing the number of trains is not favourable, as this decreases the transport capacity. In order to increase both the frequency and the absorption capability, the average speed and/or the heterogeneity of the train service must be changed.

The frequency of a train service is not only direct related to the robustness, but also to the transport capacity. From a robust perspective, less trains means less traffic and less interdependencies between the trains. A higher frequency on the other hand, yields more capacity to transport all passengers. The frequency is thus a very important decision variable in the design process, as it influences both the robustness and the transport capacity. Figure 3-3 indicates this.

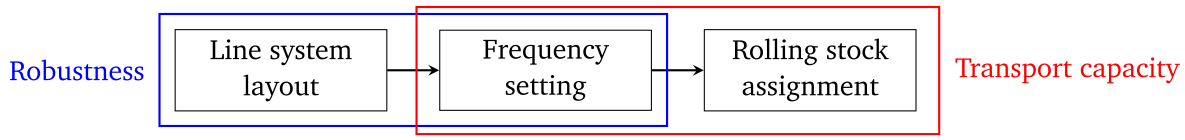

Figure 3-3: Frequency as a decisive variable

3.3 Criteria for a robust railway network

Depending on the exact definition, there are multiple criteria and indicators to measure the robustness of a railway network. For some indicators, the corresponding values can be calculated or estimated based on the line planning and frequencies. More specific performance indicators can only be measured using simulation or execution and therefore require a complete and more detailed timetable. Andersson et al. (2013) separate indicators related to the *characteristics of the network* and indicators related to *traffic performance*. The latter cannot be calculated without a complete timetable and requires execution or simulation. This yields quantitative data to determine to what extent the railway network is able to resist small disturbances and recover from large disruptions.

The scope of this thesis is to compare different line systems and evaluate their performance regarding robustness and transport capacity. Since working out a line system into a detailed timetable is very time consuming, it is more useful to compare different concepts on its characteristics. The characteristics of a line system are not very specific, yet they can be used very well to compare alternatives (Salido et al., 2008). This section therefore defines robustness characteristics which can be measured on a conceptual level without the need for a detailed timetable.

3.3.1 Line length

The length of the lines in the line system says something about the possible propagation of delays through the network (Van Oort & Van Nes, 2009b). The shorter a line is, the less stops are being affected in case of a disruption. This idea has been the foundation of the ADVD, one of the former alternative winter timetables. Figure 3-4 is a simplified example of short lines. By operating a long line, a disruption between A and B will also affect the connection between B and C. A line system with short lines does not have this problem, but a trip between A and C requires a transfer. Short lines make that disruptions are restricted to a specific part of the network, called *compartmentalization* (Snelder, 2010). The average line length in a railway network is therefore a factor for both the absorption capability and the controllability. Delays are restricted to a local level, which makes them easier to absorb and control.

To achieve shorter lines, a long line can be split up into two or more smaller lines such that the second line starts where the first line ends. This immediately shows the downside of short lines, which is the increasing need for transfers. Passengers will need to transfer trains more often if the lines become shorter and thus have a less optimal trip. This clearly illustrates a design dilemma, as there is a trade-off between robustness and optimality. Another disadvantage of short lines is the increased occupation rate of infrastructure on and around terminal stations. Turning a train takes much longer than making an intermediate stop, which increases the platform occupation time significantly.

Figure 3-4: One long line from A to C (left) and two short lines from A to B and B to C (right)

From a robustness perspective short lines are thus preferred over long lines, though not too short. A network with too much shuttle services could result in less optimal connections, increase the number of transfers and therefore make travelling by train less attractive. This could subsequently result in less passengers. On the other hand, however, a more robust network can provide more reliability for the passenger.

Indicators for line length

The length of a line can be expressed in multiple ways. A typical measure is the length in kilometres, although this is not a very practical one. There is a large difference in stop spacing on the network between the crowded Randstad area and the rest of the Dutch network, such that a 100km line cannot tell anything about the number of stops on the line. Using the number of stops is for the same reason not practical either, since a line with five stops could be a long 100 km IC line or a short SPR line of only 15 km.

A compromise is to define a number of "major" stations in the network and use the number of these stations a line attends as a measure for line length. Almost all IC stations can be considered as major stations, except for suburb stations like Amsterdam Amstel and Rotterdam Alexander. NS classifies its stations into six categories, as described by Van Hagen and De Bruyn (2002). Types 1 (very large station in centre of a large city) and 2 (large station in centre of a medium-large city) are classified as the major stations, since they are served by IC lines and located in the centre of the city. This does not work the other way around. Some stations are currently served by IC trains, but not classified as major stations and thus exceptions to the classification. This for instance applies to Heerenveen (type 4) and Driebergen-Zeist (type 6), which are served by IC trains but are relatively small stations. A list of type 1 and type 2 stations can be found in table C-1 in Appendix C.

Table 3-1: Indicator and measure for the line length criterion

Indicator	Measure	Robustness aspect
Major stations attended	Average per line	Absorption capacity & controllability

3.3.2 Traffic intensity

Section 3.2.1 has shown that the robustness (in terms of absorption capability) is amongst others depending on the use of the infrastructure. A higher frequency means more trains per hour, and thus a more intensive occupation of the network. In section 3.2, it has already been concluded that the transport capacity can be increased by either using longer trains or increasing the frequency. More trains per hour increase the capacity of the train service, but decrease the robustness.

The robustness is directly influenced by the frequency as more traffic implies less slack time and buffer between trains, shown in the capacity balance in fig. 3-2. When a train is delayed, a higher frequency will sooner cause a knock-on delay. This is the main reason the frequency in the LUD is reduced: It decreases the intensity of the train traffic. It is clear that the frequency of a line is a direct trade-off between transport capacity and robustness. From a robust perspective, a lower frequency is better. On the other hand, a lower frequency decreases the transport capacity.

Next to frequency, the *line density* has its influence on the robustness. The Dutch railway network has a high line density, since many lines have an *alternating* nature. This means that there are two or more lines from one origin to multiple destinations with a certain overlap. Figure 3-5 illustrates this idea, where there are lines from A and B to E and F, such that there are four lines between C and D. Alternating lines are used to establish a direct connection between stations and limit transfers, as well as to increase the frequency on the overlapping edge. If all lines run once per hour, passengers can still travel twice per hour from A to F. They can use the direct (purple) line, but also use the green line to E and transfer trains in either C or D. These are typical cross-platform transfers.

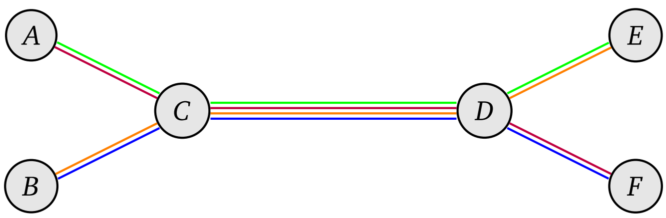

Figure 3-5: Alternating lines from A and B to E and F

Alternating lines are useful to serve passengers with minimal transfers, but are less useful in case of a disruption. The more lines sharing the same infrastructure, the more lines will be affected when something happens. Figure 3-6 is an example of such a disruption. Because of an obstruction between stations B and C, almost all other links are affected. Assuming there is no train traffic possible between B and C, there are two scenarios:

1. The blue and orange line are cancelled, reducing the service frequency in C-D, D-E and D-F.
2. The blue and orange line can short turn in C and still provide partial service (dotted lines in fig. 3-6).

If the lines are non-alternating, as shown in fig. 3-7, the same disruption will not affect passengers between D and E. There are again two scenarios here:

1. The blue line is cancelled, reducing the service frequency in C-D and unable traffic between D and F.
2. The blue line can short turn in C and still provide partial service.

Figure 3-6: A disruption in an alternating network affects multiple links and lines

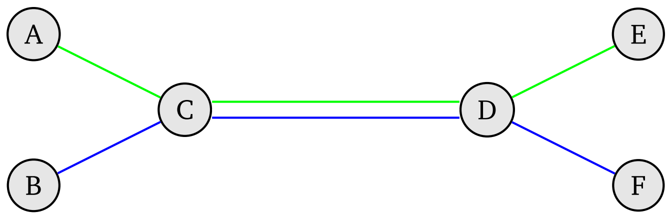

Figure 3-7: The same network as fig. 3-5 with non-alternating lines

The possible options to control the traffic in case of a disruption clearly indicates the advantages of both the alternating and non-alternating network. If the affected train series are cancelled, the alternating network is still able to reach station F, but the frequency between D-E is reduced by half. The short-turning scenario yields the same service for both networks. However, it requires controlling *two* train series instead of one. Controlling the non-alternating network therefore requires *less effort* from the control centre to establish alternative connections. Especially when stations E and F are both located in different control regions this is an advantage, because this requires adjustment back and forth. Schaafsma (2001) points out that train operators and traffic controllers have contrasting needs when it comes to the line system: *"operators benefit from long and bundled lines, though this reduces the controllability of the traffic"* (p.112). This clearly indicates that a lower line density improves the controllability of the network.

Indicators for traffic intensity

To determine the traffic intensity it is not useful to simply know the frequency of single lines. If lines (partially) share the same infrastructure, only the *sum* of frequencies says something about the occupation of the tracks. The frequency is therefore best measured by the number of trains on the same track section per hour. All track sections between two stations have the same frequency, so we actually calculate the frequency per *edge* as already explained in section 2.2. The number of trains per edge per hour is an indicator that shows how “busy” the network is.

Besides the number of trains, the number of lines per edge is an interesting indicator. This tells something about the number of affected lines if there is a disruption on the respective edge. The average number of lines per edge indicates the *line density* on the network and is a measure for controllability.

The *average* line density and frequency can say something about the traffic intensity line system as a whole, but it is also interesting to look at the extremes. The number of edges with a frequency above a certain threshold indicates how many edges are having a (too) high frequency. The third indicator therefore shows how many edges are attended by more than four trains per hour. The threshold is set to four, since four trains per hour is considered as safe and a common frequency outside the Randstad. In the LUD the goal was consequently to reduce the frequencies, mostly to four times per hour for both IC and SPR trains together. The same goes for line density. A fourth indicator shows the number of edges with more than two lines. Two lines are considered safe since most edges outside the Randstad are served by an IC and SPR line.

Table 3-2: Indicators and measures for the traffic intensity criterion

Indicator	Measure	Robustness aspect
Frequency	Average per edge per hour	Absorption capacity & controllability
Edges with frequency > 4	Sum over all edges	Absorption capacity & controllability
Line density	Average per edge	Controllability
Edges with > 2 lines	Sum over all edges	Controllability

3.3.3 Control region attendance

As already argued before in section 3.1.4, the ability to control the railway network in case of a disruption is related to the capacity and effectiveness of the different types of control centres. It is assumed that the capacity and competence of these centres is fixed, such that adding controllers does not improve the ability to control the network. The number of trains attending a control region is then a measure that says something about the *probability* the control centre has to intervene and control the traffic. Assuming that every train movement can result in a disruption, more trains in the region increase the probability of a disruption and the need for intervention.

The number of control regions a single line attends says more or less the same about the controllability, but is different from the number of trains per region and the line length. Assuming that a large disruption requires controlling effort from all control regions the effected line(s) attend(s), lines attending fewer regions require less effort and communication between regions to recover from the disruption, possibly via the OCCR. A lower number of attended control regions is preferred to reduce the need for coordination between control centres.

Indicators for control region attendance

The control region attendance is defined as the number of trains in a control region. There are five transport control regions and twelve traffic control regions with different coverage areas (see

Appendix B). Since the size of the control regions is diverse, the average number of trains per region is not a suitable measure. Moreover, another distribution of the same number of trains over the control regions does not result in another average. An absolute measure is therefore preferred.

Using an indicator that counts the number of trains in every control region is unwanted, because this yields too many indicators. Only the number of lines in the most busy control regions are therefore indicated. For traffic control, these regions are Amsterdam, Rotterdam, Den Haag and Utrecht. For transport control, these are Randstad Noord, Randstad Zuid and Utrecht. These regions are known to have a critical workload during winter weather and other major disruptions.

We also defined two indicators to calculate the number of attended control regions per line. One for the DVL regions, one for the RBC regions. This also says something about the average line length, but is measured in a different way.

Table 3-3: Indicators and measures for the control region attendance criterion

Indicator	Measure	Robustness aspect
Trains in RBC Randstad Noord	Sum over transport region	Controllability
Trains in RBC Randstad Zuid	Sum over transport region	Controllability
Trains in RBC Utrecht	Sum over transport region	Controllability
Attended transport control regions	Average per line	Controllability
Trains in DVL Amsterdam	Sum over traffic region	Controllability
Trains in DVL Den Haag	Sum over traffic region	Controllability
Trains in DVL Rotterdam	Sum over traffic region	Controllability
Trains in DVL Utrecht	Sum over traffic region	Controllability
Attended traffic control regions	Average per line	Controllability

3.3.4 Disruption risk

In section 2.7.4 the major disruptions occurring at the Dutch railway network have been described. Some of these disruptions are much more frequent during winter weather with snow and some infrastructural assets are notorious for their failure rate. These assets can be referred to as *critical points*, since they have a larger-than-average risk of a failure every time a train passes this point. Avoiding these points can therefore help in reducing the risk of a disruption. The lesser trains that pass the critical point, the less risk on a disruption.

Especially high-speed switches are known to cause an above-average amount of failures. Every movement of the switch blade therefore poses a risk of failure. Securing these switches disables their function and reduces the risk, although trains can only use the switch in one direction.

The disruption risk is not directly related to either the absorption capacity or the controllability of a railway network. Securing switches is merely a preventive measure, as it prohibits the switch from causing a disruption at all. Although the operation of high-speeds switches is thus not directly related to the robustness, it is an important aspect for the Dutch railway network during winter weather

Indicators for disruption risk

The disruption risk can be measured by the frequency a high-speed switch is attended. This is measured by calculating how often a train *operates* the switch, meaning that the actual passage of the train has a certain risk on a failure. For example: If a switch requires movement before the train can pass, the switch is being operated. If the switch can stay in the same direction, the passage of the train does not operate the switch. The number of operational high-speed switches is a second indicator. Identification of the critical points themselves will follow later.

Table 3-4: Indicator and measure for the line length criterion

Indicator	Measure	Robustness aspect
High-speed switches in use	Sum over all high-speed switches	n/a
Operation ratio	Average per switch per hour	n/a

3.4 Criteria for transport capacity

Section 3.2 concluded that transport capacity is much easier to define than robustness. The number of passengers on a train simply cannot exceed the capacity of that train, so the the transport capacity can be expressed by one single criterion.

3.4.1 Capacity shortage

To measure whether there is enough capacity or not, the demand for every train in the network has to be calculated and must be compared with the capacity of the train. The result of this calculation is the *capacity shortage*, which indicates the number of passengers that is unable to use that train.

The travel demand per train can be calculated using a passenger allocation function, which distributes the passengers over the trains in the line system. The capacity of a train is defined using the norms for train occupation (NS, 2013b). These norms are set in the concession and define the capacity of all train types. The *acceptable* norm is used during this study, since this is the common norm for peak hour train occupation. Using this norm, the capacity of a train is defined by the number of seats and two passengers per m^2 on the balcony. The corresponding calculations are further explained in chapter 4.

Indicators for capacity shortage

To determine the capacity shortage, we defined two indicators for both IC and SPR trains. This is because the shortage is calculated for both types individually. The total shortage is the sum of both values and should be as low as possible.

3.5 Summary of robustness and transport capacity

This chapter has given an overview of the factors that influence the robustness and the transport capacity of a railway network. Robustness is a very broad term and is defined in multiple ways in literature. The general notion of a robust system is the ability to adapt to a range of possible futures. Two aspects of a robust railway network have been distinguished, being the absorption capacity and the controllability. The absorption capacity defines the degree to which the network is capable of mitigating small disturbances without the need for intervention. Buffers, margins and supplements are commonly used terms to indicate additional slack to the process times of different tasks to increase the absorption capacity. These time slacks make that small delays will vanish automatically, but result in a longer travel time for passengers. Absorption capacity is amongst others measurable by the line length and the frequency of the lines.

Controllability is another aspect of robustness which defines the ability to control the network in case of a larger disruption. This is depending on the capacity and the effectiveness of the controllers, but also on the complexity of the network itself. A less complex network can increase the controllability, reducing the time a controller needs to let the network recover from a disruption. For railway networks, the controllability can be measured by the line length, frequency, line density and the number of control regions a line attends. Table 3-5 summarizes all criteria and indicators.

The transport capacity of a railway network is much easier to define than the robustness. The transport capacity of a line is defined by the number of passengers that line can transport per hour, which is depending on the capacity and thus length of the train and the frequency. Since frequency has influence on both the robustness and the transport capacity of a railway network, frequency is a very important factor. Moreover, a higher frequency results in a higher transport capacity but less robustness and the other way around. This also implies a tight relationship between robustness and transport capacity.

Table 3-5: Overview of criteria and indicators to evaluate line systems

Criterion group	Indicator
Line length	Major stations attended
Traffic intensity	Frequency Edges with frequency > 4 Line density Edges with > 2 lines
Control region attendance	Trains in RBC Randstad Noord Trains in RBC Randstad Zuid Trains in RBC Utrecht Attended transport control regions Trains in DVL Amsterdam Trains in DVL Den Haag Trains in DVL Rotterdam Trains in DVL Utrecht Attended traffic control regions
Disruption risk	High-speed switches in use Operation ratio
Transport capacity	IC shortage SPR shortage

4

Design methodology and approach

The previous chapters provided a thorough analysis of the railway planning process, the robustness and transport capacity of a line system, and how these characteristics can be measured. This chapter describes the methodology used to design *alternative* line systems for the Dutch railway network.

The goal of this study is to design a robust line system with *sufficient* transport capacity. In order to determine whether the transport capacity is sufficient or not, the number of passengers per train composition must be known. Estimation of the number of passengers requires *allocation* of the passengers over the network, which is depending on the line system itself. This implies that it is more logical to create a robust line system, determine the transport capacity and adapt the initial concept if necessary, instead of designing a line system with sufficient transport capacity and adapt it to achieve (more) robustness.

Figure 4-1 shows the method used to design alternative line systems. An underlying principle is used to initiate the design process. Every alternative is based on a different idea to achieve robustness and transport capacity. The length and the frequency of the lines determines the number of trains required to operate the line system. Initially, the frequency of all lines is set to a "basic" frequency of 2 trains/hour. The composition of the trains depends on the number of passengers. Therefore, all passengers from the OD-matrix are allocated to the trains using an allocation model, which yields a list of the travel demand per train composition. Based on the demand, the available rolling stock is assigned to the trains such that the transport capacity of the line system can be calculated. If the demand is larger than the capacity of a train, there is a shortage of capacity. Adapting the line system can reduce this shortage, for instance by increasing the frequency. This is visualized by the feedback loop in the design process. The succeeding sections elaborate further on the steps in the methodology.

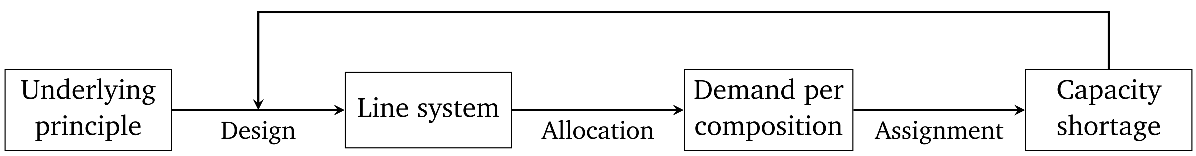

Figure 4-1: Methodology to design an alternative line system

4.1 Designing alternative line systems

There are many different possible line systems, all based on an underlying principle or objective. Several ideas from literature have already been elaborated on in section 2.3, for instance the minimization of costs or transfers. In section 3.1.4, we concluded that the robustness of a line system is depending on multiple factors, such that it is not possible to take all factors into account simultaneously. To overcome this, multiple alternative line systems are created, all with their own underlying principle. These principles are originating from the criteria that determine the robustness of a line system, presented in sections 3.3 and 3.4.

4.1.1 Different design principles

The indicators for robustness have been classified into four criterion groups, shown in table 3-5. The underlying principles to design alternative line systems are derived from these groups. Every alternative aims to optimize one of these criteria. This results in four alternatives:

1. An alternative with short lines, such that the number of major stations a line attends is constrained to a maximum. This alternative aims to reduce the *impact* of disruptions on the network.
2. An "unbundled" alternative where the line density is decreased. This alternative aims to minimize *shared infrastructure*, hence less interdependencies between lines.
3. A control-based alternative, such that lines are bound by a maximum number of (traffic) control regions. This alternative aims to reduce *coordination* between control regions.
4. An infrastructure-based alternative where the operation of high-speed switches is evaded by locking the switch in one direction. This alternative aims to reduce the *risk* on disruptions at all.

During the design process, it turned out that alternative 2 (unbundled) was inefficient and not capable of reducing the capacity shortage without changing the underlying principle. The required adaptations were so severe, there was too much overlap with other alternatives. Therefore, alternative 2 has been discontinued. The idea to unbundle the network is, nonetheless, incorporated into the other alternatives.

For all alternatives, the underlying principle is translated into a "recipe" describing the rules for a line system. Such a recipe could for instance describe that a line cannot stop at more than 4 stations. Based on this recipe, the layout of the line system is built. A few assumptions are made:

- The characteristics of train types and stations are subject to change if this yields a better solution.
  - The IC and SPR train types have their own properties. SPR trains usually stop at every station on their way, while IC trains only stop at the larger stations. These properties are subject to change if it benefits the solution, such that SPR trains are allowed to skip stations and IC trains might have extra stops.
  - As a consequence of the previous assumption, SPR stations might (temporarily) change into IC stations.
  - A *terminal* is a station where a train line may start or end. If it favours the solution, new stations may be appointed as terminals. The availability of a third track, cross-over

switch or small shunting yard close to this station is a precondition.

- Splitting and combining trains is not possible.
  - Because of the large fluctuations in travel demand during the day, trains are having different lengths. It is assumed that it is not possible to shorten or lengthen trains during the time frame this study focuses on (i.e. the morning peak).
  - Trains are not allowed to split during operation such that a split train can have two different destinations. This is because the coupling elements of the train are more vulnerable to defects during winter weather.
- Every station on the main railway network must be attended by at least one line and at least twice per hour. This is a basic concession requirement.

If the layout is complete, the frequencies for the lines are set. A precondition here is that all *stations* need to be attended at least *twice* per hour. This is because the frequency of two trains per hour is seen as a basic service. Moreover, this basic service is a requirement in the concession to operate the main railway network. The result of this step in the design process is a complete list of IC and SPR lines, consisting of the frequency and the commercial stops per line. For all lines, the maximum train length can be determined by the stations the train attends. The shortest platform length of the attended stations is the maximum train length.

4.1.2 Determining robustness

Based on the line system itself, the value of all indicators for robustness can be calculated. These values are subsequently used to determine the *robustness index*, which is the measure for the robustness of the alternative. This index is used to assess the robustness of the line system in chapter 5. The methodology and calculations for this index are also described in this chapter.

Line length

The line length is only expressed in the number of major stations a line attends. This is calculated by counting the number of major stations for every line, and taking the average. Table C-1 in Appendix C states all major stations.

Traffic intensity

The traffic intensity is measured using four indicators:

- Average frequency per edge
- Number of edges with frequency > 4
- Average line density per edge
- Number of edges with > 2 lines

The values of these indicators are calculated by listing all 227 edges on the main railway network and determine the number of lines that attend each edge. The average line density and the number of edges with more than 2 lines is directly derived from here. The frequency on every edge can be calculated in a similar way by taking the sum of the frequencies of the lines that attend the respective edge.

Controllability

The controllability is measured using nine indicators:

- Number of trains in RBC regions Randstad Noord, Randstad Zuid and Utrecht (3 indicators)
- Number of trains in DVL regions Amsterdam, Den Haag, Rotterdam and Utrecht (4 indicators)
- Average attended transport control regions per line
- Average attended traffic control regions per line

The values of these indicators are calculated by listing all lines and determining which transport and traffic control regions they attend. The average number of attended regions can be derived from here. The number of trains per region is calculated by taking the sum of the frequencies of all lines that attend the respective region.

Disruption risk

The disruption risk is measured by two indicators, illustrating the number of operational high-speed switches and the average number of switch movements per hour. These values are calculated by listing all edges with a high-speed switch and determining if attending this edge triggers switch movement. If one switch is for instance controlling the junction between stations A, B and C as shown in fig. 4-2, the switch is considered operational if both edges $A-B$ and $A-C$ are attended. Switch operation is estimated using the frequency and assuming an equal pattern over the hour. If $A-B$ is attended once per hour and $A-C$ 2 times/hour, the assumed order during the hour is $\{A-B, A-C, A-C\}$. This implies two switch movements per hour.

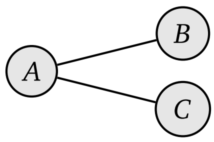

Figure 4-2: Example of a junction where attendance of both edges implies an operational switch

4.2 Passenger allocation

In order to calculate the ability of the line system to transport all passengers, the exact number of passengers per *line* is required. To determine this demand, all passengers in the OD-matrix ($\approx$ 274,000 passengers) must be allocated to the lines in the line system. This allocation of passengers is done using a model called TRANS (Warmerdam, 2004), which determines the line(s) a passenger uses to travel from origin to destination. This is straightforward if there is only one possibility, but requires a discrete choice once there are more travel options, especially when a transfer is required. At first, TRANS allocates the passengers to the different lines in the line system. Subsequently, the passengers are allocated to the trains on that line.

4.2.1 Allocation per line

To allocate passengers to the lines, TRANS is using two phases. The first phase is the generation of all possible travel options. In similar studies, these options are also called itineraries. For every origin i to destination j (called O-D pair), TRANS generates a large set of possible travel options. Subsequently, TRANS determines which travel options are realistic by comparing two options with each other regarding travel time, transfers and frequency. Costs are not considered since it is assumed that a trip from i to j is has the same price for all possible travel options. If one of the options is classified as “unrealistic”, it is deleted from the set of options. This happens for instance if the difference in travel time between two options is greater than a certain threshold (20 minutes), while having the same number of transfers. This threshold and other parameters for the comparison have a default value based on research by MOA and are not subject to change for this study. The result of the first phase is thus a set of travel options per O-D pair.

The second phase allocates the passengers to the travel options corresponding to the O-D pair using a discrete choice model. This is a mathematical function to predict the choice of a passenger based on the *utility* of the travel option (Akiva & Lerman, 1985). The utility of a travel option describes the preference of the passengers to use this travel option, based on multiple observable factors like the travel time and the number of transfers. The allocation is calculated using a Multinomial Logit (MNL) model, included in TRANS. Such a model incorporates the theory of utility maximization, which means that most passengers will choose the travel option with the largest utility (Dow & Endersby, 2004). Normally, a stochastic error is added to the utility function to account for possible preferences that cannot be observed. Since TRANS does not account for this preference, it is assumed that travel options with the exact same utility will have an even amount of passengers. Other advantages and disadvantages of the used model are discussed in section 6.2.

$$U_q = \beta_1 \cdot T_{t_q} + \beta_2 \cdot O_q + \beta_3 \cdot T_{O_q} + \beta_4 \cdot \ln C_{v_q} + \beta_5 \cdot \ln C_{n_q} \tag{4.1}$$

Equation (4.1) is the function used to calculate the utility U_q of each travel option q. The different elements used in this equation are:

- The travel time T_{t_q}, being the travel time from origin to destination using travel option q. This is calculated by multiplying the length of each attended edge b with the average speed on that edge and adding a dwelling time T_d for each station the line attends. The dwelling time includes the additional time required for deceleration and acceleration before and after the actual stop.
- The number of transfers O_q, determined via a path finding algorithm in TRANS.
- The transfer time T_{O_q}, determined via the same algorithm and the frequency of the transfer.
- A correction $\ln C_v$ for other travel options that depart short after travel option q.
- A correction $\ln C_n$ for other travel options that arrive short after travel option q.
- Weighing parameters $\beta_1 \dots \beta_5$, of which the values are shown in table 4-1.

The correction factors are indicating what happens if the passenger misses its train. If there are other travel options that depart and/or arrive shortly after the missed train, this correction factor becomes larger. Together, these factors say something about the severity of missing the train. A more detailed explanation of these factors is described in Warmerdam (2004).

Once the utility of all travel options per O-D pair is calculated, the share of passengers using each travel option is determined. Equation (4.2) shows the used function, which calculates the share S_q

Table 4-1: Parameter values for the utility function in eq. (4.1)

Parameter	Factor	Value
β_1	Travel time	-0.02704
β_2	Transfers	-0.41730
β_3	Transfer time	-0.08346
β_4	Departure correction	0.72430
β_5	Arrival correction	0.19110

of passengers using travel option q. The utility is multiplied with the frequency, since there are f travel options per hour.

$$S_q = \frac{f_q \cdot e^{U_q}}{\sum_r f_r \cdot e^{U_r}} \tag{4.2}$$

Multiplying S_q by D_{ij} yields the actual number of passengers travelling from i to j using travel option q. TRANS calculates the utility of the travel options for all O-D pairs in the OD-matrix, such that the passenger load P^l_{ij} can be calculated as well. This is the number of passengers on line l between stations i and j. The values of D_{ij} originate from the OD-matrix and have up to 20 decimals due to the different forecasting techniques applied to this matrix. Since the demand in the OD-matrix is *not rounded*, multiple partial trips can become one. This might overestimate the passenger demand, but ensures that the number of travellers is the same for all alternatives.

4.2.2 Allocation per train

Every line requires a minimum number of train compositions to operate with the given frequency. The total number of trains W per line l is depending on the complete round-trip time T^l_c and the headway H_l, as already explained in section 2.5. The number of trains is calculated by the following function:

$$W_l = \left\lceil \frac{T^l_c}{H_l} \right\rceil$$

Once the number of passengers and trains per line is known, the passengers are allocated to a specific train. This yields the travel demand per train between all stations the train attends, hence the travel demand per *edge*. The *busiest edge* a train encounters is the edge with the largest demand. The train must at least have enough capacity to transport these passengers. On a specific line, the busiest edge is different for each train since the demand depends on the time of the day. Moreover, there is a notable difference in travel demand *within* the peak hours. TRANS therefore differentiates between the *busiest hour*, the second busiest hour and off-peak hours. This is because a busy edge can have a higher demand during off-peak hours, than another edge during the busiest peak hour.

This is best explained using an example. Figure 4-3 shows an imaginary line with the travel demand shown in table 4-2, where the first hour of the morning peak is the busiest. The line is operating between s_0 and s_5 with intermediate stops $s_1 \ldots s_4$. The trips between stations, including the dwelling time at the stations, are all taking 30 minutes and so are the layover times at the terminal stations. This results in a round-trip time of 360 minutes. A frequency of 2 trains/hour yields that there are $\lceil 360/30 \rceil = 12$ trains required to operate this line. During operation, the 12 trains are spread evenly over the line.

Let train 1 depart from station s_0 just at the start of the busiest hour. This means that train 1 will operate from s_0 to s_2 in the 1st hour, from s_2 to s_4 in the 2nd hour and from s_4 it will encounter off-peak demand. In the 1st hour, the busiest edge is between s_1 and s_2 with a demand of 315 passengers. During the 2nd hour, however, the busiest edge is between s_2 and s_3 with a demand of 340 passengers. Train 1 should therefore have capacity for at least 340 passengers.

Another train in the circulation will attend the edge between s_2 and s_3 in the 1st hour of the peak, resulting in a required capacity of at least 510 passengers. This indicates that the length of all trains in the circulation of one line can vary. The desired length of a train depends on the largest demand, which depends on both the *time* and the *location*.

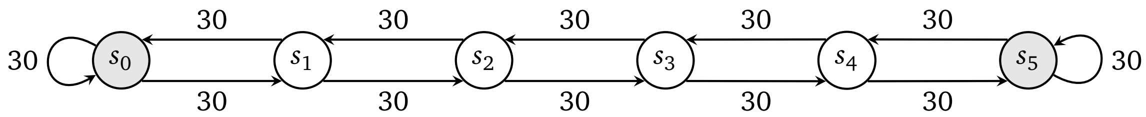

Figure 4-3: A line between terminal stations s_0 and s_5 with running- and layover times

Table 4-2: Passenger demand belonging to the example in fig. 4-3

From	To	1st hour	2nd hour	off-peak
s_0	s_1	300	200	140
s_1	s_2	315	210	147
s_2	s_3	510	340	238
s_3	s_4	480	320	224
s_4	s_5	360	240	168

Figure 4-4 shows a passenger prognosis of several lines in the morning peak which clearly indicates the difference in travel demand within the peak hours. The graph also indicates that the difference between the busiest and the second busiest hour is line-dependent, as well as the time frame of the busiest hour itself. Some lines have their busiest hour between 8:00 and 9:00, some others between 8:30 and 9:30. There is therefore no generally applicable method to deal with these differences. The Logistics department of NS uses an increment factor of 1.4 to the calculated passenger demand per line to take the "peak within the peak" into account, so does this study. Since the used OD-matrix contains the demand for two hours, an additional distribution of 52% - 48% is used to define the difference between respectively the busiest and second busiest peak hour. The off-peak hours are assumed to have 31% of the demand from the OD-matrix, based on experience from the Logistics department. Since the OD-matrix is rounded up as well, it is more likely that the travel demand is overestimated than underestimated.

The result of the allocation per train is a list of all trains required to operate the line system, along with the maximum demand the train will encounter during the day. If all trains have enough capacity to at least accommodate this demand, there is sufficient transport capacity.

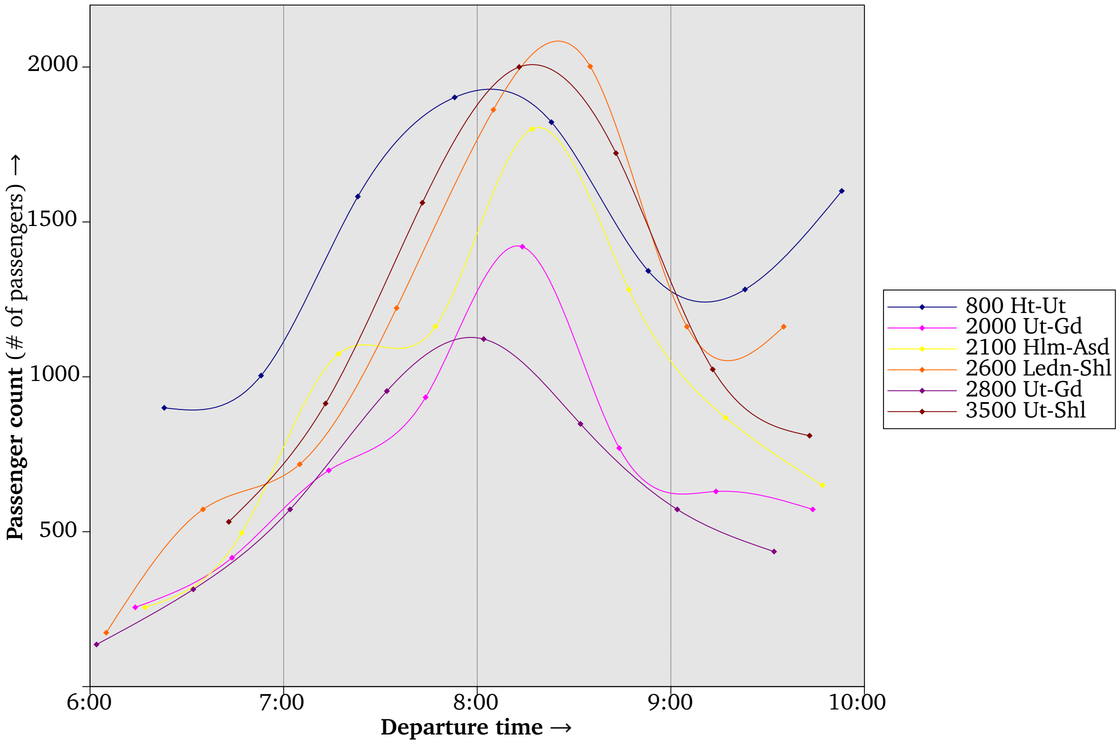

Figure 4-4: Passenger prognosis of several lines during the morning peak hours

4.3 Rolling stock assignment

Once we know the required number of trains and their minimum capacity, the actual train units can be assigned to these trains. There is a fixed number of train units available which can be coupled to form a train composition. Only units of the same type can be coupled, as already explained in section 2.5. Each possible composition has its own length and capacity and is listed in table D-1 in Appendix D. The net fleet of May 2014 is used as fleet size, shown in table 2-3 and the occupation norms are set to "acceptable". A few additional assumptions are made to simplify the problem:

- There is no distinction between passengers in the 1st and 2nd class, since the provided OD-matrix does not distinguish between passengers in the 1st and 2nd class of the train either.
- All rolling stock within the fleet is weather-tight. Some rolling stock types are more vulnerable to frost and snow than others, for instance because some types are not allowed to be treated with anti-icing as this may void the warranty. Since a certain share of the total rolling stock fleet is out of service due to maintenance, the *net* fleet consists of all *operational* rolling stock. It is assumed that all available trains in the net fleet are in fact also deployable during winter weather.
- The compositions are separately assigned to IC and SPR lines to make sure the right train types are assigned to the corresponding line types. Since the DDZ train type is deployed on both IC and SPR lines, it is assumed that the DDZ4 units are assigned to SPR lines while the DDZ6 units are assigned to IC lines.

Table 4-3: Identifiers for the rolling stock assignment model

Sets	W	Set of all trains
	C	Set of all possible train compositions
	S	Set of all train types
Parameters	D_w	Number of passengers on train w
	L_w	Maximum length of the composition for train w
	cap_c	Capacity of composition c
	l_c	Length of composition c
	$n_{c,s}$	Number of train units of type s in composition c
	N_s	Fleet size for train type s
Variables	$x_{w,c}$	Binary variable $x_{w,c} = \begin{cases} 1 & \text{if composition } c \text{ is assigned to train } w \\ 0 & \text{otherwise} \end{cases}$
	z_w	Capacity shortage on train w

4.3.1 Mathematical assignment model

The assignment of compositions to the trains can be seen as an optimization problem with the objective to match the composition capacity with the number of passengers. In other words: the *shortage* of train capacity must be minimized. There is a shortage of capacity if not all passengers can be transported, for instance if the train is too short. The resulting shortage is expressed as the number of passengers that is unable to be transported in a decent way. An integer linear optimization model has been formulated to assign train compositions to every train on the network. This model is based on similar models presented by Abbink et al. (2004) and Fioole et al. (2006) and is adapted for the purpose of this study. Table 4-3 lists the identifiers for the model.

The rolling stock assignment model can be formulated as follows:

Minimize:

$$Z = \sum_{w \in W} z_w \tag{4.3}$$

Subject to:

$$z_w = \sum_{c \in C} x_{w,c} \cdot \max\{D_w - cap_c, 0\} \qquad \forall\ w \in W \tag{4.4}$$

$$\sum_{c \in C} x_{w,c} = 1 \qquad \forall\ w \in W \tag{4.5}$$

$$\sum_{c \in C} l_c \cdot x_{w,c} \leq L_w \qquad \forall\ w \in W \tag{4.6}$$

$$\sum_{c \in C} \sum_{w \in W} n_{c,s} \cdot x_{w,c} \leq N_s \qquad \forall\ s \in S \tag{4.7}$$

$$x_{w,c} = \{0,1\} \qquad \forall\ w \in W, c \in C \tag{4.8}$$

$$z_w \geq 0 \qquad \forall\ w \in W \tag{4.9}$$

The objective function (4.3) aims to minimize the total shortage of capacity over the complete network. Constraints (4.4) define the shortage per train if and only if the demand is larger than the capacity of the assigned composition. Constraints (4.5) ensure that every train is assigned exactly one composition. Constraints (4.6) limit the length of the assigned composition to the maximum allowed train length. The constraints in (4.7) limit the maximum number of assigned train units to the fleet size per type.

The model has been implemented in AIMMS 3.14 using CPLEX 12.6. The used hardware is a Pentium i7 processor with 3.40 GHz and 16 GB RAM. Per alternative and line type, between 120 and 140 trains have been assigned a composition which gives a model with about 2,900 decision variables and 600 constraints. Solving the model does not take longer than 0.1 second.

4.3.2 Applicability of the model

To check the applicability of the assignment model, the capacity shortage for the regular timetable and the LUD timetable have been calculated after allocating all passengers from the OD-matrix with TRANS. The regular timetable has a capacity shortage of 0, which is expected. The regular timetable is made to measure and should not have any capacity shortages at all. Any shortage on a "normal" day is caused by rolling stock defects, disruptions and other unforeseen problems.

The LUD timetable has a capacity shortage of 10,955, which is 4% of all passengers in the OD-matrix. Increasing the fleet size does not have any effect on the shortage, which implies that the shortage is not caused by an insufficient amount of rolling stock. This also indicates that the trains cannot be lengthened due to platform length constraints, which corresponds to the expectations as well. The capacity shortage is likely to be *underestimated*, since the model calculates the optimal assignment. This makes that different train types can be assigned to one and the same line, which seldom happens in the daily operation. Further implications of the model are discussed in section 5.6.

4.3.3 Interchanging rolling stock

For each alternative, the assignment model is run separately for both IC and SPR lines. This makes the model less complex, but ensures that both types of lines are assigned the right types of rolling stock. In daily operation, however, not all SPR lines are operated by SPR rolling stock types. This is because there is a shortage in these types of rolling stock, such that some lines are assigned IC trains units.

While running the model, we observed the same effect. Any shortage in IC lines was mostly caused by platform length constraints, as increasing the IC fleet size did not change anything in the capacity shortage. Shortages in SPR lines were mostly caused by the fleet size, as increasing the SPR fleet therefore reduces the shortage to a minimum. The capacity shortage is thus partially depending on the *type* of the line. We therefore interchanged IC rolling stock to the SPR fleet, to give a more comprehensive overview of the shortage. Any spare train unit in the IC fleet was transferred to the SPR fleet to calculate the shortage again.

4.4 Iterations to optimize the alternative

Once the capacity shortage is calculated, the values of all indicators for both robustness and transport capacity are known. The line system can now be adapted to decrease the capacity shortage (if any). All alternatives have been designed from a particularly robust perspective, such that a large capacity shortage is expected. The alternative line systems are now iteratively adapted to reduce the capacity shortage to a minimum. In most cases it will be necessary to increase the frequency to do so, which also reduces the robustness (see section 3.2.2). Decreasing the capacity shortage will therefore likely result in less robustness as well. After each change in the line system, passengers are re-allocated over the network such that the capacity shortage can be recalculated. An iterative process is used to incrementally adjust the line system and re-assess the scores for robustness and transport capacity. This feedback loop is already shown in fig. 4-1.

The most common changes to the alternative line systems are related to the frequency on busy transport axes in the Randstad. The capacity shortages on these axes are mostly caused by platform length constraints. This implies that adding rolling stock to these lines does not have any effect on the transport capacity, since the maximum train length is already reached. In this case, increasing the frequency is the only way to decrease the capacity shortage.

It should be noted that the indicators for robustness are used for two purposes: On the one hand, the indicators are used as underlying principle to *design* alternative line systems. On the other hand, the *same* indicators are also used to *evaluate* the robustness of the alternatives. It is therefore expected that A1 will have the lowest average line length, A2 the lowest control region attendance and A3 the lowest switch operation. Due to this it is possible that the evaluation yields incorrect results. A sensitivity analysis must be performed to exclude these indicators from the evaluation and assess the effects. This is further explained in section 5.3.

4.5 Summary of design methodology

This chapter has elaborated on the methodology used to create a line system, analyse its characteristics and adapt the line system to improve the performance. Three alternative line systems are designed using this methodology, all based on a different underlying principle. The values for all robustness indicators can be calculated once the line system is complete, such that these values can be used to determine the *robustness index* of each alternative. This is further explained in the next chapter.

To assess the transport capacity of a line system, the number of passengers and the actual train compositions per line are required. A passenger allocation model called TRANS is used to allocate all passengers from the OD-matrix over the different lines in the line system. This allocation is based on utility maximization, while the distribution of passengers over their possible options is calculated using a logit model. This yields a list of travel demand per train per line.

A rolling stock assignment model is used to assign rolling stock compositions to the trains, such that the travel demand is met. The assignment model has the objective to minimize the capacity *shortage*, which is the difference the train capacity and the travel demand. Trains can only have a maximum length, which is determined by the shortest platform they attend during their trip. The capacity shortage per train indicates how many passengers are left behind at the platform, while the total shortage indicates to what extent the line system is capable of transporting passengers.

To create a robust line system with sufficient transport capacity, iterations are made. Each alternative is initially designed from a robust perspective, which yields large shortages in capacity. By increasing the frequency on the busy axes, the shortages will decrease. This also decreases the robustness of the line system, which makes that the indicator values must be recalculated. Using this iterative process, three robust line systems are created with few capacity shortage. The next chapter presents these alternatives.

5

Results

This chapter describes three alternative line systems for winter weather and presents the results of the analysis regarding their robustness and transport capacity. The first section describes the alternatives, which have been created using the methodology stated in the previous chapter. By using the criterion groups and indicators from chapter 3, the robustness index of each alternative is calculated. Section 5.2 describes the used method to compute this index and presents the first results of the comparison. A sensitivity analysis is performed in section 5.3 to check the impact of the weights on the results. Subsequently, the commercial effects of the alternatives are analysed. The operational feasibility of the alternatives will be assessed here, as well as the implications for passengers.

5.1 Alternative line systems for winter weather

Three alternative line systems have been designed to substitute the LUD during winter weather. All alternatives have been designed using the methodology as explained in chapter 4 and have their own underlying principle:

A1. An alternative with short lines, such that the number of major stations a line attends is constrained to a maximum. This alternative aims to reduce the *impact* of disruptions on the network.

A2. A control-based alternative, such that lines are bound to attend a maximum number of (traffic) control regions. This alternative aims to reduce *coordination* between control regions.

A3. An infrastructure-based alternative where the operation of high-speed switches is evaded by locking the switch in one direction. This alternative aims to reduce the *risk* on disruptions.

A fourth alternative with the underlying principle of “unbundling” the network turned out to be an inefficient line system and is therefore discontinued. The idea of unbundling is, however, used in the other alternatives to prevent effects as mentioned in section 3.3.2. This chapter describes all alternatives in detail and presents the values of the indicators for robustness and transport capacity. The LUD line system is considered the zero-alternative (A0), of which a detailed overview of the layout and frequency is available in section E.0 of Appendix E.

5.1.1 A1: Maximum number of major stations

The first alternative aims to reduce the length of the lines to a maximum number of major stations, being 4. By doing this, there will be less delay propagation in case of a disruption. The underlying idea of this alternative is similar to the ADVD; short shuttle services between the larger stations.

The recipe of this line system is straightforward: A line is not allowed to attend more than 4 major stations, as listed in Appendix C. A line can only start and end at a terminal station, which means that a third track or small shunting yard must be nearby. One exception is made to this recipe for the SPR line Apeldoorn - Enschede. This line attends more than 4 major stations, but is outside the Randstad and of minor importance.

The layout of A1 has many resemblances with the LUD and the regular line system. The largest difference is, logically, the length of the lines. The long lines in the LUD are cut into shorter lines to prevent propagation of delays through the network. The line Alkmaar - Maastricht, for instance, is cut into 3 short lines in Eindhoven and Utrecht.

Some characteristics of this alternative are:

- There is no SPR service between Geldermalsen and 's-Hertogenbosch, which means that the IC stops at Zaltbommel to serve this station.
- No direct connection between Gouda Goverwelle, Woerden and Breukelen.
- No direct connection between Naarden-Bussum and Almere Poort.

The frequencies of all lines are initially set to 2. Once the complete railway network is covered, the capacity shortage is calculated. This yields an enormous shortage, especially on the busy axes in the Randstad. The frequency on these axes is increased incrementally, until the capacity shortage is reduced to a more acceptable amount. This results in a frequency of 3 trains per hour on these busy axes, which is enough reduce the shortage. On these axes, both the IC and SPR line operate 3 trains/hour to prevent conflicts in the train paths. All other lines still have a frequency of 2 trains per hour. A detailed overview of the layout, the frequency and a map of the line system can be found in section E.1 of Appendix E.

Table 5-1 presents the values of the robustness indicators that have been calculated, along with the capacity shortage. The shortage for IC lines is due to platform constraints, since increasing the fleet size does not result in less shortage. These shortages are occurring on the line Schiphol - Eindhoven and affect a maximum of 55 passengers per train. The trains on this line are restricted to length 10, since this train stops in Zaltbommel.

The initial shortage for SPR lines is 4,551 passengers, with a maximum of 129 per train. This shortage can be decreased to 0 by enlarging the fleet, which means that the shortage is due to a lack of rolling stock. If we deploy around 20 spare IC trains to these lines, the shortage is decreased to 21.

5.1.2 A2: Maximum number of attended DVL regions

The second alternative aims to reduce the coordination between control regions by limiting the number of DVL regions the a train can attend to 2. This means that a disruption will require at most two DVL regions to respond. By using this approach, the length of the lines is restricted by the way the control regions are categorized. A2 therefore has resemblances with A1, but with more

Table 5-1: Robustness and capacity shortage for A1

Criterion group	Indicator	A1-Short
Line length	Major stations attended	2.796
Traffic intensity	Frequency	4.243
	Edges with Frequency > 4	87
	Line density	1.931
	Edges with > 2 lines	49
Control region attendance	Trains in RBC Randstad Noord	39
	Trains in RBC Randstad Zuid	38
	Trains in RBC Utrecht	49
	Attended transport control regions	1.531
	Trains in DVL Amsterdam	33
	Trains in DVL Den Haag	21
	Trains in DVL Rotterdam	17
	Trains in DVL Utrecht	37
	Attended traffic control regions	2.041
Disruption risk	High-speed switches in use	26
	Switch operation ratio	1.771
Capacity shortage	IC shortage	152
	SPR shortage	21

restrictions. The borders of DVL regions are often located *between* larger stations, which results in a completely different line system.

The recipe of this alternative is as follows: Every line may attend at most 2 DVL regions. Within these regions, lines are as long as possible to prevent too much resemblance with A1. The two attended DVL regions are preferably located in the same RBC region.

Some characteristics of this alternative are:

- There is no SPR service between Geldermalsen and 's-Hertogenbosch, which means that the IC stops at Zaltbommel to serve this station.
- No direct connection between Gouda Goverwelle, Woerden and Breukelen.
- No direct connection between Naarden-Bussum and Almere Poort.
- Unusual stations are appointed as terminal stations, like Lage Zwaluwe, Ede-Wageningen and Naarden-Bussum.
- The SPR service between Zwolle and Utrecht now turns in Den Dolder.

Like in A1, the frequencies of the lines have initially been set to 2 trains/hour. The shortages in transport capacity requires a higher frequency on almost the same axes as in A1. Increasing the frequency to 3 trains/hour yields a minimum shortage. A detailed overview of the layout, the frequency and a map of the line system can be found in section E.2 of Appendix E.

Table 5-2 presents the values of the robustness indicators that have been calculated, along with the capacity shortage. The shortage for IC lines is due to platform constraints and a shortage of rolling stock, since increasing the fleet size does reduce the shortage a little. This implies that it is not possible to use IC rolling stock types on SPR lines, where the shortage is completely caused by an insufficient fleet size. The shortage on the IC lines is caused by the line Utrecht Centraal - Amersfoort, which is the only direct connection between these cities.

The initial shortage for SPR lines is 899 passengers, with a maximum of 56 per train. This shortage can be decreased to 20 by enlarging the fleet, which means that the shortage is due to a lack of rolling stock and 20 passenger are left behind because of the platform length. Due to the large number of trains in this line system, there is no spare IC rolling stock available to deploy on SPR lines.

Table 5-2: Robustness and capacity shortage for A2

Criterion group	Indicator	A2-DVL
Line length	Major stations attended	2.133
Traffic intensity	Frequency	4.116
	Edges with Frequency > 4	84
	Line density	1.881
	Edges with > 2 lines	42
Control region attendance	Trains in RBC Randstad Noord	45
	Trains in RBC Randstad Zuid	34
	Trains in RBC Utrecht	48
	Attended transport control regions	1.412
	Trains in DVL Amsterdam	37
	Trains in DVL Den Haag	22
	Trains in DVL Rotterdam	14
	Trains in DVL Utrecht	32
	Attended traffic control regions	1.686
Disruption risk	High-speed switches in use	26
	Switch operation ratio	1.686
Capacity shortage	IC shortage	888
	SPR shortage	899

5.1.3 A3: Evading high-speed switches

The third alternative aims to evade as much high-speed switches as possible. It is allowed to pass these switches, but only in one direction. This has serious implications for the line system, since some connections are not possible any more. In some cases, the use of high-speed switches can be evaded by using other conventional switches. These must be passed at lower speed, but still keep most connections available. Most of the other high-speed switches are connecting two main crossing axes by curves or separate IC and SPR trains on four-track edges. The connection Utrecht - Shiphol is for instance controlled by these switches. In this line system, the direct connection between Utrecht and Schiphol is therefore removed.

A pair of high-speed switches near Zwolle causes are more serious problem, as this pair of switches splits the traffic to Lelystad and Amersfoort. Locking these switches in one direction will make that one of these directions becomes unavailable. Since both axes are important connections in the network, a compromise is used. From Kampen Zuid and 't Harde, a single track is used to allow traffic from and to Zwolle. This makes that only 2 trains/hour can operate in both directions, but the connection is still operational. A detailed overview of the layout, the frequency and a map of the line system can be found in section E.3 of Appendix E.

Some other characteristics of this alternative are:

- Station Wezep is not attended by trains, which means that a bus service has to be initiated to transport all 190 passengers from and to this station.
- No direct connection between Gouda Goverwelle, Woerden and Breukelen.
- The HST can only operate between Amsterdam and Rotterdam.
- Separation of IC and SPR traffic on four-track edges around Den Haag, Woerden and Rotterdam Zuid is not possible.

Table 5-3 presents the values of the robustness indicators that have been calculated, along with the capacity shortage. The shortage for IC lines is due to platform constraints, since increasing the fleet size does not reduce the shortage. The maximum shortage per train is 84 passengers, which occurs on the line Breda - Lelystad between stations Den Haag HS and Leiden.

The initial shortage for SPR lines is 958 passengers, with a maximum of 46 per train. This shortage can be decreased to 0 by enlarging the fleet, which means that the shortage is due to a lack of rolling stock. Using IC rolling stock types on some SPR lines can thus help to reduce the shortage to a minimum.

Table 5-3: Robustness and capacity shortage for A3

Criterion group	Indicator	A3-Switches
Line length	Major stations attended	2.952
Traffic intensity	Frequency	4.33
	Edges with Frequency > 4	101
	Line density	1.891
	Edges with > 2 lines	39
Control region attendance	Trains in RBC Randstad Noord	39
	Trains in RBC Randstad Zuid	31
	Trains in RBC Utrecht	50
	Attended transport control regions	1.643
	Trains in DVL Amsterdam	33
	Trains in DVL Den Haag	19
	Trains in DVL Rotterdam	12
	Trains in DVL Utrecht	38
	Attended traffic control regions	2.190
Disruption risk	High-speed switches in use	4
	Switch operation ratio	0.314
Capacity shortage	IC shortage	463
	SPR shortage	0

5.2 Creating an index for robustness

To assess the robustness of an alternative line system, a Multi-Criteria Analysis (MCA) is performed. There are many ways to perform an MCA, depending on the goal of the analysis and the number of criteria being evaluated (Communities and Local Government, 2009). For this assessment, a *weighted sum* is used to determine the *robustness index*. All indicators specified in chapter 3 are contributing to this index.

To make sure that all indicators are contributing on the same scale to the robustness index, the values of all indicators are standardized. Since the line system of the LUD is the zero-alternative, the indicator values are divided by the corresponding value of A0 and multiplied by 100 to create a new value that is relative to A0. This makes that the values of all indicators are standardized in a *linear* way. When applying the weighted sum as shown in eq. (5.1), A0 will always have a robustness index of ≈ 100 (due to rounding errors). For all indicator values holds: lower is better. This implies that a lower robustness index is preferred over a higher index as well, which makes that that the robustness index of 100 is considered as the *upper bound*. Any alternative with an index > 100 is then *less robust* than the zero-alternative.

$$\text{Robustness index}_{\text{A}x} = \sum_{w} \gamma_w \cdot \frac{V_w^{\text{A}x}}{V_w^{\text{A0}}} \tag{5.1}$$

The values V_w of each indicator w are summed using a certain weight γ_w to illustrate the robustness of each alternative Ax. These weights are used to prioritize certain criterion groups and indicators over others, since not every aspect is of equal importance. Weights are determined using an Analytic Hierarchy Process (AHP), which makes it possible to systematically structure a decision-making problem with multiple criteria (Saaty, 1990). This is done by creating a hierarchy which divides the problem into different *levels*. The idea is to estimate how much more important one criterion is, compared to all other criteria. This yields a weight for all criteria, where the most important criterion gets the largest percentage. The sum of all weights is 100%.

In chapter 3, we defined four different criterion groups for a robust railway network, along with multiple indicators for almost every group. This hierarchy is shown in fig. 5-1. The weights are determined on both levels. The hierarchy of the indicators within each criterion group is determined, as well as the hierarchy between the criterion groups themselves.

First, the four criterion groups have been evaluated. The importance of the groups (hence, their weight) has initially been estimated in accordance with an experienced transport controller. In a second stage, weights have been varied to verify the impact of the weights on the robustness index. This will be further elaborated on in section 5.3. Line length is considered less important than all other criteria, since the line length cannot be expressed in a very structured way. Traffic intensity is considered the most important criterion. The busier the network is, the more dependencies between trains and lines. Since less trains will give more slack, this has been the most important reason to deploy the LUD for instance. The control region attendance and disruption risk are positioned in-between. Table 5-4 shows the initially used weights for the criterion groups.

Secondly, all indicators *within* the criterion groups have been compared using the AHP. This is, again, initially done in accordance with a transport controller. The number of attended major stations is the only indicator within its parent criteria group and therefore has a weight of 100%. Within the traffic intensity group, the number of edges with a frequency > 4 is the most important indicator because this is more than the “basic” train service. A frequency of at most 4 trains/hour is considered safe and can be controlled well in case of a disruption. Regarding the control region attendance, the number of trains in RBC regions is considered less important than the number of

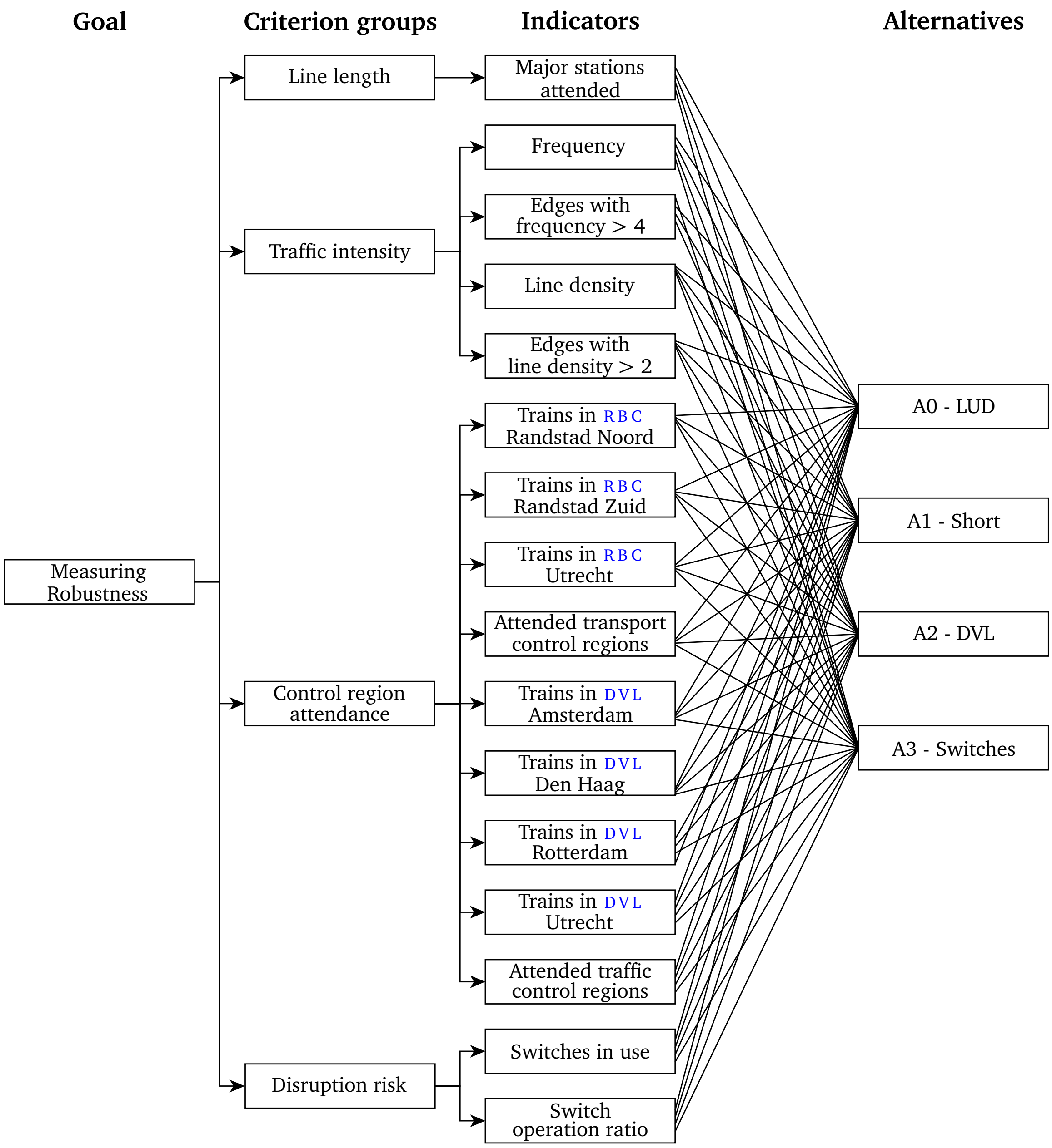

Figure 5-1: Hierarchy of the criterion groups and corresponding indicators to measure robustness

trains in DVL regions. This is because the traffic controllers are the first to respond in case of a disruption, as already explained in section 2.7. The number of trains in DVL Amsterdam and DVL Utrecht is considered more important than in the regions Den Haag and Rotterdam. This is due to the size of these regions (see table 2-4) and the fact that the largest stations Utrecht Centraal and Amsterdam Centraal are located in these regions. The operation ratio of the high-speed switches is furthermore considered more important than the number of operational switches itself. All initial AHP weights are shown in table 5-4.

Multiplying the indicator weight by the weight of its parent criterion group yields the total weight γ. Section 5.3 describes the sensitivity of the robustness index to these weights. When we calculate the weighted sum of the indicators as shown in eq. (5.1) for all alternatives, we obtain the scores

Table 5-4: Initial AHP weights for the criterion groups (a) and indicators (b)

(a) Initial criterion group weights

Criterion group	Weight
Line length	9.7%
Traffic intensity	36.5%
Control region attendance	28.5%
Disruption risk	25.3%

(b) Initial indicator weights

Indicator	Weight
Major stations attended	100.0%
Frequency	9.4%
Edges with Frequency > 4	57.4%
Line density	10.1%
Edges with > 2 lines	23.1%
Trains in RBC Randstad Noord	4.4%
Trains in RBC Randstad Zuid	4.4%
Trains in RBC Utrecht	4.4%
Attended transport control regions	5.2%
Trains in DVL Amsterdam	17.4%
Trains in DVL Den Haag	9.6%
Trains in DVL Rotterdam	9.6%
Trains in DVL Utrecht	17.4%
Attended traffic control regions	27.8%
High-speed switches in use	40.0%
Switch operation ratio	60.0%

presented in table 5-5.

The results indicate that A3 is the most robust alternative, followed by A2 and A1. All three alternatives are, according to these criteria, by far more robust than the zero-alternative. As a reference, we also calculated the robustness index of the regular line system, being 118.6. This indicates that the LUD line system is more robust than the regular line system, which is in accordance with the expectation. The succeeding sections will elaborate further on the validity of these results and how the robustness index relates to the capacity shortage of all alternatives.

Table 5-5: Results of the MCA with initial weights and standardized indicator values

Criterion group	Indicator	Weight	Real values				Standardized values			
			A0	A1	A2	A3	A0	A1	A2	A3
Line length	Major stations attended	9.70%	3.809	2.796	2.133	2.952	100.00	73.41	56.01	77.51
Traffic intensity	Frequency	3.43%	4.636	4.243	4.116	4.33	100.00	91.52	88.78	93.40
	Edges with Frequency > 4	20.95%	106	87	84	101	100.00	82.08	79.25	95.28
	Line density	3.69%	2.689	1.931	1.881	1.891	100.00	71.81	69.95	70.32
	Edges with > 2 lines	8.43%	145	49	42	39	100.00	33.79	28.97	26.90
Control region attendance	Trains in RBC Randstad Noord	1.25%	40	39	45	39	100.00	97.50	112.50	97.50
	Trains in RBC Randstad Zuid	1.25%	32	38	34	31	100.00	118.75	106.25	96.88
	Trains in RBC Utrecht	1.25%	48	49	48	50	100.00	102.08	100.00	104.17
	Attended transport control regions	1.48%	1.851	1.531	1.412	1.643	100.00	82.71	76.28	88.76
	Trains in DVL Amsterdam	4.96%	36	33	37	33	100.00	91.67	102.78	91.67
	Trains in DVL Den Haag	2.74%	18	21	22	19	100.00	116.67	122.22	105.56
	Trains in DVL Rotterdam	2.74%	14	17	14	12	100.00	121.43	100.00	85.71
	Trains in DVL Utrecht	4.96%	36	37	32	38	100.00	102.78	88.89	105.56
	Attended traffic control regions	7.92%	2.617	2.041	1.686	2.190	100.00	77.99	64.42	83.68
Disruption risk	High-speed switches in use	10.12%	35	26	26	4	100.00	74.29	74.29	11.43
	Switch operation ratio	15.18%	3.543	1.771	1.686	0.314	100.00	49.99	47.59	8.86
						Robustness index	**100.06**	**75.61**	**70.66**	**64.75**

5.3 Sensitivity analysis

The initial weights used in the MCA are arbitrary and estimated using subjective judgement. To assess the impact of the weights on the calculated robustness index, a sensitivity analysis is performed. By changing the weights of the criterion groups and the indicators, the robustness index of the alternatives will change as well. The zero-alternative will always have the same index of ≈ 100. Furthermore, the sensitivity analysis is used to exclude (groups of) indicators that have been used as design principle. This has already been indicated in section 4.4.

The varying of weights is performed using different *scenarios*. Each scenario has a different distribution of weights, such that it is possible to focus on specific criteria or exclude indicators from contributing to the robustness index. All scenarios are based on the default scenario (S1), which means that unchanged weights are the same as in S1. The first scenarios are general scenarios, used to determine the robustness index if the criterion groups and/or the corresponding indicators are weighted equally.

A second group of scenarios excludes one of the criterion groups from the analysis by changing its weight to 0% to assess the impact of the respective criterion group on the robustness index. The other criterion groups are reweighed in order of importance using the AHP process. A third group of scenarios excludes one of the criterion groups as well, while the other three groups are weighed equally. There is an additional scenario which excludes indicators for RBC attendance. This is because the value of these indicators has overlap with the value for DVL attendance. This makes the RBC indicators a partial duplicate, which might lead to incorrect results. As different indicators should not measure the same, this scenario is added to check the impact of these indicators on the outcome (Communities and Local Government, 2009).

The exact weights of the scenarios are presented in table F-1 in Appendix F. The following scenarios have been drafted:

- S1: Default AHP weight as explained in section 5.2.
- S2: Equal weight for all criterion groups.
- S3: Equal weight for all indicators within the same group.
- S4: Equal weight for both criterion groups and indicators within the same group (no weight).
- S5: Line length is excluded from the analysis. Other criterion groups are reweighed.
- S6: Traffic intensity is excluded from the analysis. Other criterion groups are reweighed.
- S7: Attended control regions is excluded from the analysis. Other criterion groups are reweighed.
- S8: Disruption risk is excluded from the analysis. Other criterion groups are reweighed.
- S9: Line length is excluded from the analysis. Other criterion groups are of equal weight.
- S10: Traffic intensity is excluded from the analysis. Other criterion groups are of equal weight.
- S11: Attended control regions is excluded from the analysis. Other criterion groups are of equal weight.
- S12: Disruption risk is excluded from the analysis. Other criterion groups are of equal weight.
- S13: Indicators for RBC attendance are excluded. The indicators for DVL attendance are reweighed.

Figure 5-2 presents the results of the sensitivity analysis in a chart. The lines in the chart indicate the robustness index for the alternatives for the weights of the thirteen scenarios. The zero-alternative A0 has a score of 100 in every scenario, which is expected since A0 is the reference. The robustness index of the regular line system is added to indicate that the LUD is more robust than the regular line system in all scenarios, which is in accordance to the expectations.

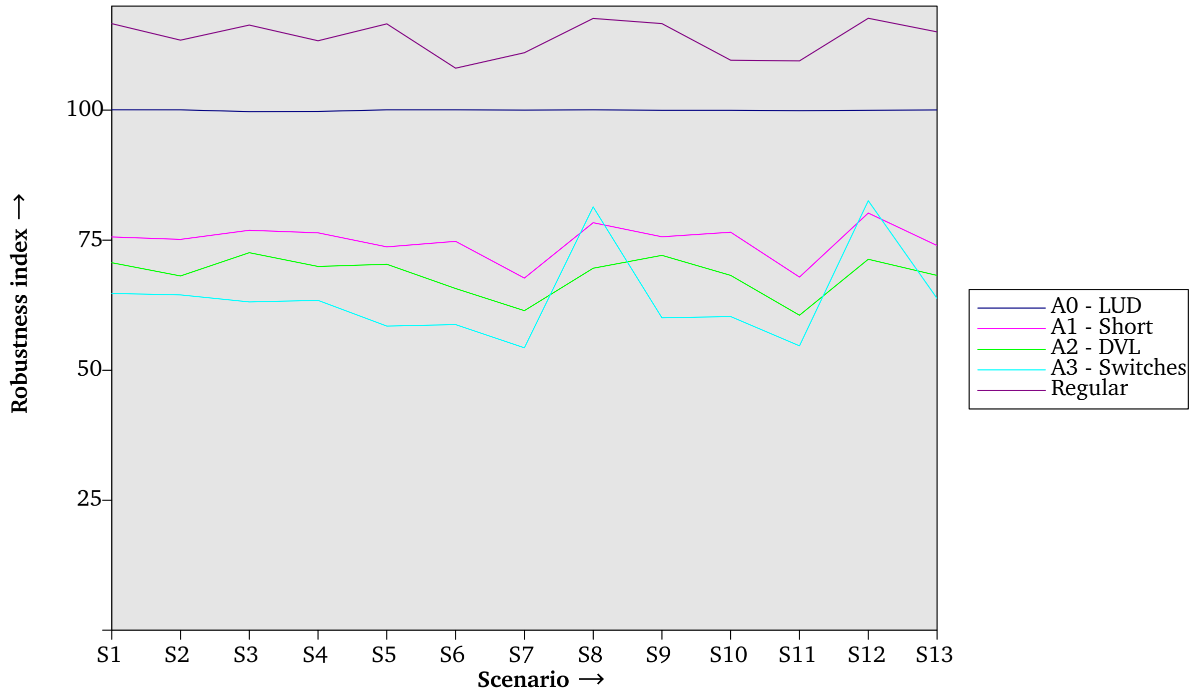

Figure 5-2: Robustness index of all alternatives using different weight scenarios

The chart in fig. 5-2 also shows that the ranking order between the alternative line systems is very stable. In almost all scenarios, A3 has the lowest robustness index, followed by A2 and A1. In S8 and S12, however, A3 is *less robust* than both A1 and A2. In both scenarios, the criterion group "disruption risk" is excluded from the analysis. We therefore conclude that the low value of the robustness index of A3 is mainly caused by this criterion group. This is also visible in table 5-5, as the scores of the indicators in this group are very low. Since A3 becomes the least robust alternative in S8 and S12, the usefulness of the number of operational switches and their operation ratio, or at least their weight, in the MCA is questionable.

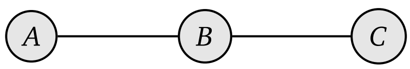

Figure 5-3: Example line from station A to C

On the other hand, the three alternative line systems are still more robust than the LUD, regardless of the scenario. Table 5-5 shows that only a few indicators have a value > 100, which indicates that their score is worse than A0. This only applies to indicators that count the number of trains in a DVL or RBC region. This effect can be explained by the method used to determine the number of trains. Let fig. 5-3 represent a line which operates with 2 trains/hour between stations A and C. All stations are located in different control regions, which means that there are 2 trains in every control region every hour. In a line system with shorter lines, there might be two lines from A to B and from B tot C, all with frequency 2. This means that the control regions of station A and C are still attended by 2 trains per hour. The control region of station B is, however, attended four times per hour. This implies that a line system with short lines has a higher control region attendance. Since A0 knows several very long lines, this explains the higher control region attendance of the alternatives.

Based on this sensitivity analysis, we can conclude that all alternative line systems are in any case more robust than the LUD, and that the robustness index is only slightly sensitive to the applied weights.

5.4 Calculation of capacity shortage

The capacity shortage of each alternative has been calculated using the models presented in the previous chapter. These shortages have already been mentioned in section 5.1, but do not give any insight in the *severity* of the shortage. A shortage of 10 passenger places for every train in the line system yields a very high total shortage, but is less severe than five trains with a shortage of 100 passenger places. This has to do with the definition of the train capacity, as the real capacity of the trains is in practice a little higher than the capacity used in this study. A slight capacity shortage per train can therefore be neglected, but is still not preferred. Figure 5-4 gives an overview of the capacity shortage per alternative per train composition. The shortages have been sorted in descending order to present the individual differences. The regular line system does not have a capacity shortage, which explains its absence in this chart.

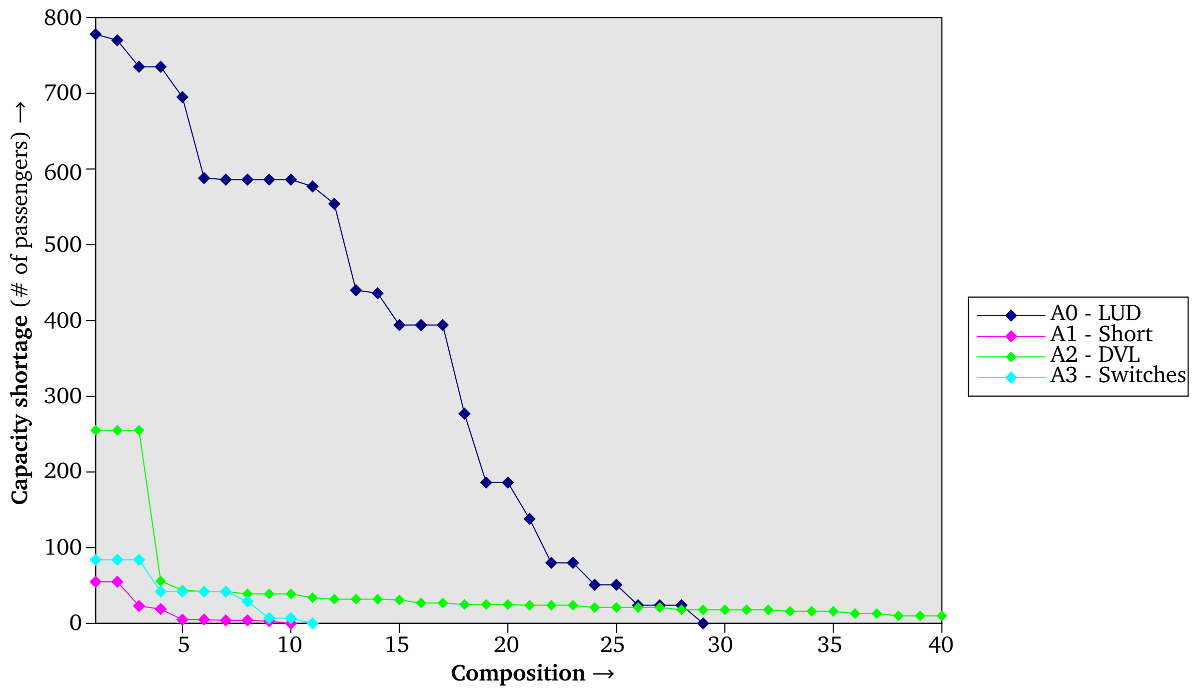

Figure 5-4: Capacity shortages for all alternatives per composition in a descending order

Figure 5-4 clearly shows the large capacity shortages during the LUD. Some trains require more than 700 additional passenger places, which indisputably results in passengers left behind on the platform. This is an unacceptable situation. If we furthermore recall that the rolling stock assignment is optimal, it is likely that the shortage is much higher in practice. All new alternatives are providing a considerable better transport capacity. A2 is the worst of these, since three trains have a serious lack of capacity and many other trains have small shortages due to the insufficient fleet size.

Now that we know the ranges of the robustness index of the alternatives and the transport capacity, we can also analyse how the robustness relates to the transport capacity. Figure 5-5 shows this relation between the robustness index and the capacity shortage. This clearly indicates that all three alternatives are, theoretically, better than the zero-alternative. The sensitivity analysis yet made clear that the robustness of A3 is much depending on the weights in the MCA, which is once more visible here. As the robustness index of the alternatives is relative to A0, the index of A0 is always 100.

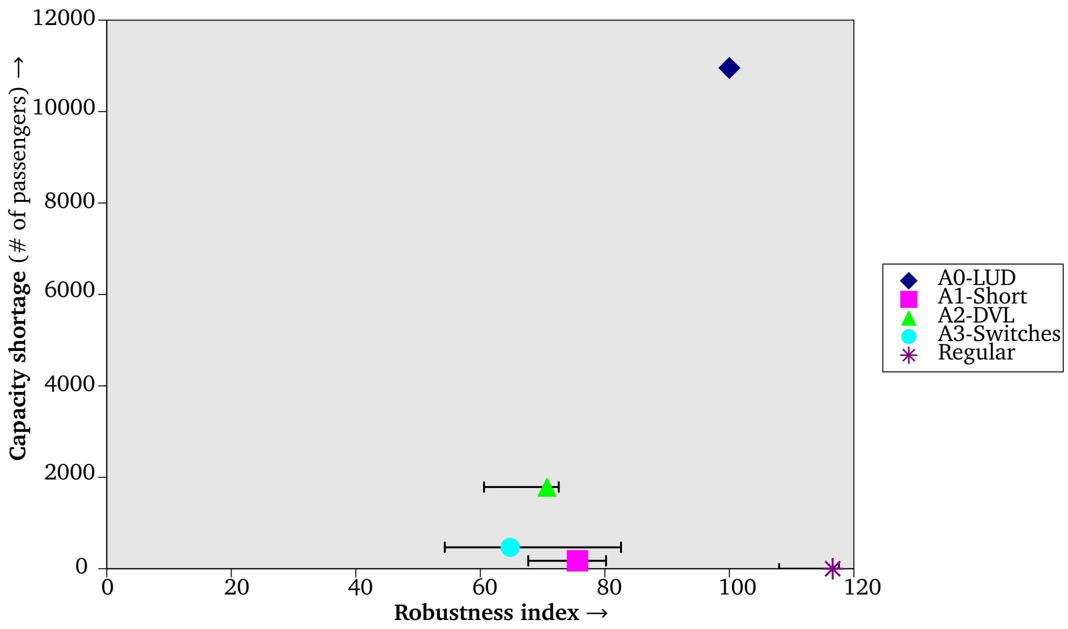

Figure 5-5: Ranges of the robustness index over all alternatives and their capacity shortage

The following conclusions can be drawn based on the robustness index and the capacity shortage of the three alternatives:

- A1 and A3 have the least capacity shortage and no unacceptable shortage per composition. A1 is the best of these.
- A2 has a relatively large shortage and requires more rolling stock than in the operational fleet.
- Depending on the weight, A3 can be the best or the worst alternative regarding the robustness index, but is still more robust than A0
- A1 and A2 have a relatively stable robustness index.

Based on these statements, we can conclude that A1 and A3 are considerably better than A2.

5.5 Other relevant criteria

Previous sections have clearly shown that the alternative line systems are interesting substitutes to the LUD, since their robustness index and capacity shortage are in all cases lower and thus better.

There are, however, many other relevant criteria that determine whether an alternative line system is suitable during winter weather or not. Most of the criteria used in the MCA do not account for the feasibility of the line system, which means that it is yet unclear if it is technically *possible* to *execute* the line system. Furthermore, we have not taken the comfort of the passenger into account until this moment. Passengers are of course benefiting from a more robust line system with less capacity shortage, but the implications for passengers regarding for instance travel time and transfers have yet not been determined.

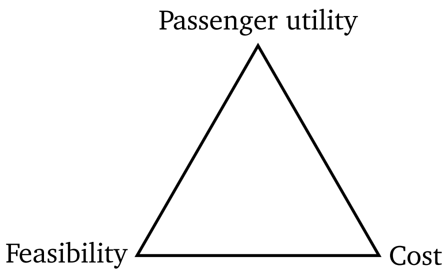

Figure 5-6: Balance between passenger utility, cost and feasibility

When creating a timetable, there is a trade-off between feasibility, passenger utility and corresponding costs as shown in fig. 5-6. In this section, we evaluate the alternative line systems on these aspects to determine the "commercial" effects of the alternatives. These criteria are harder to quantify and assess using only the characteristics of the line system and therefore evaluated in a more qualitative manner. Only the passenger utility and the technical feasibility of the line systems are addressed, since it is not possible to determine the relevant financial costs of the line systems at this stage. Costs to *operate* the line system can be roughly determined as this is depending on the use of the infrastructure and the number of carriages per train. These expenses are however not relevant, since NS is not aiming to reduce operational costs during days with extreme winter weather. Relevant expenses include the costs to develop an alternative line system to a detailed timetable and deploy this timetable in a relative short time frame. Calculation of these costs require further research.

5.5.1 Average travel time and number of transfers

One of the most important criteria for passengers is the travel time (including waiting time) and the number of transfers. It is considered as a key decision factor in determining the passengers' comfort, since passengers are very sensitive to these criteria. The regular timetable is therefore optimized to offer short travel times and a minimum number of transfers. Figure 5-7 shows the average travel time and number of transfers per passenger for all alternatives, calculated by TRANS. This figure clearly shows the relation between the LUD and the regular timetable. Both have more or less the same lines in terms of length and direction, but the frequency in the LUD is lower. This explains the larger travel time with almost the same number of transfers. The three new alternatives are all performing worse when it comes to this.

The increment in travel time does not seem very high, but is still considerable. Compared to A0, a passenger in A3 has an increased travel time of almost 1.5 minutes. Multiplied by the over 270,000 passengers in the OD-matrix, this yields around 8,000 hours of extra travel time. For A2, which has the highest travel time, this increases up to 11,500 hours. The same holds for the number of transfers. If we compare the average number of transfers with the line length, we conclude that there is a clear correlation between both aspects. The difference in the number of transfers between A0 and A3 is almost 0.1, which means that there are 27,000 additional transfers during the morning peak. This makes clear that robustness has a “price”. Passengers might be served with a more reliable train service during winter weather, but with increased travel time and additional transfers.

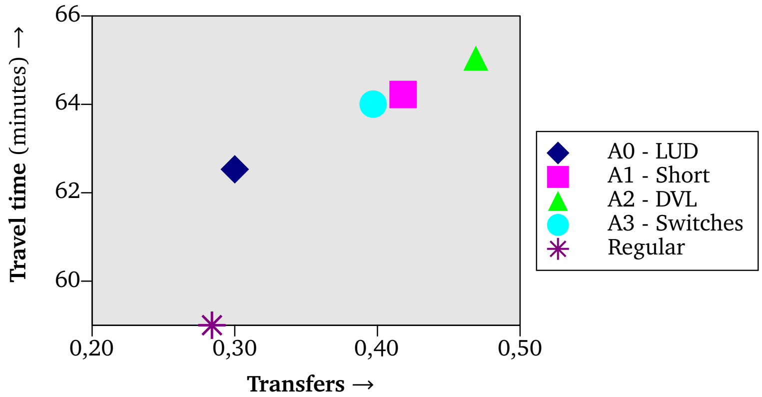

Figure 5-7: Average transfers and travel time for all alternatives

5.5.2 Capacity shortage in case of rolling stock defects

The shortage of transport capacity during winter weather is not only due to the line system of the LUD. In most of previous winters, rolling stock has broken down as a result of refreezing snow or short circuits. It is therefore interesting to determine the amount of spare rolling stock for all alternatives. The used rolling stock assignment model does not minimize the deployment of rolling stock, which means that compositions can be longer than necessary. To overcome this, we calculated the capacity shortage with a reduced fleet sizes ranging from 5% to 20% unavailable rolling stock. This “unavailability factor” is proportional among the different rolling stock types, which means that the fleet size of every type is decreased with the same percentage.

Figure 5-8 presents the capacity shortage per alternative if different shares of the fleet are unavailable. The figure indicates that all alternatives are sensitive to the availability of the fleet. If less train units are available, the capacity shortage increases rapidly. A3 has the lowest capacity shortage in most cases, which can be explained by the line length. A3 has longer lines and therefore requires less train compositions than the other alternatives. This makes that there is more spare rolling stock available.

Where A1 has the lowest shortage if all rolling stock is available, it has the highest shortage of the alternatives if only 5% has broken down. This indicates that A1 has just enough rolling stock to operate the line system, and thus is sensitive to defects. A2 is already short on capacity if all rolling stock is available, which explains why this alternative eventually has the largest shortage. Figure 5-8 furthermore shows that the regular line system and the rolling stock fleet are well in line with each other, as 10% fleet unavailability still results in only minimal shortage.

5.5.3 Infrastructure capacity at terminal stations

When a train has reached its final destination, it changes direction and prepares to operate back to its origin. In many cases, the train is being cleaned while it waits at the platform it arrived. This makes that the train occupies a platform during the layover time. In other cases, the train is

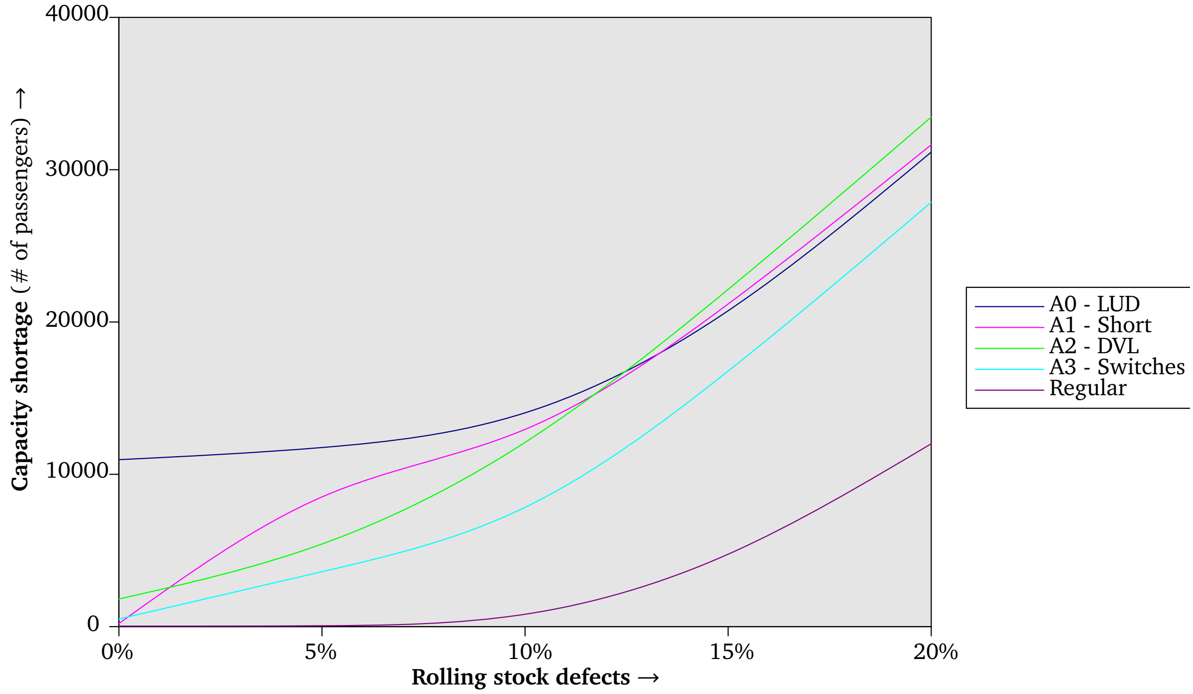

Figure 5-8: Capacity shortage in case of unavailable rolling stock

moved to a shunting yard or third track. The regular timetable and the infrastructure at and around stations are adapted to each other, such that there is enough platform capacity to turn trains. In case of a new line system, we should therefore check whether the capacity at terminal stations in enough to turn all trains. This holds especially for A1 and A2, where the lines are relatively short. Shorter lines result in more turning trains, and thus require more platform or shunting yard capacity.

Since no detailed timetable is constructed, it is not possible to determine the exact platform capacity and whether there is enough capacity for turning trains or not. It is, however, possible to analyse the number of turning trains per station and compare this with the turning movements of the regular line system and the LUD. Since these timetables have been successfully executed, we know that the number of turning movements in these line systems is feasible. This provides insight in the available infrastructure and the operational feasibility of the alternatives. A complete list of all turning movements per alternative is available in table G-1 in Appendix G, this section only summarizes the possible conflicts. Turning movements are considered as conflicts if there are 2 more turning movements per hour than in the regular line system or the LUD

Lines in alternative 1 often start and end at larger stations and common decoupling points. 44 of all 212 turning movements per hour are additional to the turning movements in the regular line system. Especially in Deventer (4), Eindhoven (5), Leiden Centraal (9) and Rotterdam Centraal (15), problems are expected.

In alternative 2, some lines are turning at less conventional stations due to the coverage areas of the control regions. 69 of all 222 turning movements per hour are additional to the regular line system. Amersfoort (4), Amsterdam Centraal (22), Dordrecht (8), Ede-Wageningen (7), Eindhoven (9) and Lelystad (8) are examples of terminals with extra turning movements. Additionally, there are also trains turning in Den Dolder, Oss and Lage Zwaluwe, which are not conventional terminal stations.

Alternative 3 has longer lines than A1 and A2 and therefore less turning movements. 38 out of 186 turning movements are additional to the regular line system and most of these are at unconventional stations. This holds for Geldermalsen, 't Harde, Tilburg and Lage Zwaluwe. Woerden (4) and Lelystad (5) are conventional terminal stations with extra turning movements.

From this analysis we can conclude that all alternatives might cause problems at terminal stations. To prevent this, some trains might have to turn on another station because there is not enough capacity. Coupling two lines into one line is a typical way to solve these problems, but results in longer lines. In most cases this has already been attempted, but was not always possible as a result of the recipe of the line system.

5.6 Implications of the results

The preceding sections have shown that the three alternative line systems for winter weather are theoretically performing better than the LUD in terms of robustness and transport capacity. The alternatives are more robust than the LUD, regardless of the weight of the criterion groups and their indicators. This is mainly caused by the line length, the traffic intensity and the disruption risk. All alternatives are performing better than the LUD in these criterion groups. Which of the three alternatives is best depends on the context.

5.6.1 Similarities and differences between the alternatives

The alternatives have several similarities and differences. A1 and A2 are quite similar, since they both have relatively short lines. Where A1 has a reduced line length in terms of major stations, the line length in A2 is constrained by the control regions. This even results in a lower average line length of A2. Regarding robustness, the sensitivity analysis has shown that A2 is always more robust than A1. A2 has, however, a larger capacity shortage and requires the complete rolling stock fleet to operate its line system. This makes that A1 can be considered as a better alternative than A2. A1 is less robust, but performs better in almost every other area.

Alternative 3 is a completely different line system than A1 and A2, as the values of its indicators are mostly higher. The low robustness index of A3 is mainly due to the fact that only few high-speed switches are used, as already shown in the sensitivity analysis. Excluding the disruption risk criterion still makes A3 less robust than A1 and A2, but still more robust than the LUD.

The most important similarity between the alternatives is the frequency on the busy axes. On these axes, the frequency is set to 3 trains/hour, where the rest of the network has the basic frequency of 2 trains/hour. In general, these axes with $f = 3$ are:

- Eindhoven - 's-Hertogenbosch - Utrecht Centraal - Amsterdam Centraal - Alkmaar
- Amsterdam Centraal - Schiphol - Leiden Centraal - Den Haag HS - Rotterdam Centraal
- Arnhem - Utrecht Centraal
- Amersfoort - Utrecht Centraal
- Utrecht Centraal - Gouda

Based on the capacity shortage of the alternatives, it can be concluded that a frequency of 2 trains/hour is acceptable to provide enough transport capacity on a large part of the network. On the busy axes in the Randstad, this frequency is insufficient.

Another important similarity between the alternatives is that any possible platform constraints are evaded by decoupling lines, which is different in the LUD. On busy axes, the train length should be maximized to transport as many passengers as possible. In the LUD, some lines are attending both busy axes in the Randstad and the outskirts of the country where the platform length is limited. This results in a limited train length, which is especially not desirable if the frequency is also reduced. An example is the line Nijmegen - Den Helder. The frequency between Nijmegen and Utrecht is reduced by half, but as the train ends in Den Helder the maximum length is 10 carriages. The same goes for the line Roosendaal - Leeuwarden, which attends one of the busiest axes on the network but is restricted to 10 carriages because of platform constraints near Leeuwarden. In all alternatives, outskirts with similar platform constraints have been decoupled completely from the busy lines in the Randstad.

5.6.2 Feasibility

Section 5.5 has already addressed the theoretical feasibility of the alternatives, indicating that all three alternatives are still concepts and require more detail before their usefulness in practice can be determined. A BHP must be created to calculate the exact arrival and departure times for all trains, including possible transfers between trains. If we assume an equal distribution of trains over the hour, it is expected that shared infrastructure between two lines with a frequency of 2 and 3 trains/hour will result in problems. In the alternative line systems this problem is mitigated by increasing the frequency of all trains on the same axis, but crossings and partially shared edges can still cause a problem. This also holds for connecting lines with a different frequency and cross-platform transfers between these lines. These transfers are very important for passengers.

Because the proposed alternatives are very different from the regular timetable, the deployment of an alternative requires more preparation time than the LUD. Where the LUD is based on the regular day plan, any other timetable requires a separate plan. Using another day plan is possible but requires intensive preparations. Nowadays, separate day plans are used to plan detours in case of extensive maintenance. The main difference is that these maintenance works are planned, such that a complete planning for both rolling stock and crew can be made weeks in advance. Deploying an alternative timetable in case of extreme winter weather is decided upon a much shorter notice. A different line system requires a new rolling stock plan and a new crew plan. This results in the following problems:

- Planning of rolling stock is completely depending on the location of all trains, which is depending on the day plan of the day before. The desired train units might therefore not be available. This implicates that the optimal solutions as calculated by the assignment model is probably not feasible, since multiple train types can be assigned to the same line.
- Crew is often licensed to operate certain types of rolling stock and drive certain routes. A different line system and rolling stock assignment requires a completely new crew planning.

Another implication of a completely different timetable is the familiarity of passengers and crew with the plan. As a result of the BHP, trains of the same line are repeating a pattern such that they arrive and depart at the same time and at the same platform every hour. This pattern results in a routine for frequent travellers and crew. A different line system requires a different BHP and thus breaks the routine, especially when some line are operating every 20 minutes. Consequently, it is likely that the platform assignment has to change as well.

6 Conclusions and recommendations

The previous chapters have described the process to assess the robustness and transport capacity of a line system on the Dutch railway network, and presented alternative line systems to improve the performance during extreme winter weather. This chapter contains the conclusions of this thesis and describes recommendations for further improvements in the future. Section 6.1 contains the main conclusions of this study and answers the research questions. The conclusions and underlying assumptions are discussed in section 6.2 to point out possible limitations of this study. Section 6.3 subsequently describes recommendations for further research.

6.1 Conclusions

For this study, the following research question has been formulated:

> **Main research question:** *Which line system and corresponding rolling stock distribution can be applied to the Dutch railway network during extreme winter weather and provide enough transport capacity to limit crowded trains, while conserving robustness for controlling train operations?*

To answer this question, we first formulated a set of criteria with corresponding indicators to measure the robustness and the transport capacity of a line system. The following conclusions are drawn:

- The robustness of a railway network can be expressed in terms of absorption capacity and controllability. These are measures of respectively proactive and reactive methods to let the network adapt itself to a range of possible futures.
- There are multiple criterion groups and corresponding indicators that can be used to estimate the robustness of a line system on the Dutch railway network in winter weather. The robustness can be measured using only the characteristics of the line system. These criteria are:
    - Line length, measured by the number of major stations a line attends. A disruption on a line propagates along the length of the line, which makes that short lines can restrict the propagation of delays to a local level.
    - Traffic intensity, measured by both the frequency on the edges of the network, as well as the line density. The number of trains per edge in the network determines how many trains will be affected if a disruption occurs. A higher frequency will result in less

buffer and faster occurrence of knock-on delays. The line density determines how many different lines are affected in case of a disruption. Unbundling the network reduces the line density and favours the robustness, but yields less direct connections for passengers.

- Control region attendance, measured by the number of trains per control region per hour and the number of attended regions per line. The Dutch railway network is controlled by dispatchers and traffic controllers, operating from respectively DVL and RBC control centres. Each control centre has its own coverage area, called the control region. If a disruption affects a line that attends multiple control regions, coordination back and forth is required to recover from this disruption. Reducing the number of attended control regions favours the controllability of the network and thus the robustness.

- Disruption risk, measured by the operation of high-speed switches. High-speed switches are critical infrastructure assets on the Dutch railway network, as their long switch blade accumulates snow and ice. These switches are causing many disruptions during winter weather, which is mostly due to movement of the switch blade. Passing these switches in only one direction therefore reduces the risk on disruptions.

- The transport capacity of a line system is depending on the length of the train composition and the frequency of the lines. Both cannot be increased infinitely due to respectively platform constraints and the capacity of the infrastructure.

- Frequency is a factor for both the robustness and the transport capacity of a line system, but has conflicting interests. Increasing the frequency yields more transport capacity, but less robustness and the other way around. This makes frequency the most important variable in the design of a line system.

Secondly, we developed a methodology to design line systems and compute the transport capacity. To do so, passengers from the OD-matrix are allocated to the different lines and trains on the lines to estimate the travel demand per train. The difference between the demand and the train capacity determines the capacity shortage. This methodology is shown in fig. 6-1.

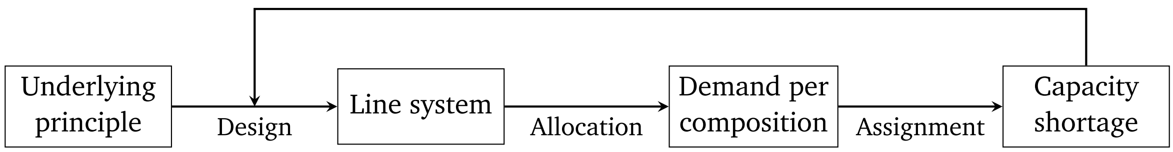

Figure 6-1: Methodology to design an alternative line system

The following methodological conclusions are formulated:

- Alternatives are best designed from a robust perspective and optimized to improve the transport capacity afterwards.

- Rounding-up the OD-matrix and increasing the demand with an additional load factor of 1.4 to account for the "peak within the peak" makes that the demand is more likely to be overestimated than underestimated. The travel demand is therefore seen as an upper bound.

- The assignment model computes the optimal assignment of rolling stock to the train compositions in the line system. Since this model does not account for the location of the fleet nor assigns the same type of rolling stock to the same line, the capacity shortage is likely to be underestimated. The computed capacity shortage is therefore seen as a lower bound.

Using the design methodology, three alternative line systems have been created. The alternatives have been thoroughly evaluated and compared to the zero-alternative, the LUD. This yields the following conclusions:

- The capacity shortage during the LUD is due to the reduced frequency. The rolling stock assignment model has proven that the LUD timetable is by far not able to transport all passengers, even if the assignment of rolling stock is optimal.
- There are alternative line systems which are theoretically more robust than the LUD and yield more transport capacity. Alternative A1 and A3 are two completely different line systems, but both better than the LUD. Both line systems have advantages and disadvantages, and should become more detailed to assess their usability in practice.
- A frequency of 2 trains/hour yields enough transport capacity on the large part of the Dutch railway network, but is insufficient on busy axes in the Randstad. In order to transport all passengers, at least 3 trains/hour should operate on the following axes:
  - Eindhoven - 's-Hertogenbosch - Utrecht Centraal - Amsterdam Centraal - Alkmaar
  - Amsterdam Centraal - Schiphol - Leiden Centraal - Den Haag HS - Rotterdam Centraal
  - Arnhem - Utrecht Centraal
  - Amersfoort - Utrecht Centraal
  - Utrecht Centraal - Gouda
- To prevent capacity problems due to platform constraints, outskirts of the country should be decoupled from lines in the Randstad. This makes that trains operating on the busy axes are not limited in length by short platforms.
- On average, the alternative line systems cause up to 2 minutes extra travel time and 0.15 extra transfers per passenger compared to the LUD. Increasing the robustness and transport capacity therefore has a negative effect on the passenger utility.
- Because all alternative line systems have shorter lines than the LUD, there are additional turning movements at terminal stations. Some of these turning movements might cause problems due to the lack of infrastructure and should be studied to assess the possibility to execute the line system. In other words, the feasibility of the alternatives should be studied.
- High-speed switches on the network have proven to fail more often during winter weather. Evading high-speed switches is, theoretically, a way to decrease the risk on a disruption and should therefore be encouraged. The usefulness of the operational high-speed switches as indicator is, however, questionable.

The answer to the main research question is as follows: There are different alternative line systems that can increase both the robustness and the transport capacity on the Dutch railway network during winter weather, compared to the LUD. This can be achieved by:

1. Shorter lines, where the outskirts of the country are decoupled to avoid platform length constraints.
2. A frequency of at least 3 trains/hour on the busy axes in the Randstad.
3. Evasion of as many high-speed switches as possible.

6.2 Discussion

The results and conclusions of this study are the result of a narrow scope and several assumptions to simplify the subject matter. This section elaborates on a number of these assumptions, models and methods and discusses their implications.

At first, it should be noted that the indicator values of all alternatives are *theoretical*, based on the *characteristics* of the line system. Although this has deliberately been the purpose of the study, the applicability of the alternative line systems is not yet known. The alternative line systems as presented in this study should be developed further in order to assess their applicability. Working out a BHP should be the first step in this process.

To determine the travel demand per line and per train, TRANS uses a discrete choice model where passengers are assumed to maximize their utility. This way, every passenger obtains a certain utility from each alternative travel option and chooses the alternative with the highest utility. The utility is, however, not only depending on the alternative but also on the passenger itself. Since decision-making is *subjective*, every passenger obtains a (slightly) different utility for the same alternative (Train, 2009). It is therefore impossible to observe the exact utility of every passenger. Only some attributes of the alternatives can be observed by others. To account for this, the utility U of alternative j for passenger n is usually described by the function $U_{nj} = V_{nj} + \epsilon_{nj}$. The *observed* factors are measured by V_{nj} (see eq. (4.1)), while the *unobserved* factors that influence the utility are captured in ϵ_{nj}. The value of ϵ_{nj} is not known and therefore treated as a random factor. It should be noted that TRANS does *not* take this unobserved utility into account and thus treats every passenger the same way.

The passenger demand per line is calculated using an MNL model, also included in TRANS. This model is used because it is relatively simple and enables fast computation of the passenger allocation. The use of an MNL models is, however, based on an important property called the Independence of Irrelevant Alternatives (IIA). This property states that the probability of choosing one alternative over another may not depend on any other alternative in the choice set (Train, 2009). For example, if alternative A is preferred over alternative B, the addition of alternative C to the choice set may not result in B being preferred over A. More specifically: "IIA requires that if a new alternative becomes available, the probabilities for the prior choices must adjust in *precisely* the amount necessary to retain the original odds" (Cheng & Long, 2007, p.584). See also the classical example of the red and the blue bus as described in McFadden (1974). Adding a travel option in TRANS always changes the ratio between the prior travel options, which makes that TRANS structurally violates the IIA property. A different choice model like probit or mixed logit could be used to change this.

The rolling stock assignment model is based on a few assumptions that affect the assignment and therefore the calculated capacity shortage. First and foremost, the assignment model calculates the optimal assignment. Nonetheless, it is not known to what extent this assignment is also applicable in practice. The train fleet is spread over multiple shunting yards throughout the country and the assignment model does not take this into account. Executing the proposed assignment could therefore result in many nightly trips to get the trains to the right shunting yard. Moreover, the model enables the assignment of multiple rolling stock types on the same line, which is not desirable in practice. Both limitations of the model could be included in the model to calculate a more realistic assignment.

Although the used models are simplified, they are only used for *comparison* in this study. The calculated demand and capacity shortage cannot represent the actual situation unequivocally, but are quite useful to determine whether one alternative is *better* or *worse* than the other.

6.3 Recommendations for an alternative winter timetable

The preceding sections have presented the conclusions of this study and the possibilities for NS to improve the train service during days with winter weather. Most of the conclusions are theoretical and should therefore be further examined to assess the effects in practice. To do so, the following steps are recommended:

- At least one of the alternatives should be expanded into a more detailed timetable. Creating a BHP is required to check if a feasible timetable without conflicts is possible at all. Section 5.6.2 already elaborated on a few possible conflicts
- The alternative line systems in this study are more robust and yield more transport capacity than LUD, but require a completely *different* BHP. This makes that passengers, crew and the operational controllers will have to abandon their daily routine and operate according a very different plan. Trains will consequently arrive and depart at other platforms and different times than everyone is used to. It should be investigated whether it is at all possible to do this, and what the preparation time would be.
- As a consequence of the above, it should be investigated if it is worthwhile to entrust the crew with a complete different plan. If the crew is not able to operate according to this plan, it is not likely to succeed.
- The alternative line systems result in more transport capacity due to optimal assignment of rolling stock. In practice, such an optimal assignment is often not possible due to constraints we have not accounted for. Once a detailed timetable is made, the transport capacity should therefore be re-calculated.
- The LUD can possibly improve if high-speed switches are locked into one direction, as many switches do not require changes in the line system. It should be examined if it possible to use other switches to prevent disruptions this way.

6.4 Recommendations for further research

Some problems have been simplified for this study. The effects of the alternative line systems can become more realistic if some assumptions are changed. A few recommendations for further research therefore include:

- In this study, the line length is measured by the number of major stations a line attends. The impact of the line length on the controllability, however, requires a slight nuance as this also depends on the auxiliary resources at the attended stations. Some larger stations are always having additional crew and rolling stock standing by to be deployed in case of a disruption, which makes it easier to control lines attending this station. Adding an indicator to measure this could improve the assessment of the controllability.
- To indicate how "busy" the railway network is, the average frequency on the edges is used. This is a relatively simple method, since the actual occupation of the infrastructure is depending on more factors (see fig. 3-2). The timetable compression method described by Goverde and Hansen (2013) gives a more specific view on the infrastructure occupation as it takes the speed and heterogeneity into account. This requires additional input like blocking times, but yields a more reliable indicator for the traffic intensity. Calculation of the infrastructure occupation could therefore be a valuable expansion on this study.

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Appendices

Appendix A Timeline of winter events

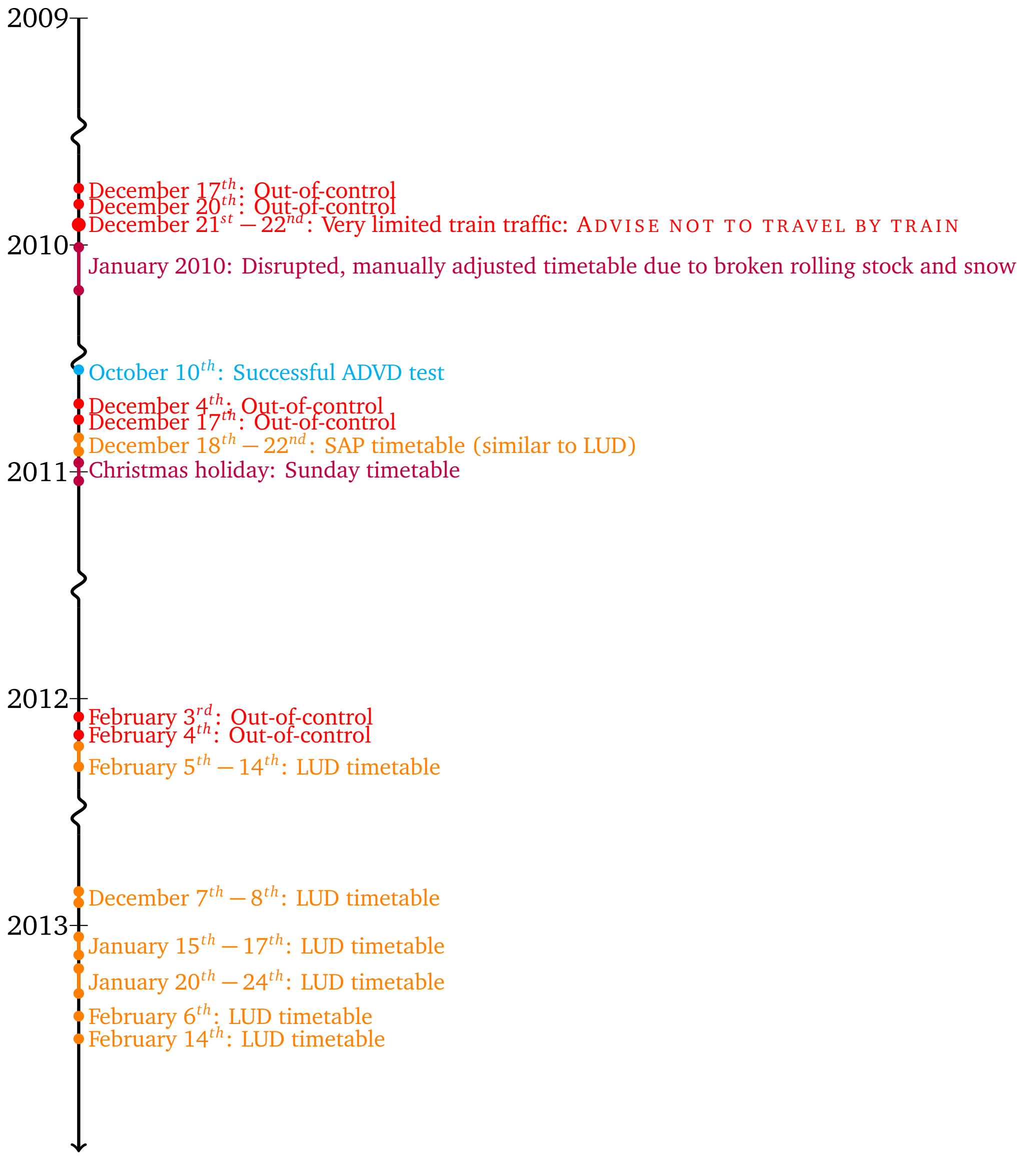

Figure A-1: A timeline of winter events on the Dutch railway network

Appendix B Control Regions

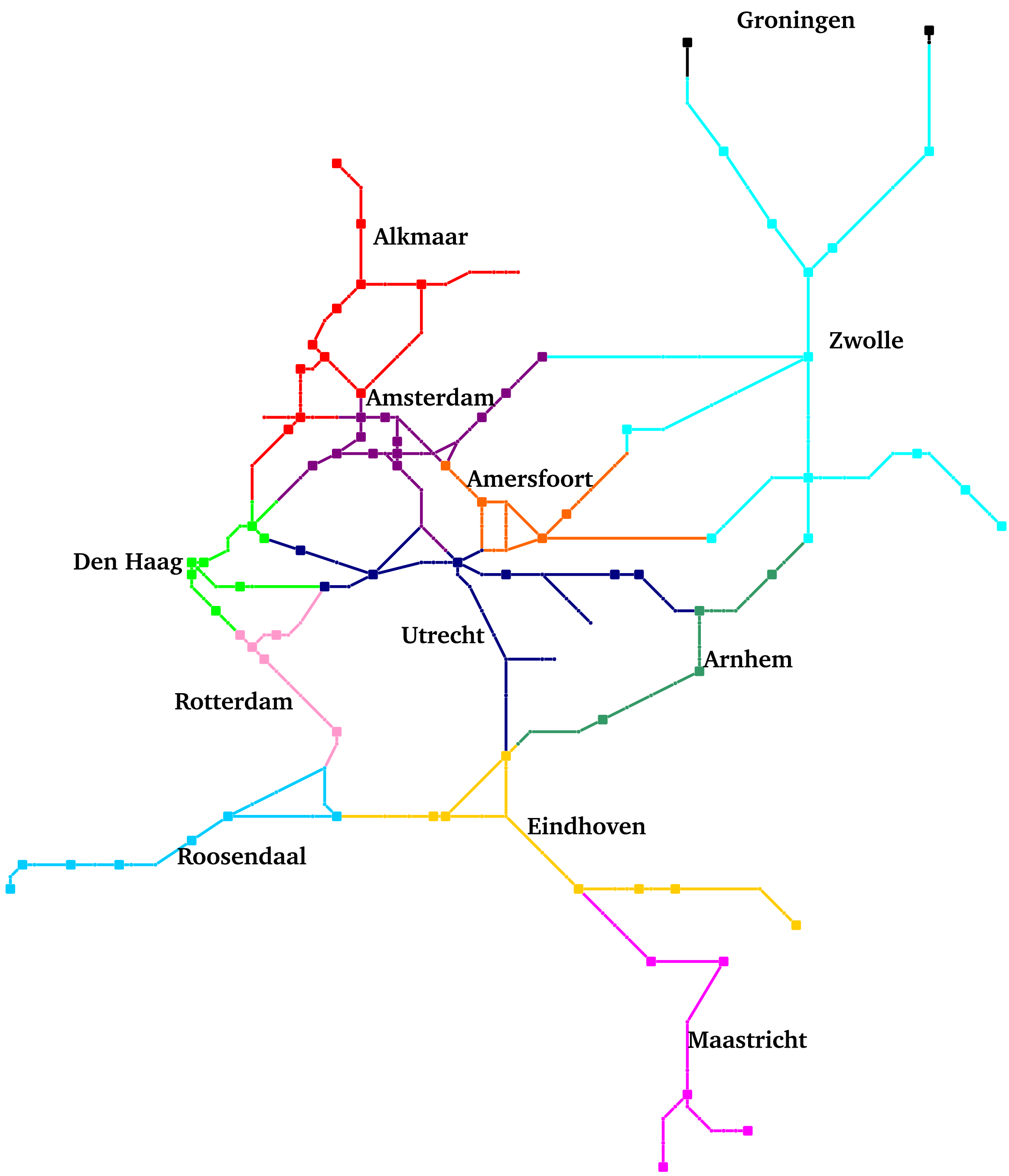

Figure B-1: Overview of the twelve *traffic* control (DVL) regions on the Dutch main railway network

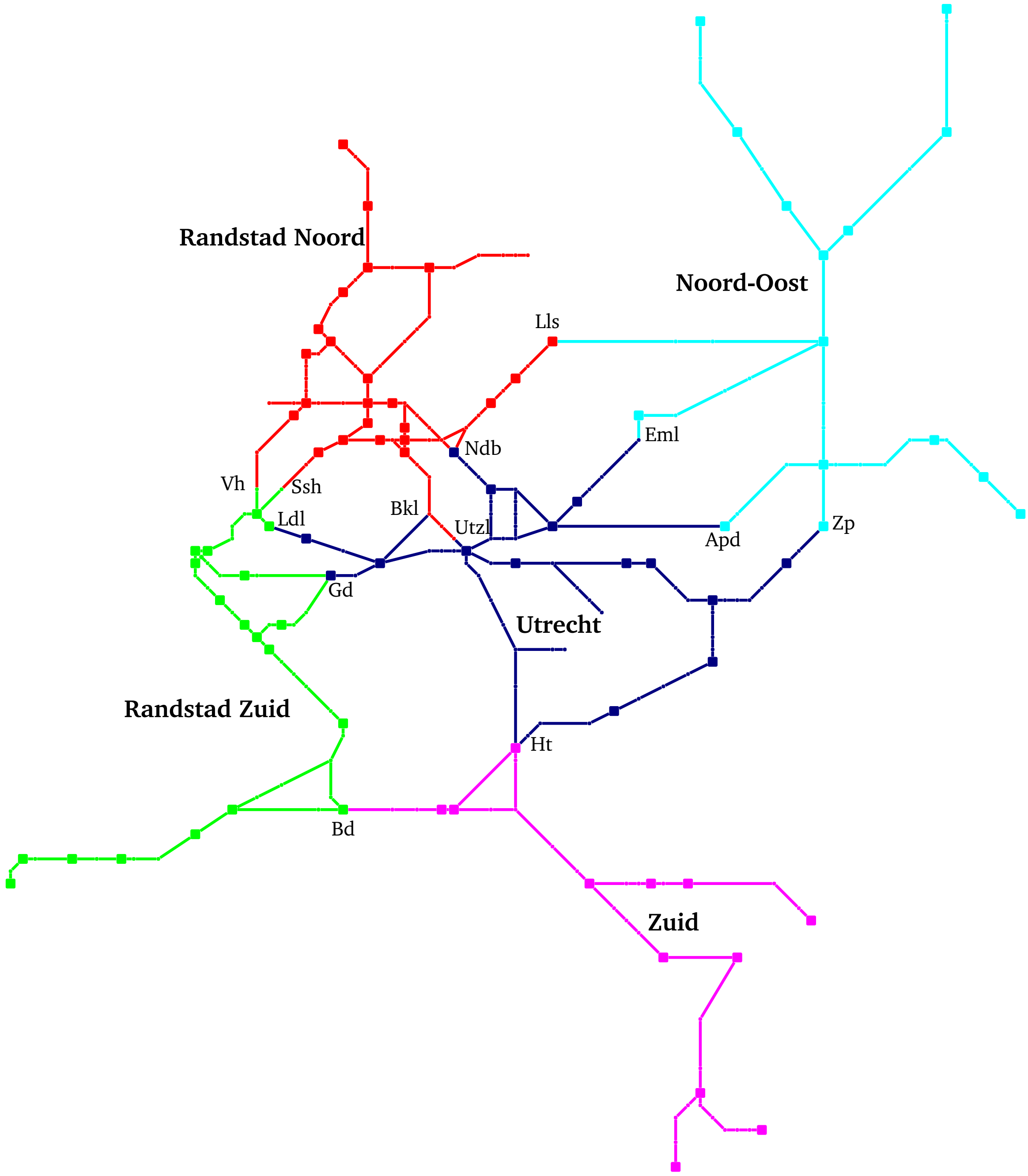

Figure B-2: Overview of the five *transport* control (RBC) regions on the Dutch main railway network

Appendix C Major stations

Table C-1: Major stations in The Netherlands (type 1 and 2 according to Van Hagen and De Bruyn (2002))

Station	Code	Station	Code
Alkmaar	Amr	Haarlem	Hlm
Almelo	Aml	Heerlen	Hrl
Almere Centrum	Alm	Hengelo	Hgl
Amersfoort	Amf	’s-Hertogenbosch	Ht
Amsterdam Centraal	Asd	Hilversum	Hvs
Apeldoorn	Apd	Leeuwarden	Lw
Arnhem	Ah	Leiden Centraal	Ledn
Breda	Bd	Maastricht	Mt
Delft	Dt	Nijmegen	Nm
Den Haag Centraal	Gvc	Roermond	Rm
Den Haag HS	Gv	Roosendaal	Rsd
Deventer	Dv	Rotterdam Centraal	Rtd
Dordrecht	Ddr	Schiphol	Shl
Ede-Wageningen	Ed	Tilburg	Tb
Eindhoven	Ehv	Utrecht Centraal	Ut
Enschede	Es	Venlo	Vl
Gouda	Gd	Zaandam	Zd
Groningen	Gn	Zwolle	Zl

Appendix D Possible train compositions

Table D-1: Possible compositions c for IC (a) and SPR (b) trains with capacity cap_c and length l_c

(a) Possible IC compositions

c	cap_c	l_c
VIRM4	478	4
VIRM4+VIRM4	956	8
VIRM4+VIRM4+VIRM4	1434	12
VIRM6	722	6
VIRM4+VIRM6	1200	10
VIRM6+VIRM6	1444	12
ICM3	299	3
ICM3+ICM3	598	6
ICM3+ICM3+ICM3	897	9
ICM3+ICM3+ICM3+ICM3	1196	12
ICM4	357	4
ICM4+ICM3	656	7
ICM4+ICM4	714	8
ICM4+ICM3+ICM3	955	10
ICM4+ICM4+ICM3	1013	11
ICM4+ICM4+ICM4	1071	12
DDZ6	763	6
DDZ6+DDZ6	1526	12

(b) Possible SPR compositions

c	cap_c	l_c
SGM2	199	2
SGM2+SGM2	398	4
SGM2+SGM2+SGM2	597	6
SGM2+SGM2+SGM2+SGM2	796	8
SGM3	345	3
SGM2+SGM3	544	5
SGM3+SGM3	690	6
SGM2+SGM2+SGM3	743	7
SGM3+SGM3+SGM2	889	8
SGM3+SGM3+SGM3	1035	9
SGM2+SGM2+SGM3+SGM3	1088	10
MAT64	201	2
MAT64+MAT64	402	4
MAT64+MAT64+MAT64	603	6
SLT4	285	3
SLT4+SLT4	570	6
SLT4+SLT4+SLT4	855	9
SLT6	437	4
SLT4+SLT6	722	7
SLT6+SLT6	874	8
SLT6+SLT4+SLT4	1007	10
DDZ4	449	4
DDZ4+DDZ4	898	8

Appendix E Alternative line systems

E.0 Alternative 0: LUD

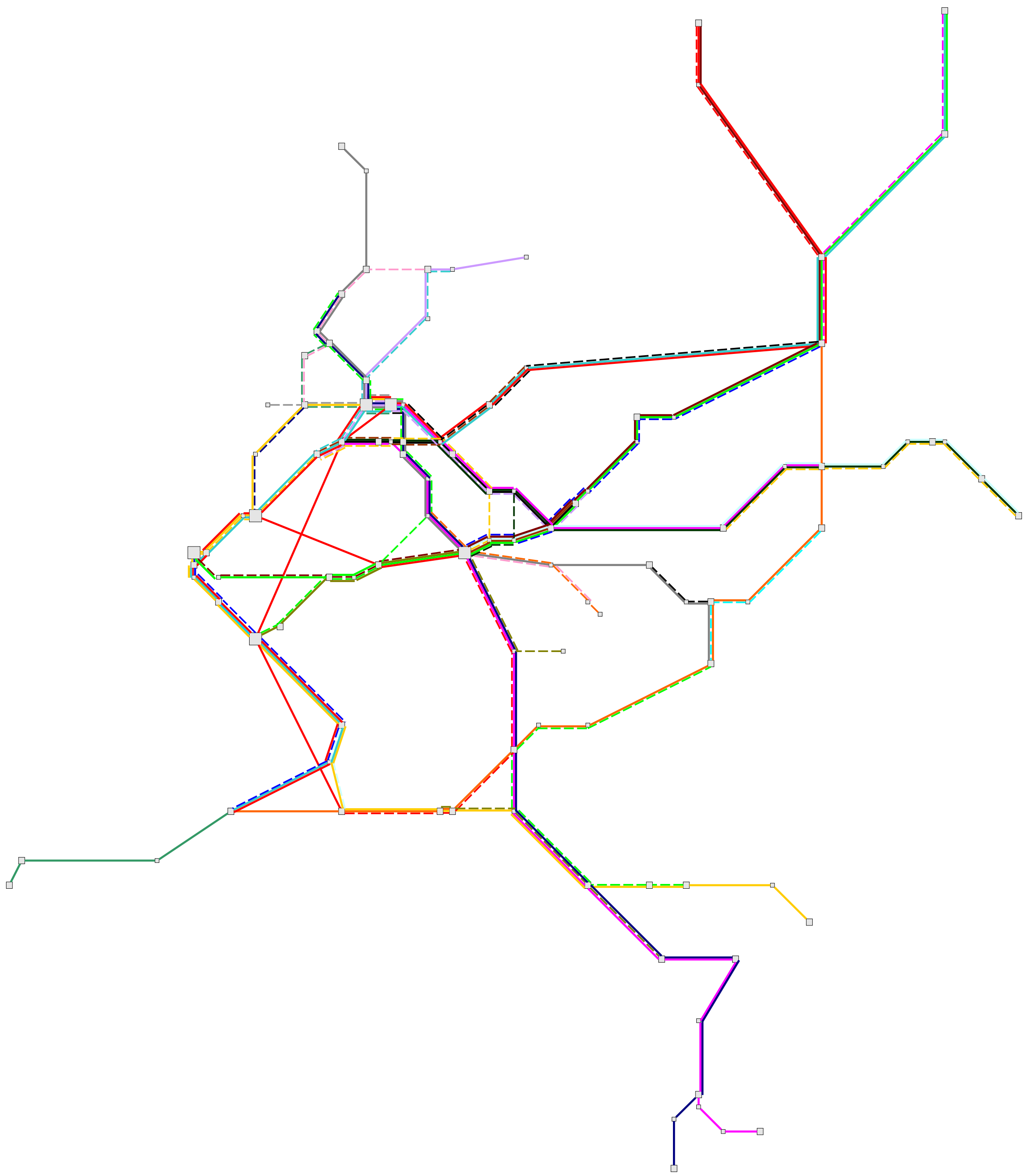

Figure E-0: Line system layout of A0. Solid edges indicate IC lines, dotted edges SPR lines

Table E-0: Detailed line system for A0 with line numbers l, frequencies f and number of trains t

	l	f	t	From	To	Comment
IC	500	1	5	Groningen	Utrecht Centraal	
	800	2	15	Alkmaar	Maastricht	
	900	2	6	Amsterdam Centraal	Breda	HST
	1500	2	6	Enkhuizen	Amsterdam Centraal	
	101500	2	7	Amsterdam Centraal	Deventer	
	1600	1	5	Enschede	Schiphol	
	1700	1	5	Enschede	Utrecht Centraal	
	1900	2	11	Den Haag Centraal	Venlo	
	2000	2	5	Utrecht Centraal	Den Haag Centraal	
	2100	2	5	Amsterdam Centraal	Den Haag Centraal	Via Haarlem
	2600	1	9	Leeuwarden	Roosendaal	Via Amsterdam Centraal & Schiphol
	102600	1	9	Groningen	Roosendaal	Via Amsterdam Centraal & Schiphol
	112600	2	6	Roosendaal	Vlissingen	
	2800	2	4	Utrecht Centraal	Rotterdam Centraal	
	3000	2	13	Den Helder	Nijmegen	
	3500	2	12	Schiphol	Heerlen	
	3600	2	13	Zwolle	Roosendaal	
	8800	2	5	Leiden Centraal	Utrecht Centraal	
	11600	1	3	Amersfoort Schothorst	Schiphol	
	11700	1	2	Amersfoort Schothorst	Utrecht Centraal	
	12500	1	5	Leeuwarden	Utrecht Centraal	
SPR	3300	2	5	Hoorn Kersenboogerd	Hoofddorp	
	3400	2	5	Hoorn	Haarlem	
	4000	2	10	Alkmaar	Rotterdam Centraal	Via Amsterdam Centraal & Woerden
	4300	2	5	Almere Oostvaarders	Hoofddorp	Via Duivendrecht
	4400	2	8	Nijmegen	Deurne	
	4600	2	7	Zwolle	Amsterdam Centraal	
	4800	2	4	Uitgeest	Amsterdam Centraal	
	5000	2	3	Dordrecht	Breda	
	5100	2	7	Den Haag Centraal	Roosendaal	
	5400	2	3	Zandvoort aan Zee	Amsterdam Centraal	
	5500	2	3	Baarn	Utrecht Centraal	
	5600	2	7	Zwolle	Utrecht Centraal	
	5700	2	8	Utrecht Centraal	Den Haag Centraal	Via Weesp & Duivendrecht
	5800	2	7	Amersfoort Vathorst	Hoofddorp	Via Amsterdam Centraal
	6000	2	4	Utrecht Centraal	Tiel	
	6300	2	3	Haarlem	Leiden Centraal	
	6400	2	5	Tilburg Universiteit	Weert	
	7000	2	6	Enschede	Apeldoorn	
	7400	2	4	Breukelen	Rhenen	
	7500	2	2	Arnhem	Ede-Wageningen	
	7600	2	5	Zutphen	Nijmegen	
	9000	1	3	Leeuwarden	Meppel	
	9100	2	6	Groningen	Zwolle	
	9800	2	5	Utrecht Centraal	Den Haag Centraal	Via Gouda
	16000	2	7	Utrecht Centraal	Breda	
	17400	2	3	Utrecht Centraal	Veenendaal Centrum	

E.1 Alternative 1: Short lines

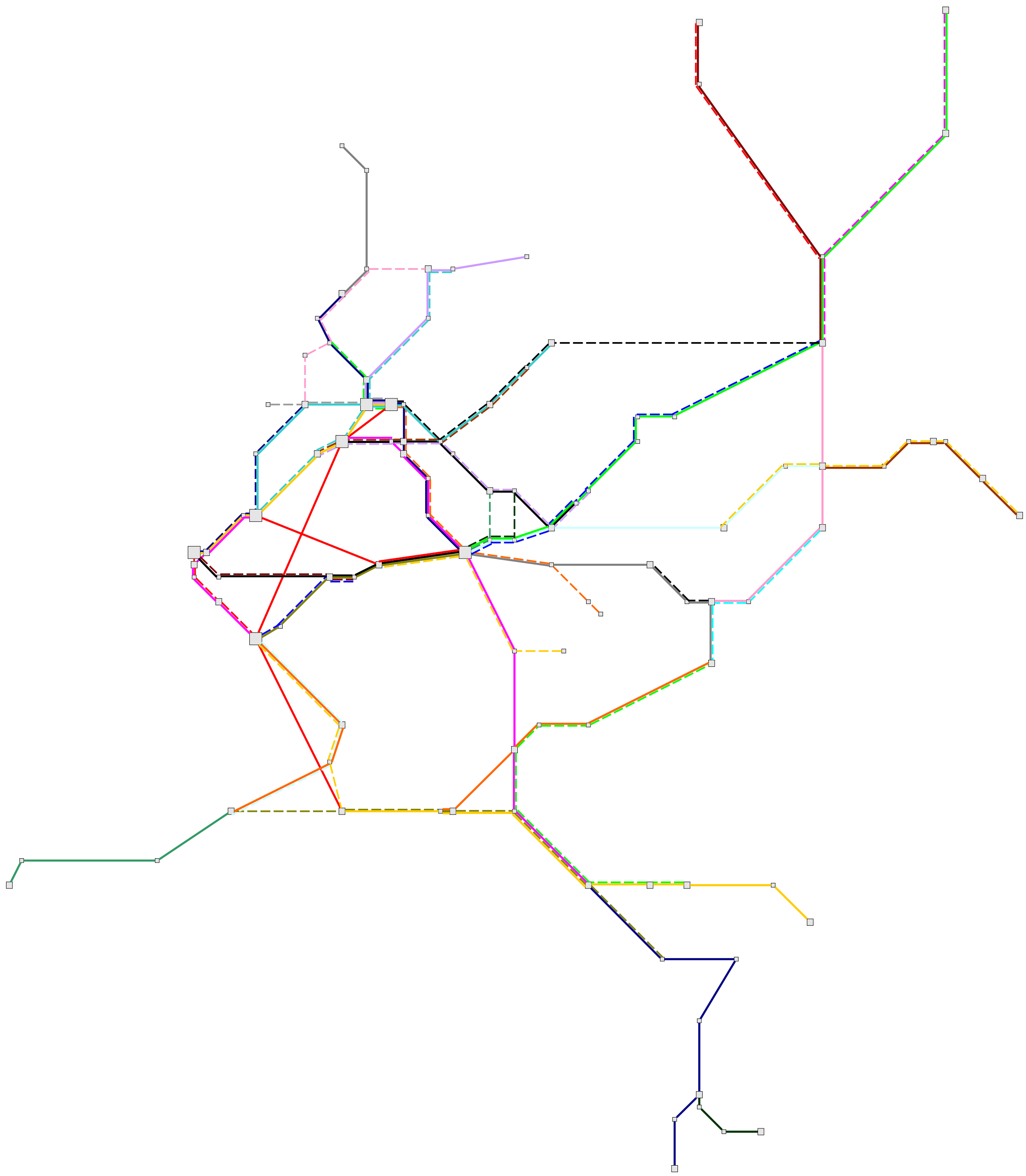

Figure E-1: Line system layout of A1. Solid edges indicate IC lines, dotted edges SPR lines

Table E-1: Detailed line system for A1 with line numbers l, frequencies f and number of trains t

	l	f	t	From	To	Comment
IC	500	2	10	Groningen	Utrecht Centraal	
	700	3	7	Amsterdam Centraal	Den Haag Centraal	Via Schiphol
	800	2	7	Eindhoven	Maastricht	
	900	2	6	Amsterdam Centraal	Breda	HST
	1500	2	6	Enkhuizen	Amsterdam Centraal	
	1700	2	6	Deventer	Utrecht Centraal	
	101700	2	5	Enschede	Deventer	
	1900	2	7	Breda	Venlo	
	2000	2	5	Utrecht Centraal	Den Haag Centraal	
	2100	2	7	Lelystad Centrum	Leiden Centraal	Via Haarlem
	2600	3	6	Leiden Centraal	Rotterdam Centraal	
	102600	2	5	Rotterdam Centraal	Roosendaal	
	2800	2	4	Utrecht Centraal	Rotterdam Centraal	
	3000	3	9	Alkmaar	Utrecht Centraal	
	103000	2	4	Den Helder	Alkmaar	
	3100	3	8	Utrecht Centraal	Nijmegen	
	3500	3	11	Schiphol	Eindhoven	Stops in Zaltbommel
	103500	2	3	Sittard	Heerlen	
	3600	2	6	Zwolle	Arnhem	
	103600	2	5	Nijmegen	Tilburg Universiteit	
	8800	2	5	Leiden Centraal	Utrecht Centraal	
	11600	2	5	Amersfoort Schothorst	Schiphol	Via Duivendrecht
	12500	2	6	Leeuwarden	Zwolle	
SPR	3300	2	6	Hoorn Kersenboogerd	Leiden Centraal	
	3400	2	5	Hoorn	Haarlem	Via Alkmaar
	4300	2	5	Almere Oostvaarders	Hoofddorp	Via Duivendrecht
	4400	2	8	Deurne	Nijmegen	
	4600	2	7	Zwolle	Amsterdam Centraal	
	4700	3	5	Uitgeest	Amsterdam Centraal	
	5000	3	5	Den Haag Centraal	Rotterdam Centraal	
	105000	1	2	Rotterdam Centraal	Breda	
	5100	2	5	Rotterdam Centraal	Roosendaal	
	5400	2	3	Zandvoort aan Zee	Amsterdam Centraal	
	5500	2	3	Baarn	Utrecht Centraal	
	5600	2	7	Zwolle	Utrecht Centraal	
	5700	2	2	Hilversum	Utrecht Centraal	
	5800	2	7	Hoofddorp	Amersfoort Vathorst	Via Amsterdam Centraal
	6000	3	7	Woerden	Tiel	
	6300	2	4	Haarlem	Den Haag Centraal	
	6400	2	6	Roosendaal	Weert	
	7000	2	6	Enschede	Apeldoorn	
	7400	3	10	Amsterdam Centraal	Rhenen	
	7500	2	2	Arnhem	Ede-Wageningen	
	7600	2	5	Zutphen	Nijmegen	
	9000	2	5	Leeuwarden	Meppel	
	9100	2	5	Groningen	Zwolle	
	9700	2	3	Rotterdam Centraal	Gouda Goverwelle	
	19800	2	3	Den Haag Centraal	Gouda Goverwelle	
	122600	2	6	Roosendaal	Vlissingen	

E.2 Alternative 2: DVL Regions

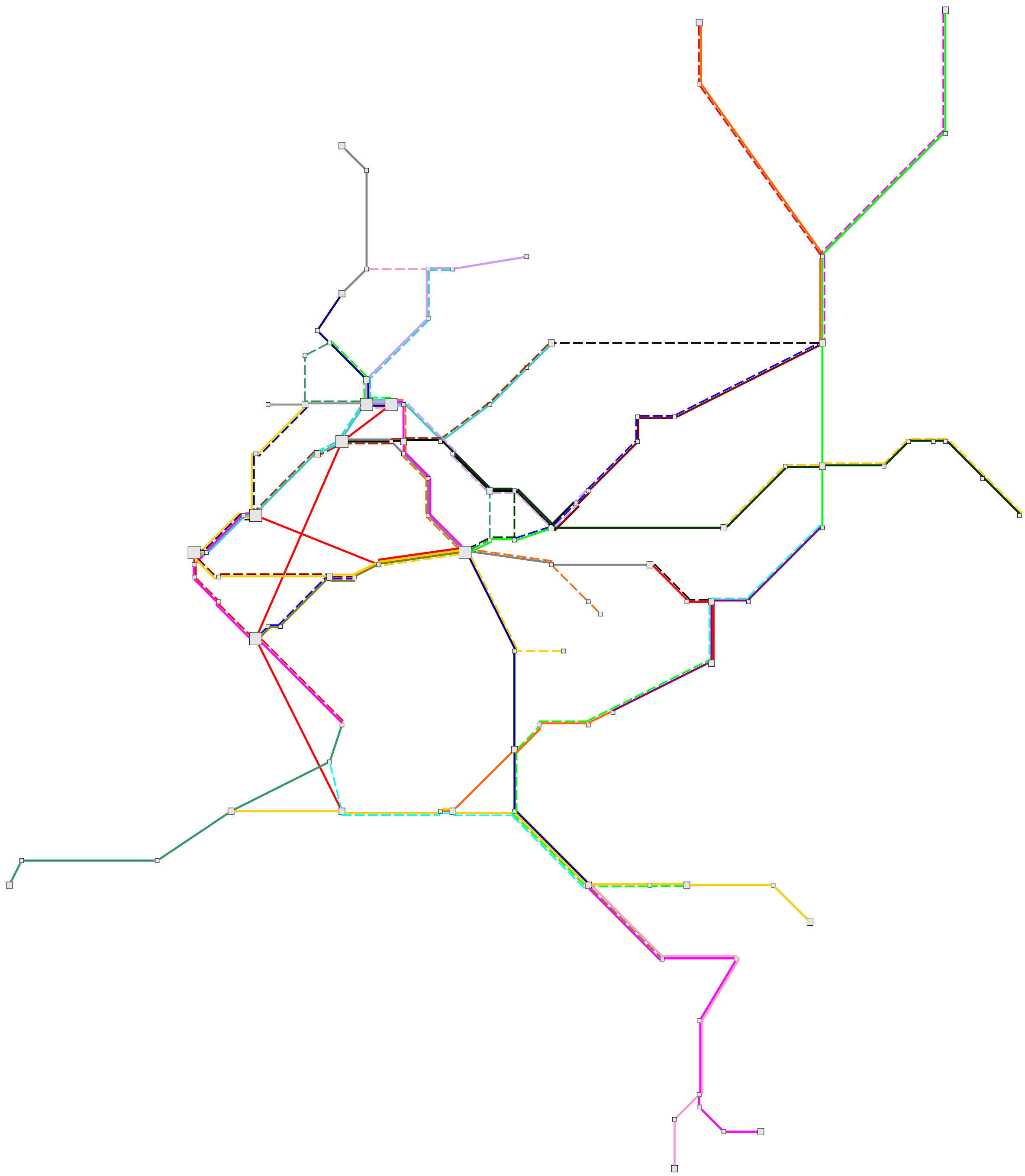

Figure E-2: Line system layout of A2. Solid edges indicate IC lines, dotted edges SPR lines

Table E-2: Detailed line system for A2 with line numbers l, frequencies f and number of trains t

	l	f	t	From	To	Comment
IC	500	2	8	Groningen	Zutphen	
	800	3	5	Amsterdam Centraal	Utrecht Centraal	
	900	2	6	Amsterdam Centraal	Breda	HST
	1500	2	6	Enkhuizen	Amsterdam Centraal	
	1600	2	9	Enschede	Naarden-Bussum	
	1900	2	9	Roosendaal	Venlo	
	2000	2	5	Utrecht Centraal	Den Haag Centraal	
	2100	2	4	Haarlem	Den Haag Centraal	
	2200	3	7	Leiden Centraal	Dordrecht	
	2600	3	11	Lelystad Centrum	Den Haag Centraal	Via Amsterdam Centraal & Schiphol
	102600	2	8	Dordrecht	Vlissingen	
	2800	2	4	Utrecht Centraal	Rotterdam Centraal	
	3000	3	6	Alkmaar	Amsterdam Centraal	
	103000	2	4	Den Helder	Alkmaar	
	3100	3	9	Schiphol	Ede-Wageningen	
	103100	2	4	Ede-Wageningen	Nijmegen	
	3500	3	8	Utrecht Centraal	Eindhoven	
	103500	1	3	Eindhoven	Heerlen	
	3600	2	5	Zutphen	Oss	
	103600	2	4	Oss	Tilburg Universiteit	
	5400	2	4	Zandvoort aan Zee	Amsterdam Centraal	
	8800	2	5	Leiden Centraal	Utrecht Centraal	
	10800	1	4	Eindhoven	Maastricht	
	11600	2	5	Amersfoort Schothorst	Schiphol	Via Duivendrecht
	11700	2	3	Amersfoort	Utrecht Centraal	
	12500	2	5	Zwolle	Amersfoort	
	12700	2	6	Leeuwarden	Zwolle	
SPR	3300	2	5	Hoorn Kersenboogerd	Hoofddorp	
	3400	2	2	Heerhugowaard	Hoorn	
	4300	3	10	Lelystad Centrum	Leiden Centraal	Via Duivendrecht
	4400	2	8	Deurne	Nijmegen	
	4600	2	3	Zwolle	Lelystad Centrum	
	4700	3	5	Uitgeest	Amsterdam Centraal	Via Zaandam
	4800	2	4	Uitgeest	Amsterdam Centraal	Via Haarlem
	5000	3	7	Den Haag Centraal	Dordrecht	
	5500	2	3	Baarn	Utrecht Centraal	
	5600	2	6	Zwolle	Den Dolder	
	5700	2	2	Hilversum	Utrecht Centraal	
	5800	2	5	Amsterdam Centraal	Amersfoort Vathorst	
	6000	3	7	Woerden	Tiel	
	6300	2	4	Haarlem	Den Haag Centraal	
	6400	2	3	Eindhoven	Weert	
	106400	2	6	Lage Zwaluwe	Eindhoven	
	7000	2	6	Enschede	Apeldoorn	
	7400	3	10	Amsterdam Centraal	Rhenen	
	7500	2	2	Arnhem	Ede-Wageningen	
	7600	2	5	Zutphen	Nijmegen	
	9000	2	5	Leeuwarden	Meppel	
	9100	2	6	Groningen	Zwolle	
	9700	2	3	Rotterdam Centraal	Gouda Goverwelle	
	19800	2	3	Den Haag Centraal	Gouda Goverwelle	

E.3 Alternative 3: Evading high-speed switches

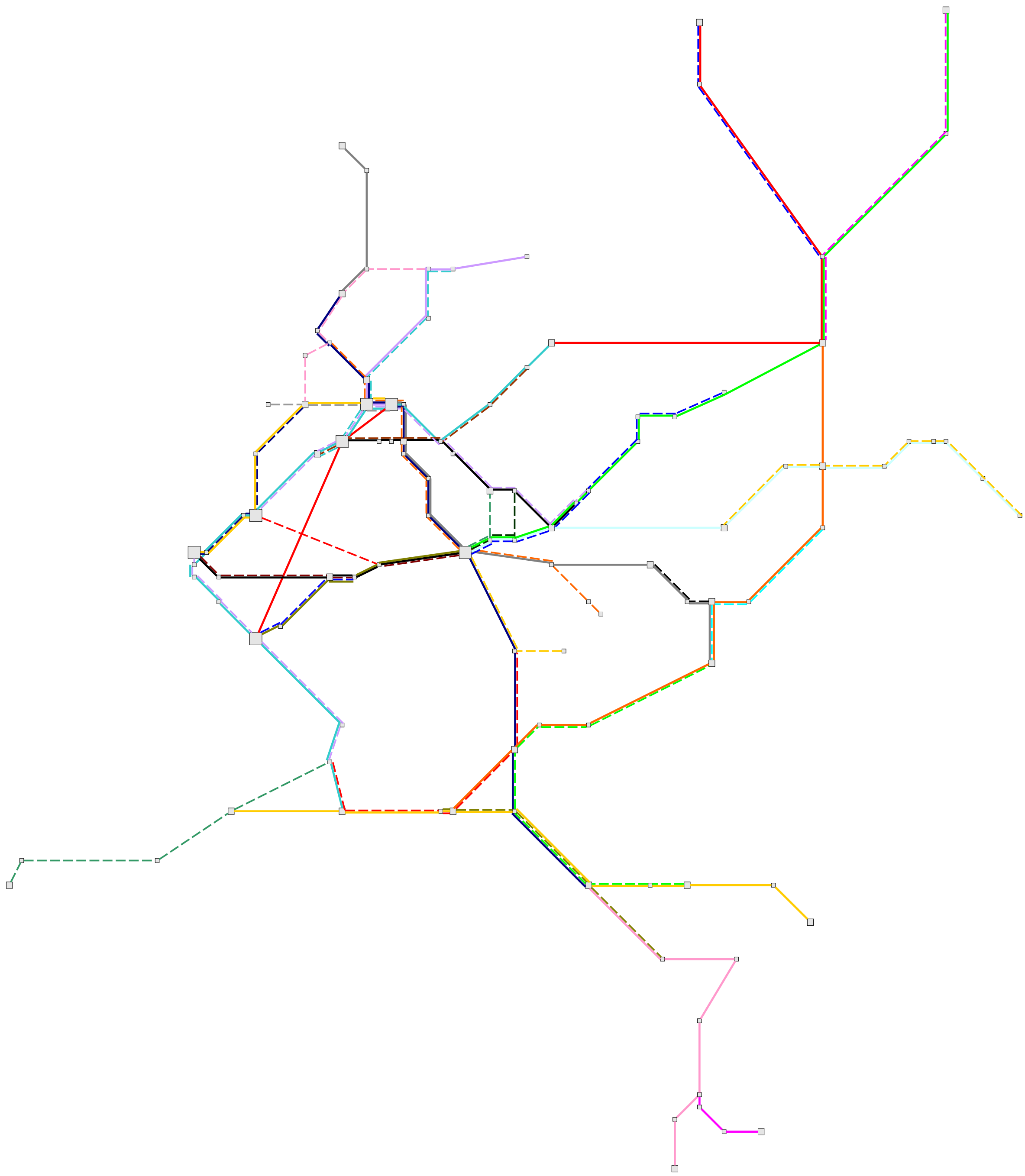

Figure E-3: Line system layout of A3. Solid edges indicate IC lines, dotted edges SPR lines

Table E-3: Detailed line system for A3 with line numbers l, frequencies f and number of trains t

	l	f	t	From	To	Comment
IC	500	2	10	Groningen	Utrecht Centraal	Stops in 't Harde
	800	3	15	Alkmaar	Eindhoven	
	10800	2	7	Eindhoven	Maastricht	
	900	2	5	Amsterdam Centraal	Rotterdam Centraal	HST
	1500	2	6	Enkhuizen	Amsterdam Centraal	
	1700	2	9	Enschede	Utrecht Centraal	
	1900	2	9	Roosendaal	Venlo	
	2000	2	5	Utrecht Centraal	Den Haag Centraal	Stops in Woerden
	2100	2	5	Amsterdam Centraal	Den Haag Centraal	Via Haarlem
	2600	3	17	Lelystad Centrum	Breda	Via Amsterdam Centraal & Schiphol
	2800	2	4	Utrecht Centraal	Rotterdam Centraal	
	3000	3	11	Amsterdam Centraal	Nijmegen	
	103000	2	4	Den Helder	Alkmaar	
	3600	2	10	Zwolle	Tilburg	
	11600	3	7	Amersfoort Schothorst	Schiphol	
	12600	2	8	Leeuwarden	Lelystad Centrum	Stops in Kampen Zuid & Dronten
	103500	2	3	Sittard	Heerlen	
SPR	3300	2	5	Hoorn Kersenboogerd	Hoofddorp	
	3400	2	5	Hoorn	Haarlem	Via Alkmaar
	4300	3	7	Almere Oostvaarders	Hoofddorp	Via Duivendrecht
	4400	2	8	Deurne	Nijmegen	
	5000	3	8	Den Haag Centraal	Lage Zwaluwe	
	5400	2	3	Zandvoort aan Zee	Amsterdam Centraal	
	5500	2	3	Baarn	Utrecht Centraal	
	5600	2	6	't Harde	Utrecht Centraal	
	5700	2	2	Hilversum	Utrecht Centraal	
	5800	3	12	Amersfoort Vathorst	Leiden Centraal	Via Amsterdam Centraal & Schiphol
	6000	3	5	Utrecht Centraal	Tiel	
	6100	2	2	Utrecht Centraal	Woerden	
	6300	2	4	Haarlem	Den Haag Centraal	
	6400	2	5	Tilburg Universiteit	Weert	
	7000	2	6	Enschede	Apeldoorn	
	7400	3	13	Uitgeest	Rhenen	
	7500	2	2	Arnhem	Ede-Wageningen	
	7600	2	5	Zutphen	Nijmegen	
	8800	2	3	Leiden Centraal	Woerden	
	9000	2	6	Leeuwarden	Zwolle	
	9100	2	6	Groningen	Zwolle	
	9700	2	3	Rotterdam Centraal	Gouda Goverwelle	
	13600	2	6	Geldermalsen	Lage Zwaluwe	
	19800	2	3	Den Haag Centraal	Gouda Goverwelle	
	102600	2	7	Lage Zwaluwe	Vlissingen	

Appendix F Multi-Criteria Analysis data

Table F-1: Indicator weights for all scenarios

Indicator	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
Major stations attended	9,70%	25,00%	9,70%	25,00%	0,00%	40,30%	25,80%	33,90%	0,00%	33,30%	33,30%	33,30%	9,70%
Frequency	3,43%	2,35%	9,13%	6,25%	3,79%	0,00%	3,79%	3,79%	3,13%	0,00%	3,13%	3,13%	3,40%
Edges with Frequency > 4	20,95%	14,35%	9,13%	6,25%	23,13%	0,00%	23,13%	23,13%	19,11%	0,00%	19,11%	19,11%	21,00%
Line density	3,69%	2,53%	9,13%	6,25%	4,07%	0,00%	4,07%	4,07%	3,36%	0,00%	3,36%	3,36%	3,70%
Edges with > 2 lines	8,43%	5,78%	9,13%	6,25%	9,31%	0,00%	9,31%	9,31%	7,69%	0,00%	7,69%	7,69%	8,40%
Trains in RBC Randstad Noord	1,25%	1,10%	3,14%	2,75%	1,14%	1,14%	0,00%	1,14%	1,47%	1,47%	0,00%	1,47%	0,00%
Trains in RBC Randstad Zuid	1,25%	1,10%	3,14%	2,75%	1,14%	1,14%	0,00%	1,14%	1,47%	1,47%	0,00%	1,47%	0,00%
Trains in RBC Utrecht	1,25%	1,10%	3,14%	2,75%	1,14%	1,14%	0,00%	1,14%	1,47%	1,47%	0,00%	1,47%	0,00%
Attended transport control regions	1,48%	1,30%	3,14%	2,75%	1,34%	1,34%	0,00%	1,34%	1,73%	1,73%	0,00%	1,73%	0,00%
Trains in DVL Amsterdam	4,96%	4,35%	3,14%	2,75%	4,49%	4,49%	0,00%	4,49%	5,79%	5,79%	0,00%	5,79%	4,39%
Trains in DVL Den Haag	2,74%	2,40%	3,14%	2,75%	2,48%	2,48%	0,00%	2,48%	3,20%	3,20%	0,00%	3,20%	2,39%
Trains in DVL Rotterdam	2,74%	2,40%	3,14%	2,75%	2,48%	2,48%	0,00%	2,48%	3,20%	3,20%	0,00%	3,20%	2,39%
Trains in DVL Utrecht	4,96%	4,35%	3,14%	2,75%	4,49%	4,49%	0,00%	4,49%	5,79%	5,79%	0,00%	5,79%	4,39%
Attended traffic control regions	7,92%	6,95%	3,14%	2,75%	7,17%	7,17%	0,00%	7,17%	9,26%	9,26%	0,00%	9,26%	14,96%
High-speed switches in use	10,12%	10,00%	12,65%	12,50%	13,56%	13,56%	13,56%	0,00%	13,32%	13,32%	13,32%	0,00%	10,12%
Operation ratio	15,18%	15,00%	12,65%	12,50%	20,34%	20,34%	20,34%	0,00%	19,98%	19,98%	19,98%	0,00%	15,18%

Appendix G Capacity at terminal stations

Table G-1: Number of turning trains per hour at terminal stations for all alternatives

Station	Regular	A0	A1	A2	A3	Station	Regular	A0	A1	A2	A3
Ah	2	2	4	2	2	Ht	0	2	0	0	0
Alm	0	0	0	0	0	Hvs	0	0	2	2	2
Almo	4	2	2	0	3	Hwd	0	0	0	2	0
Amf	0	0	0	4	0	Ledn	2	4	9	8	4
Amfs	2	2	2	2	3	Lls	2	0	2	8	5
Amr	0	4	5	5	5	Lw	3	3	4	4	4
Apd	2	2	2	2	2	Mp	0	1	2	2	0
Asd	18	14	17	22	12	Mt	2	2	2	1	2
Avat	2	2	2	2	3	Ndb	0	0	0	2	0
Bd	6	6	5	2	3	Nm	8	6	9	6	7
Bkl	2	2	0	0	0	O	0	0	0	4	0
Brn	2	2	2	2	2	Rhn	2	2	3	3	3
Ddr	2	2	0	8	0	Rsd	4	8	8	2	2
Dld	0	0	0	2	0	Rtd	8	4	15	4	6
Dn	2	2	2	2	2	Sgn	2	0	0	0	0
Dv	2	2	4	0	0	Shl	6	4	5	5	3
Ed	2	2	2	7	2	Std	0	0	2	0	2
Ehv	0	0	5	9	5	Tb	0	0	0	0	2
Ekz	4	2	2	2	2	Tbu	2	2	2	2	2
Es	4	4	4	4	4	Tl	2	2	3	3	3
Gdg	4	0	4	4	4	Ut	22	24	22	18	19
Gdm	0	0	0	0	2	Utg	6	2	3	5	2
Gn	4	4	4	4	4	Vl	2	2	2	2	2
Gvc	22	12	12	14	11	Vndc	2	2	0	0	0
Hde	0	0	0	0	2	Vs	2	2	2	2	2
Hdr	2	2	2	2	2	Wd	2	0	3	3	4
Hfd	6	6	4	2	6	Wt	2	2	2	2	2
Hlm	4	4	4	4	4	Zl	9	8	10	10	6
Hn	2	2	2	2	2	Zlw	0	0	0	2	7
Hnk	2	2	2	2	2	Zp	2	2	2	6	2
Hrl	2	0	2	1	2	Zvt	2	2	2	2	2

Appendix H Glossary

CADANS	A solver within DONS to produce a cyclic timetable.
CREWS	Tool to generate crew duties.
cross-platform transfer	A transfer to a train on the other side of the same platform, being the fastest and most comfortable transfer for passengers.
Disruption	A relatively large incident which requires adjustment of timetable, rolling stock and crew duties.
Disturbance	A relatively small perturbation in the railway system which can be handled by adjusting the timetable.
DONNA	Tool to maintain and adjust the annual plan.
DONS	The Designer Of Network Schedules tool used by Netherlands Railways to create a timetable.
Knock-on delay	Delay caused by a preceding train. For instance when the first train is delayed or still occupying the platform for the next train. Also called secondary delay.
Layover time	The required time for a train to switch direction at a terminal station. Also called turning time.
Origin-Destination matrix	A matrix $D = (D_{ij})$ specifying the amount of passengers that want to travel between origin i and destination j. Also called O-D Matrix or OD-Matrix.
OV-Chipkaart	The Dutch smartcard for Public Transport.
ProRail	ProRail is the Dutch rail infrastructure manager.
Randstad	The busy economical area in the west of The Netherlands.
SIMONE	Macro-level simulation tool used to estimate the performance of a complete timetable.
STATIONS	A solver within DONS to route trains through stations and other complex interlockings.
Stock number	The number of one specific train unit. This is the number on the train unit itself.
Train number	The number of one specific train service. Odd and even numbers specify the direction.
Train series	The number of a line in the line system. Every line has its own number which is usually a multiple of 100.
TRANS	Model to distribute passengers from an OD-matrix over the lines in the line system.

Appendix I Acronym List

ADVD	Alternatieve Dienstregeling Volgende Dag, Dutch term for the first alternative timetable designed for extreme (winter) weather circumstances.
AHP	Analytic Hierarchy Process, a method to determine weights to be used in the MCA.
BHP	Basic Hour Pattern, the foundation of a timetable which contains arrival- and departure times for all train series. This pattern is the same for every hour.
DVL	Decentrale VerkeersLeiding, Dutch for De-central Traffic Control Centre. From here, the traffic controllers monitor and control the train traffic.
ETCS	European Train Control System, a new safety system which introduces moving blocks (from level 2). Trains can run much closer together when using ETCS.
HST	High-Speed Train.
IC	InterCity Train.
IIA	Independence of Irrelevant Alternatives, a property of the MNL model which states that alternatives should be mutually exclusive.
LBC	Landelijk BijsturingsCentrum, Dutch for National Controlling Centre which is located in the OCCR. This is the national equivalent of the RBC.
LPP	Line-Planning Problem, a mathematical formulated problem to build a line planning for (PT) networks.
LUD	Landelijk Uitgedunde Dienstregeling, Dutch term for the current alternative timetable being applied during extreme winter weather.
LVL	Landelijke VerkeersLeiding, Dutch for the National Traffic Control Centre wich is located in the OCCR. This is the national equivalent of the DVL.
MCA	Multi-Criteria Analysis, a widely used method to aid decision-makers in making a discrete choice.
MNL	Multinomial Logit, a commonly used model to study discrete choices.
MOA	MarktOnderzoek en Advies, Dutch name for the market research department of Netherlands Railways.
NS	Nederlandse Spoorwegen, the main Dutch rail operator. Netherlands Railways in English.
OCCR	Operational Control Centre Rail, the main control centre for nationwide control of train transport and traffic. The LVL and LBC are combined here, which is useful during large disruptions.
PESP	Periodic Event Scheduling Problem, a mathematical formulated problem to construct cyclic schedules like a timetable.
PT	Public Transport.

R	Regional Train, in The Netherlands called Sprinter (SPR).
RBC	Regionaal BijsturingsCentrum, Dutch for Regional Controlling Centre. From here, NS Transportbesturing performs (re)scheduling operations for crew and rolling stock.
SAP	Snel Aangepast Plan, Dutch term for an alternative timetable with short preparation time. This timetable is based on the regular timetable.
SPR	Sprinter, the Dutch name for a regional train.
TB	Transportbesturing, Dutch name for the transport control *organization* who (re)schedule rolling stock and crew duties. The controllers operate from an RBC.
VL	VerkeersLeiding, Dutch name for the traffic control *organization* from ProRail who are in charge of directing train traffic, assigning platforms etc. The controllers operate from a DVL.