Master Thesis

Different look into alternatives in railway projects

Development of a decision support system to facilitate selection of alternatives by evaluating railway timetables using performance indicators

Final report (build 20150609121000)

A.W. (Allard) Katstra
Tuesday 9th June, 2015

UNIVERSITY OF TWENTE.

ARCADIS
Imagine the result

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A.W. (Allard) Katstra
s0138908
a.w.katstra@aluminus.utwente.nl
allard.katstra@arcadis.nl

University of Twente
Faculty of Engineering Technology (CTW)
Centre for Transport Studies (CTS)
P.O. Box 217
7500 AE Enschede
Drienerlolaan 5
7522 NB Enschede

ARCADIS Nederland BV
Division Mobility
ROV - Rail studies and rail consulting
P.O. Box 220
3800 AE Amersfoort
Piet Mondriaanlaan 26
3812 GV Amersfoort

Supervisors:
Ing. K.M. (Kasper) van Zuilekom
Prof. Dr. Ir. E.C. (Eric) van Berkum

Daily supervisor:
Ing. H. (Rikus) Koops

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Summary

The Dutch railway network is in the top three of highest utilized networks within Europe. In the most positive scenarios, demand forecasts for railway transport in the Netherlands show further growth between 2011 and 2020 for both passenger and freight transport of 27% and 107% respectively. Budgets for extending the infrastructure are limited. For many years the railway infrastructure and operating timetable have been optimized to deal with an increasing number of trains running on the same rail infrastructure. It has proven difficult to determine the impact of new infrastructure or a new timetable on the feasibility and robustness of operating trains.

ARCADIS detects a shift in their clients' requests from calculating the minimum interval time between two train services towards a more extensive analysis of the impact of infrastructure modifications on the feasibility of operating the timetable. Currently, analysing the operability for infrastructure alternatives on a specific timetable is a time consuming process, taking up to several weeks. The alternative selection processes often do not include secondary processes like shunting movements, and transitions between peak-hour and off-peak timetables. Therefore, ARCADIS has developed a prototype model to automate steps in the evaluation of infrastructure alternatives and to implement the UIC 406 (2004a) methodology. UIC 406 is a widely accepted methodology to calculate the occupation time rate using the concept of timetable compression. However, other indicators are required to evaluate and select alternatives.

The above leads to the following research goal: *to facilitate the selection of alternatives in railway infrastructure or timetabling projects by developing and implementing a decision support system which uses indicators and the UIC 406 methodology to evaluate timetable scenarios.*

In this research, a literature review and interviews are used to gain information about the decision making process and to determine the indicators required to select alternatives. Two products are the outcome of this research:

(1) a model to develop a passive decision support system to facilitate the selection of alternatives in infrastructure and timetable projects based on indicators and
(2) an application tool that implements the designed decision support system and can support the decision making processes

The model is capable of using headway times to evaluate a timetable realistically in a matter of seconds. The model describes the steps of the evaluation process for an infrastructure or timetable proposal, through the use of simulation software to calculating the follow-up times and the model uses that to calculate the indicators. Those indicators are an important aspect against which a timetable can be evaluated. The following four indicators are important in evaluating a timetable based on previous research into this subject by Schittenhelm (2013) and the interviews conducted with stakeholders during this research:

(a) the occupancy time rate, calculated by using the UIC 406 methodology. In this research, the methodology is extended by calculating the occupation time rate per hour.
(b) the heterogeneity of a timetable, calculated by finding the variation in headway time interval and speed with the method provided by Landex (2007).
(c) the degree of deviation from timetable planning rules, calculated by comparing the scheduled departure times with the earliest departure time according to the minimum headway time.
(d) the stability of the timetable during operation: in this research a methodology is developed that calculates the effects of disturbance to a timetable/infrastructure scenario. The indicator is a ratio between the input disturbance and the amount of disturbance that is transferred to subsequent trains.

The model contains three controls which allow the end-user to change parameters and to see the effects of those parameters on the output. These controls are (1) scenario selection, (2) level of aggregation output (1h, 2h, 24h), and (3) the running time margin.

The application tool shows that it is capable of supporting and speeding up the selection of alternatives by providing three primary checks to the alternative: the occupation time rate, the stability of the timetable, and a check whether the proposed timetable will fit. Due to the nature of this application, this model allows a very flexible way of testing the location of secondary processes in the timetable as the relation between the secondary processes and the primary process only needs to be calculated once. The stability indicator used in the application enables the end-user to see the effect of changing the distribution of margin between trains in the timetable. Therefore, a timetable with a more uniform distributed margin will be able to withstand more disturbances without transferring delays to subsequent trains. The output of the application uses modules to display the information, which allows for quick customization depending on the requirements of the end-user and type of project.

In future research, the indicators should be verified outside the Netherlands and applicability of the sensitivity-based stability indicator in a wider context should be further investigated. So far, the model has been applied to theoretical test cases. Further validation should be done by applying the tool to real-life projects, providing cases for analysis.

Acknowledgements

After an intensive period of graduating, I am finalizing my thesis by writing this section. I owe too many people a thank you for their support during this research and during my studies. A few of them deserve special mention in this report.

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Utrecht, June 7th 2015

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Chapter 1

Introduction

The demand for railway transport is high in the Netherlands. NS, the largest passenger train operating company (TOC), transports every day more than 1.2 million travellers to work, school or any other destination (NS, 2014). Besides trains moving passengers, there are more than 200 trains daily using the tracks to transport freight (ProRail, 2014c). The Dutch Ministry of Infrastructure and the Environment (I&M) has made forecast of passenger rail demand with various scenarios. The strong growth scenario predicts an increase in passenger train kilometers of up to 27% between 2011 and 2020. The growth is expected to concentrate in and around the Randstad. The same study predicts an increase of freight transport of 107% over the same period (I&M, 2014).

The infrastructure to operate trains has limitations. Unlike road traffic, trains are depending on specific infrastructure to switch tracks which makes overtaking more difficult and operating more trains difficult. Also budget for railway infrastructure projects is limited. ProRail, the Dutch infrastructure manager (IM), has to maintain and extent the infrastructure as cost efficient as possible. For many years the railway infrastructure has been optimized to deal with an increasing number of trains. This because optimizing the system is less expensive than extending the infrastructure. With its occupation, the Dutch railway network is in the top three of highest utilized networks within Europe (I&M, 2014). However, further optimizing the infrastructure and the timetable might, with the expected growth of passenger demand, in the future no longer be a viable option.

Operating a railway line requires a timetable. The timetable is closely related to the infrastructure at which it is operated. The development of a railway timetable is a complex process. A timetable must be able to withstand disturbances like delays, perturbations, and variations in operating conditions (Goverde and Hansen, 2013). This without losing functionality, so scheduled train services can be operated in an optimal way. The process of developing a new timetable involves interaction with various stakeholders, like train operating companies, the infrastructure manager, traffic control, and the capacity allocation department. Schittenhelm (2013) conducted research into railway timetable criteria and key performance indicators (KPI) to describe railway timetables. This to enhance the communication between the infrastructure manager and the train operating companies. One of the most important indicators used in that research is the occupation time rate.

A decision support system (DSS) is ideal to use in the complex and weakly-structured decision context, like the development of a timetable. A DSS is a computer-based information system designed to support - not replace - some or all phases of a decision-making process (Van Delden, 2011). The model should be interactive and user-friendly to facilitate learning. The primary function of a DSS is knowledge management, presenting an integral view of a complex system. It structures the decision making process and facilitates the communication between stakeholders.

ARCADIS detected a shift in their clients' question. Normally the infrastructure manager would ask to calculate the minimum interval time between two train services on a given infrastructure. Any additional analysis besides the interval times required a lot of time, it was prone to errors and the methodology was rigid: subsequent iterations required the same amount of time as the first iteration. Currently the client is also interested in the feasibility of operating the timetable. An early prototype was built to automate parts of the feasibility analysis. The method used in the prototype for performing the analysis is the UIC 406 methodology (UIC, 2004a).

The UIC 406 is the most accepted method for calculating the occupation time rate. It is developed and published by the International Union of Railways (Union Internationale des Chemins de fer, UIC) in 2014. The UIC released a leaflet describing a uniform (analytical) method to calculate railway occupation and capacity in Europe (UIC, 2004a). In 2013 the UIC published a new version of the leaflet (UIC, 2013).

1.1 Problem

The Dutch railway network is facing an increasing volume of traffic without the budget of large expansions of the network. And it is difficult to describe the state of the network because a proper set of performance indicators for the infrastructure is missing.

The process of creating a timetable is very complex due to the requirements of stakeholders and the required stability. And the process of calculating the effects of alternatives is a time consuming process.

That is why ARCADIS is looking for a quick, clear, easy and flexible way of evaluating alternatives in both the infrastructure design and timetable to reduce the time needed during the initial phase of a railway project. The model should support the decision making process in the initial stage of railway projects by presenting performance indicators based on the suggested infrastructure and a preliminary timetable. Starting point is the early prototype model created by ARCADIS using the UIC 406 methodology.

1.2 Research objective and research questions

The aim of this research is:

> *To facilitate the selection of alternatives in railway infrastructure or timetabling projects by developing and implementing a decision support system which uses performance indicators and the UIC 406 methodology to evaluate timetable scenarios*

This leads to the following research question:

> *How to support selection of alternatives during the strategical phase of railway infrastructure or timetabling projects by developing an application for timetable evaluation and thereby gaining insights in the direction for detailing in further phases?*

1.3 Report outline

The report outline is visualized in figure 1.1. This report starts with a brief description of the situation and the problem. The next chapter contains the methodology used during this research. Two methods used in this research are a literature review (Chapter 3) and conducting interviews. The results of the interviews are presented in Chapter 4. Based on the literature review and the interviews a model is created and the description of that model can be found in Chapter 5. An application tool is created based on the model and its functionality is tested in a case study (Chapter 6). This report finishes with the conclusions and discussion (Chapter 7).

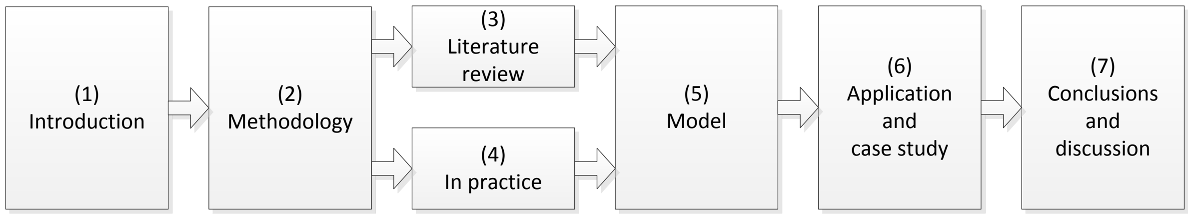


Figure 1.1: Reading guide

Note: The abbreviations used in this report can be found in section A.1 of Appendix A. Railway stations and default measuring points along the railway network are often indicted using abbreviations. An overview of the used abbreviations in this report and the related full name of the stations is given in section A.2.

1.4 ARCADIS

This research is conducted at ARCADIS. ARCADIS is one of a few firms in the Netherlands with a ProRail license to perform the engineering work for railway projects.

"ARCADIS is the leading global natural and built asset design and consultancy firm working in partnership with our clients to deliver exceptional and sustainable outcomes through the application of design, consultancy, engineering, project and management services. ARCADIS differentiates through its talented and passionate people and its unique combination of capabilities covering the whole asset life cycle, its deep market sector insights and its ability to integrate health & safety and sustainability into the design and delivery of solutions across the globe. ARCADIS has 22,000 people that generate 2.5 billion Euro in revenues." (ARCADIS, 2014a)

"As the lifeline of our societies and communities, infrastructure provides the foundation for transportation and commerce and creates healthy places to live and work. By delivering high-quality railways, road networks and waterways; supplying reliable energy and water; and facilitating communication, ARCADIS multi-disciplinary, cross-border infrastructure group brings stability, mobility, and a better quality of life to rural and urban areas around the world." (ARCADIS, 2014b)

"Transportation of people and goods is a key to keeping a local economy running. Rail and mass transit are staples of sound economic development. However, space is rare and the sector is complex. It needs to balance public opinion, residents, users, operators, owners of the infrastructure and public regulators. ARCADIS brings innovative, sustainable and practical solutions to the stakeholders all along the value chain." (ARCADIS, 2014c)

Chapter 2

Methodology

In this research, four methods are used to answer the research question. These methods are a literature review, interviews with stakeholders and experts, developing an model/application, and a case study. In this chapter there is described in short, why that method is chosen and steps taken in that method.

All the used methods have been implemented in a qualitative way. Primarily because the target population is limited, so getting a good sample is difficult. However, qualitative methods create the opportunity and the setting to get more detailed information.

The focus of the research is the Netherlands, as railways are still organized nationally and vary significantly from country to country.

2.1 Literature review

Scientific research is often described as "standing on the shoulders of giants", which means as much as: do not reinvent the wheel, but continue on the work of others. In the literature review the view points of other researchers are described and analysed. It provides the theoretical background for the researcher to get inside the subject and it gives a framework for the interviews.

The following questions will be covered:

- What are decision support systems?
- How thus the timetabling process work?
- How to model infrastructure and train characteristics to simulate railways?
- How to determine railway capacity and occupation?

2.2 In practice: interviews

The aim of this research is to facilitate the selection of alternatives. Therefore, when creating model to facilitate that selection it is crucial to know the requirements for that model. The interviews provide a way to gather information from experts in the field of timetabling and to gather requirements from potential end-users of the application tool.

The interviews are aimed at gathering information about three subjects. The first subject is the complexity of timetabling during the strategic phase. The strategic phase is used to design the infrastructure, so in that phase both the infrastructure and the timetable can still changeable. Understanding the difficulties will provide input for the development of the model. Secondly, the interviewees will need to answer questions about the indicators that would help them to evaluate alternatives in the infrastructure design and timetable. During that subject an enhanced prototype is used to provide an idea of possible indicators. Presenting indicators in a decision support system alone might not fully fulfil the requirements of the interviewees. Therefore, the third subject is the additional requirements for a decision support system.

2.2.1 Structure

In the Netherlands various stakeholders are responsible for a part of the railway system. To get information from different viewpoints and to prevent a bias in one direction four types of interviewees are approached (see table 2.1). If possible, for each type of interviewees multiple people are approached with a preference towards people of different companies. For the infrastructure manager this was not possible, because ProRail is the only infrastructure manager in the Netherlands that is not fully dedicated towards high-speed lines.

Table 2.1: Explanation interviewee types

Abbreviation	Description	Number of interviews
TA	Transport authority	2
IM	Infrastructure manager	2
TOC	Train operating company	4
E	Expert	1

The interviews are conducted in a semi-structured setting. In a semi-structured interview the topics are determined, but it is allowed to divert from the set of questions. The setting is more open, allowing new ideas or certain subjects to emphasized and explored more in-depth. This provides the opportunity to anticipate to the answers given by the interviewees. To get some kind of a structure, a topic list was constructed before conducting the interviews. This list allows the interviewer to focus on the topics and answers without having to be afraid to forget a certain topic. The topic list during the interviews is attached to this report as Appendix B.

Overall 9 interviews are conducted spread over the four interviewee types. Next to the interviews a number of additional meetings was arranged to gather more information about the railway system in general or very detailed into one element. These meetings were in a more informal setting and therefore these meetings are not worked out. In Appendix C tables have been included containing all the interviewees and the additional conversations.

2.3 DSS: model and application

In this research, a decision support model is developed to support decision makers in the selection of alternatives by speeding up the process of evaluating the infrastructure design and timetable, and by increasing the understanding the effect of infrastructure changes. The theory about methods to indicate the differences between alternatives is combined with the conclusions of the interviews into a model. The model is then implemented in an application tool. Largest aim of this research is to speed up the selection of alternatives. Automation of easy - time consuming - and repetitive operations contributes to that objective.

The process of creating the model and the application is supported by the model shown in figure 2.1. Although not all steps are followed strictly, the idea of iterating over prototypes and

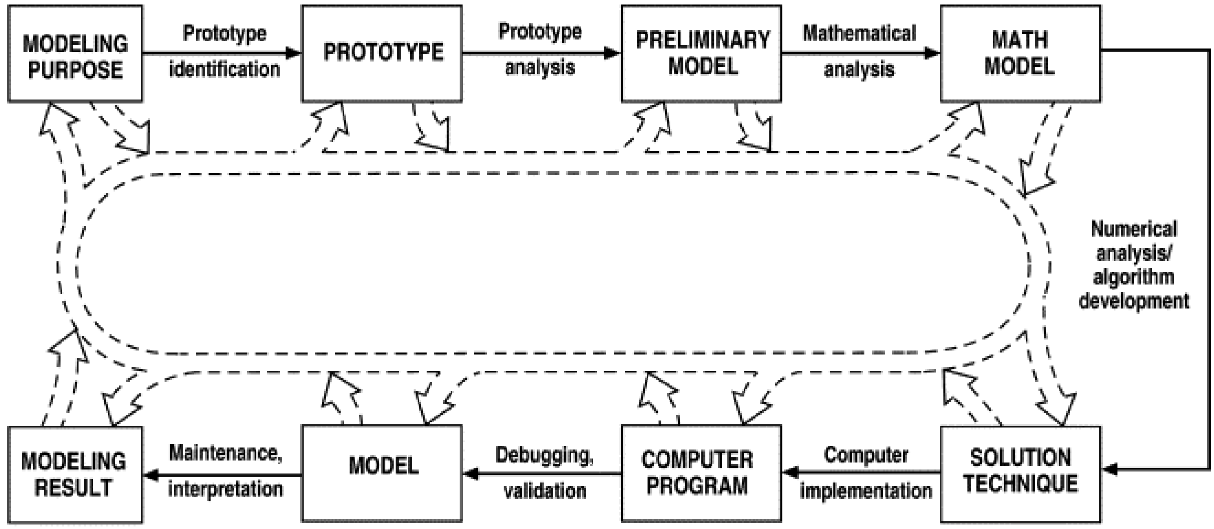


Figure 2.1: Application development model

feedback has been followed. In principle it is created to convert the output from the ARCADIS' simulation tool Xandra into the useful information for decision makers.

2.4 Case

To validate the model and the application tool, a case study has been conducted at the corridor Utrecht - Arnhem. The validation consists of comparing the output with the requirements of the interviews, to see if the output is realistic, and if the application tool will support the decision making process.

The corridor in this case study is carefully chosen based on a number of criteria. These criteria are design to optimize the efforts/benefits ratio, because of the extensive work is required to create a simulation. These criteria are:

- Existing situation of infrastructure
- Corridor with a reasonable length
- Not to many passes
- No difficult signalling procedures
- Used by multiple train types and train services (intercity, regional, etc.)
- Corridor near the limit of its capacity

Based on this set of criteria a specialist from ARCADIS advised to use the corridor of Utrecht to Arnhem. This corridor complies with all of the above criteria and has a number of additional benefits, as them being:

- Enrolled to get ERTMS in the near future
- Plans exist to implement the high-frequency railway program at this corridor, increasing the frequency of intercities from four times per hour to six times per hour.
- Projects with regards to Utrecht are always popular

The corridor is also used by NS International to operate the ICE to Frankfurt/Basel, which increases the heterogeneity at the corridor and which makes the corridor more interesting.

Chapter 3

Literature review

This literature review consists of four sections each covering another subject related to this research. The sections will start with a short introduction and the research questions used structure and limit the survey.

This chapter starts with explaining decision support systems. Then timetabling is explained by the levels of detail and the process of creating timetables. After that the modelling of trains is discussed by describing the relevant elements for modelling a timetable and modelling the infrastructure. This chapter finishes with describing railway capacity. Unless indicated otherwise this literature survey looks at the railway sector, e.g. one section will cover timetables, only timetable variants used within the railway sector will be discussed.

3.1 Decision support systems

A decision support system (DSS) is a computer-based information system designed to support - not replace - some or all phases of a decision-making process (Van Delden, 2011). A DSS is ideal to use in the complex and weakly-structured decision context. The model should be interactive and user-friendly to facilitate learning. The primary function of a DSS is knowledge management, presenting an integral view of a complex system like its functions and actors. It structures the decision making process and facilitates the communication between different stakeholders. Often it is design with work through what-if-analysis.

- What are the characteristics of a decision support system?
- Which types of decision support systems can be differentiated?

Already in 1980 Sprague looked at the difference between management information systems (MIS) and the at that moment rather new decision support systems. He stated that a typical DSS has the following characteristics:

- they tend to be aimed at the less well structured, underspecified problems that upper level managers typically face;
- they attempt to combine the use of models or analytic techniques with traditional data access and retrieval functions;
- they specifically focus on features which make them easy to use by non-computer people in an interactive mode; and
- they emphasize flexibility and adaptability to accommodate changes in the environment and the decision making approach of the user.

Haettenschwiler (2001) differentiates three types of DSS, based on the relation between the user and the system. A *passive* DSS aids the process of decision making, but is no able to give explicit decision suggestions or solutions. An *active* DSS can give explicit decision suggestions or solutions. And a *cooperative* DSS allows the decision maker to modify, complete, or refine the decision suggestions and run the program again for validation.

Lastly, Sprague (1980) also came up with a number of performance requirements for a DSS. But they are intentionally phrased using the word "should", as not all requirements equally important for each DSS. Every specific DSS should design with the best fitting performance requirements for the task at hand. The first three pertain to the type of decision making task which managers and professionals face. The latter three relate to the type of support which is needed.

A DSS should ... (Sprague, 1980)

- provide support for decision making, but with emphasis on semi-structured and unstructured decisions
- provide decision making support for managers at all levels, assisting in integration between the levels whenever appropriate
- support decisions which are interdependent as well as those that are independent
- support all phases of the decision making process
- support a variety of decision making processes, but not be dependent on any one; finally,
- be easy to use

3.2 Timetabling

Trains are operated according to a timetable. This timetable shows the days on which the train should run, the route the train is guided on through the network, and the arrival and departure times at stations.

- What is the difference between scheduling and timetabling?
- What is the function of a timetable, and what are its users?
- Which levels of detail can be distinguished in timetabling?
- How thus the timetabling process works?

3.2.1 Timetables

A timetable is an output of the process of scheduling trains on infrastructure. The scheduling of public transport timetables is also called timetabling. Goverde (2005) defines timetabling as 'the problem of matching the train line system to the available infrastructure', i.e. finding for each train a feasible schedule of arrival and departure times at the consecutive stations taking into account constrains with respect to e.g. safety and signalling systems, transfer connections, and regularity requirements.

Besides coordinating the train paths in the planning process for optimum use of the infrastructure, scheduling has a number of extra functions (Pachl, 2008):

- It ensures the predictability of train traffic
- It produces timetable data for passenger information
- It is input for:
  - traffic control
  - locomotive and rolling stock usage

– crew scheduling

Each of the functions described by Pachl (2008) is useful for another user. Goverde (2005) listed the potential users of a schedule as:

- (potential) passengers
- (passenger and freight) train operators
- Train personnel
- Dispatchers
- Traffic controllers
- Infrastructure maintenance planners
- Connecting public transport providers

The most commonly used way of displaying a timetable during the process of timetabling is the version like described by Pachl (2002) in the definition of a timetable: *'A survey (table or diagram) of all scheduled trains running on the same portion of a line'*. Here a distinction can be made between a section of a line and the occupation of the platforms of a train stations.

Although it is possible to create a traffic diagram for a whole day, in the railway sector a traffic diagram is often only created for the basic hour (BHP or BUP, *basisuurpatroon*, in Dutch). This shows the scheduled trains for a line during the most common hour of the day. At larger train stations a similar diagram is drawn to indicate the occupation of the platforms. That station traffic diagram is called the *basisspooropstelling* (abbreviated BSO) in Dutch. In the appendix examples of the traffic diagram and the station traffic diagram are added.

3.2.2 Planning horizons

Timetabling starts as early as ten year in advance. Predictions of the traffic volume are made based on the current demand and the predicted growth. Main question of the infrastructure manager during that period is whether the infrastructure is capable to handle the traffic volume. Whereas the train operator is looking towards rolling stock management. As the time progresses the timetabling problems are becoming more detailed. Around five years before the start of the timetable the line planning is made and the train operator is looking to amount of crew needed to operate the trains. The problems and tasks to take are distinguish in the planning horizon. The period more than 2 years before operating the timetable is called the strategic level.

Most sources use the phases of strategic, tactical and operational planning (UIC, 2013; Huisman et al., 2005; Crainic and Laporte, 1997). Although Huisman et al. (2005) state that NS has divided the operational planning phase into two parts, namely operational by which they mean the basic scheduling problems that occur every two months and the short term meaning the detailed modifications for the individual days.

The UIC couples the infrastructure planning with the timetabling process by describing the different levels of the planning horizon for the infrastructure. Table 3.1 shows an overview of the planning horizon stages.

Table 3.1: Overview planning horizons of timetabling and infrastructure planning

Period	**Timetabling**	**Infrastructure**
>2 years	Strategic	Planning
>1 year	Tactical	Construction
6/year	Operational	Operation and maintenance
daily	Short-term	

Crainic and Laporte (1997) described for each of the three main planning horizon stages the goals of that period and the tasks involved with that stage.

Strategic planning (at firm level) involves the highest part of management. The general development policies and operating strategies are made at this point. Determining the offered level of services to customers and tariff policies for the next couple of years. This is the moment for scheduling large capital investments over a long time horizon. These investments can be upgrading or adjustments of the physical network, the building of main facilities and the acquisition of new rolling stock. Also the line planning is made, which services to offer the customer without switching lines.

Tactical planning aims to an efficient and rational allocation of exciting resources to improve the performance of the whole system. The line planning is detailed into a preferred general timetable without incorporating the day-to-day information. In this timetable a lot of general principles are chosen like route choice and type of service to operate.

Operational planning focusses on the details: rolling stock circulation, crew scheduling and small maintenance activities are determined in this stage of scheduling.

3.2.3 Process of timetabling

Timetabling is the process between determining the transport demand and creating the schedules to operate trains. The next section contains the steps required during timetabling followed by a section showing the studies conducted during timetabling.

Steps towards a timetable

The planning horizon looks at time stages before the start of operating the timetable, but besides the horizon there are some steps to take to come to a reliable timetable. Goverde (2005) defined the following (chronological) steps to take:

1. Transport demand
2. Network design
3. Line systems
4. Timetabling
5. Rolling stock circulations
6. Crew schedules and rosters

Knowledge about the transport demand is needed for getting a reliable view towards a vision about the (near) future of railway transport. This is the input for (re)designing the network. According to Goverde (2005) after designing the network the line planning is made. But actually this is rather strange, it is hard to determine in detail the design of the network without knowing the line planning, because the line planning determines which route are necessary and thus influencing the location of e.g. the point switches. The UIC (2013) follows this reasoning without explicit explanation. With the demand, line planning and physical design as the input, it becomes possible to start the timetabling process. The generated timetable will be the input for the scheduling of rolling stock and crew schedules.

Vromans et al. (2006) summarized the step into a diagram (see: figure 3.1). He divided the step of rolling stock circulations into rolling stock planning for operating the timetable and shunting movements.

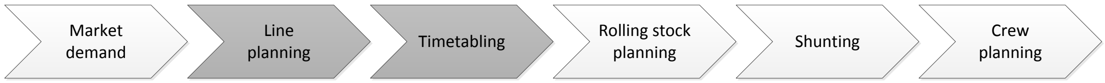


Figure 3.1: Sequence of interdependent railway planning steps Vromans et al. (2006)

Timetabling studies

There are different types of problems when creating a new timetable (UIC, 2013). Timetabling studies are focus on the following problems:

- Bottlenecks
- Timetable structure
- Timetable alternatives
- Quality of service

And the scope of these studies can vary based on the following items (UIC, 2013):

- Future or existing infrastructure
- Scope of the analysed infrastructure (large network or switch area),
- Static model or stochastic model
- Capacity model and data processing
- Traffic simulation system
- Purpose of the study

3.2.4 Indicators evaluating timetables

Schittenhelm (2013) researched timetable evaluation criteria and indicators in Denmark. This to enhance the communication between the infrastructure manager (IM) and the train operating companies (TOCs). That research formulates six timetable evaluation criteria. These criteria are:

- Systematic timetable
- Capacity consumption of railway line sections
- Robustness of the timetable
- Societal acceptance of the timetable
- Attractive transfer options
- Travel time

Two of the criteria are outside the scope of this research, therefore they are not considered relevant (Societal acceptance of timetable based on external independent organizations and attractive transfer options).

The 13 indicators that he proposes are each allocated to one of the six timetable evaluation criteria. The indicator for a systematic timetable is called the systematic timetable index, which is based on the most used timetable pattern time-wise. The capacity consumption is calculated using the UIC 406 (UIC, 2004a) methodology. The robustness of the timetable is calculated with a number of small indicators, the most important one being the degree of deviation from planning rules with regard to time supplements. For travel time, the proportion of travel time prolongation for a travel relation comparing the timetabled extra travel time to a theoretical direct non-stop train is used as the indicator.

3.3 Modelling

In the operation of trains are a number of uncertainties. Weather conditions, train characteristics, number of passengers, driving behaviour, etc. will create differences in the running time of trains. To get an indication (simulation) models are created to approach the real world situation. In this section more about the modelling of a railway system.

- How to calculate the running time of a train?
- How to model the infrastructure?
- Which tools are available to simulate the calculations?

3.3.1 Timetables

Next to the infrastructure is the timetable, a combination of both is needed to operate trains. This part will explain the theoretical background of the elements and calculations behind a timetable.

Creating a timetable with a good quality starts by using realistic scheduled times. Individual times typically consists of the following components (Goverde, 2005):

- a nominal running time for ideal or average traffic conditions
- a margin for deviations to the ideal traffic conditions
- scheduled waiting time to create a uniform timetable

A timetable is not realistic when a lot of delays cause a low operation punctuality. There are two types of delays: primary delays are caused by disturbances in the process like problems with the infrastructure, rolling stock or the weather. Secondary delays are disturbances caused by conflicting train paths or waiting for delayed trains.

Running time calculations

The calculation of nominal running times is based on the principles of train dynamics, the physical principle that in order to get movement the sum of resistance factors needs to be compensated by a force of driving. Examples of those resistance factors are the rolling resistance, air resistance, and gradient resistance.

The speed profile of a train can be constructed using five general regimes (see: figure 3.2). In the acceleration regime the tractive effort exceeds the total resistance. In acceleration calculations are based on the maximum level of acceleration possible by the type of rolling stock within the acceptable limit of its cargo. In speed holding enough traction is supplied to balance the traction and the sum of resistance. Coasting is the regime in which no traction power is applied, the train will slow down through the force of resistance. Finally, controlled braking is used to reduce the speed of the train so it can stop at a specific location. The last regime is called standing, this regime is used at stations.

A speed profile is constructed based on the five regimes and the speed limits of the infrastructure. From the speed profile the nominal running time can be extracted.

In the railways when talking about the running time of a train, it means the nominal running time of the train plus a margin and then rounded to the next nearest full minute (Goverde, 2005; ProRail, 2014d). Mathematical notation:

$$scheduled\ running\ time = \lceil nominal\ running\ time + running\ time\ margin \rceil + 1 \tag{3.1}$$

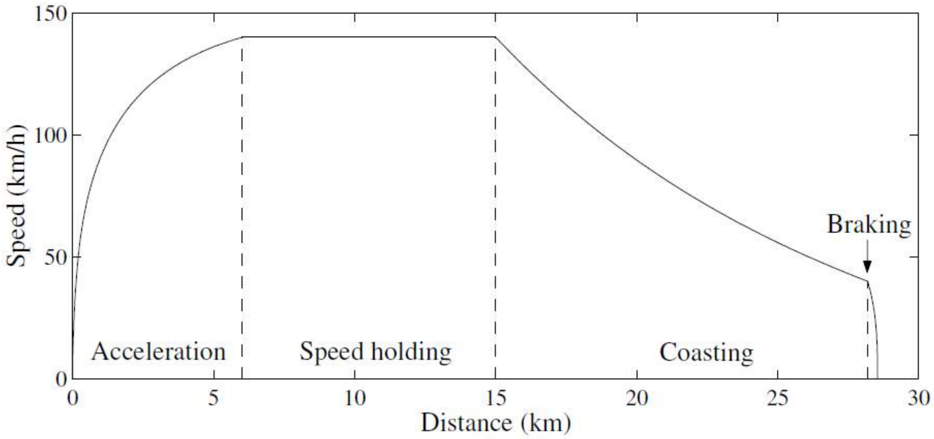


Figure 3.2: Speed profile with coasting regime (Goverde, 2005)

Running time margin

Generally running time margin is added to the nominal running time Goverde (2005). This margin has multiple purposes, figure 3.3 shows three purposes.

First, the margin gives trains the opportunity to get back at their schedule when, for some reason, they had to travel at a lower speed (i.e. track conditions or people alongside the track). Second, the margin can be used to get back at schedule when a train is delayed in its departure. At nominal running time the train will catchup with the amount of time scheduled as margin. The third option for margin is not for catching up delays, but for another good cause: energy savings. A train running on schedule has, at the end of the line section, some margin left. This margin can be used for coasting and therefore saving energy without affecting the timetable.

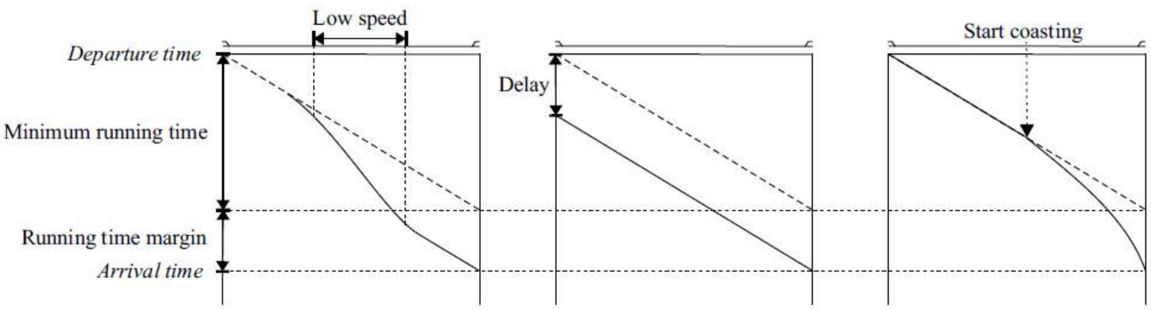


Figure 3.3: Time-distance diagrams demonstrating usage of running time margin (Goverde, 2005)

Usually the running time margin is a percentage of the nominal running time. In the Netherlands the margin is 5% and then rounded to the nearest minute. For freight trains no margin is added on top of the nominal running time, this because the speed of freight train paths is lower then the feasible speed in practice (ProRail, 2014d).

Buffer time and scheduled waiting time

Buffer time is added to the timetable to compensate other processes then the running time. So buffer time can be used to absorb arrival delays or variations in the alighting/boarding process.

Scheduled waiting time is time loss added due to restrictions in the infrastructure. An example are two trains that have a cross platform connection, but where the second train has

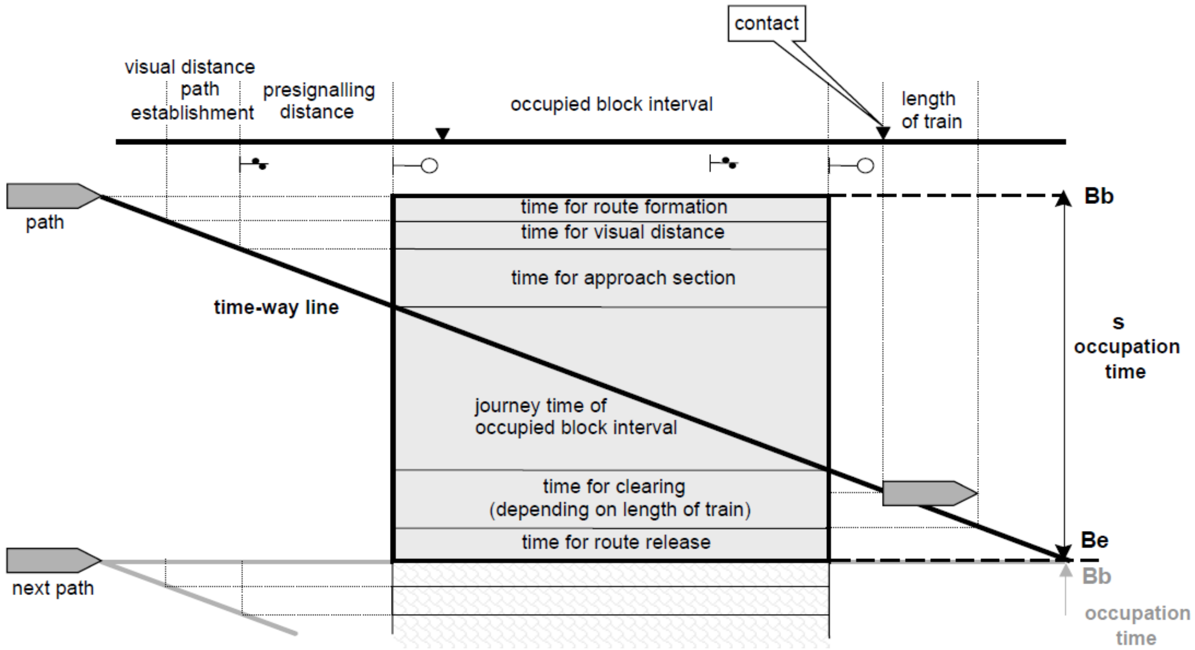


Figure 3.4: (Schematic) elementary occupation time (UIC, 2004a)

to wait after the departure of the first train because they have to share the same infrastructure exiting the station.

The difference between these two elements is that the buffer time is flexible while the scheduled waiting time is always a time loss.

Blocking times and minimum headways

In most countries separation of trains on the track is done using signalling (see section 3.3.2). Signs (lineside or within the cabin) divide the rail network in block sections which can only be entered when that section is not occupied by another train. The length of a block section depends on the projected velocity of train at that point.

The blocking time is the time a section of track (e.g. block section, interlocked route) is allocated exclusively to a train movement and therefore blocked for other trains (Pachl, 2008) The blocking time begins by issuing a train movement onto the section, locking the section for opposing trains. The time the section is blocked ends when the train moves outside the blocked section and passes the clearing point. Figure 3.4 shows the elements between beginning and ending the blocking time of a train (paths).

By calculating the blocking time for each train at every block section it becomes possible to create a diagram of a train path with the according blocking times. This diagram is also referred to as the blocking time 'stairways'. [1]

In more detail, section 4.1 explains how blocking times and minimum headways are combined into a follow-up-times matrix.

[1]With 'moving block' technology (ERTMS Level 3) the stairway will turn into a 'slide'

3.3.2 Infrastructure

With regards to the railway network design, this section will cover the level of detail, the different components in the network and the separation of trains.

Level of detail modelled

The railway network consists of many elements. Depending on de level of detail more elements and more information about those elements is required. Regardless of the level of detail the system is represented with basic nodes and links. Nodes are used to indicate locations and links are the connections between two nodes. At different levels of detail the nodes and links may contain different information.

In a macroscopic model the nodes contain information like name, coordinates, type (station, shunting yard, junction, etc.); For links information will be stored like length, type of line (high speed, passenger, freight or mixed), number of tracks. When looking at a microscopic model, the nodes represent point switches, signals or starting points of speed limitations. And the links will hold more detailed information as the gradient, permissible speed, curve radius, etc.

Figure 3.5 shows an image by Marinov et al. (2013) with the different aggregation levels of modelling a station and a junction. Where at microscopic level point switches are regarded as nodes, in the macroscopic level the whole station is seen as one node.

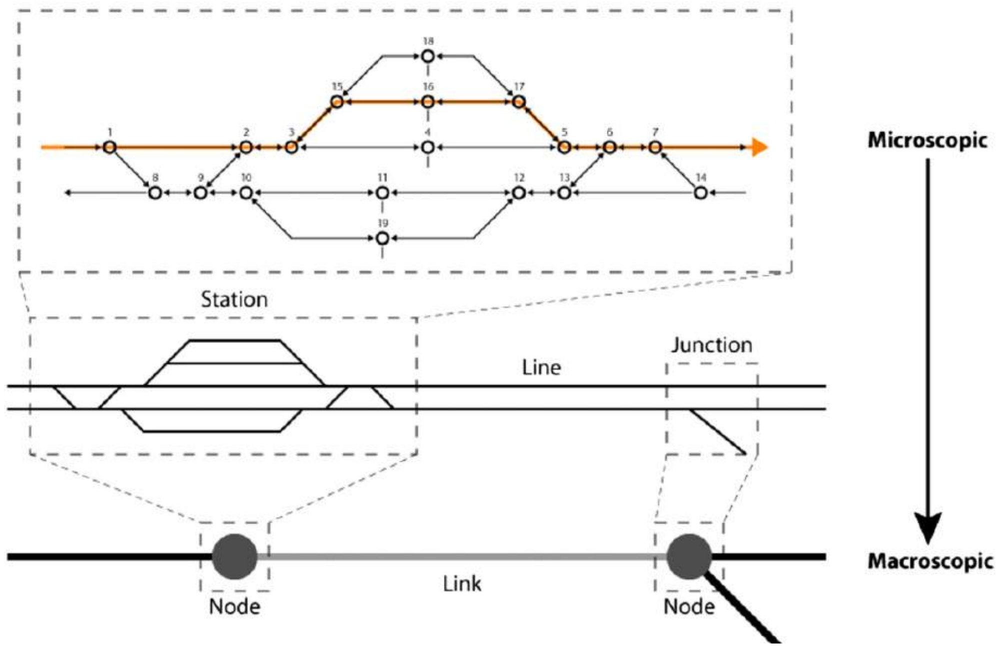


Figure 3.5: Top: Microscopic representation of station as an aggregate of nodes and links. Bottom: Macroscopic basic node-link-node structure (Marinov et al., 2013).

The right level of aggregation should be chosen when modelling a system, this is depending on the information available and the level of detail (accuracy) required for the analysis. Marinov et al. (2013) notes a microscopic model is required for calculating running times, creating timetables and simulations.

Meso components

Looking towards the railway system on a meso-level there are a number of components.

Corridors represent the main international and national connections. Usually they stretch over several hundred kilometres. Sometimes corridors overlap with one another (UIC, 2013).

Lines are the links between stations.

An **interlocking** is the arrangement of points and signals interconnected in a way that each movement follows the other in a proper and safe sequence (Pachl, 2002)

Station is a place where passengers can board and alight, but in timetabling a station is also a place designated in the timetable by name (Pachl, 2002).

Junctions are elements in the train infrastructure network where trains can change tracks and thus direction. Junctions are used for train movements only, junctions are not used for shunting (UIC, 2013).

Besides dividing the network in the above components the network is also divided into sections. The term 'train path line sections' is used to refer to sections which are considered the same based on their market conditions, e.g. Enschede - Deventer. 'Line sections' is used to divide the network in segments which are similar due to their characteristics like signalling system, number of tracks and branching lines. This last definition is also used to split the network in parts used for capacity analyses (UIC, 2013).

Micro components

In addition to meso component, Radtke (2008) describes the infrastructure elements at micro level necessary for feasible simulations. These components are:

- Length of a link
- Permissible speed
- Speed indicators and speed boards
- Release contact and clearance location
- Track circuits
- Electrification
- Overlaps
- Stop boards
- Interlocking technique
- Exclusion of routes (dependant links for simulation)
- Signalling system
- Blocks and routes
- Gradient
- Radius

Train separation

Compared to cars, trains have a large braking distance. Trains are travelling at high speed and the braking distance is often longer than the driver can monitor. Therefore, it is not possible for a train driver to stop in time when he sees a predecessor has stopped. That is why railway lines are divided into block sections. Generally when a train is inside a block section it is not allowed for another train to enter the same section.

There are three basic theoretical principles of train separation (Pachl, 2002):

- relative braking distance
- absolute braking distance (e.g. ERTMS level 3)
- fixed block distance (e.g. NS '54)

With trains separation by relative braking distance, the distance between two following trains equals the difference between the braking curve of the first train and the braking curve of the second train plus a fixed safety distance. Although this looks efficient, it gives problems with the interlocking. The second train must be full braking distance away from a point switch before it is locked. Running over the switch and locking it in position requires time. Another problem occurs when the first decelerates faster than expected or when an accident happens with the first train. Then, the second train will not have enough time to stop, resulting in a collision. Train separation in relative braking distance it therefore purely theoretical.

Absolute braking distance separates trains so the second train has a full braking distance when the first train instantly comes to a full stop. The distance between the two trains therefore equals the full braking distance of the second train plus a fixed safety distance. This method of separation is currently not used often because of a lack of suitable and available technology. With the introduction of ERTMS level 3 it should be possible to get this implemented.

The most common principle of train separation worldwide is running in fixed block distance. During normal operation the distance between two following trains is the length of one block plus the full braking distance of the second train plus the fixed safety distance. The blocks in this system are fixed, meaning that they are defined beforehand.

At the Dutch main lines maintaining the fixed block distance is primarily done using 3-aspect line-side signalling. The line-side signals are called block signals. Figure 3.6 provides an example of two following trains and appropriate status of the block signals.

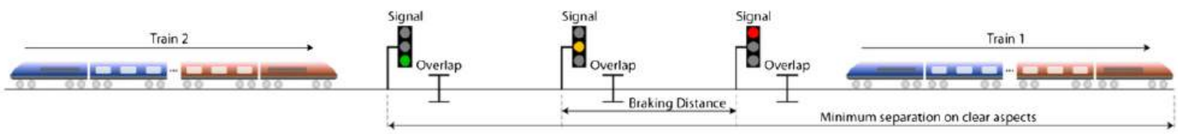


Figure 3.6: Example of 3-aspect signalling, showing minimum separation between two consecutive trains (Marinov et al., 2013)

Knowing which principle(s) of train separation are active is crucial when modelling a timetable. Train separation has a large influence on the interval times between two trains and therefore with the modelling of a timetable. Unless otherwise stated, simulations and calculations are made using the NS '54 fixed block distance principle.

3.3.3 Used simulation applications in the Netherlands

To calculate a timetable or elements of the timetable simulation application can be used. Most of the applications used in the Netherlands are developed in-house and dedicated for the railway sector. The first three models are (almost) exclusively used by ProRail or NS (Middelkoop, 2010). ARCADIS works primarily with Xandra.

DONS 'Designer of Network Schedules' is an automatic timetabling system. Based on the infrastructure and a set of criteria with regards to the line planning and required connections, DONS tries to find the optimal timetable for the entire (national) network. It can also give feedback which conflicts between train paths arose during calculation.

Simone 'Simulation model for networks' calculates the performance of a timetable by simulating the timetable on the infrastructure. The performance is measured in delays, spread, propagation, dampening and occupation.

Roberto *'Rij- en opvolgtijd berekeningstool'* can calculate in batches the running time and interval/intersect times for infrastructure and train combinations. In DONS default values for the intersect and interval times are used in the calculations. With Roberto situations can be calculated in which the default values do not comply with the required traffic volumes and dedicated calculations are needed.

DONNA Donna is an application used by ProRail to schedule and divide the capacity of the network. It offers railway users access to the capacity, schedule and potential conflicts (ProRail, 2014b). Donna is also used by operators to submit the formal (daily) request for capacity to ProRail.

Xandra Xandra is the application used by ARCADIS to calculate running and headway times of trains and train combinations.

3.4 Capacity and occupancy

Determining the capacity for roads is relatively straightforward because it will be merely determined as the vehicles per hour. Railway capacity is more difficult to determine because the capacity depends on the infrastructure, the timetable and the rolling stock (Landex, 2008).

Defining the capacity for a railway system is difficult. Highways are known to have a capacity of approximately 1800 passenger car equivalent (PCE) per lane per hour. On a normal highway cars are able to overtake each other, therefore it is possible to reach the capacity with a heterogeneous traffic flow. For rail this is not an option, when a train stops another train cannot overtake it without the appropriate infrastructure. So the capacity of a railway line is heavily related to its operation.

The following questions will be answered in the next sections:

- What are the parameters in railway capacity?
- How can railway capacity be classified?
- What indicators can be used to tell something about railway capacity?

3.4.1 Capacity balance

Figure 3.7 shows a conceptual string model for describing the railway capacity. It shows the correlation between the number of trains that can be operated and the elements indicating the quality of service (average speed, heterogeneity and stability) (Oldenziel, 2014). From the model can be deduced that capacity is mixture of the number of trains, the stability of the timetable, the level of average speed achieved and the heterogeneity of the operation (Landex, 2008). For instance, there is a market demand for more trains without reducing the punctuality. This might be possible, but then the average speed of trains will be lower and the mixture of trains becomes more homogeneous by operating more trains with the same speed and stop pattern.

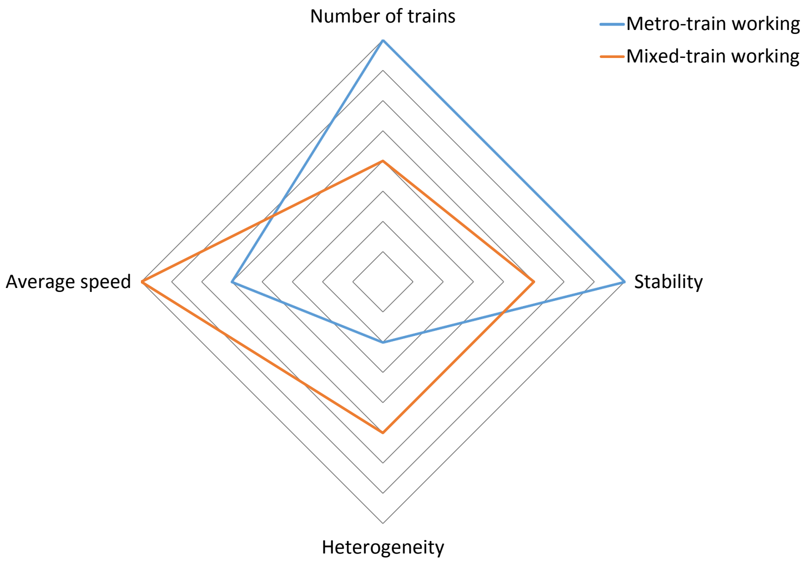


Figure 3.7: Capacity Balance (UIC, 2004a)

Although this capacity balance is a conceptual sting model, it is possible to visualize the 'capacity' or 'occupancy' characteristics of a line section by calculating the elements of this model.

Number of trains

The number of trains to operate is limited by the difference operating characteristics between different train types. Faster trains will catch up with slower trains at the line section. The measurement for the number of trains is simply the number of trains operated (Landex, 2007).

Heterogeneity

A timetable is considered homogeneous when all trains are operated with the same characteristics. The more the characteristics differ the less homogeneous the timetable will be or said otherwise the timetable becomes more heterogeneous. The characteristics that can differ are for example speed and stopping pattern.

The heterogeneity can be calculated by finding the variation in headway times and speed by taking the ration between the headway time at the departure station ($h^D_{t,i}$) and the following headway time ($h^D_{t,i+1}$). This value is multiplied by the same ratio measured at the arrival station (A). To make the value independent from the number of trains measured, the number is divided by the number of headways minus 1 (h_{N-1}) (Landex, 2007).

$$Heterogeneity = 1 - \frac{\sum \left(min\left(\frac{h^D_{t,i}}{h^D_{t,i+1}}; \frac{h^D_{t,i+1}}{h^D_{t,i}}\right) \cdot min\left(\frac{h^A_{t,i}}{h^A_{t,i+1}}; \frac{h^A_{t,i+1}}{h^A_{t,i}}\right)\right)}{h_{N-1}} \tag{3.2}$$

Figure 3.8 shows in a train path diagram the difference between a homogeneous (a) and heterogeneous (b) timetable and the effect of train sequence on the occupation rate (c).

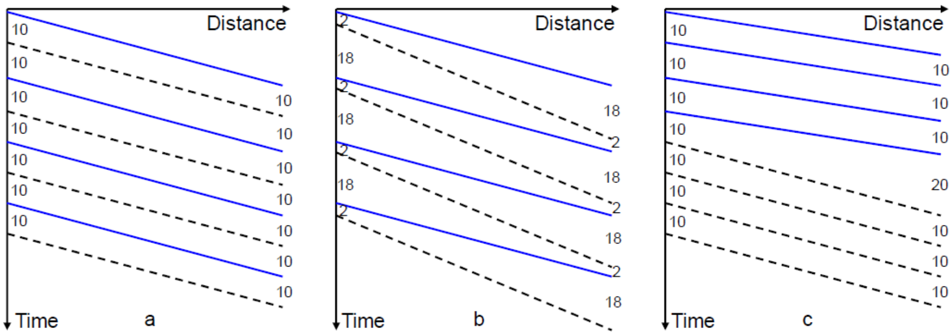


Figure 3.8: Timetables with different degree of homogeneity (Landex, 2008)

Stability

Landex (2007) describes a stable railway system as the opposite of a complex railway system ($stability \approx 1 - complexity$). The complexity is calculated by analytically analysing the conflicts between train routes, the so-called conflict rates. This method is time consuming and hard to automate.

Goverde (2005) models the railway system as a max-plus linear system. Max-plus algebra is mathematical representation where the addition of two numbers consists of their maximum, whereas the multiplication of two numbers is the usual plus. For example, 3 plus 5 equals 5, and 3 times 5 equals 8 (Quadrat, 2009). The max-plus algebra is often used performance evaluation of timed events. The stability of a railway system is tested based on the eigenvalues of the state matrix. The maximum eigenvalue represents the minimal cycle time of the timetable.

Andersson et al. (2013) uses critical points creating a measure of robustness. Critical points are locations where trains are delayed in and become even more delayed. They refer to locations in the timetable where trains are scheduled to enter a line or to overtake in a very time-sensitive manner. The number of critical point, their locations and the corresponding RCP values (robustness in a critical point) together form the measure of the robustness.

3.4.2 Capacity terminology

De difficulties of defining capacity in the railway sector has lead to dividing capacity in different categories.

Theoretical capacity (TC) The capacity found when scheduling trains running without a stop with ideal minimum headway and within a strictly perfect mathematically generated environment is called the theoretical capacity. The intensity calculated in this way can never be driven in operation because there is no buffer to correct for operation, human factors or delays. It is a purely strict mathematical indication of the infrastructure (Abril et al., 2008).

Practical capacity (PC) Practical Capacity (Kontaxi and Ricci, 2009) or commercial capacity (Abril et al., 2008) is a more practical limit of a representative intensity, where realistic assumptions are used in the calculation. Operational factors like mixture of different train types and priorities are taken into consideration. The practical capacity is more realistic then the TC and could be scheduled for real operation.

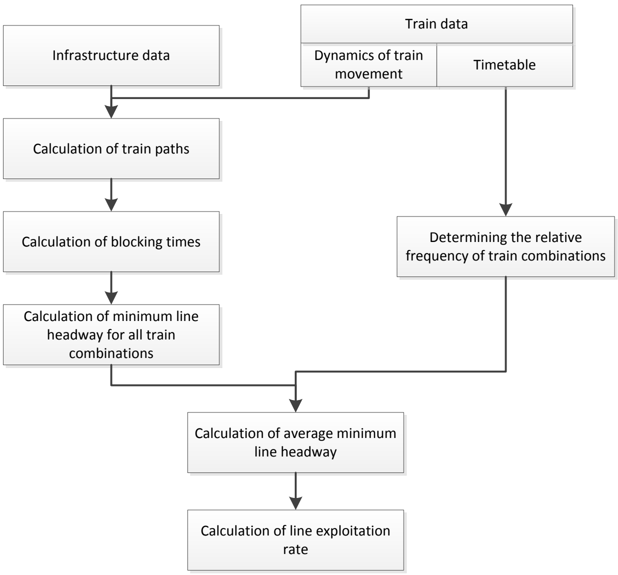


Figure 3.9: Steps of analytic capacity research (Pachl, 2002)

Used Capacity (UC) Used Capacity reflects the actual traffic and operations occurring over the network. Often this is lower than the practical capacity (Abril et al., 2008).

Available Capacity (AC) The Available Capacity (Abril et al., 2008) or Residual Capacity (Kontaxi and Ricci, 2009) is the difference between the Practical Capacity and the Used Capacity. It indicates the amount of additional traffic that could be handled on the track. If new train paths are to be added then this is useful capacity. Otherwise it this capacity is lost.

3.4.3 Calculating capacity

The used capacity is an important indicator for the infrastructure managers because it shows if the load on the network is within boundaries. This indication can be provided using simulations of operating a timetable or by analytical calculating the occupation of the railway lines (Pachl, 2002). The main disadvantage of using simulations is that this method can be time-consuming (UIC, 2013).

Pachl (2002) describes steps to calculate the capacity using a method called timetable compression. These steps are shown in Figure 3.9. Input for this calculation is the current or proposed infrastructure, data containing information about switches, gradients, speed limits, etc. and the timetable. For each train, the continuous position of the train at the corridor is plotted against the time, this is called a train path. For operation different time buffers are added to the train paths. Examples of possible time buffers are additional run time (i.e. 5%) or extra dwelling time at stations.

Blocking time compression determines the occupation of a section of infrastructure by removing all time buffers between the trains. The train paths are then placed end to end, to compress the timetable as much as possible. An example of a timetable showing the blocking time ‘stairway’ and a compressed version of the timetable can be found in Figure 3.10.

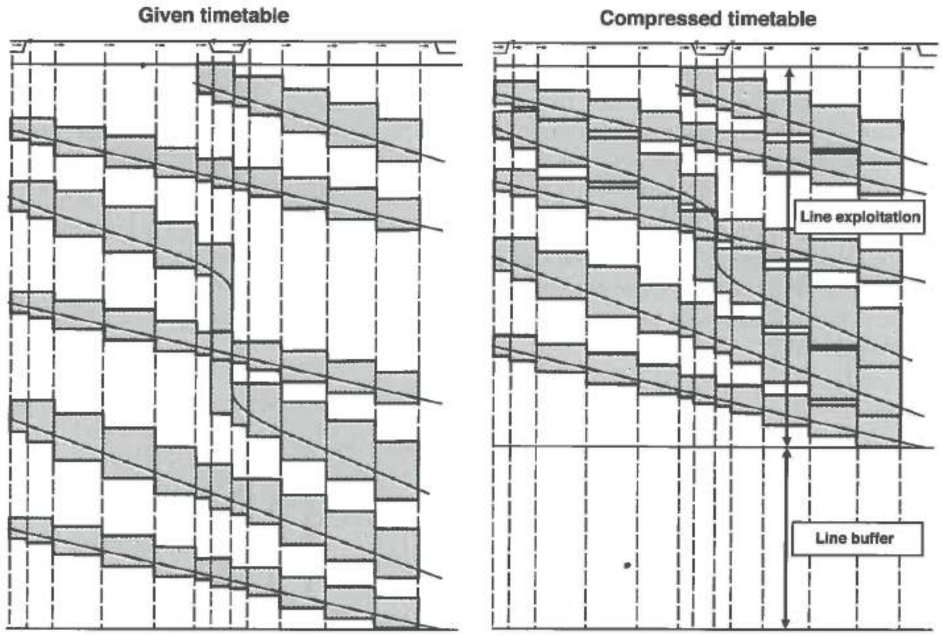


Figure 3.10: Visualization of the Consumed Capacity (Pachl, 2008)

3.4.4 Occupancy (UIC 406)

Europe has different railway environments, they differ for example in length of the network, operating speed and the occupancy rate. When comparing the railway environments this can easily lead to different interpretations and misunderstandings. Therefore the International Union of Railways (UIC) provided guidelines to compare the capacity of the different railway environments using a capacity indicator (UIC, 2013).

The work-flow outlining the process of evaluating the capacity and determining the capacity limit is called the UIC 406 method. The work-flow consists of five steps to calculate the capacity consumption and the capacity limit. The leaflet which describes the work-flow is also called UIC 406.

In 1996 the first rough idea was published. That document was called the UIC 405. The leaflet 405 described purely verbal how to improve the utilization of infrastructure (Lindner, 2011). When the leaflet 405 no longer lived up to the expectations due to the introduction of computer models, the UIC started a new working group research the subject of capacity management (CAPMAN) (Oldenziel, 2014). One of the deliverables of the CAPMAN working group was the UIC 406 leaflet containing the description the 406 methodology (UIC, 2004b).

The leaflet published in 2004 describes a simple, but fast and effective way to evaluate the capacity utilization of railway lines. However it is possible to expound the UIC 406 method in different ways, which will lead to different results (Landex et al., 2006). In June 2013 the UIC published a 2nd edition of the UIC 406 leaflet. This edition is a complete overhaul of the report. The methodology has not changed in essence, but the description is more comprehensive and it contains a lot of scenario outlines.

Calculating the capacity indicator

The method of the UIC follows the steps of Pachl described in section 3.4.3. But instead of determining the relative frequency of the trains, the method of the UIC uses the exact train combinations to create a blocking time stairway. Using timetable compression the percentage of usage with regards to the reference time (occupation rate) can be calculated using the following formula (UIC, 2013):

$$Occupancy\ Time\ Rate\ [\%] = \frac{Occupancy\ Time}{Defined\ Time\ Period} \cdot 100 \tag{3.3}$$

Other analytical occupation methods

There are other analytical methods then the UIC code 406 to calculate the occupation of railway infrastructure. Most of those methods are specialized in calculating the occupation at a specific element of the rail network system. Next a few calculation methods will be described briefly, briefly because more information about these methods is hard to find.

In the United Kingdom they use measure called the CUI method for conducting capacity analysis (Khadem Sameni et al., 2011; Armstrong et al., 2011). It is based on the minimum headways derived from the local rules of driving. The train paths are minimized for timetable compression. Then two types of headways are defined, a fast one is used when the preceding service does not stop at the next station and otherwise the slow headway should be used.

The Italian Infrastructure Manager uses an analytical method known as the RFI method. The capacity is defined by considering the average minimum headway interval between trains together with an additional time and a supplementary time (Dicembre and Ricci, 2011 adapted from Galatola et al., 2004). The additional time increases the average minimum interval by 2/3, while the supplement adds 0.25 minute for every station at the line.

Mussone and Wolfler Calvo (2013) proposed a model to calculate the capacity of a complex node. This is useful when other methods (like the UIC 406) are not capable of handling many stations in a small area. The model uses a set of inequalities linking together the capacities of each elementary component (i.e. lines, station tracks and simple nodes) of the system.

Overall the current standard for analytical capacity analysis is the UIC code 406.

3.4.5 Projects that used UIC 406

Schittenhelm and Landex (2013) identified a first common list of Danish railway timetable criteria. Based on that common list, a series of existing and newly developed key performance indicators (KPI) for railway timetables is created. The degree of systematic of a timetable can be indicated using timetable patterns. Robustness of a timetable depends highly on the complexity of the planned railway traffic. And they use timetable fix points to measure the robustness of the proposed timetable. Next to that they looked into a number of soft indicators like societal acceptance and passenger satisfaction. The UIC 406 is also proposed as one of the indicators. According to Schittenhelm and Landex (2013) the UIC 406 improves cooperation and communication between IM and TOC, also on international level. They also propose to improve the UIC 406 methodology by handling stations bordering to a railway line sections of analysis separately and not as being a part of the analysed line section.

Khadem Sameni et al. (2011) looked at the South West Main Line, one of the congested lines in Great Britain. The line section is important for both commuter traffic to London as freight traffic to the Port of Southampton. In this study, they implemented the suggestion to improve the UIC 406 for meso capacity analysis with the aim to reduce the capacity consumption. The UIC 406 is used to calculate the average capacity utilization per train. To determine which train to remove from the timetable, a meso capacity index (eq. 3.4) is introduced which is calculated by dividing a micro capacity index (i.e. load factor) by the macro capacity index (avg. utilization). Based on this technique Khadem Sameni et al. (2011) could advise which train to remove from the schedule.

$$Meso\ capacity\ index = \frac{Micro\ capacity\ lost}{Macro\ capacity\ gained\ by\ omitting\ the\ train} \tag{3.4}$$

$$= \frac{n_{cl}}{C_b - C_a} \tag{3.5}$$

n_{cl} : Number of carriages lost
C_b : Capacity utilisation before omitting the train
C_a : Capacity utilisation after omitting the train

In the same study Khadem Sameni et al. (2011) also looked at adding extra trains to the schedule. They looked at a line section in the suburban railway network of Copenhagen, Denmark. The UIC 406 describes the process of adding trains to the timetable to calculate capacity, but it does not tell which trains to add to the schedule. The analysed line section knows two train series with a different stopping pattern (heterogeneous). The research showed that it is possible to add a lot more trains of one train series than from the other one. Based only on the macro capacity index Khadem Sameni et al. (2011) could not create an advise, so again the meso capacity index was introduced. This time the potential load factor was used as the micro capacity index.

Landex also conducted multiple studies into the applicability of the UIC 406. In one study (Landex, 2009) he focusses on the applicability of the method at single track lines. The case studied is again the suburban railway network of Copenhagen. He concludes that it is possible to used the UIC 406 for both single track line sections and double track line sections, but that with single track lines the division of lines into sections is of major importance. Because a wrong division can lead to the paradox that adding an addition train reduces the capacity consumption. Landex (2009) also concludes that the UIC 406 is suitable for estimating the capacity consumption in case of unscheduled single track operation.

3.5 Conclusion

Based on the research of Schittenhelm (2013) there can be concluded that there are four relevant timetable evaluation criteria, each being evaluated by one or more indicators. These criteria and indicators are:

- Systematic timetable
  - Systematic timetable index
- Capacity consumption of railway line sections
  - UIC 406
- Robustness of the timetable
  - Degree of deviation from planning rules
- Travel time
  - Proportion of travel time prolongation for a travel relation (comparing the timetabled extra travel time to a theoretical direct non-stop train)

There are two methods described in the literature review to calculate the robustness of a railway system. Both methods are difficult understand and to implement in a model.

Furthermore, there can be concluded that developing a proper infrastructure design and developing a timetable for operating on that infrastructure is a complex process.

Chapter 4

Timetabling process in practice

This chapter covers the results of the interviews. It starts with explaining more in-depth the link between infrastructure and time, or actually infrastructure and the consequence of changing infrastructure on the timetabling process. That section is followed by a description of the ProRail 'core-process' and process of timetabling during the tactical phase. Then the complexity of the processes is explained based on examples given in the interviews followed by the requirements and indicators provided by the interviewees with regards to the design of the decision support system.

4.1 Relation between infrastructure and time relations

Railway infrastructure can be translated into time relations. This will be demonstrated following the example provide in figure 4.1. After the basic explanation, the effects of changes in the infrastructure on the time relations will be described for a number of cases.

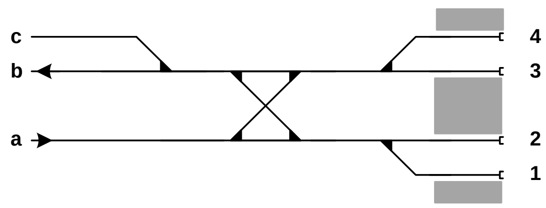


Figure 4.1: Example track layout

The above layout is a terminus station with four platforms (1 till 4) which is connected to a line section (a and b). A third direction (c) is used for shunting movements towards a yard.

Following the normal rules of operation on the Dutch network, trains towards the terminus station will come from direction a of the line section. Departing trains will be routed towards direction b. Additional trains for the peak period will come from the yard (direction c) going towards one of the platforms to leave into direction b after boarding passengers. After the peak periods trains from the a-direction will alight passengers at one of the platforms and the empty train will then be routed towards the yard (c).

Following the example infrastructure (and Dutch normal rules of operation), a number of train routings are possible:

- From the corridor (a) towards one of the platforms (1-4): 4 routes

- From one of the platforms (1-4) towards the corridor (b): 4 routes
- From the yard (c) towards one of the platforms (1-4): 4 routes
- From one of the platforms (1-4) towards the yard (c): 4 routes

Some of the above routes are possible to operate parallel without a conflict, while other combinations of routes are conflicting each other. When routes are conflicting, the routes have to be operated in series instead of parallel.

4.1.1 Examples (non-)conflicting routes

In figure 4.2 two examples are given for combinations of routes. In the first (left) example one route is set for a train entering the station from the line section and travelling towards platform 2 (route a-2). The other route is a train leaving the station at platform 3 and travelling towards the line section (3-b). The routes do not share any of the infrastructure and therefore it is possible to operate the routes parallel.

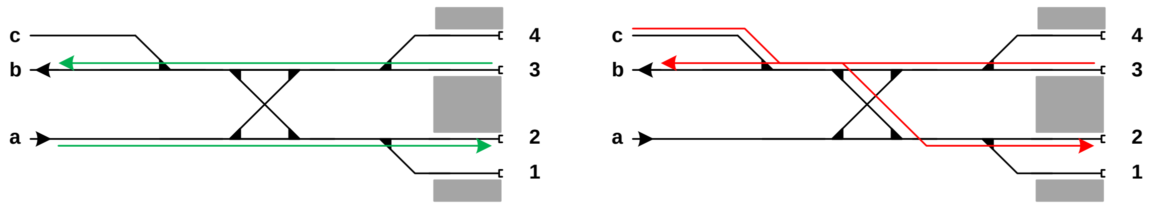


Figure 4.2: Example non-conflicting and conflicting routes

In the right example, one route is set from the yard towards platform 2 (c-2) and another route is set from platform 3 towards the line section (3-b). As visualized in the figure, a part of the stations infrastructure is shared by both routes. Therefore it is not possible to operate the routes parallel and one of the trains will have to wait for the other one. The waiting time for the second train is determined by the time needed for the first train to clear the shared infrastructure. After clearing that section, the infrastructure becomes available and the route for c-2 can be set by traffic control.

The above examples describe intersecting train routes, but the same applies for trains following each other. In figure 4.3 two train routes are displayed that do not intersect but follow each other. The first route is a regional train departing from platform 3 (3-b). This train has a number of stops at the line section before the next larger station where a following train can overtake. The intercity train leaving from platform 4 will follow the regional train (4-b). Following Dutch operating rules, trains should be scheduled without conflicts, so the departure time of the intercity train is limited by the time needed by the regional train to clear the shared infrastructure. In this case the follow-up time between the two trains is defined by the time needed for the regional train to clear the infrastructure (so the running time to the next larger station) minus the time needed by the intercity train to reach the last occupied section by the regional train.

4.1.2 Follow-up-times matrix

The relation in time between setting two routes can be entered in a follow-up-times matrix. Each cell describes the minimum time between two routes needed to operate without conflicts. The sequence of trains is of great importance, as reversing the order will give other follow-up-times. An empty cell in the follow-up-times matrix is indicating that the train routes can be operated without conflicts (so parallel). Table 4.1 shows an example of a follow-up-times matrix

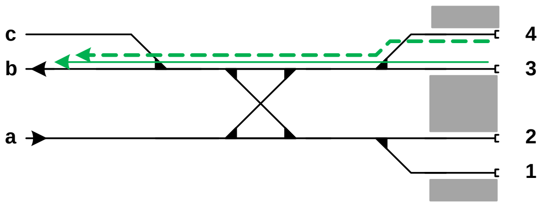


Figure 4.3: Example two consecutive routes

for the infrastructure used in the examples, a number of links in the matrix is hidden to keep the example matrix uncluttered.

Table 4.1: Example follow-up-times matrix

			excluded route							
	#		1	2	7	8	9	10	15	16
		route	4-b	3-b	a-2	a-1	4-c	3-c	c-2	c-1
actual route	1	4-b	2,2	2,2			1,7	1,7	3,1	3,1
	2	3-b	2,2	2,2			1,7	1,7	3,1	3,1
	7	a-2			3,4	3,4			2,0	2,0
	8	a-1			3,4	3,4			2,0	2,0
	9	4-c	1,4	1,4			3,2	3,2	7,5	7,5
	10	3-c	1,4	1,4			3,2	3,2	7,5	7,5
	15	c-2	0,5	0,5	1,7	1,7	0,5	0,5	0,5	3,6
	16	c-1	0,5	0,5	1,7	1,7	0,5	0,5	0,5	3,6

4.1.3 Relation between changes in the infrastructure and the follow-up-times matrix

The previous sections explains the link between infrastructure and minimum time between trains. Changing the infrastructure will have consequences for the headway times in the follow-up-times matrix. Therefore it is possible to conclude that infrastructure can be represented as a follow-up-times matrix.

But what will happen to the headway times in the follow-up-times matrix when (minor) changes are carried out to the infrastructure? Next, a couple of examples will be given to get an idea what could happen when the infrastructure changes.

Adding additional infrastructure (e.g. bypass)

Infrastructure with a lot of conflicting routes is more difficult to operate than an infrastructure with fewer conflicts. That is why during the engineering of a track layout often the aim is set to reduce the number of conflicts (given a set of constraints). One way of reducing the number of conflicts is by introducing a bypass. Figure 4.4 shows the track layout used in earlier examples and the same layout with an additional bypass. Routes 2-b and 4-c are conflicting and they have to be operated in series. While in the second layout it is possible to operate both routes without a conflict. The total time required to operate both routes will decrease, and therefore the available capacity will probably rise.

To describe the effect of the bypass in numbers: in the left track layout 16 routes are possible resulting in a follow-up-matrix containing 256 relations, 232 relations are conflicting and their

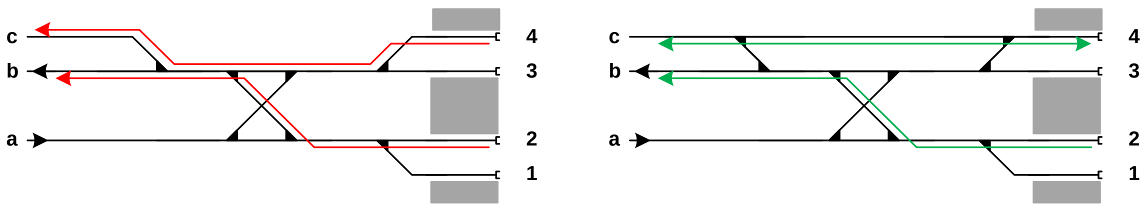


Figure 4.4: Example how change in track layout can solve conflicting routes

cells contain a follow-up-time. In the right layout the same number of routes and relations are possible (respectively 16 and 256) but only 216 routes are conflicting. The level of improvement is also depending on the frequency of the used routes.

Change distance between signals

On a Dutch line section the distance between signals is often equal to, or larger than, the braking distance of the slowest train. Given the right circumstances it is allowed to place additional signals at half the braking distance (note: the aspects of the signals will change accordingly). Great benefit of this construction is the reduction in headway time when leaving a station. A reduction in headway time will also reduce the time between two routes and the associated value in the follow-up-times matrix.

Increasing line speed

An increase of the line speed is highly beneficial on a line section with trains with the same characteristics (i.e. stopping pattern and speed profile: high homogeneity). By increasing the line speed the first train will clear up section more quickly allowing the second train to departure earlier. The headway time will decrease and so will the associated value in the follow-up-times matrix.

On the other hand, at line sections with a low homogeneity this effect will be much less or even negative, as regional trains will require more time to accelerate to the line speed. The intercity accelerates less often and it has a greater benefit of the increase of speed.

4.1.4 Level of detail calculating the nominal running time

The level of uncertainty in timetable analysis depends on the method used to calculate the nominal running time of trains. In general, four methods for calculating railway running times can be defined.

- estimation based on rules of thumb
- quick calculation
- simulation

Rules of thumb

When the running time is calculated in an earlier phase of the project or when the question regards a slight modification of an actual situation, experts are able to determine (the difference in) the running time based on a rule of thumb. For example, scheduling an additional stop on the open track will take approximately 3 minutes. The estimated running time of the train with an additional stop will be the old running time with 3 minutes.

Quick calculation

It is also possible to calculate the difference using physics. In a simplified form it becomes possible to estimate the difference in running time with more certainty than using the rule of thumb. But still, it is an approximation because the simplified equations do not reflect the real world and the input is often also estimated. Equations 4.1 till 4.5 show an approximation of the time required for an additional stop.

$$\begin{aligned}
\Delta t &= t_{stop} - t_{non-stop} && (4.1)\\
&= (t_{decelerating} + t_{dwell} + t_{accelerating}) - \frac{x_{braking} + x_{accelerating}}{v_0} && (4.2)\\
&= \left(\frac{v}{a_{dcc}} + t_{dwell} + \frac{v}{a_{acc}}\right) - \frac{\frac{1}{2}\cdot a_{dcc}\cdot(\frac{v}{a_{dcc}})^2 + \frac{1}{2}\cdot a_{acc}\cdot(\frac{v}{a_{acc}})^2}{v} && (4.3)
\end{aligned}$$

$$v = 36 \text{ m/s} \approx 130 \text{ km/h};\ a_{dcc} = 0.5 \text{ m/s}^2;\ t_{dwell} = 60 \text{ sec};\ a_{acc} = 0.4 \text{ m/s}^2$$

$$\begin{aligned}
\Delta t &= \left(\frac{36}{0.5} + 60 + \frac{36}{0.4}\right) - \frac{\frac{1}{2}\cdot 0.5\cdot(\frac{36}{0.5})^2 + \frac{1}{2}\cdot 0.4\cdot(\frac{36}{0.4})^2}{36} && (4.4)\\
&= 222 - 81 = 141 \text{ sec} && (4.5)
\end{aligned}$$

In equation 4.4 estimations are used, but for the trains in the Netherlands the acceleration curves determined. The same applies for the parameters that influence the deceleration of the train. Combining the two in a "simple" application provides the opportunity to estimate the required time more certainty (see equation 4.6).

$$\begin{aligned}
\Delta t &= t_{stop} - t_{non-stop} && (4.6)\\
&= (t_{decelerating} + t_{dwell} + t_{accelerating}) - \frac{x_{braking} + x_{accelerating}}{v_0} && (4.7)\\
&= (59.2 + 60 + 172.9) - \frac{1078 + 4121}{36.1} = 148.1 \text{ sec} && (4.8)
\end{aligned}$$

Simulation

The above methods are possible when a rule of thumb is available or when the problem is sufficiently small to calculate the outcome by hand. When the running times for an entire line section or corridor need to be calculated that data is often not yet available.

When the question becomes to large, a simulation is probably a better solution than calculations by hand. Often, simulation models have more parameters so the estimations tend to be more accurate and when the layout of the infrastructure changes it is quicker with recalculating all the values.

4.1.5 Concluding remark about infrastructure and time relations

In railway timetabling the infrastructure is always transformed to a matrix of conflicts and the time required between two conflicting routes. Therefore each track layout has other values in the follow-up-times matrix. Differences between layouts can be evaluated by comparing the values in the follow-up-times matrix.

4.2 Process of timetabling (tactical phase)

The development of a new timetable takes about one year. ProRail allocates the available railway capacity amongst all parties as honest, efficient and effective as possible. In order to operationalize this they developed a process with a number of feedback loops with the train operating companies. This process of developing a timetable consists of seven steps (ProRail, 2014a):

1. Developing a Basic Hour Pattern (BHP)
2. Receiving requests for capacity demand from TOCs
3. Resolve possible conflicts
4. Create draft capacity allocation
5. Receive responses towards the draft
6. Create final capacity allocation
7. Start operating the timetable

In explanation to the list, at the first step of the process the IM defines, in cooperation with the TOCs, the Basic Hour Pattern (BHP). This BHP contains for every line section how many trains can be operated and in which frequency.

In the second step, the TOCs use the BHP to request the capacity needed for their operations.

After the request, the IM combines all the requests. If a conflict occurs, the IM tries to resolve all conflicts. Most of the times these conflicts can be solved by applying minor changes to the BHP. When that is not an option, the concerned TOCs are asked to change there request. If also that is not an option, then a special commission will be asked to resolve the matter.

Next a draft version of the capacity allocation will be published. TOCs can review that draft, and respond to the IM. After that the final draft will be published. A few months later the new timetable will be in operation.

The time between the publication of the final capacity allocation and the operation is needed for the TOCs to create the rolling stock and crew schedules. After the finalizing the annual timetable changes towards that timetable are only possible when it does not interfere with the other train paths.

4.2.1 Congested infrastructure

During the development of the annual timetable capacity bottlenecks can emerge for the year following or for future years. These bottlenecks do not have to be related to train following, but can also caused by noise limitations, rail safety or external safety.

Whenever a capacity bottleneck is spotted, ProRail will declared that section of the network congested (ProRail, 2014d). In the six months following the declaration a capacity analysis has to be performed. This analysis is used to find the cause for the congestion and defining the problem. After that, ProRail has another six months to come up with a capacity enhancement plan, which is created in consultation with the operators involved.

The outcome of the capacity enhancement plan can be both infrastructure related as well as timetable related.

4.2.2 Stakeholders in timetabling process

In the Netherlands there are three types of stakeholders in operation of the railway network. Transport authorities (TA) assign transport operating companies (TOC) to operate railway lines. The infrastructure managers (IM) are responsible for the infrastructure of the railway network and allocating capacity.

ProRail is the largest IM of the Netherlands. Their responsibility is to construct, maintain, manage, ensuring safety and allocating capacity for the main railway network (ProRail, 2014e). The other infrastructure managers, Infraspeed, is responsible for the HSL South.

The Ministry of Infrastructure and the Environment (I&M) is the concessionaire for the main railway network. They assign the TOC to operate the main lines for the next period. In the entire past and at least till 2025 the Dutch Railways (NS) is the train operating company. For the regional lines, the transport authorities can be provinces or governance of metropolitan areas.

Dutch Railways (NS) is the main train operating company in the Netherlands. In general, the regional lines are operated by other operators then the NS, those operators are Arriva, Connexxion, Syntus and Veolia. Deutsche Bahn and NS International are operating cross border connections. Further more there are about 20 operators for moving freight by rail.

Table 4.2: Relevant parties involved

Level	**Transport authority**	**Infrastructure manager**	**Train operating company**
International lines	I&M	ProRail, Infraspeed	Deutsche Bahn and NS International
National lines	I&M	ProRail	NS
Regional or decentralised lines	Provinces, metropolitan areas	ProRail	Arriva, Connexxion, Syntus and Veolia

4.3 ProRail "core-process" (strategic phase)

ProRail, as the Dutch infrastructure manager, has a lot of infrastructure renewal and upgrade projects every year. To smoothen and structure the process of these projects, ProRail has created and adopted the ProRail core-process. It is a walk-through of all the steps to take and products to deliver to reach the best design or solution. It is an internal document, but suppliers are aware of the core-process which enables them to really be customer-focused.

The ProRail core process knows four stages for a project:

1. Preliminary stage
2. Alternatives study stage
3. Plan execution stage
4. Construction stage

The "preliminary stage" aims at determining the customer requirements and the internal project start-up at ProRail. During the "alternatives study stage" research starts into possible solutions for the problem to solve. After approving the set of alternatives, further research is conducted into the alternatives to reach the approval of one preferred solution. During the "plan execution stage" even more research is conducted into the preferred solution and minor adjustments to that. Eventually a detailed preferred solution is approved and the design of the preferred solution is passed on to the "construction stage".

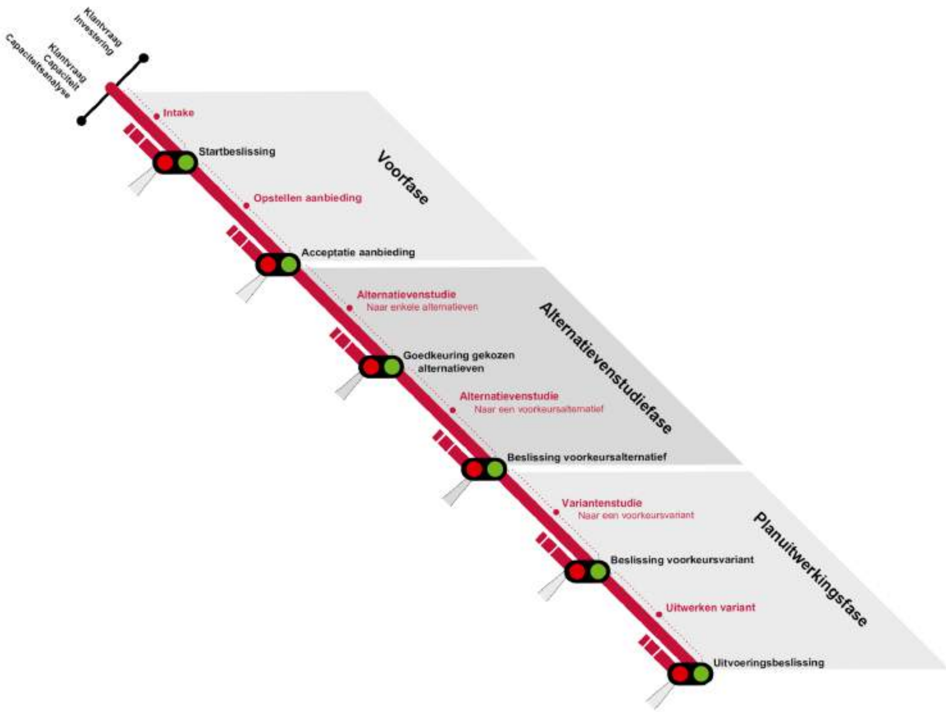


Figure 4.5: ProRail core-process (partly)

Also the core-process describes the decision points (go/no-go) inside a project. At the end of each stage a decision moment is scheduled, but also inside each stage is an interim decision point. During the "alternatives study stage" a set of alternatives is approved at the interim decision point. The set of alternatives is the starting point compare different directions towards a solution. At the end of this stage an alternative is chosen. This preferred alternative is designed at a higher level of detail during the "plan execution stage".

The decision makers of the go/no-go milestones vary from project to project. The variation has a lot to do with responsibilities and finance. For example, a modification of the infrastructure that is requested by a province to improve accessibility, allows for an increase of train frequency. The Ministry of Infrastructure and the Environment related to the project because of national interests, but the province has to finance the costs of improvements. Also the size of a project plays an important part in the position of the decision maker inside his/her organisation.

4.4 Complexities of timetabling during the strategic phase

Timetabling is a complex process. This sections contains the elements mentioned by the interviewees regarding the complexity of timetabling from their perspective.

Taking decisions in infrastructure projects are often conducted by the programme manager at the infrastructure manager or the higher management (e.g. project controller at I&M). This creates a vacuum in knowledge between the specialists who designed the infrastructure and associated timetables and the decision maker. The higher the person in charge corresponds (without the exceptions) with fewer knowledge about timetabling. This means that output shown by the model should be sufficiently clear that it is understandable with only little or no additional explanation.

In large projects like the high-frequency railway programme (PHS) it is not sufficient to look at corridors. The impact of such projects has an influence on the whole railway network. That is why in that kind of projects the timetable for the whole network is recalculated. The process of creating an entire new timetable currently requires almost a year. This time is needed to identify all needs of the railway users, define the variables and solve potential conflicts. It happens that after the calculation of the timetable the scope is moving due to minor changes in the requirements specification. New requirements or setbacks in the construction have their influence on the timetable. Time and power to recalculate the entire timetable is not available. Indicating the potential differences between the baseline scenario and the proposed modifications should already be very helpful in de process of deciding on the modification.

General focus on the points to improve is critical. One of train operating companies describes that during the timetabling process conflicts occur regularly. They think that is because of a difference in focus. While the operating companies mainly focus on frequency of connections, according to them, ProRail is having a focus on reducing the running time. The last does not necessarily help pursuing the first. Another problem described is the difference between the strategic phase and the tactical phase of timetabling. In construction projects ProRail is focussing on the technical minimal headway times, while the department responsible for timetabling primarily focusses on default headway times (see: ProRail, 2014d). This is also why it is possible that the current timetable is operated without major problems, while according to the norms it should not be possible.

NS knows two phases of disturbances. In the first phase of a disturbance train traffic is adjusted within the boundaries of the basic-hour pattern. When the disturbance continues for a longer period or the disturbance expounds, the second phase is started. The second phase is known as the "adjustment scenario" (Dutch: *bijsturingsscenario*), for many types of disturbances a adjustment scenario is created. During the second phase the basic-hour pattern is released. To check whether it is possible to operate the timetable during the first phase of a large disturbance, now their simulating the timetable of a whole week. If it is possible to operate that timetable, it is assumed that the movements necessary for the first phase of a disturbance are also possible. Another issue is the transition between the first phase of disturbance and the phase of an adjustment scenario. Both the robustness of the timetable and the robustness of the adjustment scenario are tested, but the transition between those two scenarios is not tested.

Planning rules are stated to ensure that there is sufficient time scheduled between two train movements. But the feasibility of the timetable with a certain infrastructure design is checked using expert judging. If possible this judgement is annexed by a reliability analysis based on the numbers provided by similar or related corridors.

4.5 Indicators

During the interviews a prototype of the output is shown to the interviewees. The question asked: “What do you like, what not and what would you like to see additionally?” This section covers the indicators.

The occupancy time rate indicator shows in a single percentage the relation between the time needed to operate a sequence of trains using the technical minimal interval times and the time scheduled operate that sequence. The occupancy time rate (OTR) is covered in section 3.4.4. The interviewees liked the idea behind the OTR, but they had difficulties placing the value of the indicator into context. They want to know which value represents the maximum occupancy and the effect a lower or higher value of the OTR has on the feasibility of the timetable. The UIC proposed table of values, based on simulation studies, which could represent the maximum values. But it is a proposition and therefore it can not directly used as a norm. The interviewees indicate that some kind of reference (i.e. baseline scenario or other alternatives) is needed for the indicator to be of use.

The first indicator is the capacity balance, as described in literature section 3.4.1. The capacity balance shows in one diagram the number of trains, heterogeneity, stability and the average speed. Because of the conceptual nature of the indicator, the interviewees were presented with diagram based on fictional data. The responses to this indicator were positive, many of the interviewees quickly understand the nature of the diagram and the information presented. Again, this indicator needs a reference to be able to interpret the results. But when comparing alternatives this indicator give a fast overview of the differences.

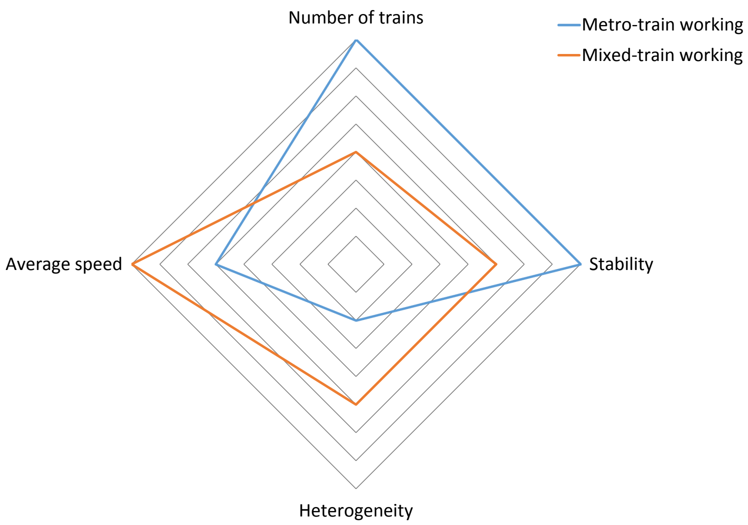


Figure 4.6: Capacity Balance (UIC, 2004a)

All interviewees indicated that they want to know more about the robustness or stability of the timetable. At NS they indicated that the use the program Simone for that kind of studies. Robustness is a wide subject and no uniform approach in the Netherlands to address this subject. But according to the interviewees the model can be of great benefit if it would find a way to indicate the feasibility, stability or robustness of the timetable or infrastructure.

One of the interviewees indicated that discussions in projects often are about the question “is it possible to operate train X, Y and Z within a certain time frame?”. Also at ARCADIS they indicated that it is a question often asked by the client. With the proposal the interviewee also indicated that it would probably hard to presented the information in a indicator, because multiple sequences will be asked.

4.6 Additional requirements for the support system

During the interviews an example is given, based on the literature study, which indicators could be calculated and what the possible outcome would be. Answers on the question which indicators or outcome the interviewees would like to see in DSS application like this were not identical. The technique of evaluating timetables and infrastructure using multiple methods is rather new, hence the scientific gap, which results in not tightly formulated specifications.

In early stages of a project often there is no detailed timetable available. Many of the available simulation models test the feasibility by looking at scheduled departure times. It would be a large benefit if a method would be available to look at the feasibility without knowing the scheduled departure times. This way the focus shifts from feasibility of the timetable to the feasibility of a number of successive trains.

Both NS and ProRail would like to gain insight in the operational feasibility. So not only testing the primary timetable but also the secondary processes like shunting. E.g. is it possible to "aftrappen" and "bijplaatsen" between the rush hours? But also the possibilities to use other available infrastructure when the primary route fails. Adding these processes to the analysis would definitely tell something about the robustness of the timetable.

Not all lines in the Dutch railway network are at their maximum capacity. At lines outside the Randstad and at the regional lines the occupancy rate is most likely to be lower than on lines with the Randstad. For the concessionaires of the regional lines it would be very useful to get an indication of the amount of capacity left at the corridors to fill up with extra trains. This requires not only to calculate the occupancy rate, but also test if it is possible use the remaining part.

4.7 Concluding remarks

No general consensus can be found amongst the interviewees in the indicators to use. But the following list of indicators are the indicators that mentioned most often based on the information presented.

- Occupation time rate
- Capacity balance
- A robustness indicator
- Feasibility of operating the timetable
- Comparison with baseline

Regarding the requirements a number of situations are described which the interviewees would like to see in the DSS covered. In general these can be summarised as the operational feasibility, the flexibility, and the location and impact of conflicts. Though not specified as such, but the DSS should be able to incorporate multiple scenarios and comparison with a baseline scenario. Not only differences in the timetable, but also differences in the infrastructure (i.e. other follow-up-matrix), disturbances and the effect of adjusted trains (i.e. combination of different timetable and follow-up-matrix). Based on the above information the indicators should also indicate direction to the possible conflicts and the impact of the conflicts.

Chapter 5

Model

This chapter covers the model proposed in this research as a blueprint for creating a decision support system for selecting promising alternatives in railway infrastructure and timetabling. First a short recapitulation is given and explanation of some of the design choices. Then the model is being described in more detail. This chapter ends with some limitations of the model.

5.1 Recap and design choices

This section contains a recapitulation of the information already provide in the previous chapters, together with the design choices for this model.

5.1.1 Location of model in the process in railway infrastructure projects

This research aims at reducing the time required in the stage of alternative selection of railway infrastructure projects. Figure 5.1 visualizes the location of this model. A project at the Dutch infrastructure manager ProRail knows four stages (for a more detailed description see section 4.3).

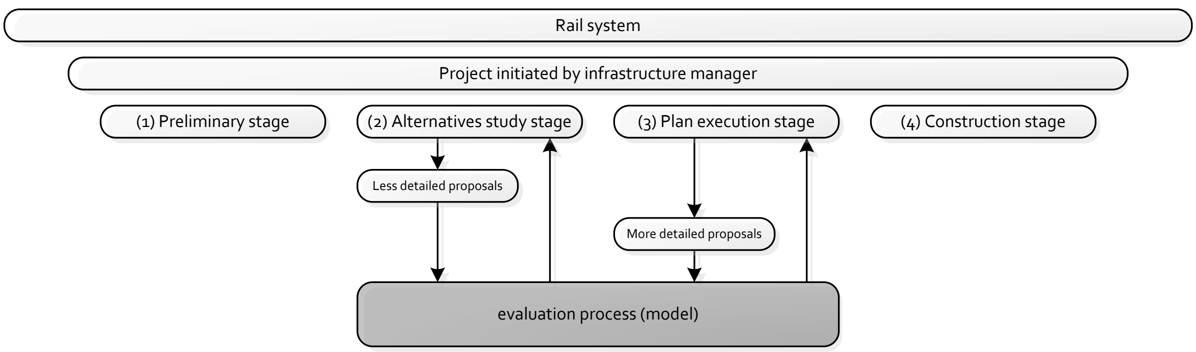


Figure 5.1: Location of model in process

The aim of the "alternatives study stage" is to come up with a set of feasible alternatives. Modifications are generated and they need to be tested for feasibility. This model enables a quick insight in that feasibility. The model output is presented as feedback to the project work-group. Multiple iterations are possible before all alternatives are modelled and the set of alternatives is approved. During the "plan execution stage" more in-depth research is conducted into the alternatives. The changes made in this stage are again modelled, the same process can be used for that.

5.1.2 Required output

From literature:

- Systematic timetable index
- Capacity consumption of railway line sections
- Degree of deviation from planning rules
- Proportion of travel time prolongation for a travel relation

From interviews:

- Occupation time rate
- Capacity balance
- A robustness indicator
- Feasibility of operating the timetable
- Comparison with baseline

5.1.3 Suggested controls

Controls set parameters to certain values so the user can see the effect of changing the parameters. During the interviews these controls were not discussed, but based on the stories and impressions the following list with controls is suggested. Later in this chapter more about the controls.

- Scenario selection
- Level of aggregation output (1h, 2h, 24h)
- Running time margin

5.1.4 Design choices

The capacity balance is one of the indicators that should be implemented. When searching methods for calculating the sub-indicators it was found that the average speed is difficult to calculate. This because the average speed is not about the absolute average speed, but about the average speed compared with other line planning alternatives. Because the line planning has a large influence on the heterogeneity, and because the (difference in) average speed is also incorporated in the heterogeneity, this indicator is removed from the capacity balance in this research.

Both during the literature review and the interviews, no easy applicable method was found for calculating the robustness of the timetable with the data available. Based on that conclusion a new indicator is developed which is based on a sensitivity analysis approach.

Both, the systematic timetable index and the proportioin of travel time prolongation for a travel relation are not added to the model. During the interviews, no reason was found to add those indicators into the model.

For the capacity consumption, the choice is made to re-use algorithm of the occupation time rate using the schedule norm times. This because these are the default values used by timetable schedulers during the tactical planning horizon, so it gives the best insight in used capacity under current regulations.

5.2 Model process

This model is based on a certain process. Somewhere during the study phase of a project, alternatives are created for the infrastructure and ideas about the timetable to operate. These proposals are not yet perfect. They are analysed during the “pre-calculation” step, where the proposals are transformed from drawings and sketches into a follow-up-matrix (as described in section 4.1) and additional explanatory variables. The model transforms these data into indicators and tables. The indicators and tables can be modified by the end-user with a number of controls, like selecting scenarios, level of aggregation and amount of margin. With the output the end-user gets more understanding of the problem and the solution space, which acts as feedback to create new proposals.

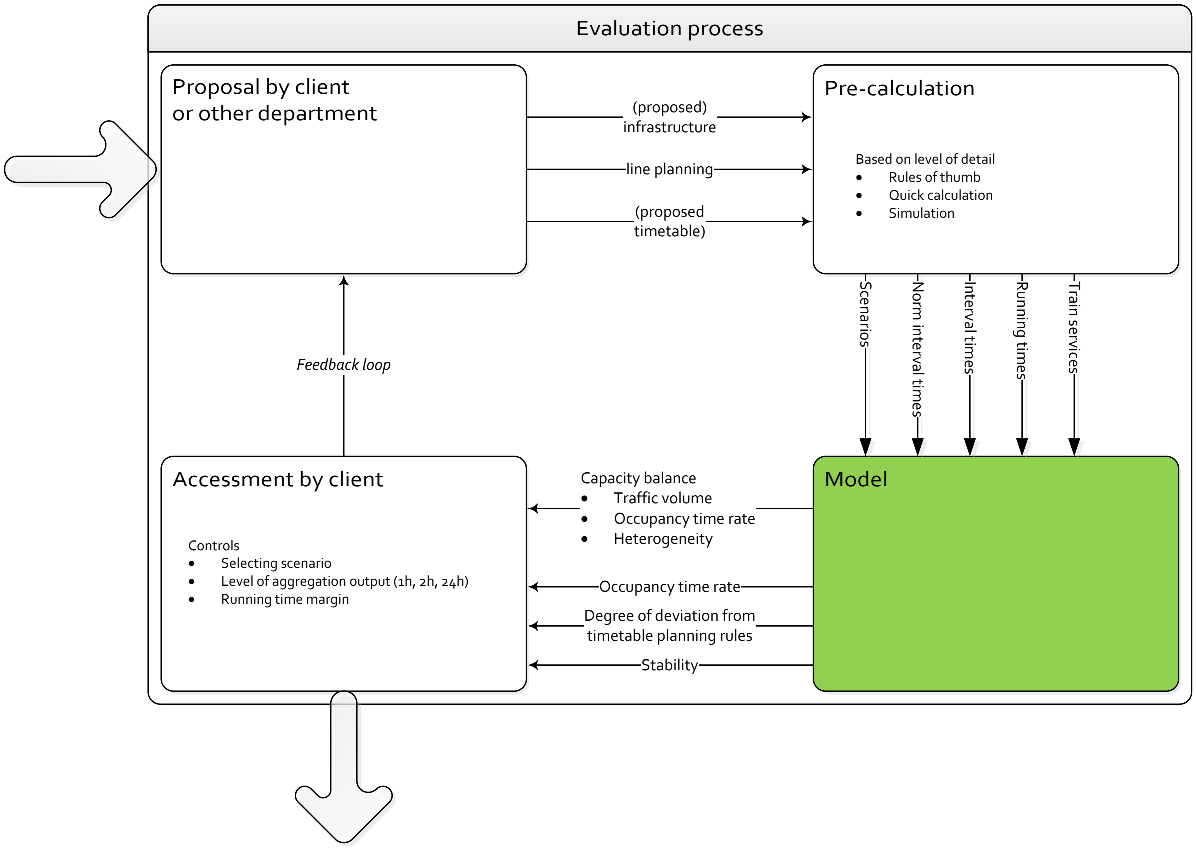


Figure 5.2: The model

5.3 Model elaborated

5.3.1 Data

Three sets of information are needed to apply the model. First, a detailed model of the infrastructure design. Secondly, information is needed about the line planning and the train configurations that are going to be operated at the line section. Lastly, a train order is need with (optional) a set of departure times.

Infrastructure

The detailed infrastructure model consists of a number of elements, as enumerated by Radtke (2008) and covered in section 3.3.2 of this report. The data is for the model can be generated by combining a number of prefabricated products. Next an overview is given of the products and the variables that can be extracted, the detailed description of the process between the products to the model is outside the scope of this research.

- OBE-bladen
  - Length of a link
  - Permissible speed
  - Speed indicators and speed boards
  - Release contact and clearance location
  - Track circuits
  - Electrification
  - Overlaps
  - Stop boards
  - Exclusion of routes (dependant links for simulation)
- OS-bladen
  - Signalling system
  - Blocks and routes
- Civil design drawings
  - Civil design
  - Gradient
  - Radius
- Other (but known)
  - Interlocking technique

Line planning and train configurations

The line planning describes which train services are operated at the line section. Additionally it also describes which train types are used to operate the services. The characteristics of the trains in operation at the line section are needed as input for the simulation. Figure 5.3 shows in an organized manner the line planning of our case corridor.

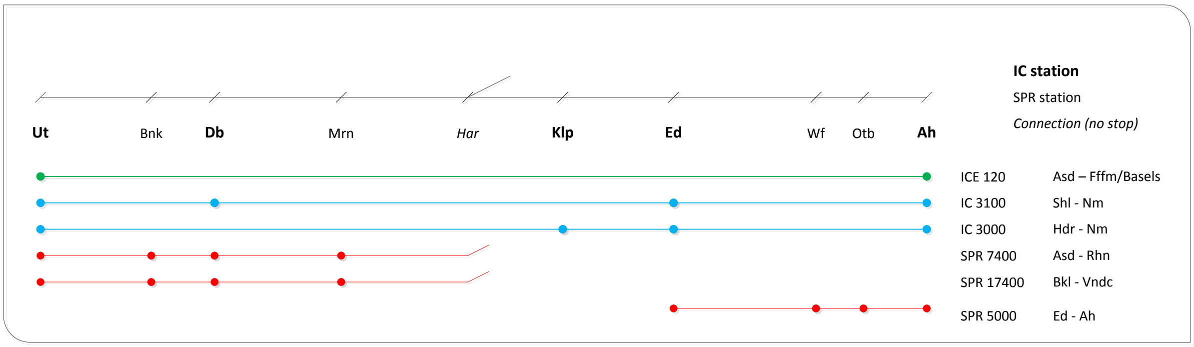


Figure 5.3: An example of a line planning

With characteristics of the train types is meant the acceleration curve and the deceleration curve. This curves are used to determine the speed profile of the train services. For most of the train configurations in operation in the Netherlands this information is already available.

Timetable

Although a complete timetable (with departure times) is not required for the model to work, the order of trains is needed to perform the assessment. With train order is meant the sequence in which the trains are operated. If the departure times are known, then a more detailed assessment of the feasibility of the timetable can be calculated.

Multiple train sequences or even complete timetables will lead to multiple scenarios in the support system.

5.3.2 Pre-calculation

The pre-calculation stage of the process model is created to modify the data relevant of the analysis into input variables for the application. The following steps will have to be taken to calculate the right input variables.

1. **Create infrastructure model**
   The design of the current infrastructure or the proposed infrastructure has to be transferred into a simulation model. In order to produce the right information, the measuring points of the running time and interval times have to be determined also beforehand.
2. **Determine conflicts**
   The next step is to determine the conflicts between trains services. As discussed in section 4.1 the follow-up-times have to be determined between all train services that cannot run in parallel, because they share some section of the infrastructure.
3. **Run simulation model for each of the train series / configurations**
   For each train service and every train set configuration, the running time needs to be simulated. Next to that the time between the train services with conflicts need to be determined.
4. **Determine scenarios**
   Based on the information provided by the customer, or on the basis of experts judgement, scenarios have to be created to provide an answer to the customers questions. Often this is the timetable the customer would like to operate, but also alternatives.

5.3.3 Input model

Train services (see table 5.1)

Each train service is a distinct entity in the model. Each train service that is operated with multiple train configurations needs to be split into multiple entities, because a change in train configuration has influence at the running time and clearing block sections.

The model expects the information as presented in table 5.1.

Nominal running times and dwell times (see tables 5.2 & 5.3)

The model expects the nominal running time between measuring points for each of the train service entities in order to calculate the heterogeneity. Heterogeneity can only be calculated between to measuring points at which the running time of all passing trains is given.

Table 5.1: Input: train services

trainID	Service number	Service type	Origin	Destination	Entering system	Leaving system	Configuration
1	3101	IC	Shl	Nm	Ut	Ah	VIRM 4+6
2	3001	IC	Hdr	Nm	Ut	Ah	VIRM 4+6
3	7401	SPR	Asd	Rhn	Ut	Har	SLT 4+4
4	17401	SPR	Bkl	Vndc	Ut	Har	SGM 3+3
5	7501	SPR	Ed	Ah	Ed	Ah	SGM 2
6	7001	ICE	Asd	Fffm	Ut	Ah	ICE-3M
...	...	...	...	...	...	...	...

Measuring points are defined logically along the route. Every station is a measuring point and every intersection where trains enter or exit the system need to be marked as a measuring point.

In the input a distinction created between the nominal running time between measuring points and the dwell time at stops. This to keep the flexibility of adding additional margins to the running time or for example to measure the effect of reduced dwell time.

Table 5.2: Input: nominal running time (minutes)

trainID	Ut	Bnk	Db	Mrn	Har	Klp	Ed	Wf	Otb	Ah
1	0,00		7,70		8,40		6,13			9,88
2	0,00				13,77	3,10	5,12			9,88
3	0,00	5,02	3,37	4,48	4,85					
...	...	...	...	...	...	...	...	...	...	...
7	8,72		14,85				9,03			0,00
8	18,03					5,37	9,03			0,00
9	6,00	3,05	4,78	5,12						
...	...	...	...	...	...	...	...	...	...	...

Table 5.3: Input: dwell times (minutes)

trainID	Ut	Bnk	db	mrn	har	klp	ed	wf	otb	ah
1	1,00		1,00				1,00			1,00
2	1,00					1,00	1,00			1,00
3	0,70	0,70	0,70	0,70						
...	...	...	...	...	...	...	...	...	...	...
7	1,00		1,00				1,00			1,00
8	1,00					1,00	1,00			1,00
9	0,70	0,70	0,70	0,70						
...	...	...	...	...	...	...	...	...	...	...

Follow-up-times matrix (see tables 5.4 & 5.5)

The follow-up-times matrix represents the minimal time between the departure of one train and the departure of the next train. The times are often calculated at the first departure station or the entrance point of the system. For more information see section 4.1. An empty cell indicates that the two trains can be operated independently of each other.

The follow-up-times matrix can be generated for the technical minimal follow-up time between two trains or for the follow-up time between two trains according to the scheduling norms of the infrastructure manager.

Table 5.4: Input: technical minimal follow-up-times matrix (minutes)

TrainID	**1**	**2**	**3**	**4**	**5**	**6**	**...**
1			2,89	2,96	28,5		...
2	6,16		2,59	2,59	28,3	10,9	...
3		8,19	4,2				...
4	5,69					9,66	...
5		-18					...
6	1,77						...
...	...	...	...	...	...	...	...

Table 5.5: Input: Planning norm follow-up-times matrix (minutes)

TrainID	**1**	**2**	**3**	**4**	**5**	**6**	**...**
1			4	4	30		...
2	7		4	4	29	12	...
3		9	5				...
4	7					11	...
5		-17					...
6	3						...
...	...	...	...	...	...	...	...

Scenarios (see table 5.6)

The variable scenarios contains multiple scenarios, whereas a scenario consists of two elements: the train order and the departure times. The train order is always necessary, as it determines which train services are scheduled following each other. The departure times are used to test the operation feasibility and robustness.

The order of trains can be differently ordered than chronology with the departure times. For example, a regional trains with an origin along the corridor (i.e. halfway the corridor), can limit an intercity train which will depart earlier from the measuring point. Then in the train order element this regional train is mentioned earlier, although is departures after the intercity.

The element departure times contains the proposed departure times for each of the trains in the train order element. The departure time will be defined at the point where a trains will start in the corridor, so its origin if that is within the corridor or else the point where the train enters the evaluated section.

Table 5.6: Input: scenario

orderID	**trainID**	**scheduled departure time**
1	11	37
2	7	44
3	5	66
4	8	61

5.3.4 Model calculations

Occupation time rate

The occupation rate is calculated following the methodology prescribed by the UIC (2013). Following the theory about timetable compression, the UIC 406 is designed to calculate the first point in time a train can be operated with regards to all preceding trains.

```
for all trainID in trainOrder do
  if first iteration then
    beginOccupation(1) ← 0.0
  else
    beginOccupation(iteration) ← MAX(possibleStartsOccupation(trainID))
  end if
  for all trainID in trainSeries do
    if not intervalTime(firstTrainID, secondTrainID) = empty then
      possibleStartsOccupation(iteration, trainID) ←
          beginOccupation(iteration) + intervalTime(firstTrainID, secondTrainID)
    else
      possibleStartsOccupation(iteration, trainID) ← empty
    end if
  end for
end for
return occupationRate ←MAX(beginOccupation)/evaluatedTimePeriod
```

Heterogeneity

$$Heterogeneity = 1 - \frac{\sum \left(min \left(\frac{h^D_{t,i}}{h^D_{t,i+1}}; \frac{h^D_{t,i+1}}{h^D_{t,i}} \right) \cdot min \left(\frac{h^A_{t,i}}{h^A_{t,i+1}}; \frac{h^A_{t,i+1}}{h^A_{t,i}} \right) \right)}{h_{N-1}} \tag{5.1}$$

With:
$h^D_{t,i}$ = headway time at the departure station
$h^A_{t,i}$ = headway time at the arriving station
h_{N-1} = number of headways minus 1

Sensitivity analysis / robustness

In the Netherlands, there is no standard for calculating the robustness or stability of railway infrastructure and its timetables. Also no straight forward method could be found in the literature to calculate the robustness. But, as every interviewee more or less indicated there is a need for some kind of indicator for the robustness.

The proposed methodology has elements of a sensitivity analysis. Every train in the timetable gets a random delay between zero and an increasing value (α), the distribution of randomness is uniform. This α starts at zero and every run (β) this α will become higher. With a run is meant, calculating the entire timetable once. If the delay of one train would cause the next train to run off schedule, this second train would still get an additional delay next to the delay transferred by the first train. The output is a ratio between the sum of delays given to the system and the sum of delays that comes out of the system. In essence this number shows the amount of delay that is transferred from preceding trains onto trains following.

This process is repeated a number of iterations at value α (default: 25 iterations). And till α reaches a maximum value (default: 500 seconds).

for $\alpha = 1$ to 500; stepsize = 10 **do**
  for $\beta = 1$ to 25 **do**
    for all *trainID* **in** *trainOrder* **do**
      - Input delay i = random between 0 and α
      - Determine earliest possible departure time for train i
      - Output delay i = transferred delay + input delay i
      - Determine earliest possible departure for conflicting trains
    end for

$$ratio(\alpha, \beta) = \frac{\sum_{i=1}^{\#trainOrder} output\ delay(i)}{\sum_{i=1}^{\#trainOrder} input\ delay(i)}$$

  end for

$$ratio(\alpha) = \frac{\sum_{\beta=1}^{25} ratio(\alpha, \beta)}{\beta}$$

end for

Output for this method is an array of averaged ratios at each of the values of α. This can then be plot in a graph with the α value on the x-axis and the corresponding ratio (for α) on the y-axis.

In section 6.4.1 a comparison has been made towards the changes in the sensitivity analyses when different timetable schemes are being used.

5.3.5 Controls

The model contains three controls which allow the end-user to change parameters and to see the effects of those parameters on the output: selecting scenario's, selecting the level of aggregation for the output and the running time margin.

Selecting scenario

When more than one timetable is entered into the model, the control "selecting scenario" should become available. This creates the opportunity for the user to select an alternative timetable or the evaluate another corridor section.

In theory when all conflicts (read: interval times) are entered correctly, it is possible to enter an unlimited number of timetables to (automatically) evaluate the timetables.

Aggregation levels

The indicators should be able to display their output at different aggregation levels. The control should switch between the output for a specific hour (1h), peak-hour (2h) or for the entire day

(24h).

Running time margin

As described in section 3.3.1 the nominal interval times need to be increased due to scheduling norms. Besides those norms, one of the controls of the support system is an additional margin, like those in the scheduling norms, to increase the margin between trains. By adjusting this control, the model should show the effects of adding additional margin to the occupation rate and to the stability of the timetable.

5.3.6 Output

This model has a number of indicators as output, these indicators are summed up in this section.

Occupancy time rate

The occupancy time rate presented as a percentage, calculated following the algorithm covered in section 5.3.4 of this chapter.

Capacity consumption

The capacity consumption is the occupation time rate determined by using the schedule norm follow-up-times matrix. Therefore the same algorithm can be used as the previous indicator, but with different input values.

Capacity balance

The capacity balance is a spider diagram containing the following elements: number of trains, heterogeneity and stability. For each of the elements the output value from the calculation will need to be matched with a scale from 0 to 10. The average speed is excluded as mentioned in section 5.1.4.

The number of trains is a measurement of the traffic volume. At the aggregation level of 1 hour, then it should display the number of trains in that hour. At higher aggregation levels the average number of trains is more sufficient. Depending on the size of the project the number should be converted to a value between 0 and 10 for displaying it in the capacity balance, where 10 is the maximum number of trains possible.

The heterogeneity is calculated using the algorithm covered in section 5.3.4. The output is a percentage. The value of that percentage times 10 equals a scale between 0 and 10.

For the stability, further research is needed to convert the sensitivity analysis into a number relating to the stability.

Sensitivity analysis

The sensitivity analysis as calculated using the algorithm described in section 5.3.4 should be presented as a chart. Displaying on the x-axis the amount of disturbance and on the y-axis the ratio between input delay and output delay. As the algorithm produces multiple runs, every run will be displayed in the chart. On top of all runs an additional line will be plotted with the average values.

Possibility to operate timetable

For each train in the timetable, the earliest possibility to operate is calculated. Based on the interval time using the follow-up-times matrix and the difference in departure time, it is possible to determine for each train if it can operate according to the departure time.

There are two ways to display this possibility to operate. First, by creating a table with the timetable, one column could be added displaying with true or false if it is possible to operate that train at that departure time.

Another way to display this indicator is to present the scenario in a timetable and display the proposed departure time and the earliest departure time according to the follow-up-times matrix.

Margin between trains with regard to departure times

Where the previous indicator shows the possibility to operate trains at there departure time, the margin-indicator shows the margin between the trains during operations. This margin can be presented separately for each train, or the separate values can be combined in a pie-chart displaying for the entire timetable the spread of the margin.

5.4 Limitations

This model only applies to line sections and corridors, it cannot offer a network wide solution.

ARCADIS is using the program Xandra to calculate the nominal running time. Xandra works with distinct time steps, which means that the level of detail for the output of Xandra will be in seconds. The follow-up-times matrix as the input for CATO will also rounded to seconds, as are the timetable related indicators.

Chapter 6

Application CATO and case study

To validate the model, the model is applicated in a tool. The application tool is used in a case study that has been conducted at the corridor Utrecht - Arnhem. This to compare the output with the requirements of the interviews, to see if the output is realistic, and if the application tool will support the decision making process.

This chapter is divided into two parts. The first part contains the design decisions for the application and a description of the application tool itself. The second part has a focus on the case study and some specific scenarios testing the application.

6.1 Application design decisions

The application tool developed during this research is called CATO. The next sections contain the design decisions made during the development of this tool.

6.1.1 Software

The model is implemented in an advanced spreadsheet program. This allows the experts to use, maintain and improve the model without the need to learn a specific programming language. Another pro of using a spreadsheet program is the availability of the software. No expensive licences are necessary and interoperability with other operating systems is often guaranteed.

6.1.2 Calculating the occupancy rate per hour

The UIC 406 (UIC, 2013) contains an appendix with an example of how to calculate the compression rate for a node. The example is created based on certain track layout and the interval times between the possible routes. Next a timetable is given which indicates the order of the trains.

In the elaboration of the calculationsẃork flow, the situation is created that the compressed starting point of the first train in the second hour is earlier than the last train of the first hour. This situation is possible because the route of first train has no conflict with the route of the last train.

Regarding this situation the work flow according to the UIC should be the following:

- *For the calculation of the compression value it is proposed to insert the first trip at the bottom of the calculation table again (last trip). Hence there is no "open end".*
- *If the repetition of the first trip is not excluded by the last trip of the defined time period, the second or even the third trip has to be added. Calculating the exclusion values however is not necessary any more.*

The first bullet repeats the problem that we do not want an open end and therefore we should grab the first train of the evaluated period. The second bullet suggests to look further if there is no conflict between the last train of the evaluated period and the first train. The problem with this method is that your are grabbing trains of a next period into the evaluating period, and therefore calculating a large occupation time rate than in real life.

The problem the UIC tries to solve is that the first train starts at $t = 0$, which the first train of the next period can start at $t < 0$. First, a problem with the method chosen by the UIC is that the occupancy time rate will change when selecting another train as the reference train. Second, we are looking for a method in which it is possible to calculate the occupancy time rate for all the hours in the schedule of one day.

This research suggests two possible solutions to get a realistic occupancy time rate in this situation. In the first solution, the first evaluated period (e.g. the first timetable hour of a day schedule) will not be calculated or it will be accepted that the first hour has the probability of being not-representative. Because this problem only occurs in the first evaluated period. The second solution moves the focus of the evaluation to the first train in which the compressed departure time is larger than the last train of the evaluated period, hence the same train as grabbed by the UIC. But instead of using comparing its departure time with the departure time of the first train (0,0), we will look at itself one evaluating period earlier.

The benefits of the proposed solutions are that the occupancy time rate will the same regardless of the picked reference train and that it is possible to evaluate more periods next to each other. In the application the first solution will be implemented.

6.1.3 Modular output

The model describes the output for the decision support system, but often in projects boundaries are given regarding the output. Also, certain indicators can be more useful in certain projects. Therefore all the output of the indicators is created in a way that the output sheet can be customized with modules.

6.2 Description of CATO

The next section contains a description of the required input, followed by the output sheet of the application and the indicators it is displaying.

6.2.1 Input

The input is created in the same way as described in the input section of the model (see 5.3.3). For the creation of the follow-up-times matrix pre-calculation is required using a simulation model. ARCADIS has its own simulation model called Xandra.

"ARCADIS employs the simulation model Xandra to evaluate existing and new solutions to diverse railway issues. The model describes the movements of train stock and processes connected

to it, for instance power consumption, stopping times and passing over of trains. It contains civil infrastructure (e.g. point switches and arcs), stock (mechanical and electrical characteristics), timetables (numbers of trains including combining and splitting them, frequencies, times, etcetera), power supply, safety and traffic management (prioritizing of trains). On the basis of these data the most efficient timetable, the optimal positions of signals and the power supplies, amongst other things, can be determined." (ARCADIS, 2001)

But calculations between the running times created by Xandra and the follow-up-times matrix required by CATO is a job for a specialist.

6.2.2 Output

Two sheets are created for the output of the application. Figure 6.1 shows one of those output sheets, designed for evaluating 24-hour timetables. The other sheet is design for the situation in which only the BHP is known (1h output sheet).

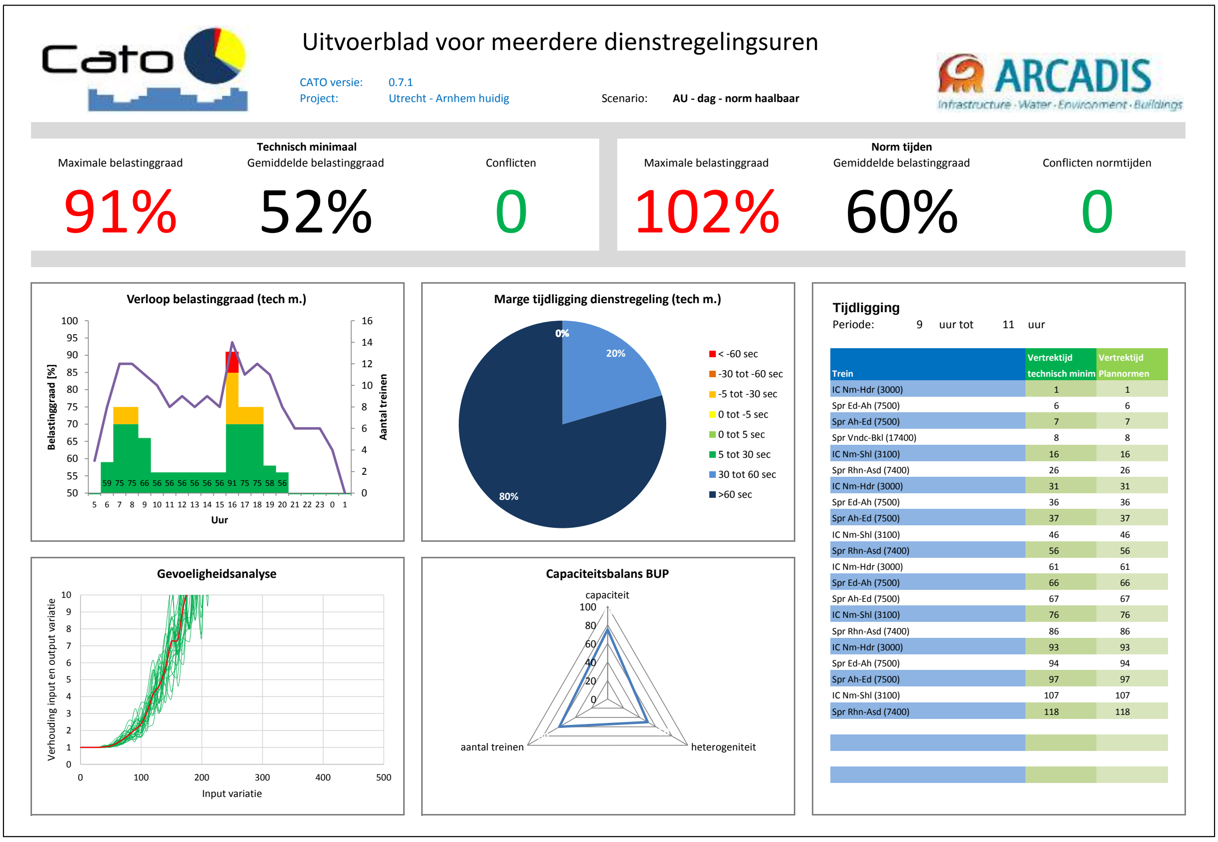


Figure 6.1: Example output sheet CATO for the Arnhem-Utrecht corridor

Occupancy time rate and practical capacity

In the output sheet, the left upper block with indicators shows from left to right the occupancy time rate for the busiest hour, next to that the occupancy time rate for the entire scenario and last number is showing the number of trains that is not able to depart at the proposed departure time.

The right upper block contains the same numbers as the left block, but instead of taking the follow-up-times matrix for the technical minimal times, the right block is calculated with the follow-up-times matrix for scheduling norms.

According to the model the occupancy time rate should be plain percentages. But to support the user of the application even more, the plain percentages change colour when they reach higher values. The ranges of the different colours are linked to the UIC 406 suggested values for peak-hour and whole-day time rates (UIC, 2004a).

In the middle section, the left chart shows (for a 24-hour timetable) the course of the occupancy time rate along the day. This chart also contains a line indicating the number of trains operated during the hours.

Margin between trains with regard to departure times

The centre chart shows in a circle the margin between trains, both positive as 'negative' margin. The size of the sector indicates the amount of trains within the whole are having that amount of margin.

In a sheet for specialists, it is possible to see for each train what its margin is towards the conflicting train and the id of the conflicting train. With that sheet is it possible to to fit or optimize the timetable. Besides optimizing the timetable it is possible to train combinations with the lowest margin. To create a more stable timetable it is also possible to create more margin between those trains by changes in the infrastructure.

Possibility to operate timetable

On the right-side of the output sheet a table is displayed with a part of the timetable. It is possible to change the visible timetable hours in the table by changing the parameters located above the table. The first column shows the train service. The second part shows the departure time. If it is not possible to operate a train service at the departure time according to the follow-up-times matrix, then behind the departure time, in red, the time shortage is displayed. The last part shows the same information but then related to the scheduling norms follow-up-times.

Capacity balance

The capacity balance spider chart is located in the bottom-centre of the output sheet. With the number of trains, heterogeneity and stability in the corners.

Sensitivity analysis

The bottom-left chart shows the individual sensitivity runs in green lines. For now the number of iterations is set to 25. The red line shows the average of the runs. Later in this chapter more about the sensitivity analysis and information it is providing (see section 6.4.1)

6.3 Case study Utrecht-Arnhem

To verify the capability of the model developed earlier and to test the application created to speed up the process, a case study has been conducted at the corridor Utrecht Arnhem. This also gives the opportunity to get a first validation of the model and application.

6.3.1 Input

The input for CATO is created using the designs of the current layout for the corridor Utrecht-Arnhem, provided by ProRail. The basic information about the timetable and the types of trains used at the corridor were gathered using the on-line customer timetable application of NS. In all, information as presented in table 6.1 is used during the simulation.

Table 6.1: Train services and equipment (origin and destination presented for the uneven train services)

Train services	**Origin**	**Destination**	**Equipment type**	**Length**	**Maximum speed**
IC 3100/3101	Shl	Nm	VIRM 4+6	271 m	160 km/h
IC 3000/3001	Hdr	Nm	VIRM 4+6	271 m	160 km/h
SPR 7400/7401	Asd	Rhn	SLT 4+4	139 m	160 km/h
SPR 17400/17401	Bkl	Vndc	SGM 3+3	157 m	120 km/h
SPR 7500/7501	Ed	Ah	SGM 2	52 m	120 km/h
ICE 120/121	Asd	Fffm / Basel	ICE 1x8	201 m	220 km/h

The infrastructure design is then modelled into Xandra. That combined with information on the timetable is used to calculate the nominal running times.

Creating a realistic 24-hour timetable

The peak-hour timetables (BHP) are available provided by ProRail, but peak-hour timetables are not realistic, because between peak-hours the frequency of trains is reduced. Therefore a realistic 24-hour timetable has to be created.

NS provided this research with the realisation data for a whole month. This data is also used to generate the 24h-timetable. The next work-flow has been followed to construct that 24h-timetable:

1. Remove all measurements that are not the entrance/starting point within the scope of the project. This gives us all the trains that have been on the corridor during that month.
2. Filter all the trains that are driven at weekdays. During the weekend often a different timetable is operated.
3. Determine all the possibilities, so a distinct list of the combination time and train number.
4. Next, for each of the distinct time and train number count the number of time that combination has been operated during the month.
5. Filter all trains that are operated more then 10 times that month.

The result of the above work-flow can be found in appendix E.3. The result is verified by comparing the 24h-timetable with the basic hour pattern for the rush hour (see appendix E.1).

Scenarios

Three scenarios are entered into the application:

1. Baseline (current timetable)
2. Conflict-free according to technical interval times
3. Conflict-free according to scheduling norm times

6.3.2 Outcomes of CATO

Occupancy for the baseline scenario

The occupancy time rate in figure 6.2 shows high maximum values and low averages. Figure 6.3 explains this low average by displaying the occupancy time rate for each individual hour.

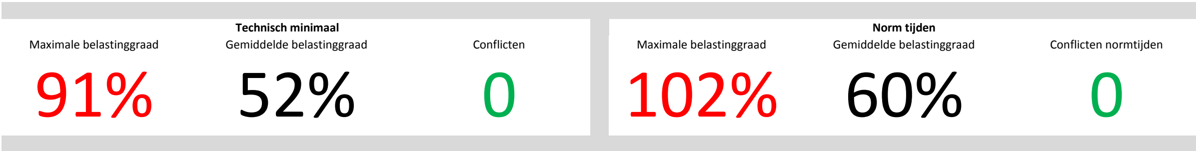


Figure 6.2: Occupation time rate and practical capacity

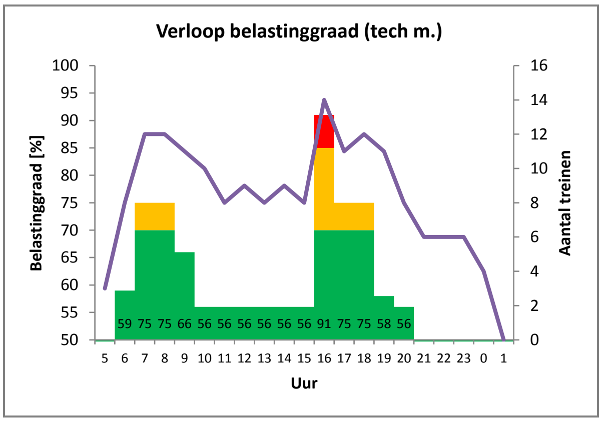
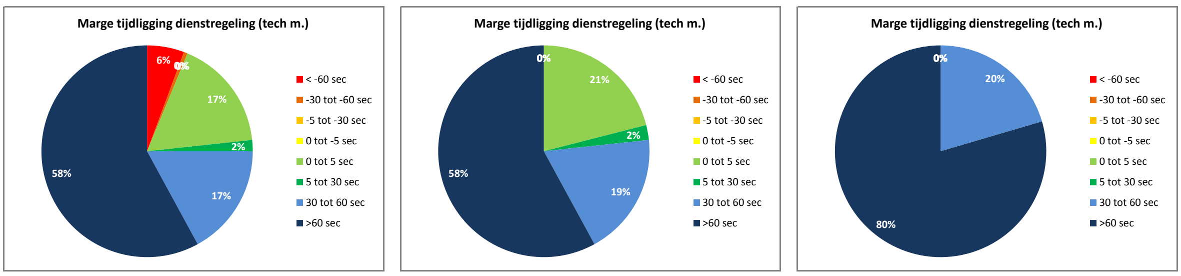


Figure 6.3: Occupation time rate along the day

Margin between trains with regard to departure times

The margin between trains is displayed for each of the scenarios individually in figure 6.4.

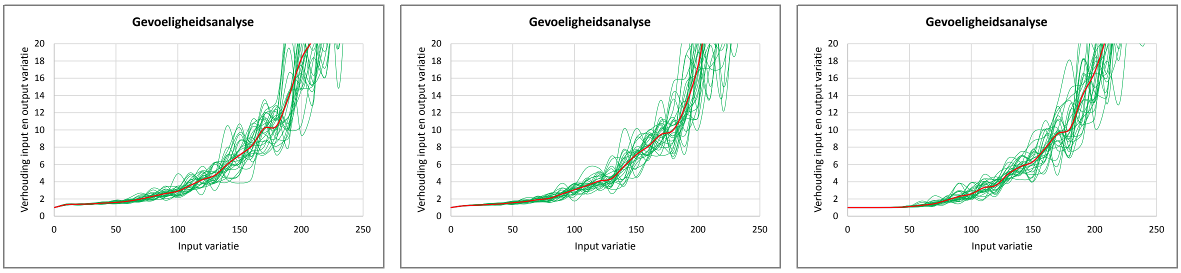


(a) *Scenario 1* (b) *Scenario 2* (c) *Scenario 3*

Figure 6.4: Results comparison factors in sensitivity analysis

Sensitivity analysis

The outcomes of the sensitivity analysis algorithm for the individual scenarios is located in figure 6.5. Although the differences are small, after reading section 6.4.1 they should become visible.



(a) Scenario 1 *(b) Scenario 2* *(c) Scenario 3*

Figure 6.5: Sensitivity analysis

6.4 Application case

Besides the general scenarios and additional set of scenarios is analysed.

6.4.1 Sensitivity analysis

Section 5.3.4 of the model description covers the sensitivity analysis indicator. This indicator is created to get insight into the robustness of a timetable. After implementing, a test case is designed to how the indicator performs in different scenarios.

At the corridor Utrecht - Arnhem a fictive sequence of trains is created which takes about 15 minutes to operate, scheduled in tight succession. This sequence is used to create three scenarios, in each scenario multiple hours of trains will operated and each hour contains two times the sequence. The scenarios differ in the distribution of the sequences along the hour. In scenario 1a, the first sequence starts at minute 0 and the second sequence starts at minute 20, leaving a gap of 20 minutes at the end of each hour. The second scenario (1b) contains one sequence starting at minute 0 and the other sequence starts at minute 30, leaving a gap of ten minutes after each sequence. In the last scenario (1c) the trains are not scheduled in tight succession, but the timetable is created in a way that the margin between successive trains is distributed equally.

Another set of scenarios is created in which the sequence contains not three but four trains. And again in the first scenario the two sequences start at minute 0 and 20 and in second scenario the sequences start at minute 0 and 30.

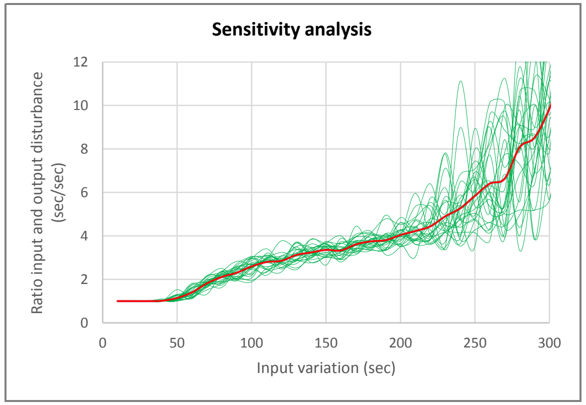
From left to right and from top to bottom the output for scenarios 1a till 2c is presented in figure 6.6 on page 59.

Table 6.2: Sensitivity analysis timetable scenarios with blocks of three trains

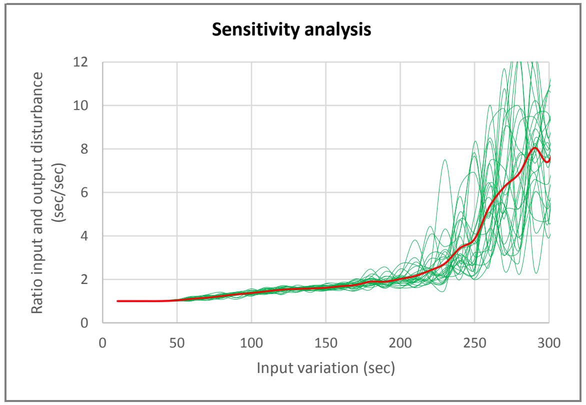
Omschrijving	Scenario 1a	Scenario 1b	Scenario 1c
IC Shl-Nm (3100)	0	0	0
Spr Asd-Rhn (7400)	4	4	7
IC Hdr-Nm (3000)	13	13	20
IC Shl-Nm (3100)	20	30	31
Spr Asd-Rhn (7400)	24	34	38
IC Hdr-Nm (3000)	33	43	50

Table 6.3: Sensitivity analysis timetable scenarios with blocks of four trains

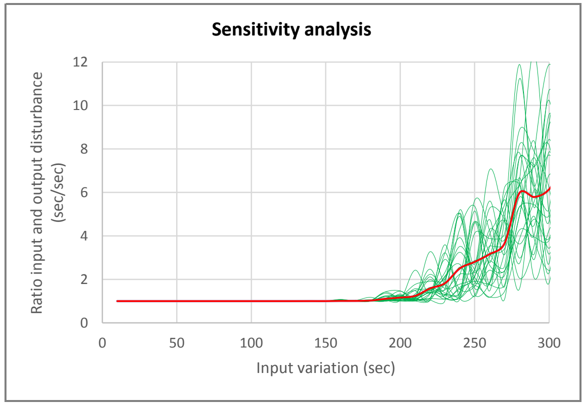
Train service	Scenario 2a	Scenario 2b	Scenario 2c
IC Shl-Nm (3100)	0	0	0
Spr Asd-Rhn (7400)	4	4	6
IC Hdr-Nm (3000)	13	13	18
Spr Bkl-Vndc (17400)	17	17	23
IC Shl-Nm (3100)	24	30	31
Spr Asd-Rhn (7400)	28	34	36
IC Hdr-Nm (3000)	37	43	47
Spr Bkl-Vndc (17400)	41	47	52



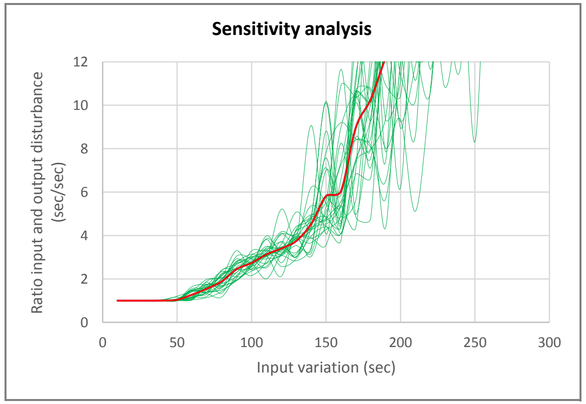
(a) Scenario 1a



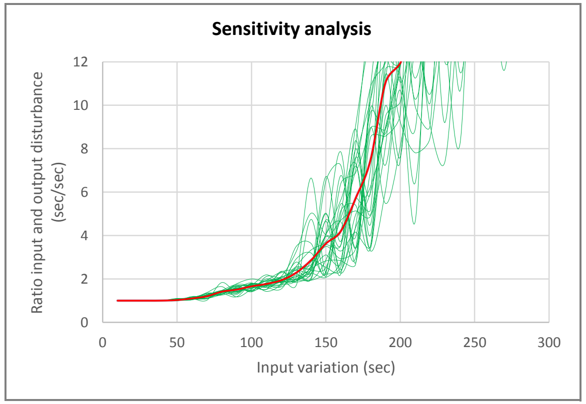
(b) Scenario 1b



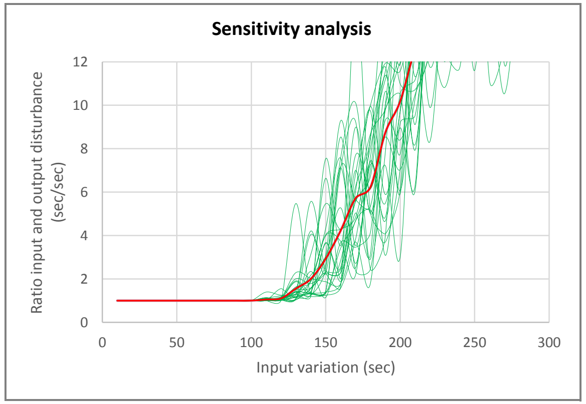
(c) Scenario 1c



(d) Scenario 2a



(e) Scenario 2b



(f) Scenario 2c

Figure 6.6: Results comparison factors in sensitivity analysis

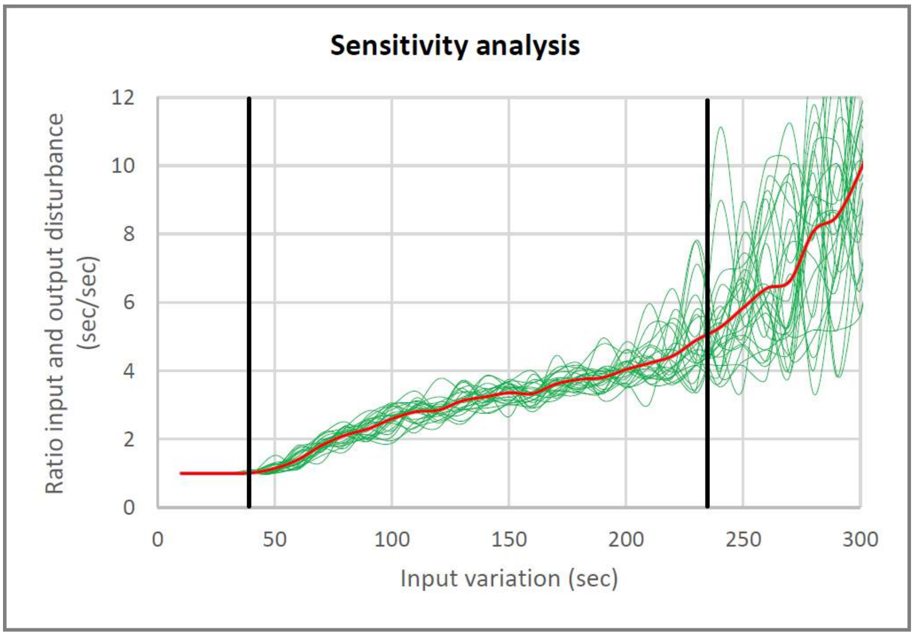


Figure 6.7: The three areas shown

Looking at the pictures generated by the model, a number of conclusions can be made, see Figure 6.7. The diagrams can be divided into three sections.

Section 1 No transfer of disturbances to subsequent trains, this is called the first phase of disturbances. The ratio between the input and output disturbance in section 1 equals 1.

Section 2 A part of the disturbance are transferred to successive trains, but there is no transfer of disturbance to next hour. The hour contains in itself sufficient margin to reduce the impact of the disturbance. The angle of inclination of the ratio depends on the number of trains in one sequence. This because more trains are effected by the disturbance.

Section 3 Catching up delays is not possible within the hour, so disturbances are transferred to the next hours and it has an impact on all other trains. This results in an unstable increase of transferred disturbance.

The distribution of margin between trains in the hour influences the second section. The location of the tipping point on the x-axis between section 2 and 3 will not shift. The value of tipping point on the y-axis will be higher. Distributing margin equally amongst all trains in the timetable will produce a more stable timetable.

An increase in the number of trains in the sequence has a high influence on section 2. The tipping point between section 2 and 3 will move to the left, and the height of the ratio will change.

The tipping point between sections 1 and 2 is determined by the train path pairs with the smallest headway. Therefore, the tipping point between section 1 and 2 is very arbitrary.

The important information in this indicators is the angle of section 2, the height of the tipping point between sections 2 and 3, and the x-value marking the tipping point between sections 2 and 3. Section 3 itself is not relevant, as the system then unstable.

Chapter 7

Conclusions

This research aimed at creating a (passive) decision support system that in early stages of a project enables a quick, clear, easy and flexible way of evaluating railway timetables given certain infrastructure. Currently two methods are available for evaluating this combination. One, using high-level running times and headway times. And secondly, in a complex form using dynamic simulations.

With the model proposed in this research it is possible to support decision makers during the strategic phase of timetabling with the design and evaluation of a timetable. Till now there was no method and no capable model available that could evaluate a timetable based on multiple indicators. The feasibility of timetables during the strategic phase was tested based on expert judgement, without a protocol. The model created during this research offers boundaries to evaluate timetables, as well as effects of changes in the infrastructure. This enables decision makers to select a timetable alternative in a structured way.

During this research a difference in focus has been detected between timetabling during infra-related projects (strategic planning horizon, >2 years ahead) and the creation of the actual timetable during the tactical planning horizon (<2 years). In projects the focus of follow-up-times is at the technical minimal headway times, while later in the process at tactical level the planning norm times are used as a default. This change of focus will result in failure of the timetables created during the project, when they are submitted a few years later for operation.

Current timetable analysis for infrastructure projects often do not include processes like the day-start of the timetable, shunting trains, transitions between peak-hour and off-peak timetables, etc. These secondary processes are hard to analyse in early stages of a project because of the lack of information. In the proposed model the process time of these manoeuvres only have to be calculated once, therefore, this model allows a very flexible way of testing the location for secondary operations in the timetable.

During the interviews it was found that there is no clear view in the criteria and indicators to use for developing and evaluating timetables. Both in literature and in practice it seems desirable to calculate both a robustness indicator as well as the occupation time rate.

The model proposed in this research, and the application created based on that model support the selection of potential alternatives using three primary checks: the occupation time rate, a sensitivity analysis and a check if the proposed timetable will fit. With regards to those three checks the following can be concluded:

- The methodology proposed in UIC 406 (2013) provides a guideline on how to calculate the occupation time rate and the methodology is accepted by the stakeholders. However the proposed maxima for 24h-timetables and peak-hour timetables are not accepted by everyone. In this research, the UIC 406 methodology is extended by determining the occupation time rate per hour and combining these values in a plot. The plot indicates the course of the indicator throughout the day.

- No easy to understand and implement method for calculating the robustness was found during the literature study and no clear method arose during the interviews. But almost every interviewee requested insight in the robustness of the timetable. In this research, a methodology is developed that determines the robustness of a timetable using a sensitivity analysis. In this sensitivity analysis every train is disturbed by a random value (between zero and α). A ratio will be calculated between the sum of all input disturbances and the sum of all output disturbances. For every value of α this process is done a number of iterations. The value of α will then be raised and the process repeated.
- With the list displaying the timetable, it is possible to check if the proposed timetable can be operated. Trains that are not able to operated are highlighted providing a method to optimize the timetable or give direction in the location for infrastructure design improvements. The number of conflicts is also shown in a separate indicator.

The application, developed based on the proposed model in this research, is applied on the corridor between Utrecht and Arnhem. It shows that the model is able to help evaluating the timetable based on a robustness indicator and the occupation time rate. It can simply and effectively show the occupation time rate and robustness of a timetable. And even without having specific departure times it is able to tell something about the sequence of trains that can be operated. By adding an additional set of follow-up-times, it even possible to tell the difference between two infrastructure design operating the same timetable. Although the note has to be added that calculating a new set of follow-up-times requires a new external simulation.

During the evaluation of the timetable, the application also detects conflicts between trains whenever a train is not able to be operated at its departure time due to a conflicting train. The relation between those two trains can be valuable information in changing the timetable or to provide direction for optimizations in the infrastructure.

7.1 Discussion

This research focussed specifically to the Dutch situation, because the railway sector is quite different organised in the countries around the Netherlands. Incorporating other countries would have resulted in the risk of becoming bogged down in the differences, with all the consequences for time required to conduct this research. Secondly, a part of this research is based on 9 interviews and a number of additional conversations. This is a rather small number, but is tried to cover all the expects by spreading the interviews amongst different stakeholders in the infrastructure and timetabling process.

The focus of this research is at the alternative selection stage of the ProRail "core-process", because following the decision making tree there are the strategic decisions to take. But during the interviews the position of metropolitan areas and the provinces was discussed. Although they are not part in the actual decision making process, the value their opinion tends to grow. In the last 10 years these parties have gained more knowledge about the train product, so they are more aware of the costs and benefits.First from a strategic point of view their position has become stronger, because I&M is looking more for regional support and acceptance.And secondly, their share of investing in railway projects is rising because they are willing to carry the additional costs to improve the rain product in their own region.

During research no uniform set of timetable evaluation criteria and indicators is found. By combining information from literature and taking interviews it is tried to create that set of indicators, despite that the interviews did not provide a clear answer. Schittenhelm (2013) was able in his research to get all the relevant parties for this problem at one table. This resulted in a discussion between the stakeholders which had to end with a uniform answer. The nature of this research obstructed this way of working and such a discussion (initiated by ProRail or I&M) could be of much added value for optimizing the suggested model.

In this research a sensitivity analysis is proposed as a way to provide insight in the stability or robustness of a timetable. Although the comparison between different timetable provides us with useful information on how to interpret that sensitivity analyses, that thus not provide a validation. The validation of this sensitivity analysis could be done using real information about the operational performance of a corridor. Using the same information, it can also be tested if this model is able to predict catching up delays.

The corridor at the case study (Utrecht-Arnhem) knows multiple train services and different service levels (sprinter, intercity, international). Unfortunately, freight trains are not scheduled to use this corridor. Adding freight trains to the scenario probably would have had a negative influence on the capacity of the corridor, as the homogeneity would decrease.

The DSS application is designed for calculation “on the fly”. This is possible because the selected methods do not rely on heavy calculation power and running time. But the main benefits of a DSS is the opportunity it offers to let the decision maker “play” with the design choices and the different scenarios. The software behind the presented application does not offer sufficient protection of the source code. Should ARCADIS want to distribute the results of the application to the client, then a solution for this problem has to be searched for this problem.

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Appendix A

Abbreviations

A.1 Used abbreviations in report

Abbreviation	Full
AC	Available Capacity
BHP	Basic Hour Pattern
DSS	Decision Support System
ERTMS	European Rail Traffic Management System
HSL	High-Speed Line
IM	Infrastructure Manager
IC	InterCity
ICE	InterCity Express
KPI	Key Performance Indicators
I&M	Ministry of Infrastructure and the Environment
NS	Nederlandse Spoorwegen (Dutch Railways)
OTR	Occupation time rate
PC	Practical capacity
SPR	Sprinter
TC	Theoretical capacity
TT	Timetable
TOC	Train Operating Company
TA	Transport authorities
UIC	Union Internationale des Chemins de fer (International Union of Railways)
UC	Used Capacity

A.2 Abbreviations of stations and measuring points

Source: OV in Nederland, 2015

Abbreviation	**Full name**
Ah	Arnhem
Amf	Amersfoort
Asd	Amsterdam CS
Bkl	Breukelen
Bnk	Bunnik
Db	Driebergen-Zeist
Ed	Ede-Wageningen
Es	Enschede
Esd	Enschede Drienerlo
Fffm	Frankfurt Hbf
Har	De Haar aansluiting
Hdr	Den Helder
Hgl	Hengelo
Klp	Veenendaal-De Klomp
Mrn	Maarn
Nm	Nijmegen
Otb	Oosterbeek
Rhn	Rhenen
Ut	Utrecht Centraal
Vndc	Veenendaal Centrum
Wf	Wolfheze

Appendix B

Interview topic list

- Introduction
  - Aim of this research
  - Content of interview
  - Background interviewee
- Complexities of timetabling during the strategic phase
  - How are the relationships between your organisation and other stakeholders?
  - What issues occur during infrastructure related projects?
  - Which information is needed to be able to make those decisions?
- Showing the enhanced prototype
  - Is the information presented clear and understandable (if necessary with little explanation)?
  - Which additional information is required (for you) to complete the model?
- Additional requirements
  - About which types of situations should the support system provide information?
  - What controls would you like to have?

Appendix C

Interview summaries

Table C.1: Explanation interviewee types

Abbreviation	Description
TA	Transport authority
IM	Infrastructure manager
TOC	Train operating company
E	Expert

Table C.2: Overview interviews

Interviewee	Organisation	Date	Type	Section
Mark Oldenziel	Nederlandse Spoorwegen	June 13, 2014	E	C.1
Huug van Aardenne	ProRail	December 3, 2014	IM	C.2
Jaap de Ruijter & Paul Bik	Nederlandse Spoorwegen	December 8, 2014	TOC	C.3
Erik van Weelden	Nederlandse Spoorwegen	December 15, 2014	TOC	C.4
Ankie Hectors	ProRail	December 16, 2014	IM	C.5
Rob Kniesmeijer	Ministry of I&M	December 17, 2014	TA	C.6
Andre Buikhuizen	Province of Groningen	January 7, 2015	TA	C.7
Ruud van Munster	Nederlandse Spoorwegen	January 8, 2015	TOC	C.8
Henk Struijk	Connexxion	January 19, 2015	TOC	C.9

Table C.3: Additional conversations

Person	Organisation	Date	Type
Tijs Huisman	ProRail	September 4, 2014	IM
Martijn Brouwers	ARCADIS	September 19, 2014	E
André van Es	ARCADIS	November 7, 2014	E
Gerben Scheepmaker	Nederlandse Spoorwegen	December 17, 2014	TOC
Jasper Iddink	Nederlandse Spoorwegen	January 28, 2015	TOC
Mark Oldenziel	Nederlandse Spoorwegen	May 18, 2015	E

C.1 Mark Oldenziel - NS

Company / Department	Nederlandse Spoorwegen
Function	PgM Groot-Utrecht
Date	June 13, 2014
Location	NS Headquarters, Laan van Puntenburg, Utrecht

C.1.1 History of the 406

Mark Oldenziel was the Dutch representative within the UICs' Capacity Management (CAPMAN) project. This working group contained representatives of many of the IMs' in Europe. The working group was responsible for creating the UIC code 406 leaflet.

There was a leaflet 405 created in 1996 regarding capacity. Do to the rise of computer models, the leaflet became outdated. An international working group was created out of persons from the different IMs. The UIC 406 leaflet was the outcome of the working group. After publishing the leaflet the working group continued by "validating" the working method by running simulations for different line sections in six countries.

C.1.2 Capacity Balance

In the leaflet a figure is posted of the capacity balance. This figure and the concept behind it is purely a conceptual framework, describing the four relevant variables in capacity occupation and how they are linked (see: 3.4.1. This conceptual model was originally used at ProRails predecessor to get a feeling about capacity.

C.1.3 Link to real punctuality

The working group looked at the stability of the line section by simulating a timetable and adding additional train paths when capacity was available. This study was done using simulation tools and the target was to define blocking time percentages at which operation of the timetable was no longer feasible. Although recommended limits are published, a link between the percentages and the feasibility was not found.

Perhaps it is possible to find a link between the blocking time percentages and a operational timetable by looking a punctuality data of ProRail. That data is recorded.

C.2 Huug van Aardenne - ProRail

Company / Department	ProRail
Function	PjM High-Frequency Rail Transport Programme
Date	December 3, 2014
Location	ProRail Headquarters, Moreelsepark, Utrecht

C.2.1 Relationships

The Dutch government has the ambition to increase the amount of transport via rail, by shifting transport from other modes towards the rail. Instead of looking towards individual bottlenecks, the High-Frequency Rail Transport Programme (Dutch abbreviation: *PHS*) looks integral at upgrading the railway system to implement wishes and creating a future resistant infrastructure.

Incidents like the extreme winters in 2009/2010 and 2010/2011, but also the accident in 2012 near Amsterdam Westerpark have caused extra pressure from the politics and the internal organisation on the high-frequency programme. The focus tends to shift from more trains, to fewer disturbances and then more trains.

C.2.2 Issues

The shift in focus led to new and altered wishes, which are hard to implement in the projected *PHS* timetable. This timetable is created in 2010 for the whole Dutch network. Recalculating the entire timetable could take up to one year to carry out. Time and power to recalculate the entire *PHS* timetable is not available, so in most of the cases a global assessment is carried out to identify possible conflicts.

C.2.3 Adding value

Huug would like to have more insight in the feasibility of a timetable. Questions like, what is the reliability of the timetable and the probability of success, are related to that. In-depth questions about railway capacity are outside the scope of the *PHS* programme.

Also he wants to get more information about the impact of certain measures. This information should help reviewing measures, support the decision making process and communication back to the requester.

Huug expects that this method has a lot of potential to help explain and convince others why certain ideas are not possible or to show the effects of these measures.

C.2.4 Requested scenarios

Comparing scenarios should be possible.

C.3 Jaap de Ruijter & Paul Bik - NS

Company / Department	Nederlandse Spoorwegen
Function	
Date	December 8, 2014
Location	NS Headquarters, Laan van Puntenburg, Utrecht

C.3.1 Relationships

NS is the largest (passenger)train operator in the Netherlands. They both have the tools and the experience to develop a timetable for their network. Because of the large quantities, whenever it is not possible to drive according to the timetable generated by NS, they declare a conflict as their product weakens in strength. Conflicts happen quite often as ProRail is optimizing the running time of connections and NS rather wants to have more frequent connections.

NS applies the same phases as in the literature for structuring the timetabling process. The strategic phase is first phase and also the only phase in which NS is looking at the infrastructure. Based on conflicts between the desired timetable and existing infrastructure, a prioritized list of infrastructure wishes is created. This list is the input for infrastructure changes process which is coordinated by ProRail.

C.3.2 Issues

ATB and the NS'54 regime are declining business. Probably in the near future large parts of the Dutch railway network will be equipped with ERTMS. Because of the duration of the conversion of both track side and train equipment, dual-signalling will be introduced. At this moment both NS and ProRail are having difficulties with their software to modelling the impact of dual-signalling.

Frequently the NS marks the wrong train as problematic. For example, a certain train often has a delay causing passengers to miss their connecting train. The next train does not have a delay, so the next connecting train is overcrowded. Often than the last connecting train is extend while the delay of the first train is the problem.

C.3.3 Available knowledge

The department of Paul and Jaap looks at a strategic level to timetables, infrastructure, rolling stock forecasts, tendering for concessions, procurement of materials and personnel. The department only produces semi-finished products as input for other departments, for example the department responsible for timetables during the tactical phase of timetabling.

C.3.4 Adding value

DONS (Designer Of Network Schedules) is a tool used to design timetables. Based on a graph model and a set of design rules, this program tries to find the best performing timetable. The program uses default interval and intersect times to determine the gap between trains. If from analysis follows that certain default value can not be match, a more detailed interval will requested. ProRail will then calculate this value using ‘Roberto’. NS would like to calculate these problems on their own.

C.4 Erik van Weelden - NS

Company / Department	Nederlandse Spoorwegen
Function	Infra management
Date	December 15, 2014
Location	ARCADIS, Piet Mondriaanlaan, Amersfoort

C.4.1 Background

Inside the NS organisation there is thought about infrastructure in three layers. First ideas for changes come through the department of communication and strategy. The department of infra management than creates, in combination with ProRail, a detailed plan. The third layer thinks about the plans for the construction phase: phasing the construction plan and creating a alternative plan for travellers (e.g. fewer trains, deployment of buses), this is done by the logistics department.

NS knows two phases of disturbances. In the first phase of a disturbance train traffic is adjusted within the boundaries of the basic-hour pattern. When the disturbance continues for a longer period or the disturbance expounds the second phase is started. The second phase is known as the “adjustment scenario” (Dutch: *bijsturingsscenario*), for many types of disturbances a adjustment scenario is created. During the second phase the basic-hour pattern is released.

C.4.2 Relationships

Whenever railway infrastructure is changed or upgraded ProRail will create a Customer Requirements Specification (CRS). This document contains the wishes from both the infrastructure manager as the train operators. During the first part of a project the conflict in this document will be discussed and solved. The outcome of this process is a System Requirements Specification (SRS) that should not contain any conflicts.

C.4.3 Issues

A question often asked at infra management is the margin to execute a timetable under a given pack of infrastructure. With this the uncertainty play a huge role, if the margin in a timetable can be increased it will reduce that uncertainty.

Another issue is the transition between the first phase of disturbance and the phase of an adjustment scenario. Both the robustness of the timetable and the robustness of the adjustment scenario are tested, but the transition is not.

C.4.4 Adding value

Secondary processes are processes related to executing the timetable, but that are not part of the main timetable. Examples of secondary processes are the transition between a rush hour timetable and the off-peak timetable or the train movements between the station and the yard. Often in simulations these train movements are not taken into account.

NS wants to know the bandwidth of the flexibility and if possible expand that bandwidth.

C.5 Ankie Hectors - ProRail

Company / Department	ProRail
Function	Corridor manager
Date	December 16, 2014
Location	ProRail Headquarters, Moreelsepark, Utrecht

C.5.1 Relationships

Decisions in large projects are not made by ProRail. And the government looks at the railways mostly from decision to the next decision. Often this implicates smoothing the little problems and creating scoring opportunities for the minister. Nowadays the Ministry asks more justification/foundation about costs predictions from the railway sector than before the dividing of NS.

In the Netherlands there are around 60 freight operators. These freight operators are united in a union: KNV. This union is represented by two people, which makes them vulnerable and only a small player.

C.5.2 Issues

The largest bottlenecks in de Randstad are caused by freight transports and international trains. This is because of the fixed timeslots these trains have to meet in order to cross the border.

There is a difference between the set of requirements for timetables during the strategic phase (infrastructure planning and line planning) compared with the tactical phase, where capacity is assigned. In the strategic phase the focus is on the technical minimal headway times while during the tactical phase the focus is more on the default interval times. This is also why it is possible that the current timetable is operated without major problems, while according to the norms it should not be possible.

To check whether it is possible to operate the timetable during the first phase of a large disturbance, now their simulating the timetable of a whole week. If it is possible to operate that timetable, it is assumed that the movements necessary for the first phase of a disturbance are also possible.

Ankie describes a difference in perception among people who are not directly from the railway sector. If you would tell them that an increase in railway safety (more buffer) will cause a decrease in capacity, they will answer with: "can't you do both?" It would be nice to show them why that is not directly possible.

C.5.3 Adding value

They are still searching for the right definitions, but at ProRail they are now talking about the make-ability (Dutch: *maakbaarheid*), feasibility (*uitvoerbaarheid*) and reliability (*betrouwbaarheid*) of timetables. Feasibility in this case is the function the train operating companies would like to see optimized (large buffer), but it also is the potential to solve small disturbances.

Feasibility nowadays is tested via expert judgement, and if available the reliability analyses figures of the line section. Creating insight in the feasibility can help during a project.

Also the possibility to tell something about the make-ability and feasibility of a timetable without having detailed timetable would be useful. It is tried at the corridor Utrecht - Den Bosch for the high-frequency program, and there it provided added value.

C.5.4 Indicators

- Capacity balance
- Robustness
- Sum of intervals between specific trains

C.5.5 Requested scenarios

Ankie would like to see if it is possible with the proposed method to display the differences between conventional signalling and ECTS. Thus it increase the capacity and therefore lowering the occupancy under the current timetables?

Another request is modelling the influence between short dwell times and normal dwell times, and than specifically onto the feasibility of the timetable.

C.6 Rob Kniesmeijer - I&M

Company / Department	Ministry of Infrastructure and the Environment (I&M)
Function	PjM at Directorate-General for Mobility and Transport (DGB)
Date	December 17, 2014
Location	Ministry of I&M, Plesmanweg, The Hague

C.6.1 Relationships

I&M follows ProRail in their journey from problem definition till the formal decision for a preferred solution (Dutch: *nota voorkeursvariant*). During this process there are a number of Go/No-Go moments, some of these decisions have to be made by I&M. The customer requirements specification (CRS) is one of the products created by ProRail that has to be formally approved by I&M. The project supervisor from I&M then follows the remaining part of the project to guarantee the scope approved in the CRS is not changing along the journey. The actual decision for a preferred solution has to be taken by the minister.

An example, between Schiphol and Almere the demand his higher than the railway system at this moment can transport. Together, I&M, NS and ProRail are looking into possible (short-term) solutions for this problem (e.g. extra trains, other rolling stock, longer trains). After this identification a strategy is formulated how to solve the problem for the long-term.

Requests by provinces or the municipality regions are taken into consideration, but they do not have a vote in the actual decision making process. Afterwards, feedback will be provided to these organisations why or why not their requests are fulfilled.

C.6.2 Available knowledge

During the decision making process the actual information to decide on is abstracted a number of times. At I&M knowledge is available about specific rail related subjects in order to abstract the information from ProRail to different levels of detail.

Looking more in-depth at the detailed products created in the "kernproces" of ProRail e.g. FIS and RVTO, the project supervisor has sufficient knowledge of the subjects and the content to assess globally if the products follow the scope of the CRS. But in general I&M does not act based on the information provided in those products.

C.6.3 Adding value

ProRail needs to use all information available to come up with the best alternative for the problem. And they have to explain why the provided solution is the best solution. Perhaps that some of the elements of this research can be an explanation for certain design solutions. The feasibility of a timetable is a requirement and therefore less interesting as a criteria.

This tooling can have a benefit when used to weigh alternatives and after that to weigh the variations. But overall Rob believes that the ideas behind this research will not be a direct benefit for I&M because it focusses on a lower abstraction level. The projected information provided will more likely be background information in the process to come to a preferred solution.

C.7 Andre Buikhuizen - Province of Groningen

Company / Department	Province of Groningen
Function	Senior policy manager / project manager
Date	January 7, 2015
Location	Province of Groningen, Martinikerkhof, Groningen

C.7.1 Relationships

The northern secondary lines (Dutch: *noordelijke nevenlijnen*) are not part of the mainline network. These lines are being operated by Arriva. The concessionaire for these lines are the provinces of Groningen and Fryslân. The province of Groningen checks the punctuality of Arriva's trains to see if they comply with the minimum required punctuality according to the concession rules. But instead of imposing a fine when the punctuality rule is violated, they try to leverage for product improvements.

To be stronger in negotiations related to public transport, the provinces of Groningen, Fryslân and Drenthe have combined their powers. If the meeting is about railways, then the province of Overijssel will join the three.

The province is no concessionaire towards NS, so there is no direct contact between them. Should the province want a change towards the NS timetable, they would play it via I&M. Often after that NS and the province will create contact and negotiate the terms of the change. Additional costs will then be paid by the province.

Often, ProRail is not interested in projects requested by the province of Groningen. They will not say it out loud, but probably they do not think it is within their core business. This phenomena is ”ondersteund” by the example that it can take months to get a project manager from ProRail assigned to a project or that plans created by a ”gerenomeerd” engineering firm are first checked and redone before any action is taken.

C.7.2 Available knowledge

At the province of Groningen there is a team of four people with experience and knowledge about timetables and timetabling. It is not their core business to work on railway related projects, so the knowledge is sufficient to understand the basic principles and to create a basic drawing of a timetable. They are not able to create rolling stock and crew schedules.

C.7.3 Indicators

When the province evaluates a timetable they are looking at indicators like the minimal frequency, time of the first train of the day and the time of the last one and connections between the trains of Arriva ”onderling” and with the trains of NS.

C.7.4 Requested scenarios

Andre would like to have more insights in space available at the infrastructure, first at a high level and later on in more detail. So what is the capacity of the infrastructure and to which frequency it is possible to drive without changing the infrastructure.

C.8 Ruud van Munster - NS

Company / Department	Nederlandse Spoorwegen
Function	Commercial manager North-East Region
Date	January 8, 2015
Location	NS Regional office, Koggelaan, Zwolle

C.8.1 Relationships

In the last 10 year the regions became more and more of influence. They have gained more knowledge about the train product and often they carry the additional costs to improve the train product in their own region. Good examples for this are night trains or an increase of frequencies.

Also, for investments in railway infrastructure the Ministry of Infrastructure and the Environment (I&M) is looking more and more for regional (financial) support and acceptance to get projects to a successful conclusion. And the focus of decision making is moving towards social cost-benefit analysis.

C.8.2 Available knowledge

Ruud has no practical knowledge of timetabling, but he does have sufficient understanding of timetables to interpret management information and to ask a specialist the right questions to enhance the result.

C.8.3 Adding value

Ruud was very interested in the blocking time diagram. It gives a good perspective of the amount of margin in the timetable and the problems that can occur.

C.8.4 Indicators

Ruud focusses a lot on the robustness of a timetable. Often his office conducts studies into the delay absorbing capacity of a timetable. Simone is the application used by NS to conduct those studies.

C.9 Henk Struijk - Connexxion

Company / Department	Connexxion
Function	Senior advisor timetabling
Date	January 19, 2015
Location	Connexxion, Europalaan, Utrecht

C.9.1 Relationships

The strategic phase of timetabling and infrastructure planning is further away than the running time of the current concession. Even though in the planning process Connexxion is asked for their professional opinion towards infrastructure reconstructions.

If it is not possible for Connexxion to drive their timetable, they will submit a declaration of congestion. This because it is the only way to formally discuss timetable related problems with the infrastructure.

At the line Arnhem-Doetinchem Connexxion operates the same line as Arriva. Both are operating a 2 times per hour frequency, but with a 15 minute offset. The revenues are divided between the two companies based on the time travellers checked in their PT-chipcard.

C.9.2 Available knowledge

Driving trains is probably not a core-business of Connexxion hence they have only two people with experience of creating a railway timetable. For Henk, the knowledge available comes from his time as a train driver in the early days of his career and from his time as planner of the tram line from Utrecht to Nieuwegein/IJsselstein.

Because of the limited knowledge about railway timetabling within the company, Henk is operating at timetable horizon levels. He submits the request to ProRail for the new timetable, but he is also responsible for the day-to-day train movement requests.

C.9.3 Adding value

Sometimes request by the concessionaire can lead to problems. An example given by Henk is the plan to add a stop at station Westervoort in the concession. When this happens, it will be hard to create a feasible timetable.

For Connexxion the model can offer a way to fight against NS and ProRail.

For smaller train operating companies the number of compositions is very important. Fewer compositions means less costs for the offered service. And rolling stock is rather expensive.

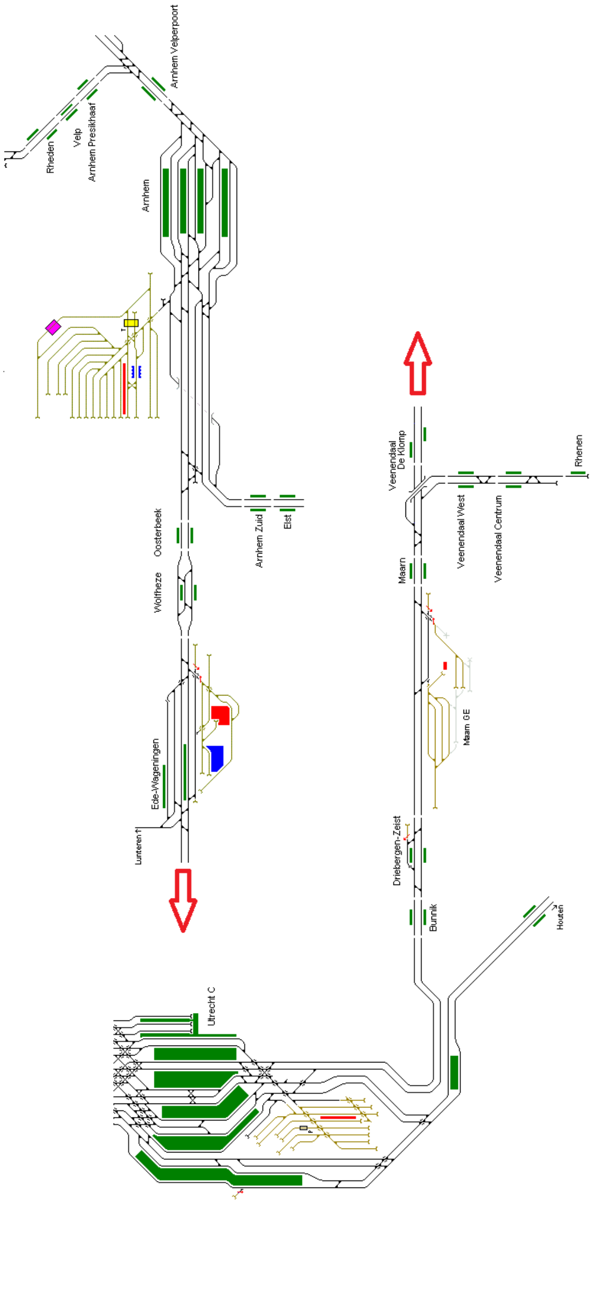
C.9.4 Indicators

Connexxion wants as few conflicts as possible, and by conflicts they mean train path crossings, level crossings and competitors.

Also insight in the robustness of the timetable is a requested parameter. With robustness they mean if there is sufficient time available to operate the timetable.

Appendix D

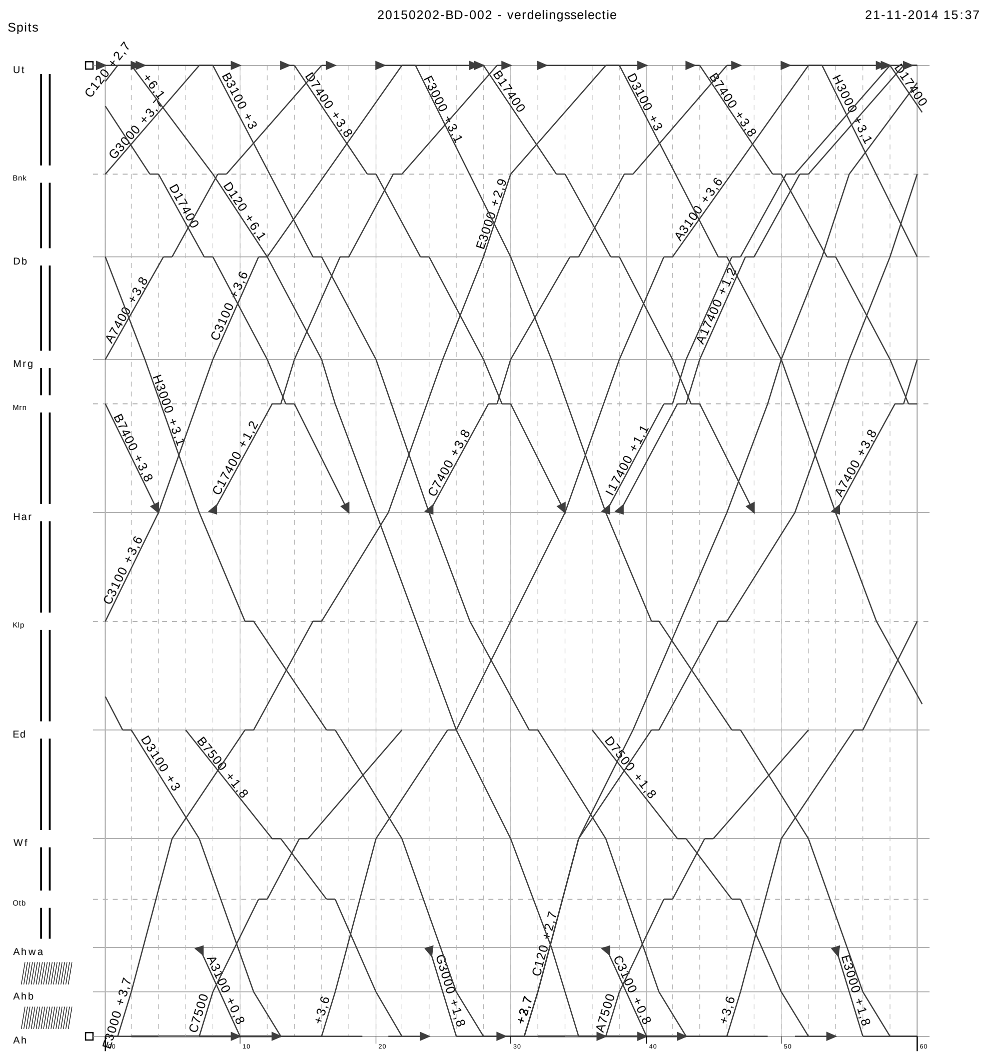
Layout Utrecht - Arnhem



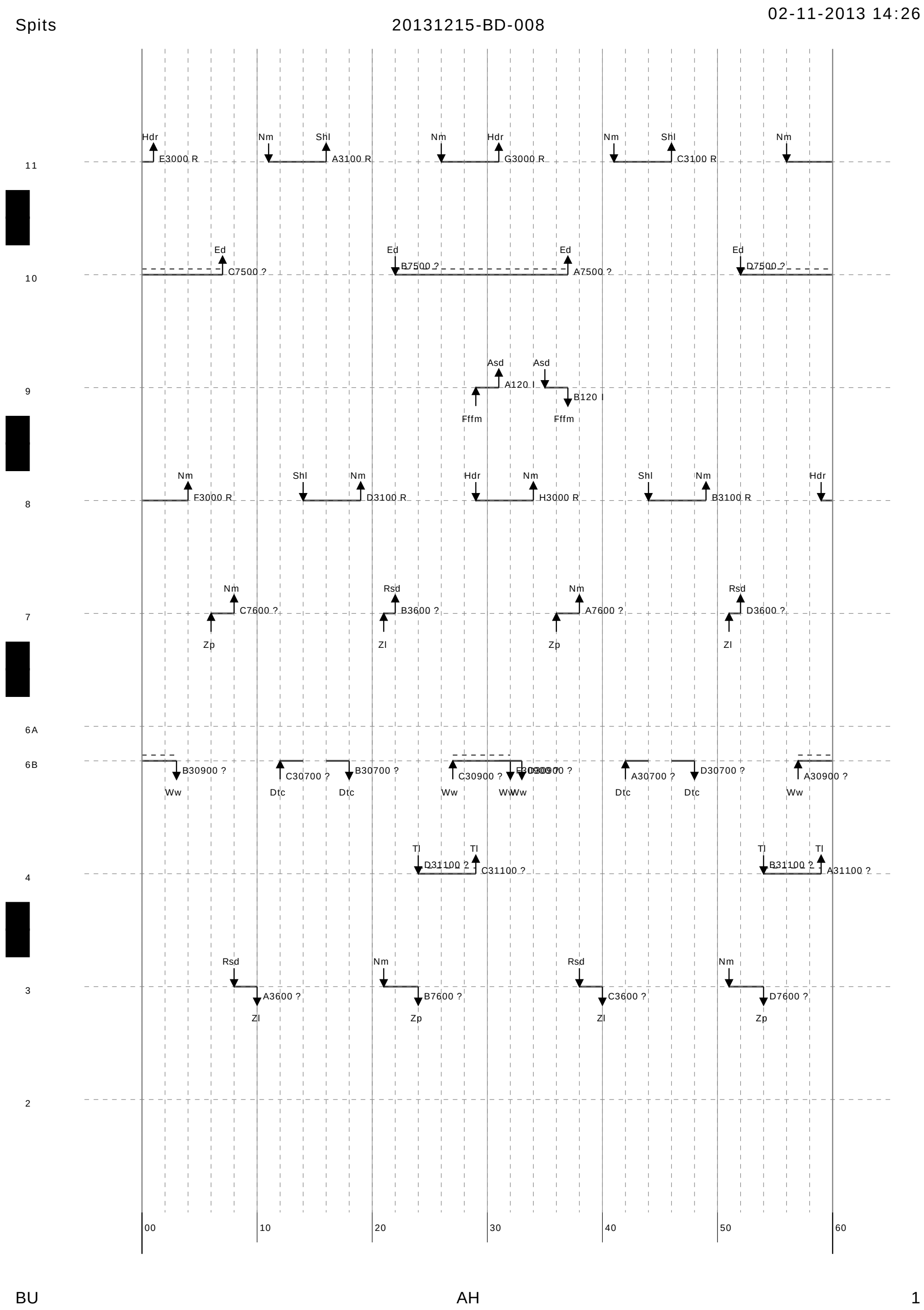
Appendix E

Timetable diagrams

E.1 Basic hour pattern: Utrecht - Arnhem (rush hour)



E.2 Station traffic diagram: Arnhem (rush hour)



E.3 Timetable: Utrecht - Arnhem (24h)

Direction ->		Utrecht -> Arnhem							Arnhem -> Utrecht					
Departure at ->		Utrecht (Ut)					Ede (Ed)		Arnhem (Ah)				De Haar aansl. (Har)	
	Uur	3101	7401	3001	121	17401	7501		3000	3100	120	7500	7400	17400
	5		44	53		58				46		37		
	6	8	14	23		28	6		1	16		37	25	38
		38	44	53		58			31	46			55	
	7	8	14	23	32	58	6		1	16		7	25	8
		38	44	53			36		31	46		37	55	38
	8	8	14	23			6		1	16		7	25	10
		38	44	53			34		33	46		37	55	37
	9	8	14	23			6		1	16		7	25	8
		38	44	53			36		31	46		37	55	
	10	8	14	23			6		1	16		7	25	
		38	44	53			34		33	46		37	55	
	11	8	14	23	2		6		1	16		37	25	
		38	44	53					31	46			55	
	12	8	14	23			6		1	16	31	37	25	
		38	44	53					33	46			55	
	13	8	14	23	2		6		1	16		37	25	
		38	44	53					31	46			55	
	14	8	14	23			6		1	16	31	37	25	
		38	44	53					33	46			55	
	15	8	14	23	2	28	6		1	16		37	25	
		38	44	53		58			31	46			55	
	16	8	14	23		28	6		1	16	31	7	25	8
		38	44	53			34		33	46		37	55	37
	17	8	14	23	2	28	6		1	16		7	25	8
		38	44	53		58	36		31	46		37	55	38
	18	8	14	23			6		1	16		7	25	8
		38	44	53			36		31	46		37	55	38
	19	8	14	23			6		1	16	31	7	25	
		38	44	53			34		33	46		37	55	
	20	8	14	23			6		1	16		37	25	
		38	44	53					31	46			55	
	21	8	14	23			6		1			37	25	
		38	44	53					31				55	
	22		14	23			6		1			37	25	
			44	53					33				55	
	23		14	23			6		1			37	25	
			44	53					31				55	
	0		14	53			6		1			37	25	

Yellow coloured are the hours that have an exact match with the basic hour pattern of the corridor.