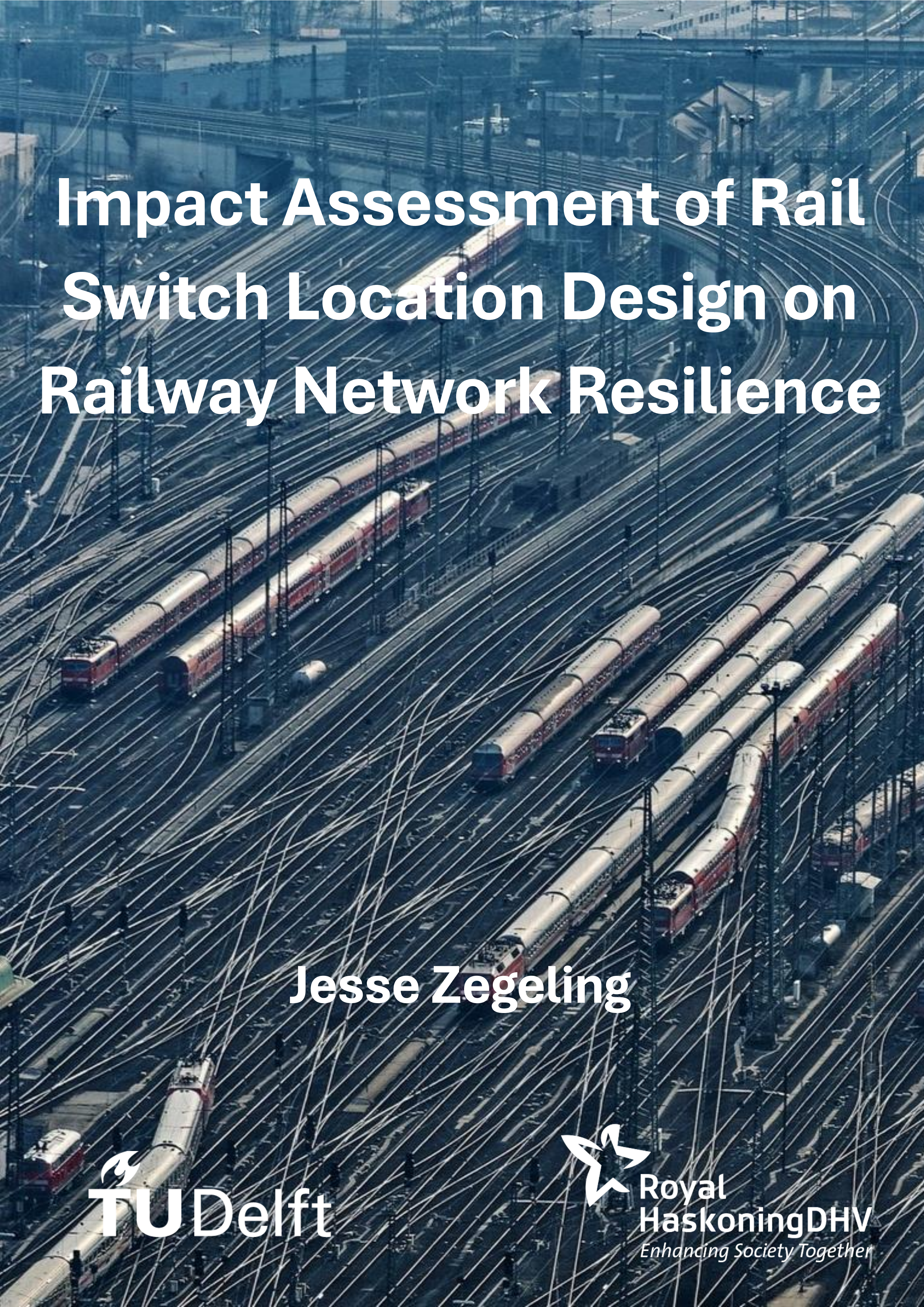

Impact Assessment of Rail Switch Location Design on Railway Network Resilience

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TU Delft

Royal HaskoningDHV
Enhancing Society Together

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Preface

This Master thesis report represents the culmination of my study Civil Engineering at TU Delft. After my 6 year period at the Montessori Lyceum Herman Jordan in Zeist I decided to go to Delft to do my Bachelor in Civil Engineering. Since I was young I always had an interest in infrastructure, mobility and in particular railways which made the choice for this study perfect. Combining this with playing volleyball at a high level I finished my Bachelor after four years with a thesis about a very special railway line in Austria for me: the Montafonerbahn. In my first year of my Master Transport & Planning I earned 64 ECTS which was quite surprising to me because I still spent around 25 hours per week in the sports hall for playing and coaching the talented boys of our club. Despite focusing more on playing volleyball in the Eredivisie at Prima Donna Kaas Huizen during my second year and earning only 12 ECTS, I am pleased that I was able to work on my Master thesis in this third year.

All public transport, but also boats and planes have always been special to me where the latter will undoubtedly not be appreciated by some of the readers. Playing at home with the BRIO trains I had and making different track layouts all the time which was at older age until now changed to Märklin model trains has a lot to do with this thesis. Travelling several times a week for seven years from the meanwhile renovated station Driebergen-Zeist to Delft was often an interesting challenge. Many delays, disruptions with the strangest causes and other problems, led to frustrations, interesting detour routes and thinking about how disruptions could be resolved more quickly which made the topic of this Master thesis really interesting to me.

I would like to express my sincere thanks to everyone who has provided invaluable support throughout this project. First of all, I would like to thank Royal HaskoningDHV for the internship and especially my company supervisors: Wouter and Nigel. Our weekly meetings were very useful and I learned a lot from practice. I thoroughly enjoyed my time in Utrecht over the past nine months, thanks to the fantastic colleagues who made it such a positive experience. I am also thankful for the contributors who participated in the interviews for their useful answers. Spending the entire day riding along with a train driver across the Netherlands was a fantastic and highly educational experience and I want to thank Lucas for arranging this opportunity.

Secondly, I would like to thank my committee at TU Delft. Egidio, Maria and Niels: Thank you for all insightful meetings and feedback I got from you. The meetings were helpful and steered me in the right direction with the planning of my thesis. I also want to thank Olga from TU Delft Elitesports for the guidance and assistance in the past years.

Moreover, I have to thank my family, friends and teammates for their support during this process. First of all, my parents, for their consistent support and encouragement throughout my academic journey as well as for my passion for volleyball. Although I may have played less games this season, I can proudly say that I nevertheless became a two-time Dutch champion and won all other existing trophies as a coach with the boys under 17 at the highest level this season. I want to express a special thank you to my father for his invaluable assistance in preparing many exams and also for his thoughtful feedback on this thesis. His insights have significantly contributed to the refinement and improvement of this work. Finally, a big thank you to my fellow students, who have become friends as well. Their support during both my Bachelor and Master made my time in Delft incredibly enjoyable.

I hope you all enjoy reading this thesis. It has been a pleasure conducting this study and I hope this will improve the resilience of our railway network in managing disruptions effectively.

Jesse Zegeling

Odijk, June 2024

Summary

Train travel offers a pleasant and comfortable experience. However, increasing population, climate change and road congestion, e.g., are leading to overcrowded trains. With more trains on the tracks, railway systems require greater resilience which is the capability of a railway system to recover from disruptions. Switches can play a major role during disruptions as they enable trains to be rerouted onto other tracks, allowing them to bypass the disruption but switches also facilitate overtaking, meet-pass operations at stations as well as diverging and merging at junctions. Since switches consist of numerous parts and the fact these are moving infrastructure elements they are subject to failure itself. Maintenance is expensive and ProRail, the Dutch infrastructure manager, only has a limited budget from the government and if certain switches are only used during disruptions it sounds logical to remove those switches. However, by locating them well, especially on the busiest lines in the Netherlands, capacity can be kept high, also during disruptions. To maintain the infrastructure, more financial resources are required, especially if the government aims to reduce road traffic and increase passenger train usage for sustainability reasons. With more budget, the current infrastructure can be maintained better and more frequently, resulting in less disruptions and a more reliable service for passengers. With on average 50 disruptions per day in the Netherlands with both small and huge impact, it is important to get insights into the relationship between resilience and the location of the switches. Although certain switches might not be necessary, these could be important to reroute trains in case of a disruption. This removal of switches decreases the flexibility for trains tremendously and results in more cancellations and delays during disruptions. The main research question of this thesis therefore is: **What is the impact of rail switch locations on the trade-off between railway network resilience and costs?**

A model is constructed to evaluate the impact of switch configurations for given infrastructure layouts and a set of disruption scenarios. A sensitivity analysis is performed to assess the influence of different switch locations on resilience and overall costs of the railway system. Specifically, for costs and resilience four key performance indicators (KPI) are chosen: number of used switches, rate of cancelled services, punctuality and time to recover. The locations of the disruptions follow from an analysis of disruption events in which a ProRail database is used that includes all disruptions (140,000) on the Dutch rail network in a time period of 6.5 years. A broken train (26.3% of the total number) is the disruption with the highest occurrence in the Netherlands with an average duration of 1 hour and often located in the larger stations. The second most occurring event deals with persons near or at the tracks (16.2%) and this happens often near larger stations, at railway crossings or near foot paths parallel to railway lines.

Scores for each given infrastructure layout are calculated by subtracting the resilience from the costs. Resilience is calculated by subtracting the rate of cancelled services and the time to recover from the punctuality, where all of these KPIs are multiplied with a corresponding weighting to indicate the importance of each KPI. These weightings are determined in a best-worst method where all KPIs are weighted against each other which is done in eight interviews with experts in rail. In the trade-off between costs and resilience there is one double track layout that scores above the threshold score for all simulated disruption scenarios which is calculated by using threshold values for all four KPIs given by the rail experts in the interviews. Seven other double track layouts also score above the threshold score of -2.75 for two out of three disruption scenarios.

This means that a good infrastructure layout (score higher than -2.75) contains four switches on both sides of a larger station. Also, the two stations on both sides of the larger station should contain four switches. These stations are located approximately 5.2 km from the larger station and should contain these switches on the opposite side of the larger station which enables high short turn capacity, as

well as enough rerouting possibilities in case of a single track usage of the line. This best switch configuration for a double track layout is visualised in Figure 0.1.

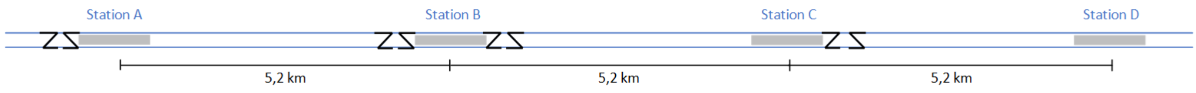

Figure 0.1: Optimal switch configuration layout for a double track line. Station B is the Intercity station, all other stations are only used by Sprinter trains.

The worst layout has on both sides of the larger station tail tracks that offer low capacity and score low in the trade-off between costs and resilience. It is even possible to keep capacity at 100% and therefore keep the rate of cancelled services at 0%, although this decreases punctuality which was ranked as less important by the interviewees: 'It is more important that many trains still run during a disruption with some delay than that trains are running with minimum frequency but all on time'. This is because passengers do not want to wait on platforms and therefore this waiting time should be decreased. If the distance between two stations increases and the distances between switches also increases, capacity will shrink during a partial blockage of the line. If switches are located every 5 to 6 km it is possible to keep eight trains per hour per direction running, where these will be running in pairs close by each other over the single track part to shorten waiting times for trains coming from the opposite direction. The scores are ranging between positive 12.5 and negative infinite. If the score is lower than -2.75 a new switch configuration should be found by performing a sensitivity analysis. If the score is below -12.125 the model should be redefined as shown in Figure 0.2. If the score for all simulated disruption scenarios for one layout is higher than -2.75 a layout scores good on resilience and costs. Both threshold scores come from rail experts that were asked for threshold values for the four KPIs.

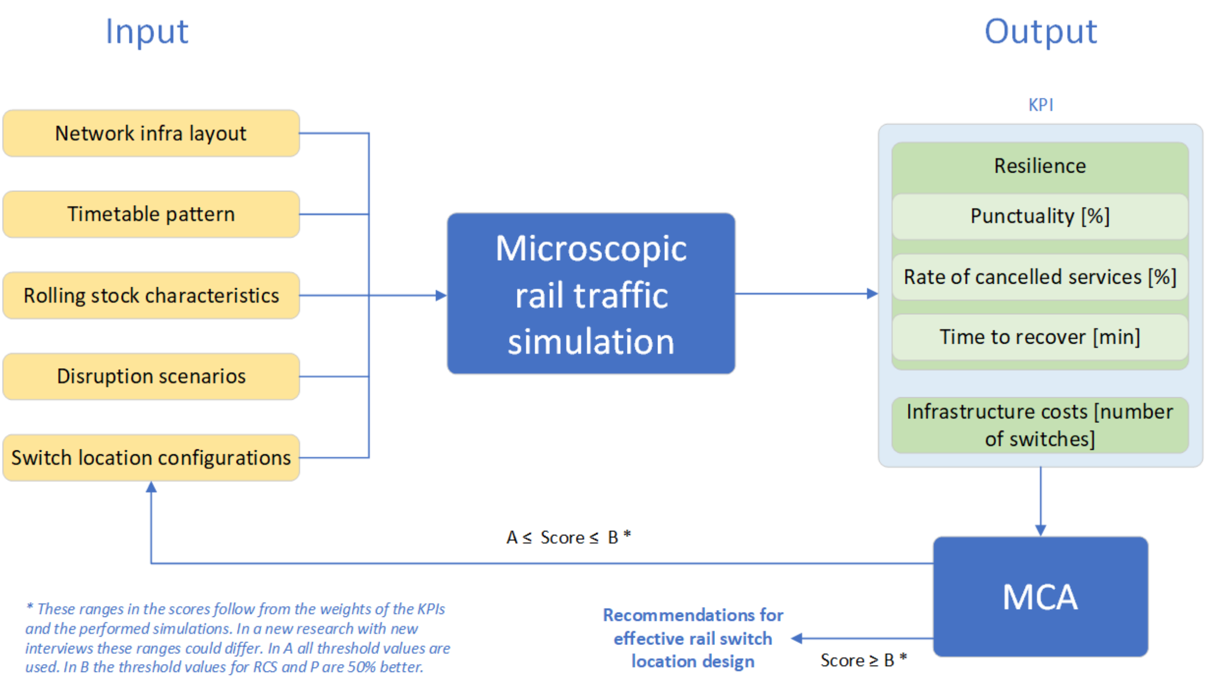

Figure 0.2: Explanation of the model.

A case study is performed to validate the model and this is done for the Dutch railway line between Utrecht Centraal and Arnhem Centraal which is used by the Intercity corridor Nijmegen – Arnhem – Utrecht – Schiphol / Amsterdam. The renovated station Utrecht Centraal contains only 59 switches (instead of 167 before the renovation) which increased punctuality, speed and capacity, but decreased flexibility in case of a disruption. For trains on the Intercity corridor arriving at Utrecht Centraal it is difficult to short turn since the essential tracks in both directions are far away from each other. There are possibilities to short turn, but these have only limited capacity which means that trains are already being short turned in Amsterdam or cancelled completely. A disruption between Utrecht and Arnhem therefore also affects train traffic between Utrecht and Amsterdam which is not wished for. At every larger station like Utrecht Centraal and Arnhem Centraal, but also Driebergen-Zeist and Ede-Wageningen all regularly scheduled trains should be able to short turn. To be specific, these stations also fulfil a regional hub status for buses and during a longer lasting disruption through passengers can also change travel mode at those stations.

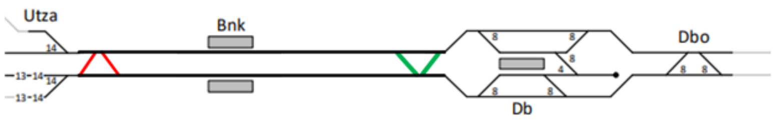

Figure 0.3: Proposed switch layout between Utrecht Centraal and Driebergen-Zeist.

Two new situations with switch configurations between Utrecht Centraal and Driebergen-Zeist are proposed and simulated as shown in Figure 0.3. The first proposed solution is the addition of the four green switches west of Driebergen-Zeist in Figure 0.3. The second proposed solution is the addition of the four green and the four red switches east of Utrecht Centraal. These locations are chosen since all other simulated disruptions scored higher than -10, but a situation with only one track available between Utrecht Centraal and Driebergen-Zeist resulted in a score of -13.78. Therefore the goal is to increase the score to a similar level as how all other disruption scenarios score. These scores cannot be compared to the scores of the model because the line in the case study is three times as long as the line in the model. The current rerouting options by using the present infrastructure are shown in Figure 0.4. First, only the proposed green switches near Driebergen-Zeist are simulated which resulted in the left rerouting options in Figure 0.5 and then also the proposed red switches have been simulated which resulted in the right rerouting options in Figure 0.5. The additional switches at Driebergen-Zeist appeared to have more positive impact (the score increased with more than 2 points) than the additional switches east of Utrecht Centraal (the score decreased again with -0.5). This could be caused by the fact that there are also switches even closer to Utrecht Centraal that could be used which makes these proposed red switches near Utrecht Centraal useless. The main differences between the rerouting options in Figure 0.4 (current situation) and Figure 0.5 are the usage of two platform tracks at Driebergen-Zeist.

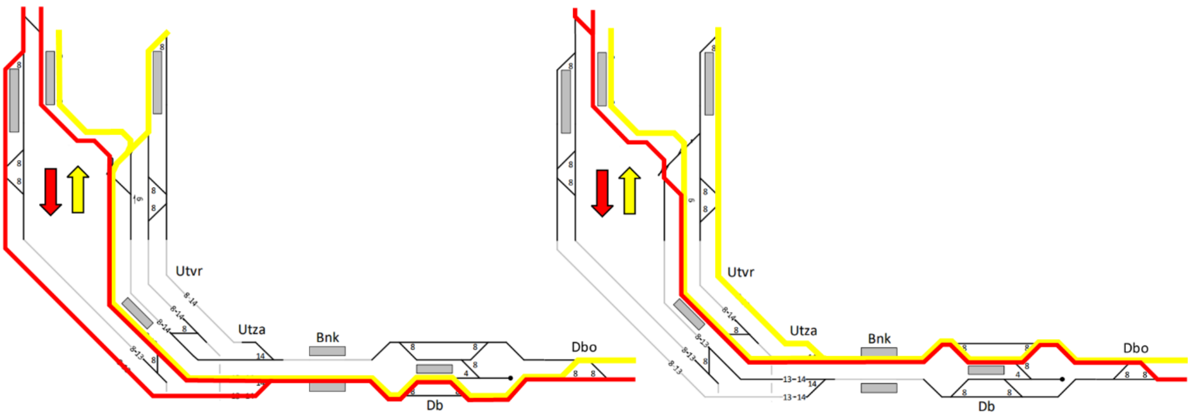

Figure 0.4: Current rerouting possibilities with a broken train at station Bunnik (Bnk) by using the present infrastructure. Left the situation with a broken train at Bunnik track 1 which is the upper track and on the right a broken train at track 2 which is the bottom track in Bunnik.

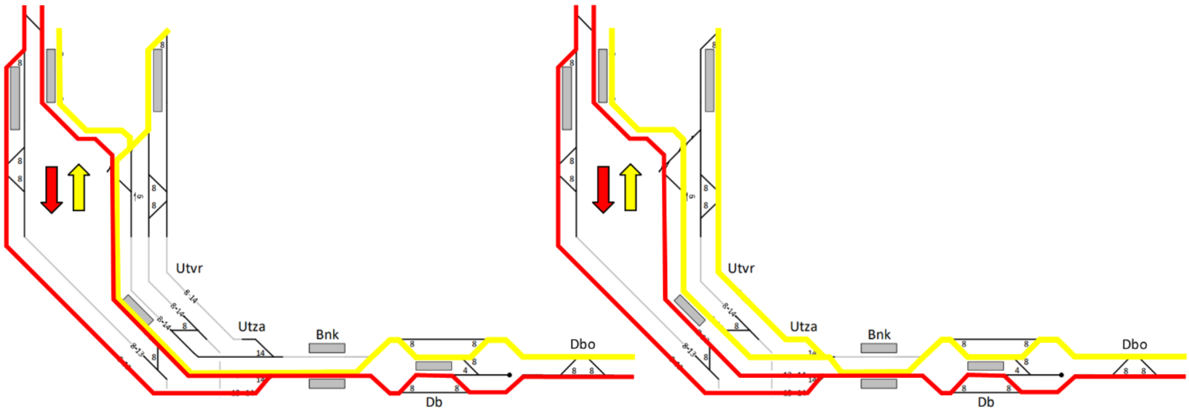

Figure 0.5: Rerouting possibilities with a broken train at station Bunnik (Bnk) track 1 (upper track) by using the green switches of Figure 0.3 (left) and green and red switches of Figure 0.3 (right).

Not only switches should be added between Utrecht Centraal and Driebergen-Zeist as shown in Figure 0.3 but NS and ProRail could think of better solutions during disruptions which results in more trains on the tracks. If the tail track at Driebergen-Zeist gets extended and it can accommodate the longest possible Intercity trains, trains should be able to short turn there. In case of a disruption between Utrecht and Eindhoven on the other important Intercity corridor Amsterdam – Utrecht – Eindhoven, trains should be rerouted towards Driebergen-Zeist since short turning in Utrecht is difficult. If the line is closed between Utrecht and Arnhem trains should be rerouted to Houten Castellum where two tracks are available for trains to short turn. This will lead to some minor delays but this results in higher capacity during disruptions and still high punctuality. Also, passengers between Utrecht and Amsterdam will be less affected by disruptions east or south of Utrecht in case trains are short turned in Driebergen-Zeist or Houten Castellum.

In literature no papers have been found that investigated the impact of different switch locations on resilience. This indicates a literature gap and the goal of this research was to address this gap by defining resilience of a railway system quantitatively and identifying possible quantitative key performance indicators to evaluate it. Four KPIs are found and these are used to quantitatively score different switch location configurations. A disruption analysis is performed to determine the most frequently occurring disruptions in the Netherlands including the average duration and the corresponding locations. From the model it follows that the addition of switches increases resilience because of higher flexibility during disruptions but the location of these switches is also important. Switches should be located around the larger stations for high short turn capacity. If only one track is available during a disruption it is still possible to have a capacity of eight trains per hour per direction but for this, also smaller stations located at 5-6 km from the larger station should have switches. By looking at the trade-off between costs and resilience the layout shown in Figure 0.1, having four switches on each side of the larger station and also switches at smaller stations nearby, scores the best. Layouts with other switch configurations, e.g., having a third track at the larger stations, also score high, but due to the higher number of switches, these score lower in the trade-off than the optimal layout in Figure 0.1. Besides having switches as described above, NS and ProRail can also think of shortening block distances and alternative disruption management plans of where trains could be short turned to keep capacity high, also on other routes.

Glossary and abbreviations

Table 0.1: List of abbreviations.

Abbreviation	Meaning
ARAMIS	Advanced Railway Automation Management Information System
C	Costs [number of switches]
DB	Deutsche Bahn, can be translated to ‘German Railways’
DM	Disruption management
DMP	Data management plan
FIS	Functioneel Integraal Systeemontwerp, can be translated to ‘Functional Integral System design’
HREC	Human Research Ethics Committee
IC	Intercity
KPI	Key Performance Indicator
NS	Nederlandse Spoorwegen, can be translated to ‘Dutch railways’
ÖBB	Österreichische Bundesbahnen, can be translated to ‘Austrian Federal Railways
P	Punctuality [%]
PHS	Programma Hoogfrequent Spoor, can be translated to ‘Timetable with high frequent train service’
RCS	Rate of cancelled services [%]
RHDHV	Royal HaskoningDHV
SW	Number of used switches
SBB	Schweizerische Bundesbahnen, can be translated to ‘Swiss Federal Railways’
SPR	Sprinter, a regional (local) train in the Netherlands
T	Time to recover [min]
TIS	Trein incident scenario, can be translated to ‘train incident scenario’
TU Delft	Delft University of Technology
UIC	Union internationale des chemins de fer, can be translated to ‘International Union of Railways’

Table 0.2: Glossary.

Word	Meaning
Bathtub model	Resilience curve: model that describes three phases until the performance of the train service is back where it should be.
Contingency plans	Pre made plans by NS and ProRail what to do during a disruption including timetables aiming high predictability for passengers and staff. For all different kind of disruptions on different locations it is already clear i.e. which train series are being cancelled, where trains will short turn and which stations will be skipped or will have an additional stop.
Decoupling point	Stations where passengers still can go to during disruptions and where trains could change their direction by using switches. Described in the contingency plans.
Dwell time	The time a train stops at each station.
Initial delay or primary delay	A delay of a train which is caused by that train.
Interlocking area	An area such as stations or junctions where switches are located and interlocking dependencies between switch direction and signal aspect are imposed to guarantee safe train movements and where train movements can be allowed or denied in accordance with safety rules.
Microscopic rail traffic simulation	A simulation having a high level of detail for the infrastructure, e.g. exact station layouts, exact locations of switches and signals, and also a high level of detail for different types of trains.
Modal share	The percentage of travellers using a particular mode of transportation.
Rerouting	Sending a train via a different track through a station or between two stations than originally planned.
Resilience	The capability of a railway system to go back to normal conditions after a disruption if a certain disruption management strategy has been applied.
Robustness	The ability to withstand design errors, parameter variations and changing operational conditions and is not related to switch locations configurations.
Rust riding	An arrangement that is made to prevent rust in or at switches and on regular tracks. The arrangement is that every track and switch that contains a track circuit needs to be used at least every 24 hours by at least 20 axles.
Secondary delay	Knock-on delays arising as a consequence of another delayed train.
Short turning	A train ending its trip short of the planned terminus station to begin the return trip in order to get back on schedule. Measurement that can be taken in case of a delay or line blockage.
Siding	A track at the side of a railway line. Can be used to turn trains or put away a train in case of a defect.
Switch location configuration	A design in which a certain amount of rail switches are located in a certain order and direction and have a certain location.
Tap in / tap out	Ticketing system where passenger tap in with a chipcard before the start of the journey at the station or in the train and tap out at the end of their journey.
Track circuit	An electric system that detects the absence of a train on a certain section of the track.
Turning track	A track near a station that is used to turn trains. For train drivers a small platform is available to walk outside the train to the other side.

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1. Introduction

Cities all over the world are growing rapidly. This is also the case in the Netherlands where many people move from the rural area to the Randstad area (Zayed, Gabr, & Hussien, 2023). This will result in busier trains within, to and from cities. In the year 2030 ProRail, the Dutch rail infrastructure manager, expects a 45 percent increase in railway demand (Treinreiziger.nl, 2018). With only 189 billion passenger kilometres in the year 2018, this will grow to 210 billion in 2030 and almost 230 billion in 2040. Based on the highest growth scenario this will even raise to 246 billion passenger kilometres (NS, sd).

The higher railway demand is not only because the (urban) population is growing, but also because of the fact that people are less willing to travel by car, or on longer distances, by plane anymore as they did in the past, e.g. because of an increase in congestion on the roads and sustainability reasons (Karman, 2023) (Venneman, 2022). During rush hours Dutch trains are often fully packed (Nandram & Dekker, 2023). With even more passengers in the near future causing overcrowded platforms this will lead to safety issues (Schneider, Krueger, Vollenwyder, Thurau, & Elfering, 2021). To avoid these problems the frequency of the trains should increase. This will be executed in 2030, when there will be eight instead of the currently four or six Intercity trains per hour per direction on the busiest lines of the country (SpoorPro, 2019).

Adding more trains in the timetable, however, means that the railway industry needs more capacity, as well as a larger system resilience. Resilience is the capability of a railway system to go back to normal conditions after a disruption if a certain disruption management strategy has been applied (Bešinović, 2022). With the growing demand there is more likelihood that the intended utilization of the railway network might lead to disruptions, which can then lead to big delay propagations. Actually, the Dutch railway network is already close to saturation which means that there is not much space left to increase the frequency of trains while keeping the reliability of the service high as it is right now (van Velzen, 2018). Switches can be relevant in the resilience of the railway system because they provide possibilities for trains to change their routes in specific interlocking areas and switches also allow overtaking or meet-pass operations at stations as well as diverging and merging at junctions (Spilt, sd). It is therefore crucial to understand the relation between resilience and the design of the infrastructure especially in terms of the locations of the switches.

With around 5000 disruptions per year on the Dutch railway network due to infrastructure, rolling stock or other failures it can be said that switches are an essential component of the network to still guarantee (a part of the) operations under disrupted conditions (Rijden de Treinen, 2023). By using the switches during disruptions, trains can be rerouted on alternative tracks in case these are available and bypass tracks which may be blocked due to maintenance or unexpected failures/malfunctions of rolling stock and/or infrastructure and signalling. Since a switch consist of numerous parts and because switches are moving infrastructure elements they are prone to failure itself (Litherland & Andrews, 2022) (Hamadache, et al., 2019). Therefore, switches need more maintenance than normal straight tracks, meaning that costs to install and especially maintain switches can be significant over time due to the need of frequent maintenance interventions. For this reason, ProRail, decided to 'Japanize' the Dutch railway network (Weeda, van Touw, & Hofstra, 2010). Japanization denotes the reducing of the number of switches in the main stations such as Utrecht Centraal (van de Velde, 2011). This has been a solution to reduce the maintenance costs and to decrease the number of switch failures. In Utrecht Centraal, the number of switches was reduced from 167 to only 59 (Treinreiziger.nl, 2018). Other positive outcomes from this significant reduction in the number of switches are that there are more straight tracks and corridors through the stations causing higher speeds when trains arrive at the station. Also, the follow-up times between trains could be decreased, meaning that more trains can use the same track and thus increasing frequencies (Dollevoet, 2020). Punctuality in Utrecht Centraal also increased from 88.5 to 92 percent (Treinreiziger.nl, 2018). Due to the reduced amount of switches there are less rerouting possibilities and probably resulting in higher rate of cancellations in Utrecht Centraal although no numbers for this are found.

Allocating more switches offer options for train rerouting during disruptions, although that might accordingly increase chances of disruption events as switches are statistically subject to failures, if not regularly maintained. Removing switches could hence result in a potential saving in maintenance costs, although that might eventually result in a reduced possibility for train rerouting and track blockage overtaking in case of disruptions, thereby affecting overall rail transport quality and the resilience of the rail system in efficiently recovering the planned train service.

1.1. Research objective

This thesis aims to investigate where switches should be located to have a balance between high operational resilience and low (maintenance) costs. The location of the switches will be examined by performing a data analysis on where disruptions in the past 10 years on the Dutch railway network took place.

A literature review is performed on the flexibility of railway operations under perturbed conditions and how switches can play a significant role in this. There have been studies about railway disruptions and resilience like Bešinović (2019) and Fikar et al. (2016) that have investigated the impact of railway disruptions. There will be an increasing number of disruptions, as this is the trend of the last years and the impact will also increase due to increasing transport demand and climate changes. In the model that Fikar et al. (2016) describe trains are rerouted in case of sudden closures, delays are calculated and the model also compares different disruption scenarios. Ghaemi et al. (2017) explored a model for optimal short turning based on the available infrastructure and does not make use of new infrastructure. Measuring resilience quantitatively was examined in Goverde and Hansen (2012) where five performance indicators were defined to evaluate timetables. A part of these indicators is also useful to assess a timetable during a disruption in which the switch location configuration has the focus. These are the indicators considering capacity, delays and cancellations. Also Nicholson et al. (2015) described performance indicators to measure resilience quantitatively by means of the maximum deviation (delay), the time to recover from the disruption and the deviation area which is the area under the graph of the deviation versus the time to recover. Van Essen and Bulsink (2018) have investigated different switches for short turning in Almere (Netherlands), but not different locations along a railway line and they focused only on the widening of an existing concrete deck. No papers were found about the relationship between switch location, resilience and costs, hence there is a literature gap as it is not clear what the effect is of a given infrastructure design on the resilience and there is no clear relationship between resilience and switch location. The objective of this research is therefore to address this literature gap by defining resilience of a railway system quantitatively and identifying possible quantitative key performance indicators to evaluate it. Based on these definitions, it is a goal of this thesis to analyse the relationship between resilience and the configuration of switch locations. This will be done by means of a set of simulation experiments in a microscopic rail traffic model. The defined indicators for resilience will be used to assess different switch location configurations under different disrupted situations. With the results of this research the Dutch railway manager ProRail can optimize the locations of switches and therefore decrease the impact of an unforeseen disruption.

The main research question is:

What is the impact of rail switch locations on the trade-off between railway network resilience and costs?

To answer this main question, four sub-questions are formulated:

1. *What is the state-of-the-art on switch location design to improve resilience of the railway network?*
2. *How can different types of railway disruption affect railway operations related to switch locations?*
3. *Which key performance indicators can be used to quantitatively measure the resilience provided by a given switch location design configuration?*
4. *What is the relationship between switch location, costs and railway resilience under different disruption conditions?*

These sub-questions will also form the structure of the final report. Every sub-question will be answered in a different chapter. In Chapter 2 the research methodology will be discussed and there it will be made clear how the sub-questions and finally the main research question will be answered as good as possible.

1.2. Scope

During disruptions not only the train timetable is disturbed meaning that trains need to use other tracks but rolling stock and crew (drivers and conductors) might not be on the right location in case of cancellations and delays. This research will mainly perform a sensitivity analysis which will use microscopic rail traffic simulation to assess the impact that different switch location configurations have in terms of network resilience and costs for different infrastructure layouts of the interlocking areas and thus rolling stock and crew management are not taken into account. These interlocking systems are designed to permit the safe movements of trains within the railway system (Winter, Johnston, Robinson, Strooper, & van den Berg, 2005) and interlocking is an arrangement of switches and signals interconnected in a certain way that changing these elements is only possible in a proper and safe sequence (Goverde, 2022). An interlocking area can be specified as an area such as stations or junctions where switches are located and interlocking dependencies between switch direction and signal aspect are imposed to guarantee safe train movements and where train movements can be allowed or denied in accordance with safety rules (Bonacchi, Fantechi, Bacherini, & Tempestini, 2016).

In this research only the switches will be looked at and this will be investigated in a model with several infrastructure layouts. In these layouts only two types of trains are running: Intercity trains and regional (Sprinter) trains in a Dutch timetable during peak hour. These are the hours in which infrastructure is almost being used at full capacity and therefore close to saturation. For the Intercity trains, a Dutch double-decker VIRM-10 will be used and for the Sprinter trains a Dutch SLT-10 will be used. Cargo trains are not included in this research as there are only a few lines that are being used by cargo trains (Rijksoverheid, sd). There is a difference between disturbances and disruptions. Disturbances are relatively small perturbations, for example when a train is delayed by a couple minutes, and can be exterminated by retiming and rerouting in stations (Cacchiani, Veelenturf, Kroon, & Toth, 2014). This thesis aims to focus on disruptions which have higher impact than disturbances such as track blockages providing lower capacity during the disruption. Complete line closures and partial line closures are taken into account, as well as track blockages in stations. Disruptions leading to, e.g., temporary speed limits will not be investigated.

1.3. Thesis outline

The structure of this report is as follows. Chapter 2 provides the research methodology for this thesis which will explain all methods that will be used and how all sub-questions will be answered. Next, in chapter 3 the results of the literature review are given. That chapter also shows the results of conducted interviews with people with high expertise in rail and it will answer sub-question 1. An analysis of all disruption events in the Netherlands has been carried out in chapter 4 which also answers sub-question 2. The key performance indicators that are used to assess rail resilience are described in chapter 5 which answers sub-question 3. The equation how scores are calculated for a specific switch layout configuration is also given in this chapter. These two chapters are input for the microscopic rail traffic simulation model which is described in chapter 6 where also the model results are given. Hereafter, a case study is performed in chapter 7 and is conducted to validate the results of the model. Lastly, the conclusions are presented in chapter 8. Chapter 9 shows all used references and this is followed by Appendices A to G.

2. Methodology

This chapter describes the research methodology on how the different sub-questions will be answered which can help to come to an answer to the main research question. In this research a method is developed to determine potential locations for switches to be able to run as many trains as possible during disruptions. The methodology is explained in Figure 2.1 which shows the complete structure of this research.

The literature review combined with interviews will answer sub-question 1 and can be found in chapter 3. In the literature review the impact of disruptions on train traffic will be investigated as well as rescheduling options that are used in the Netherlands. Eight interviews are performed in total with people from NS, RailExperts, ProRail and Royal HaskoningDHV to obtain more knowledge and insights about switches, disruption management and to obtain understanding of the issues related to railway infrastructure and operations. The four companies are important stakeholders in the Dutch railway sector and the interviews aim to gather insights from these different perspectives.

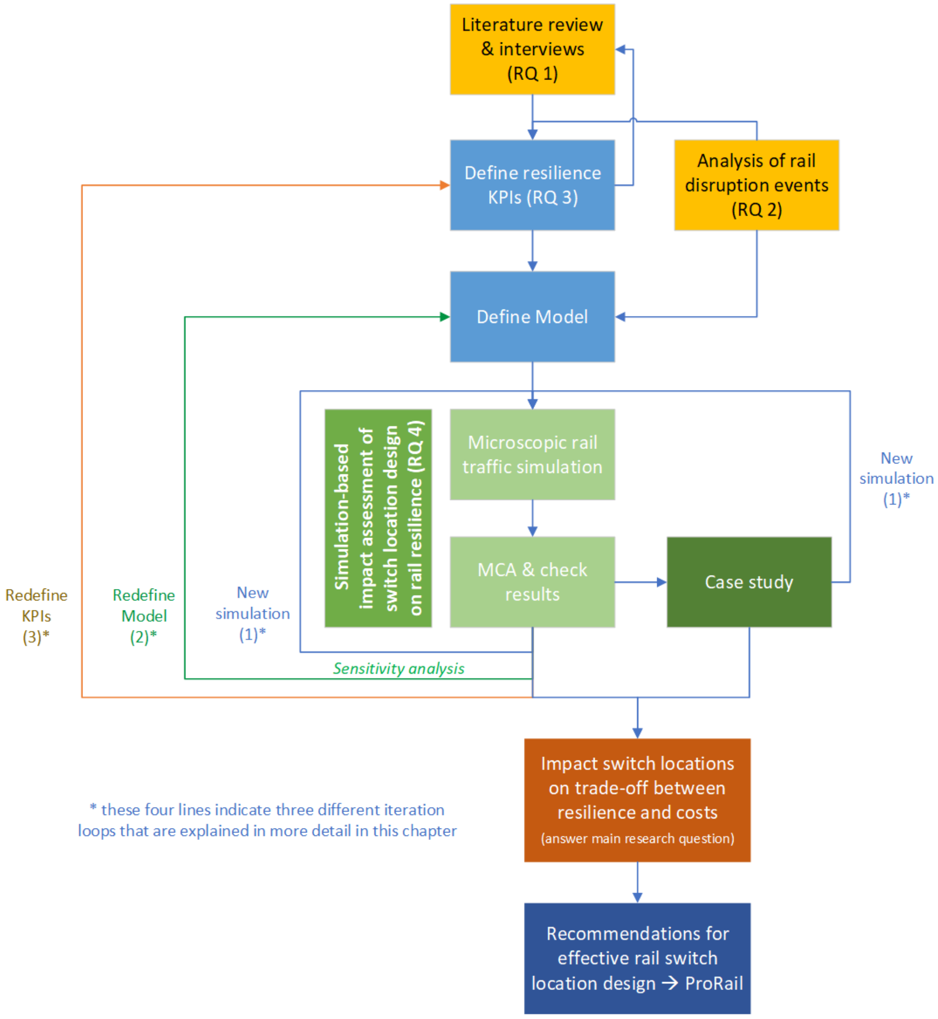

Figure 2.1: Research methodology.

An analysis of disruption events in the Netherlands will give an answer to sub-question 2 and is performed in chapter 4. ProRail has a big database with all events that happened on the Dutch railway network in the past. This includes cause, duration, date, time, location and impact. The data is not made public since it may contain sensitive parts about, e.g., collisions. In Python the data will be analysed and maps of the Netherlands are plotted that will visualise all disruptions complying to the conditions in the code. These conditions will highlight specific causes that appear to occur regularly and next it is possible to obtain knowledge where these disruptions with high occurrence happen more often than on other locations. The key performance indicators that are found in literature will be weighted against each other by using the best-worst method. How this method works is further explained in chapter 4. The same eight interviewees will be used to perform this best-worst method and by using their expertise the weights for the different indicators that can measure resilience quantitatively are calculated to see which key performance indicators are most and least important. As the main question suggests, a trade-off between costs and resilience is made. The resilience key performance indicators are therefore weighted 50% in total which also applies to the costs. This chapter will also give an answer to sub-question 3.

After defining a model with simplified layouts with different switch location configurations a simulation-based impact assessment of switch location design on rail resilience will be done. This part will answer sub-question 4 and consists of three steps: choosing the switch location configuration, using a microscopic rail traffic simulation model and conducting a multi-criteria analysis. Chapter 6 starts with a flow chart of the block 'define model' from Figure 2.1 to explain this block in detail. This chapter also shows the different layouts and presents the model results. Different standardized infrastructure layouts with different switch configurations are being simulated during disturbed situations. Where these disruptions will be located, how long and how many tracks are blocked follows from the disruption analysis which is performed in chapter 4. The beginning of chapter 6 will also describe different available software packages that can be used and weigh the advantages and disadvantages to find the most suitable software for this research. The multi-criteria analysis will assess the infrastructure layouts and this is also explained in chapter 4 that also describes that a certain layout is considered to be good or not good enough dependent on the threshold values retrieved in the interviews. Four lines with three different colours are shown in Figure 2.1 that all visualise a different iteration. The iterations marked with a '1' and the text 'New simulation' is a loop that is used after the disruption is started in the software and the best train rescheduling needs to be found. Some trains will be cancelled but it could be possible after the first simulation that more or less trains should be cancelled or that trains should be retimed slightly to optimize train performance. Also other minor inputs in the timetable are possible: short turning a train at a different track, letting a train wait at a certain station preventing a red signal stop along the open line and also a reordering of different types of trains is possible.

By changing the input (number of switches and the corresponding locations) slightly, the results could change significantly resulting in a layout that passes the requirements that are established in chapter 4. This is part of a sensitivity analysis as noted in Figure 2.1 and further explained in chapter 6. This sensitivity analysis is part of the green iteration loop which redefines the model and creates a new switch configuration. Also, if small mistakes in the model are found or other operational or general characteristics should be changed, these can be solved by using this iteration loop. In case the results are not improving after dozens of iterations and the in chapter 4 defined threshold values are not reached it could be considered to redefine the KPIs and the corresponding threshold values (yellow iteration loop in Figure 2.1) based on the gained knowledge or redefine other model inputs than the switch configuration again (green iteration loop).

To check the results obtained by the model a case study in a real-world situation will be performed in chapter 7. Since the infrastructure layouts in the model will be standardized with specific block lengths, number of signals, maximum speed and a regular timetable, it is interesting to investigate if the layouts that will score better than others, will also score better if these switch configurations will be applied in the case study. A specific Dutch train line will be chosen that has high frequent train services in which a disruption immediately affects many passengers. By using the obtained knowledge from the model in which certain switch configurations could have scored better than others, switches in the case study will be relocated, added or removed to improve capacity during disruptions. For the case study the same kind of disruption scenarios as in the model will be used which follow from the disruption analysis.

The conclusions are presented in chapter 8 and will summarize the answers to the four sub-questions and will finally give an answer to the main research question. Recommendations for future research will also be given. The discussion of the model results are presented in the final section of chapter 6. Other discussion topics will be described in the conclusions chapter. Also, recommendations for effective rail switch location design will be given that are based on the model results. Besides these recommendations for a generic case also recommendations for the case study will be given. In case more recommendations could be given that are not related to switch locations, e.g., about signal (locations) and block lengths, these will also be shared with ProRail.

3. Literature review

In this chapter the results of the literature review are shown and presented. It is investigated what influences the impact of disruptions and how these can be resolved as fast as possible. Also, the resilience of railway operations under perturbed conditions and how switches can play a significant role in this will be examined. The survey methodology of the literature review can be found in Appendix A. First in Section 3.1, an overview of the results of the literature review is given. Moreover, Section 3.2 presents the results from conducted interviews with experts in rail switches. Finally, the conclusion of the literature review can be found in Section 3.3. The list of all used references in this document is presented in the reference list in chapter 9. This chapter also answers sub question 1: *What is the state-of-the-art on switch location design to improve resilience of the railway network?*

3.1. Overview results literature review

This section gives an overview of the obtained results from the literature review. The first subsection discusses the impact of disruptions on train traffic. Then, in section 3.1.2 papers regarding switch location designs, resilience and found key performance indicators are discussed. Finally, section 3.1.3 gives information about disruptions in general, how these occur and why and what kind of strategies are used the Netherlands. How disruptions are solved in four other European countries can be found in Appendix A.

3.1.1. Impact assessment

As stated in the introduction, this research is restricted to disruptions which have influence on train traffic. During a disruption, a track or a complete line is blocked or there is a temporal speed restriction based on the circumstances, for example. This causes delays and cancellations in train operations resulting in inconvenience for passengers and the need of finding alternative travel routes. The faster the system recovers from the disruption the more resilient the railway system is (Bešinović, 2019). From the start of the disruption there are three phases until the performance of the train service is back where it should be. These phases are visualized in Figure 3.1 where the first phase consists of degradation of the timetable and transition to a new plan. In the second phase the timetable has a high reliability and a steady disruption timetable although being downsized: passengers know what they can expect. In the third phase recovery takes place and there is a transition back to the normal situation (Bešinović, 2022). A goal of this research is to lift the height of the second phase to increase capacity under disruptions.

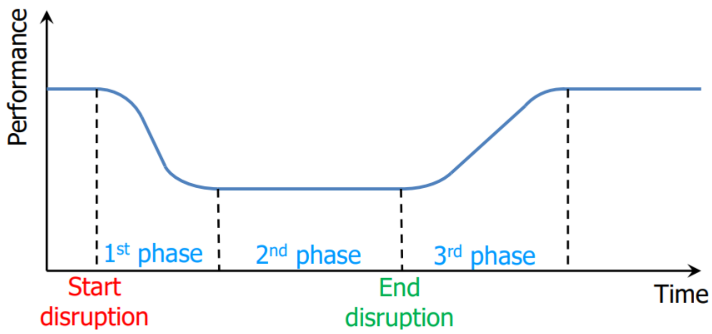

Figure 3.1: Resilience curve / Bathtub model (Bešinović, 2022).

Due to increasing transport demand, climate change and even events like possible terrorist attacks, the amount of disruption as well as the disruption impact will increase in the future (Bešinović, 2019). Although out of scope, a method to decrease the impact during disrupted train traffic is suggested to provide real-time information via displays and announcements at all stops and in all trains (Cats & Jenelius, 2014). A so-called 'three-level attack strategy' was constructed where distinctions are made with edge attacks (disruption between two stations), station attacks (station is closed and trains cannot pass through it) and line attacks (whole line breaks down). This strategy is designed for impact analysis of disruptions regarding different scenarios and the results show that the removal of a few lines, stations or edges with a high betweenness during a disruption will result in a big decline in the efficiency of the network (Yin, Han, Li, & Wang, 2016). The duration of the disruption can also be predicted with models where the duration is modelled as a conditional probability distribution. In another model the consequences of the passenger costs are assessed and short turning measures are determined based on quantiles of the disruption duration distribution. These three models are then used to develop a framework to analyse the impact of the duration of the disruption (Zilko, et al., 2018).

The relationship between disruption locations and resilience is investigated by identifying which specific railway tracks have the highest impact on the train traffic on the specified region that will be analysed. In a model the Brenner Pass has been used with track blockages of at least 24 hours and it presents the results what the most negative effects of the blockages are. It is however not a model that couples switch locations based on the disruption data analysis (Fikar, Hirsch, Posset, & Gronalt, 2016). This paper also presents a decision support system which investigates the impact of sudden rail closures. This system helps finding which disrupted railway lines have the highest impact on train traffic, passengers and the industry. The model is for complete line closures of at least 24 hours which means that it can find rerouting solutions for freight trains especially on a line like the Brennerbahn between (Germany,) Austria and Italy. The model is also used for partial closures, but only for 24 or even 72 hours. A disruption with a (partial) line closure for only a couple of hours and the influence at passenger train services is not being researched.

Another paper investigated the relationship between resilience and historical failure data. This is also part of the current research where a disruption database from the Netherlands is used to find railway lines with high amount of disruptions and locations where the impact on train traffic is higher than average in case a disruption occurs. The reliability of switches is a huge problem causing delays to trains. Most part of the research is however about improving switches to decrease the number of disruptions and introducing functionally redundant subsystems in case a switch does not work properly which is out of scope for this thesis (Bemment, Goodall, Dixon, & Ward, 2017).

The European Union demands a modal shift for freight traffic from road to rail in the future. The goal is to achieve a 30% modal share by 2030 for rail freight which is more economical and emits nine times less emissions. When distances over 700 km are shifted from road to rail freight this could save 40 million tonnes of CO_2 per year and raise the modal share of rail for freight to 36% in the European Union (European Union Agency for Railways, 2023). This, however, requires improvements in the rail infrastructure to make rail more resilient (Woodburn, 2019). Currently, road networks all over Europe are more resilient, as rail networks are much sparser than road networks, which affects modal share. Trucks have more rerouting possibilities than trains in case a disruption arises and accordingly, disruptions for cargo have way more impact on railway networks than on road network as there are fewer opportunities of rerouting on rail (Rich, Kveiborg, & Hansen, 2009). The same applies to passenger rail and cars, where cars use the much higher resilient road network and can take another route. This new route might be a few minutes or even seconds faster than the previously navigated route in case of a traffic jam, due to an accident or a long queue in front of traffic lights (Alvarez, Lerga, Serrano-Hernandez, & Faulin, 2018). The impact of disruptions on rail systems is huge and this was examined in (Mo, Cao, Li, & Wang, 2022). This paper predicts the impacts of disruptions by defining two metrics, stay ratio and travel delay, which can be convenient to assess the impact and compare the impact on a certain station or node with another one or compare it with another disruption.

The impact of a disruption can differ per location. For instance, a comparison with a signal failure causing a total blockage on the tracks between Warffum and Usquert in the north of the province of Groningen versus the line between Schiphol Airport and Amsterdam Zuid. Between Warffum and Usquert trains only run every 30 minutes while there are 16 trains running per hour per direction between Schiphol Airport and Amsterdam Zuid (Hofstra, 2022). So, the location of the disruption influences the impact of the disruption. Even a signal failure of only 15 minutes around Schiphol Airport will cause more trouble than a signal failure of more than one hour in the neighbourhood of Usquert. Not only the number of trains and as a result from that also the number of passengers is related to the location and its impact. When a disruption around Schiphol Airport occurs this will also influence many other train lines and routes causing delays and even cancellations on other trains that did not even go to from or via Schiphol Airport. **Disruption location** and **number of passengers** that are hindered by the disruption are therefore good indicators for comparing different switch location configurations.

3.1.2. Design methods of switch locations in relation to resilience and costs

Switches are mainly located near stations and at junctions and these locations are invented during the design phase of the railway line. In a FIS, which means 'Functioneel Integraal Systeemontwerp' and which can be translated to 'Functional Integral System Design', it is possible to examine how tracks are designed and why certain locations for switches were chosen. The FIS of the PHS 4 track section Rotterdam – Schiedam is researched and the conclusion is that there are many factors influencing switch locations (Wildschut, Bos, & Tigchelaar, 2021). After the renovation of Rotterdam Centraal it is made possible that trains from certain direction can still reach certain platforms at the station for which switches are necessary. The life cycle cost of 27 rail switches in Czech Republic are estimated around six million euros based on a 30-year evaluation (Vitásek & Měšťanová, 2017). Dutch infrastructure manager ProRail estimates the costs at 500,000 euros per switch and gives extra priority on good preventive maintenance (ProRail, sd). Building more switches to provide more rerouting possibilities and thus assuring a more resilient network will rise costs significantly and increases chances of switch failures as well. Switches require space and not everywhere space is available to locate a switch. Especially switches that are being used for higher speeds are bigger and require therefore more space. It is also important to look at certain train movements that will be used very often and the vertical alignment is finally also of importance as switches are not allowed to be located on a slope in the Netherlands. The type, size and location of the switch all influence the costs of the switch and if the costs of the different switch locations are known these can be compared to each other and therefore **costs** is a good key performance indicator for switch location configuration (Ling, 2005). A key performance indicator, or shortened KPI, is something measurable that examines the performance of something over time. The result of it is a number and can be compared to investigate which option under different circumstances is better and which is worse (Qlik, sd).

Another issue, when looking at switches in general, is that every switch needs to be used at least one time per day. This rust riding is an arrangement that is made to prevent rust in or at switches and on regular tracks. The arrangement is that every track and switch that contains a track circuit need to be used at least every 24 hours by at least 20 axles (Infrasite, s.d.). In the case part of a track or a switch is not used for more than 24 hours, a reliable operation cannot be guaranteed. A solution for this is that a regular passenger train uses two switches directly after each other to shortly move to the other track and immediately going back to its scheduled track. Of course, this must fit in the timetable and should not disturb train traffic coming from the other direction. This rust riding applies thus to regular switches as well, but in those cases, it is timetable-wise not a huge problem, because these switches are used anyway in the timetable.

In switch location design short turning needs to be paid attention to as this is of utmost importance when there is a line blockage. All trains that are still running towards the blockage should somehow go back and for this, switches can play a significant role. Switches near large stations where trains can use other tracks in case of an unavailable track are convenient, but these should be located on smartly chosen locations. In literature, many papers were found about switch component design and how these can be improved to increase resilience, but only one paper was found about switch location configuration design. That paper analysed different types of switches in the city of Almere in the Netherlands and investigated where to locate these to improve capacity on the train line through Almere (van Essen & Bulsink, 2018).

Papers on optimizing short turning and decreasing passenger delays were found in bigger amounts and the latter can be investigated i.e. by using Mixed-Integer Linear Programming (MILP) Algorithms. Flexible stopping and flexible short turning are more likely to have effect in situation with relatively high operating frequencies and in the case that trains are allowed to have large delays. It is concluded that using flexible stopping and flexible short turning have as a result that there are less passenger delays compared to either or neither of these measures. Also, shortening the recovery duration will cause less delay propagation (Zhu & Goverde, 2019). The optimal short turning station also depends on the penalties that are given for a train cancellation and a delayed arrival at the destination. With a low penalty for cancelling trains results from a microscopic short turning model showed that the best solution is to have multiple short turning stations (Ghaemi, 2018). However, cancelling trains means lower capacity and that is not what is aimed for. If the penalty increases the mentioned model finds optimal solutions for short turning at the final station before the disruption. The model is also used in a case study for a bigger station like ‘s-Hertogenbosch. With a disruption of 1 hour short turning was needed from all directions and was easily applied due to the cyclic nature of the Dutch timetable (Ghaemi, Cats, & Goverde, 2017).

On days with harsh weather there might be multiple disruptions at the same time. The predefined contingency plans are useless because these conflict with each other. Traffic controllers are requested to use their own experience without any guideline to adjust the timetable which can lead to suboptimal solutions. In these cases, it is important to know how the network is designed and where all switches are located. Short turning and overtaking are essential in case of a single disruption but in case of more disruptions even more essential. A multiple-disruption rescheduling model has been developed which reschedules all trains at the same time every time a new disruption occurs. This results in less delays and cancelled trains compared to a sequential approach which solves all disruptions one by one with the previous rescheduling strategy as a reference (Zhu & Goverde, 2021).

Since there are only few papers found on rail switch location design it is required to produce a new strategy. By performing a sensitivity analysis which computes performance and costs of different switch location configurations (van Keulen & Wang, 2015). These alternatives will be assessed by key performance indicators on resilience, switch locations and costs. The performance of railway systems can be measured with the following indicators suggested by Goverde & Hansen (2012):

- **Infrastructure occupation:** the share of time required to operate trains on a given railway infrastructure according to a given timetable pattern and can be computed using the timetable compression method. The UIC recommends an infrastructure occupation of at most 75% in peak hours and 60% for off-peak periods for mixed traffic and high-speed lines. For suburban these guidelines are higher (85% and 70% respectively).

- **Timetable feasibility**: the ability of all trains to adhere to their scheduled train paths and a KPI for this is the amount of scheduled train paths conflicts with a norm of zero conflicts.
- **Timetable stability**: the ability of a timetable to absorb initial and primary delays so that delayed trains return to their scheduled train paths. A KPI for stability can be the **settling time** in which the delays must have been absorbed and also the size of the **initial delay**.
- **Timetable robustness**: the ability of a timetable to withstand design errors, parameter variations and changing operational conditions. A KPI could be the **percentile of the process times**.
- **Timetable resilience**: the flexibility of a timetable to prevent or reduce secondary delays which are knock-on delays (delays caused by another delay) using dispatching (retiming, reordering, rerouting). Possible KPIs can be **punctuality**, **average delay**, **maximum secondary delay** and the **actual (simulated) average track occupation** for delay scenarios with rescheduling.

Infrastructure occupation is a good indicator as it tells how much percent of the infrastructure is in use and also **timetable feasibility** would be good as this indicator aims to have zero conflicts, also during disruptions. Timetable stability and robustness will not be used for this research because the stability only refers to absorbing initial and primary delays, but this research is about disruptions with delays and cancellations and is thus a phase further, while timetable robustness is the ability to withstand design errors, parameter variations and changing operational conditions and is not related to switch locations configurations (Goverde & Hansen, 2012). Resilience can be measured with punctuality and average delay as stated above but there are more performance measures. There is a difference between departure and arrival delay, and also between departure and arrival punctuality.

Another possible indicator is **platform consistency** which can be low during disruptions as trains are being rescheduled. Passengers would however prefer a high consistency as they then know what they can expect and are not requested to move to another platform with all luggage at the last moment (Bunt, 2020). Platform consistency can be explained as the sum of the total number of trains that did not arrive at the planned platform and the planned track divided by the total number of arrived trains (Lo, Pluyter, & Meijer, 2015).

In the Danish S-tog network the general measures of disturbances are termed **regularity** (delays) and **reliability** (cancellations). Hofman et al. (2006) describe regularity by using Equation 1 and considers traffic to be stable when regularity exceeds 95%.

$$Regularity = \left(1 - \frac{\#LateDepartures}{\#TotalDepartures}\right) * 100\% \qquad (1)$$

Additionally, Hofman et al. (2006) calculate reliability using Equation 2 which must be higher than 97% over the day for the Danish network.

$$Reliability = \left(\frac{\#ActualDepartures}{\#ScheduledDepartures}\right) * 100\% \qquad (2)$$

Reliability, explained by Equation 2, will be further used as '*the rate of actual departures*' as this term is more unequivocal. Regularity, however, gives the same information as punctuality and will therefore no longer be considered.

Nicholsen et al. (2015) define three measures for **resilience**: maximum deviation, time to recover and deviation area where the latter the area is under the graph visualized in Figure 3.2. It is a goal to keep the deviation area [s^2] as low as possible; an exact number for this depends on the type of disruption. The deviation can be interpreted as the total delay of the trains which increases rapidly at the moment the disruption happens. Delays are then slowly decreasing and after passing the recovery threshold the train service is back to normal as can be seen in Figure 3.2. To simplify this, it is possible to look at the bathtub model described in section 3.1.1. The bathtub model has a similar look where the duration of the disruption is located on the x-axis and on the y-axis the downsized capacity. In this bathtub it is also the goal to decrease the area of the graph by increasing capacity or decreasing the duration of the disruption. For deviation area and bathtub area it is good to mention that the switch location configuration does not influence the duration of the disruption as a switch location configuration cannot fix the signal failure or clean up the tracks after a collision meaning that these KPIs are difficult in practice for this research. However, when the duration is known on beforehand it is possible to use the deviation area and a certain switch location configuration can then also ensure that the delays of all trains are minimized and after a time is again under the specified threshold value. A deviation area is measured in seconds squared and with a time to recover of 1 hour and an average deviation of 10 minutes this deviation area becomes more than 2 millions seconds squared which is difficult to visualize. The deviation should not be used as KPI as this overlaps with punctuality KPIs. Therefore the time to recover [min] is a better key performance indicator to use to analyse the performance of a certain switch location configuration under a disrupted situation.

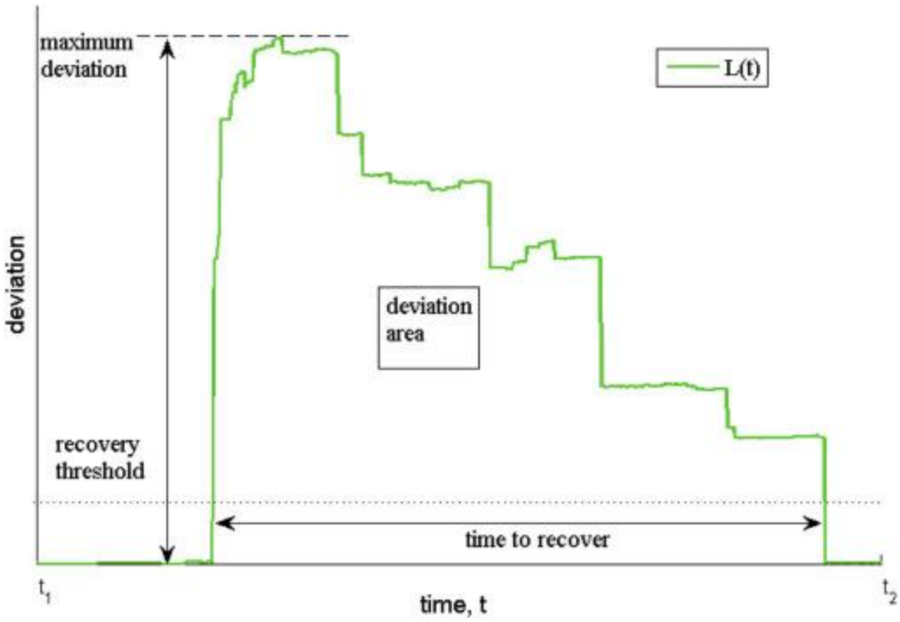

Figure 3.2: Resilience KPI (Nicholson, Kirkwood, Roberts, & Schmid, 2015).

Other key performance indicators that Nicholson et al. (2015) define consider punctuality, resource usage, energy consumption, connectivity, journey time and transport volume. **Punctuality** can be described as the sum of departure delays to all services departing from station S during time period T. Other papers express punctuality as a percentage of the number of trains that arrive (or depart) within a certain time margin at station S during time period T (Denti & Burroni, 2023). **Resource usage** can be used for track usage meaning the average number of trains passing a point (signal) per hour during time period T and also for rolling stock meaning the total number of rolling stock units in use during time period T. **Energy consumption** is, as the name suggest, about the average consumed energy and is not relevant for the optimisation of switch locations. **Connectivity** can be measured with the average interchange time of all interchanges at station S during a given time period T. **Journey time** is the average journey time in seconds of all journeys that make scheduled stops at the stations in the model during time period T. The last KPI Nicholsen et al. (2015) mentions is the **transport volume** which are the total available passenger kilometres calculated by multiplying the total number of travelled kilometres by the number of available seats. These KPIs are not used because energy, change possibilities and passengers are out of scope for this research. The latter KPI, transport volume, is in public transport terms also more difficult because it can be distinguished in available seats or the total number of passengers that can be transported which are the available seats and the number of standing places.

In addition to searching for performance indicators in railway traffic, it is also imaginable trying to learn from the road industry. In road traffic, congestions are a major problem and therefore indicators like duration and distance of the disturbance exist. A road indicator like the effect of the disturbance indicating the number of effected vehicles is also useful researching train disruptions, where vehicles should be replaced by trains (Calvert & Snelder, 2017). Other indicators mentioned by Calvert & Snelder (2017) are the **congested travel density** which is the number of vehicles in congestion times the congestion length (or time), **the link capacity** describing the maximum number of vehicles (or trains) on a certain road (or railway line) during a disturbance and **redundancy** indicating the number of available alternative routes. The link capacity will not be used as this also overlaps the capacity of the railway line. 'Congested travel density' will neither be used as it implies the number of vehicles in congestion times the congestion length (or time) and because congestion in terms of railway traffic is different (trains can be delayed and a congestion will arise, but this will not provide a traffic jam such as on highways with hundreds of trains on a few kilometres) this KPI will not be used. From road traffic, **redundancy**, can be further investigated as KPI, but as this term is complicated as well, redundancy is called '*number of alternative routes*'. Also, the **capacity** of the railway line will be used indicating the maximum possible number of trains per direction which can cross a certain section. This KPI also includes the importance of the researched train line. A line with a high capacity is a line which is used by many trains and a disruption over there will have massive impact while a line with low capacity will be a side line with few trains and if a disruption takes place the impact will be lower regarding number of trains and thus passengers affected.

3.1.3. Disruptions

As already is known, the Dutch railway system almost is close to saturation which means that there is not a lot of space to add more trains. Also trains in the Netherlands are jam packed during rush hours. Train passengers however expect good train service, because railways are in general known for their superior safety, good organization and the ability to transport a lot of passengers. However, these smooth operations can be interrupted by various unexpected causes and these disturbances can induce significant delays that can propagate over the whole railway system and finally cause train cancellations. These disturbances can ensure that other travel modes might become more popular under passengers resulting in more congestion and thus less sustainable travels (Sharma, Pellegrini, Rodriguez, & Chaudhary, 2023).

3.1.3.1. Different kind of disruptions

According to *rijdendetreinen.nl* there are one hundred causes for disruptions on the rails (Rijden de Treinen, 2023). A train can break down and not be able to ride any further after a system restart causing delays or cancellations. There might occur switch or signal failures and collisions with people or vehicles are unfortunately also still commonplace. Failures in the power supply, broken bridges, animals on the tracks, broken overhead wires, copper theft and a lot of different weather-related disruptions are some other examples of disruption causes (Rijden de Treinen, 2023). All these causes can be categorized into three main groups (NS, sd):

- Technology

- Weather
- People

With technology causes, the broken trains, switch, signal, overhead wire and railway crossing failures are meant. Harsh weather can cause delays and cancellations when there is heavy snow fall, a strong wind, in case of a thunderstorm, frost at the overhead lines or on the tracks which causes slippery tracks. Also, in the case of hot weather there might be problems on the tracks. Tracks are made of steel and can warp when temperatures are rising (ÖBB, 2019). Third, people can cause a lot of delays. Some people that walk on tracks, children that are playing on the tracks, people that jump in front of a train, but also human errors by train drivers, conductors that let trains depart late because they allow passengers to board the train even after scheduled departure time, strikes and there are many more reasons. In Appendix B all disruption causes can be found. These are sorted in a list and are based on the analysis in chapter 4.

3.1.3.2. Disruption management in the Netherlands

In the Netherlands there are different management strategies prepared in the case of a disruption. When a disruption of a certain magnitude occurs on a specific track it is already known in advance which trains need to be cancelled and which tracks can be used for short turning. These strategies will be discussed in this section. In these management strategies also cargo trains are included, but in this research only passenger trains will be looked at as mentioned in the introduction. The main aim is to bring passengers as quickly as possible to their destination which means minimal delays and minimal inconvenience to passengers (ProRail, 2014). The major parts that influence the quality and capacity of the train service are visualised in Figure 3.3. The first principle is that the infrastructure layout should be robust. The infrastructure should be designed for the main function which is conducting the regular daily timetable. A robust infrastructure layout must be able to deal with a certain number of delays without the need of a disruption management strategy. Therefore, timetable robustness means the effectiveness of timetable adherence after a certain disruption (Goverde, 2005). The second ring in Figure 3.3 is about reliable assets meaning that the reliability of the present infrastructure and rolling stock should be high and as a result of that there are few disruptions.

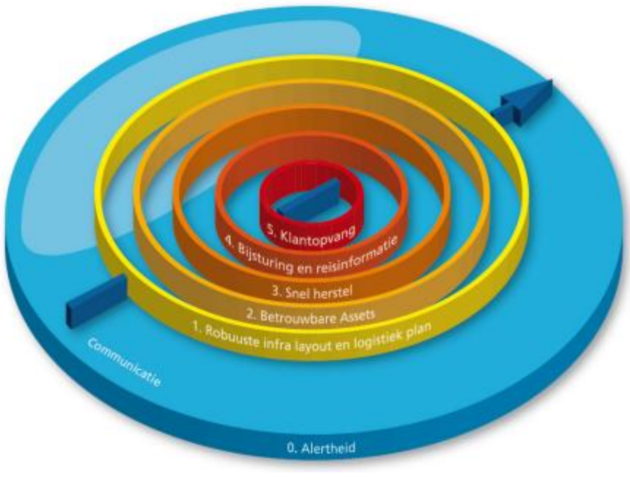

Figure 3.3: Robustness railway system (ProRail, 2014).

The third principle is that the recovery of the system in the event of a disruption takes place quickly. Then, the fourth is about the disruption management and the fifth about how passengers should be accommodated when train traffic is disrupted. This thesis is about the first (switch locations), third (fast recovery) and fourth (disruption management) principles of Figure 3.3. How disruption management takes place in the Netherlands will be further elaborated in this subsection.

ProRail has made a philosophy for the disruption management (DM) and what should be done in each different case. Table 3.1 shows a translated version of the overview of the disruption management philosophy.

Table 3.1: Overview of disruption management philosophy in the Netherlands (ProRail, 2014) - translated by author.

Underlying goal	DM philosophy	DM principle	Elaboration
Undisturbed travel	Prevent that DM is necessary	• Robust logistics plan for small disturbances • Low disruption chance • Fast system recovery	
Reduce time to intervention and recovery time …	Aim is to achieve optimal performance of a corridor	• Corridor DM is responsible for controlled process on corridor • Decide on time for DM • Match actual demand versus actual capacity • Actualize control goals	• Deaerate in time (preventive cancellation) • Acceptance of order (rerouted trains, empty rolling stock etc.) • Overview of actual riding possibilities (disruptions, construction works etc.)
… and reduce delay propagation.	Control oil slick effect	• In DM, no merging of corridors that are regularly separated • Do not reroute trains via other railway lines (only international trains) • Cancel trains or trains depart according to original timetable • DM only in "decoupling points"	
	Design infra for its main function	• DM services may not hinder main functions	
	Only invest in additional infra used for DM if there are positive costs and benefits	• DM uses as much as possible infra that is needed for main function • DM services only in "decoupling points" and "diverging points"	

In addition to Table 3.1 there is a specific version for cargo trains which is not relevant for this research. For international trains predefined rerouting options should be ready in case the railway undertaking needs it. Table 3.1 denotes some difficult words that need some explanations. Decoupling points are needed at every corridor and express the stations where passengers still can go to during disruptions and where trains could change their direction by using switches. At these locations it should also be possible to let Intercity trains overtake slow Sprinter trains by delayed Intercity trains. Moreover, these stations are important to deaerate the railway line which means that the trains can be cancelled because of problems downstream and that these trains are able to short turn and go back to their origin.

Decoupling points are already predetermined in the Netherlands. There is a list of all train stations in the Netherlands and a corresponding column if the station is just a stop, a Sprinter decoupling point, an Intercity decoupling point or a turning station. The larger a station is, the more important it is that the station still can be used in case of a disruption. With larger, the number of passengers is meant, as well as passengers that change trains. If a station is smaller but has important bus connections which connects with a big area which is highly populated, it is also important that the station can be used as a decoupling point. Intercity decoupling points are Intercity stations with a lot of passengers and in case of a disruption that station should still be used by Intercity and Sprinter trains. For Sprinter decoupling points the same applies, however, in case of a disruption these are requested only to be used by Sprinter trains. All other train stations are just called ‘train stops’ and during disruptions it is aimed that these are used as much as possible. Some of these stops can become a turning station during a disruption. It is then possible to bring passengers closer to the location of the disruption than if only the decoupling points are being used. As the name suggests, trains can change their direction of travel at turning stations, but there are not everywhere diverging switches available. Diverging switches, or in Dutch ‘overloopwissels’, are two switches directly after each other allowing trains to change to the other track and immediately going back to the track the train came from (Historische collectie Nederland, sd) (Gutter, 2016).

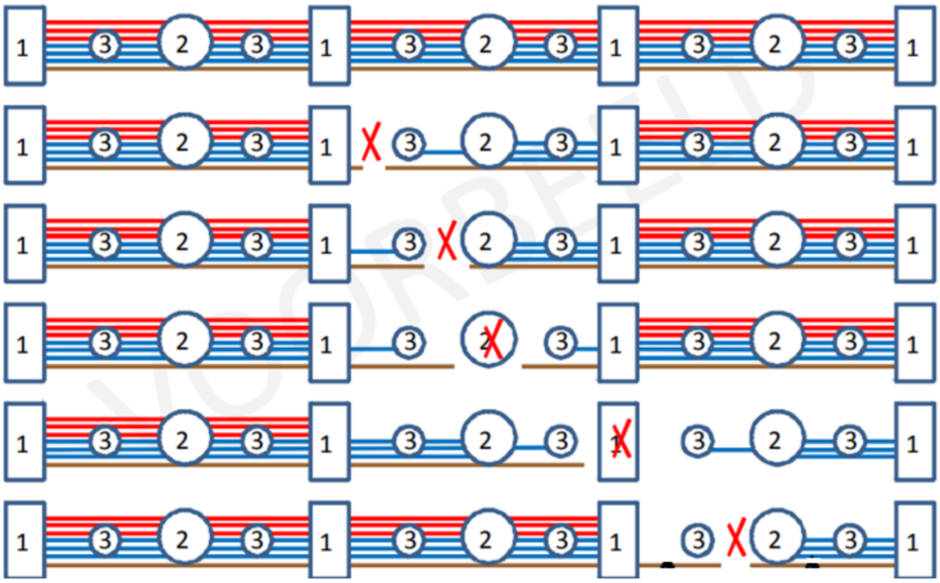

Figure 3.4: Decoupling points, turning stations and stops (ProRail, 2014).

Figure 3.4 shows different variants of disruption locations and how and where trains are short turned. The rectangles are the Intercity decoupling points, the big circles are the Sprinter decoupling points and the small circles with the ‘3’ inside are the regular stops with turning possibilities. Although cargo trains are not examined in this research, they can be seen in Figure 3.4 represented by the brown lines. Cargo trains are waiting close to the disruption, as short turning does not make sense. The red Intercity trains are all changing their direction at the bigger stations and Sprinter trains are either short turning in the bigger and sometimes in the smaller circled stations. The frequency of the trains is indicated by the amount of lines. Every line represents a train service per 30 minutes which means that six Intercity, six Sprinter and two cargo trains per hour are running. Figure 3.5 shows a map of the Netherlands with all decoupling points that can be used for the disruption management. International trains are being rerouted if possible and for this there are also plans available in case an

ICE or Eurostar cannot use the tracks between Utrecht and Arnhem or Rotterdam and Amsterdam for example. This rerouting strategy is depicted in Figure 3.6.

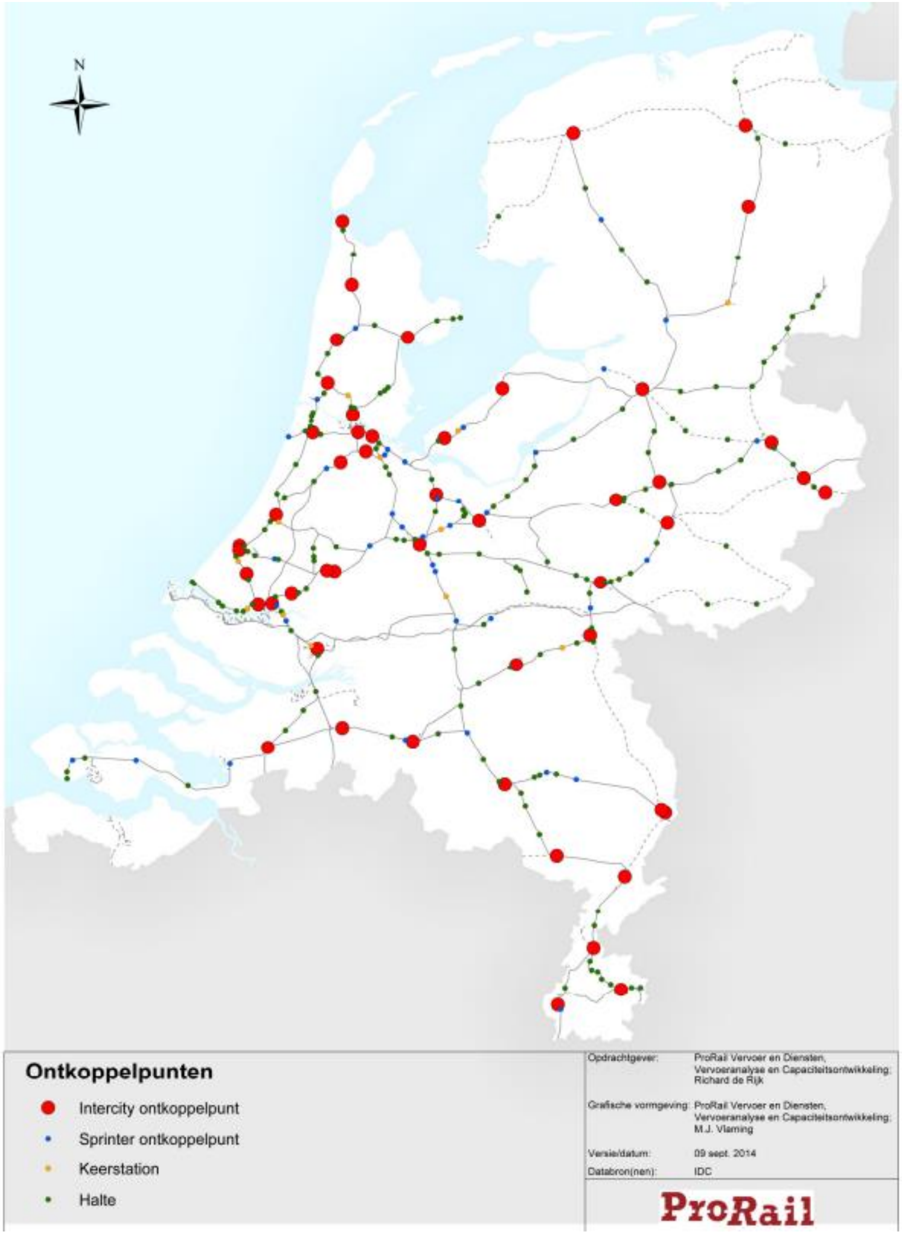

Figure 3.5: Decoupling points (ontkoppelpunten) in the Netherlands in 2014 (ProRail, 2014).

Figure 3.6: Rerouting options for international trains (ProRail, 2014).

The Dutch disruption management can be summarized with the following points:

- In case of partial blockages on lines with low or average frequencies the goal is to operate 50 percent of all trains.
- In case of partial blockages on lines with high frequencies (10-12 trains per hour) the goal is to operate a maximum of four trains per hour per direction.
- Due to balance constraints, the number of trains in both directions should be equal.
- For deaerate sidings and turning tracks are essential.
- Alternatives are being designed for passengers to have at least one train per hour per type of train (Intercity or Sprinter) towards the final decoupling point before the disruption location.
- When on a certain train line trains are being cancelled this should be done in both directions.
- Through passengers with Intercity trains should use other train lines to bypass the disruption.
- Sprinter passengers are transported to the final Sprinter decoupling point.
- Long train lines are more important than short train lines, although the capacity of the trains should be considered as well.
- If a train turns at a decoupling point, the train remains of the same type (Sprinter remains Sprinter and Intercity remains Intercity).

- A train from the Randstad area may leave 15 minutes late from timetable to be able to have higher capacity during the disruption.

During a disruption it is also possible that at another location a different disruption takes place and that the second disruption influences the strategy applied. In such cases, it is more difficult to find the best solution. By using the models that are described in section 3.1.2 this can possibly be solved.

3.2. Interviews

There are more than 6000 switches in the Netherlands (ProRail, 2023). It is important to examine the pros and cons for having more or less switches accurately which will be done by conducting interviews with eight people from Royal HaskoningDHV (4), NS (2), RailExperts (1) and ProRail (1) that have a strong expertise in rail switches. To obtain the most complete impression of opinions, people that design the switch locations are asked, as well as the people that use the switches every day and who are always in the middle of the disruptions: the train drivers. Two passenger train drivers from NS are asked and one cargo train driver from RailExperts is asked to obtain insights from all rail users. Although crew rescheduling is not part of this research, it might be interesting to ask train drivers for their opinion how this can be improved which can be used for future research.

For the preparation of the interviews a list of topics and questions is made. During the conversations new questions arose, but these were mainly about these three topics:

- The renovation of Utrecht Centraal and the removal of 108 switches
- Current disruption management in the Netherlands
- Weightings and threshold values for the in chapter 5 defined key performance indicators

Before the first person was asked if he or she wants an interview and participate in this research it is important to follow the Ethics regulation of the TU Delft. For this, three forms were required to be filled in and finally to get approval by the TU Delft Human Research Ethics committee in accordance with the TU Delft Research Data Framework Policy. These include a Human Research Ethics Checklist (HREC), an informed consent and a Data Management Plan (DMP). The informed consent can be found in Appendix D. The results from the interviews are given in sections 3.2.1, 3.2.2 and 3.2.3.

3.2.1. Renovation of Utrecht Centraal and the removal of 108 switches

The station Utrecht Centraal was renovated until 2016 and the most important difference is that trains are now running in corridors. The number of switches was reduced from 167 to 59 and the punctuality of Utrecht Centraal increased from 88.5% to 92%. These are facts and are confirmed by all interviewed experts. The corridors are visualized in Figure 3.7 in which all lines represent a corridor that are all disentangled. For example, an Intercity from Rotterdam to Amersfoort (yellow line) should not wait anymore for a red signal for the crossing Intercity from Amsterdam to Nijmegen, but can now use the built fly-overs. An advantage from using these corridors is that a delay of a certain train in a specific corridor stays in that same corridor and does not influence trains on other routes which was in the previous Utrecht Centraal often the case. Trains can also enter the station at higher speed which also influences the follow-up times on the platform tracks. Some trains however have a long dwell time enabling connections to other trains. This is irritating for through passengers and also for train drivers if they have a stop of 7 or 8 minutes.

Figure 3.7: Corridors at Utrecht Centraal (De Ingenieur, 2016).

When a disruption happens on a difficult location, for example a broken train in the station or on one of the switches in front of the station, there are very few options to reroute trains which indicates that this station would score poor on flexibility. ProRail has actually gone to the limit with the removal of switches and some experts including train drivers said that some (partly crucial) connections are missing (Sporenplan, 2023):

- An Intercity from Amersfoort can only short turn at track 9
- An Intercity from Amsterdam can short turn via the Sprinter tracks 14 and 15, although capacity there is not sufficient to accommodate all Intercity trains and the Sprinter corridor is impacted by this short turning as well.
- If tracks 20 or 21 are closed, trains cannot ride on the whole route because there are no alternative routes on the tracks towards Utrecht Centraal.
- From Arnhem/Nijmegen there is no direct train service towards Rotterdam/Den Haag.

Also during construction works or in case in the future a new timetable model is supposed this is hard to achieve because these corridors are fairly fixed. Adding switches at the tracks towards Utrecht Centraal would create some redundancy. A few experts mentioned the differences between the Dutch and Swiss rail network including the infrastructure. In Switzerland trains are almost all day long riding on full capacity while in the Netherlands NS apparently conducted research into the expected number of passengers for each train. This results in coupling and decoupling before and after rush hours requiring extra train drivers for these shunting movements. In Utrecht Centraal these shunting movements are difficult because the train yards can only be reached from certain platforms. From train yard Cartesiusweg most of the trains should go via tracks 20 and 21 which is difficult because those tracks are also used 6 times per hour. If only one small thing happens, things are going wrong and trains are stacking.

3.2.2. Disruption management

Both NS and ProRail aim to have a high predictability for their passengers and staff and for that reason pre made contingency plans are constructed. For all different kind of disruptions on different locations it is already clear i.e. which train series are being cancelled, where trains will short turn and which stations will be skipped or will have an additional stop. Also the total delays will stay low as there are still many margins in the timetable. However, six out of eight experts said that during a disruption it is most important that trains are still running and these experts have the same opinion that trains are being cancelled too easily. Comparing to Germany where Deutsche Bahn almost does not cancel trains at all and continues train journeys with very high delays is not a solution either. A solution somewhere in between would be great, because it is most important that passengers arrive at their destination. Passengers would rather arrive late at their destination than do not arrive at all if the train is cancelled. If a disruption takes multiple hours it could be a solution to couple trains to increase capacity, but in case of a 1 hour disruption this is too comprehensive. Also trains that only run between two (larger) stations during a disruption could be a solution, eventually in combination with the longer trains as mentioned before. This also ensures that punctuality far away from the disruption is not influenced, but this option would also result in chaos when passengers are required to change trains at stations that are probably even not large enough to accommodate all these amounts of travellers.

Many experts mentioned Utrecht Centraal again as problem in the discussion if NS is cancelling trains too easily. If there is a disruption near Abcoude (between Utrecht and Amsterdam) all Intercity trains from the south will short turn at 's-Hertogenbosch or even already at Eindhoven and from the east these will short turn at Arnhem. This means that these trains are cancelled in Utrecht and passengers that are going from the east or the south to Utrecht are hindered by a disruption that is even not on their route. This is also the case when the disruption is for example in Veenendaal or Zaltbommel. Most of the trains from Amsterdam Centraal or Schiphol are short turning at Bijlmer ArenA or are even completely cancelled where only a small part is able to short turn at Utrecht Centraal by using the Sprinter tracks 14 and 15. Potential solutions are to short turn at Driebergen-Zeist and Houten Castellum in this example, but during renovation the tail track of Driebergen-Zeist is made not long enough for the longest Intercity which is not a clever option as all experts mentioned.

3.2.3. Removal of switches in the Netherlands

The more switches, the higher the flexibility, but more switches also increase the costs for constructing, building and maintaining. The number of switch failures is not that bad and has decreased by the past years. Because of using not complete contracts between ProRail and contractors certain important parts of maintenance were skipped, but this has become better and therefore the sensitivity to interference has decreased. The story that switches cause disruptions is actually high spreadsheet management. If switches are maintained better, they will break down less.

In the Netherlands trains are running in many different corridors and that is why in Utrecht Centraal so many switches were removed without causing big problems during the regular undisturbed timetable. If a switch is not used at all in regular service or only in very few cases ProRail decided to remove those switches decreasing flexibility and resulting in problems in case of a disruption.

Looking at Utrecht Centraal it is obvious that the number of switches in the old situation was too much, but nowadays certain connections are missing and a few more switches to change tracks in case of a disruption would have been better. Especially if the number of switches is low, it is really important to keep all infrastructure maintained well. The location of the switch is also important and thus the required amount of regular checks and maintenance. The so-called 'King-switch' at Utrecht Centraal dividing the IC track from Amsterdam into platform tracks 18 and 19 is more important than a switch in rural area, for example in Krabbendijke. For ProRail, on the other side, the costs are really important as ProRail has a limited budget from the government. For that reason it is understandable that they tend to remove switches, but to keep flexibility high (or make it higher in case of Utrecht) the budget for ProRail should increase. This will lead to higher flexibility during disruptions and also the possibility of changing corridors in the future.

3.3. Conclusions literature review

In literature twelve articles were found about disruption management strategies in different countries, e.g. 'Handleiding specificeren bijstuurinfra' from ProRail (2014), Jacobs (2003), Gerrits & Schipper (2018) and Network Rail (2023). Also, papers with specific topics that are related to this research, but that are out of scope, were found. These papers were about crew rescheduling or train rescheduling and did not mention the relationship between resilience and switch location configurations. Yin et al. (2016) and Fikar et al. (2016) studied the impact of disruptions in a suburban railway system and on the Brennerpass while Mo et al. (2022) predict the impact of disruptions on passengers using stay ratio and travel delay as metrics and concluded that disruptions have high impact on train service.

Some papers studied the performance of short turning which is necessary in case of a blockage of the tracks. Ghaemi (2018) showed that multiple short turning stations might be a solution when a low penalty is given to cancelling trains. A timetable rescheduling model is proposed in Zhu & Goverde (2019) including flexible stopping, short turning, retiming, reordering and cancelling trains. Zhu & Goverde (2021) discovered a multiple-disruption rescheduling model which reschedules all trains during multiple disruptions and this resulted in less delays and cancelled trains compared to a sequential approach solving all disruptions one by one. All these models make use of the current infrastructure and were not looking at the switch locations and whether these could be improved. Unfortunately, no articles were found that investigated the relationship between switch location configurations and resilience which also answers the sub-question. This means that there is a literature gap as this has never been researched before and this research will try to fix this gap.

Several key performance indicators were introduced in section 3.1.2 and a summary of the in section 3.1.2 useful indicators to measure resilience quantitatively can be found in Table 3.2. In chapter 4 the KPIs are defined that are used in this research including the methods for the weightings and how the different switch location configurations are evaluated against each other.

Table 3.2: Key performance indicators from literature.

KPI name	KPI definition	KPI unit
Costs of infrastructure	The amount of costs for designing, constructing, building and maintaining new switches, crosses, signals. Zero if no changes are made (Ling, 2005) (Vitásek & Měšťanová, 2017) (ProRail, sd).	Euros (€)
Infrastructure occupation	The share of time required to operate trains on a given railway infrastructure according to a given timetable pattern and can be computed using the timetable compression method. Maximum 75% for mixed traffic or high-speed lines, maximum 85% for suburban lines. Both during peak hours which is part of the topic of this research (Goverde & Hansen, 2012).	Percentage (%)
Platform consistency	The sum of the total number of trains that did arrive at the planned platform and the planned track divided by the total number of arrived trains. This KPI can be divided in two parts: the first will be the consistency compared between normal and disrupted timetable and the second part will be the platform consistency during the downsized timetable. Goal is to keep the consistency high, if possible above 75% for both sub-KPIs (Lo, Pluyter, & Meijer, 2015).	Percentage (%)
Rate of actual departures*	The number of actual departures divided by the total number of departures. This value is aimed to be higher than 95%	Percentage (%)

	(ProRail, 2024). During a disruption it is still the goal to have a reliable timetable, nevertheless downsized to at least 50% of the trains still running (Hofman, Madsen, Groth, Clausen, & Larsen, 2006).	
Punctuality	The number of trains that arrived maximum 5 minutes after arrival time divided by the total number of arrived trains (including cancelled trains). This value is aimed to be higher than 91.5% (ProRail, 2023) (Nicholson, Kirkwood, Roberts, & Schmid, 2015) (Goverde & Hansen, 2012).	Percentage (%)
Timetable feasibility	The amount of scheduled train paths conflicts with a norm of zero conflicts (Goverde & Hansen, 2012).	# conflicts
Capacity*	It is the maximum possible number of trains per direction which can cross a certain section (Goverde & Hansen, 2012) (Calvert & Snelder, 2017) (Nicholson, Kirkwood, Roberts, & Schmid, 2015).	# trains per direction
Number of alternative routes	The number of available alternative routes (on a line or at a station) in case of a disruption, where a higher redundancy is better (Calvert & Snelder, 2017).	# alternative routes
Time to recover	The time between the delay of the system increasing above a small threshold value, and it returning below this threshold (Nicholson, Kirkwood, Roberts, & Schmid, 2015).	Minutes

*It is good to make a distinction between two types of disruption for these two key performance indicators: rate of actual departures and capacity. Figure 3.8 distinguishes a full blockage in the upper situation and in the bottom one situation where there is still one track available between stations B and C. Considering rate of actual departures as a KPI where during a disruption still 50% or more trains are desired, this would be the case between station A and B, as well as between stations C and D, because between B and C no traffic at all is possible. The other 50% of the trains should then be able to short turn at stations A and D. In the bottom situation with a partly blocked line, at least 50% is desired between B and C, while between A and B and between C and D it is the goal to have no cancellations. Switches are not drawn in the figure but are available to use the single available track between B and C in both directions. Short-turning for Intercity trains only takes place at Intercity stations, while Sprinter trains should be able to short-turn at Intercity stations or bigger Sprinter stations and not at the smallest train stations as these probably might have very few passengers impacted by the disruption, causing too much spendings on infrastructure for only small change in impact.

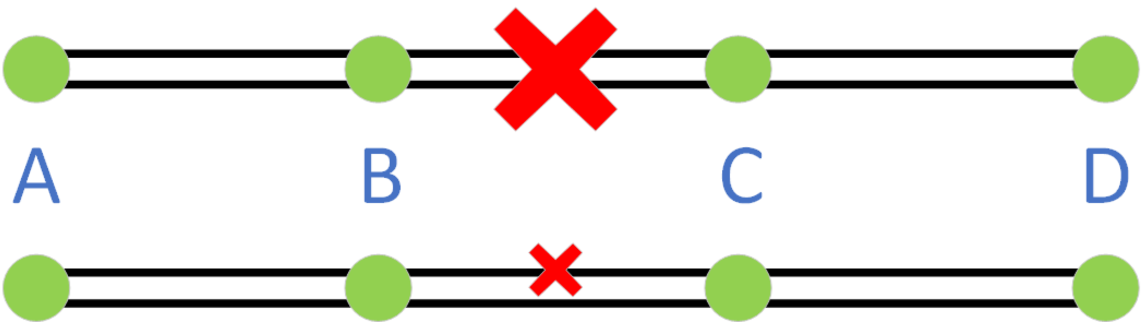

Figure 3.8: Distinction between fully and partly blocked lines.

4. Analysis of disruption events

In this chapter the results of the disruption analysis will be analysed and an answer to sub-question 3 will be given: *How can different types of railway disruption affect railway operations related to switch locations?* The complete Python code can be found in Appendix B. This chapter is divided into four subsections. First, the database of disruptions is explained and some general graphs and maps are made. Section 4.2 explains TIS codes identifying the impact of a disruption. Next, section 4.3 shows the results of the analysis and in 4.4 conclusions of this analysis are drawn.

4.1. Database of disruptions

ProRail is the Dutch railway network manager and has a big database with all events that happened in the past. All disruptions including cause, duration and more are stored in one database at ProRail (ProRail, 2023). Since the database may contain sensitive data because of details describing a collision, for example, the data is not made public. Special arrangements are made: the not-sensitive part of the data is made available for the research and the data will only be used for this research. After finalising the disruption data analysis three aspects can be acquired. Firstly, an attractive area for the case study can be chosen. The line Warffum to Usquert is accordingly not a good example because of the low frequency on that line. It should be an area with high impact if a disruption takes place. In the later stage of the model where simulations are executed it is especially interesting to expose how switches can help to decrease the impact of all disruptions. The second aspect that can be obtained is the locations of the tracks that should be blocked during the simulation phase of the model. Based on the big database with disruptions from the past seven years and the exact locations of the disruptions by means of coordinated some so-called hotspots of disruption locations can be found and used. The final thing that is useful for this research from the analysis is the impact of each disruption. It is possible that there is a line with not that many disruptions compared to other lines but if a disruption takes place, the impact on train traffic is tremendous which is interesting to investigate. There are probably an endless number of conclusions possible, but only the outcomes relevant for this research will be mentioned.

The database coming from ProRail contains data from 18 June 2017 until 6 December 2023. In these 6.5 years of data almost 140,000 disruptions happened with 87 different reasons for the disruptions. The pie chart in Figure 4.1 shows that a broken train has the highest chance of causing a disruption.

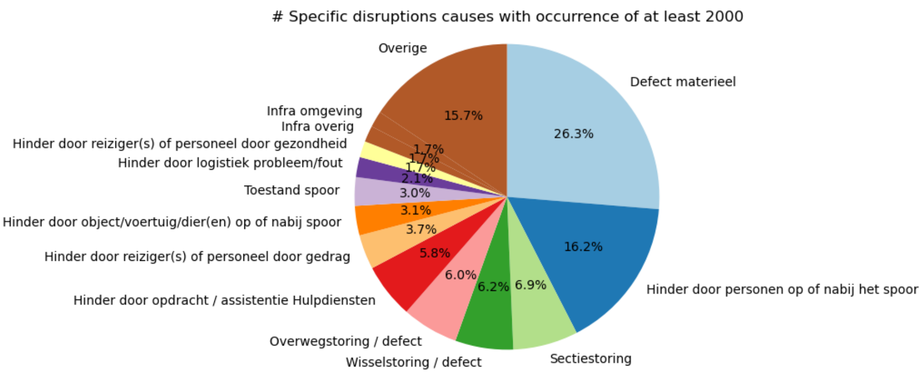

Figure 4.1: Disruption causes in percentages (ProRail, 2023).

More than 20,000 disruptions were caused by persons at or nearby the tracks as can be seen in Figure 4.2. This is different compared to the graph coming from 'Rijden de Treinen' which is shown in Figure 4.3. 'Rijden de Treinen' only uses the disruptions that have impact on multiple trains, while in the ProRail dataset also small disturbance caused by passengers are included increasing the number of occurrences of persons at or nearby tracks in Figure 4.1 and Figure 4.2. The exact number of occurrences of all disruption causes can be found in Appendix B. As can be seen, Figure 4.2 uses ‘section failure’ instead of ‘signal failure’. A section failure results in a red signal because the system thinks a train uses the next section/block. In Figure 4.3 these failures are counted as signal failure.

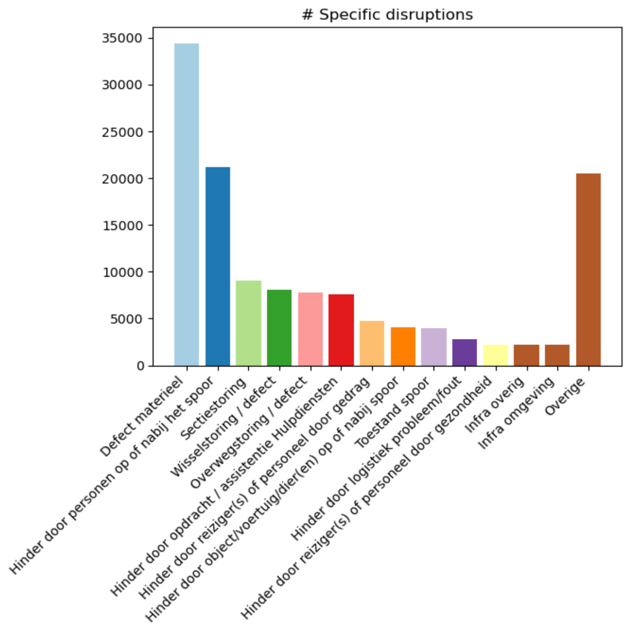

Figure 4.2: Disruption causes in absolute numbers (ProRail, 2023).

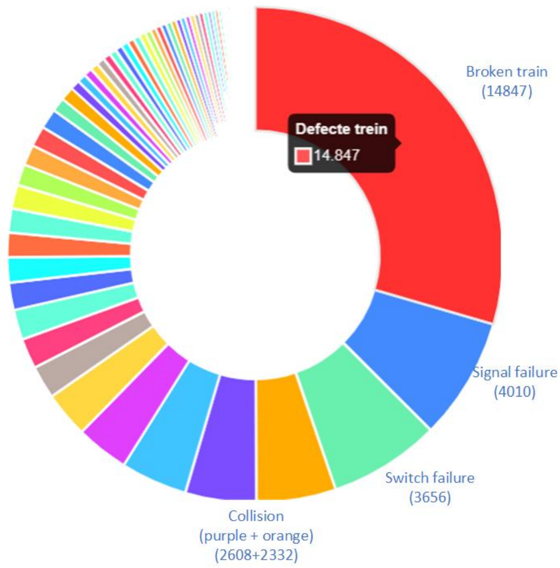

Figure 4.3: Disruption causes (Rijden de Treinen, 2023).

To get insights where these broken trains, signal failures, persons at or near tracks or other types of disruptions take place, a map of the Netherlands with all disruption locations is required. This map can indicate at which type of infrastructure (single track, double track, stations with specific characteristics) disruptions take place more often than on other locations. Due to the huge database a map indicating all locations of disruptions appeared to be completely full of dots on all railway lines (Figure 4.4). Even disruptions on railway lines that are only used for steam trains or by trains in the Efteling theme park are marked on the map.

Figure 4.4: All disruptions in the Netherlands (June 2017 – December 2023) (ProRail, 2023).

4.2. TIS codes

As the cause and the impact of the disruptions are unclear in Figure 4.4 new graphs were made where the data was filtered. The impact of a disruption can be categorized by using TIS codes and these are explained in Table 4.1. TIS stands for 'Trein incident scenario' which can be translated to Train incident scenario.

Table 4.1: ProRail TIS codes (ProRail, 2023).

	Very limited Light green	**Limited** Yellow	**Serious** Orange	**Very serious** Red
TIS 1 **Disruption train service**	**TIS 1.1** More than 30 minutes delays of more than 5 minutes	**TIS 1.2** More than 30 minutes delays and cancellations	**TIS 1.3** Total blockage. Train service is not possible	**TIS 1.4** Total blockage. Train service not possible in area or busy junction
TIS 2 **Fire**	**TIS 2.1** Fire on the tracks with possible influence on train traffic, like a verge fire	**TIS 2.2** Small fire in a train or at a station. Garbage bin. Burning smell in train.	**TIS 2.3** Big fire in train. Compartment or raging fire	**TIS 2.4** Big fire (with unknown magnitude) in station or tunnel
TIS 3 **Collision & Derailment with victims**	**TIS 3.1** Collision train with: person, big livestock, moped rider, cyclist, infrastructure element	**TIS 3.2** Collision with shunting part or small road vehicle	**TIS 3.3** Derailment with victims or collision with other train or big road vehicle	**TIS 3.4** Derailment with victims or collision with other train or big road vehicle causing (part of) the train to tilt or deform
TIS 4 **Dangerous materials**	**TIS 4.1** Incident with dangerous materials where the danger is limited to the source area	**TIS 4.2** Fire involving hazardous substances	**TIS 4.3** Gas release with health hazard outside the source area	**TIS 4.4** Spill or leakage of hazardous liquids with health hazard outside the source area
TIS 5 **Suspicious behaviour, bomb threat**	**TIS 5.1** Anonymous bomb threat. Suspicious behaviour or object along the tracks	**TIS 5.2** Suspicious object or bomb discovery in a train or along the tracks	**TIS 5.3** Suspicious object or bomb discovery in train at station or in a tunnel	**TIS 5.4** Bomb explosion in a train, station or tunnel

4.3. Results of disruption analysis

Figure 4.5 shows all switch failures and Figure 4.6 shows all broken trains where the colour indicates the impact of the disruptions. These colours correspond to the last number of the TIS code as mentioned in the first row of Table 4.1. The radius of the circle markers increases linearly since certain switches have failed more often than others. The bigger the circle the more switch failures on that location took place. The big red circle near Amsterdam is a switch at the Watergraafsmeer train yard that broke 172 times and impacted rail traffic a lot by looking at the colour. Analysing Figure 4.5 and Figure 4.6 is easier than Figure 4.4 as the map is clearer, although for drawing conclusions a zoom in function is recommended. Since many switches have failed multiple times, the colour is based on the TIS codes that occurred most. The colour of the switch failure at Amsterdam Watergraafsmeer indicates 172 times a 'red' TIS value, but there are also other colours for that switch. However, that specific switch had most of the time a TIS value of 1.4 giving it a red colour. By looking at the dataset this switch indeed broke often, but on many days this switch was indicated as broken multiple times. This switch failed actually for almost a half year and has had one other failure that was independent from that.

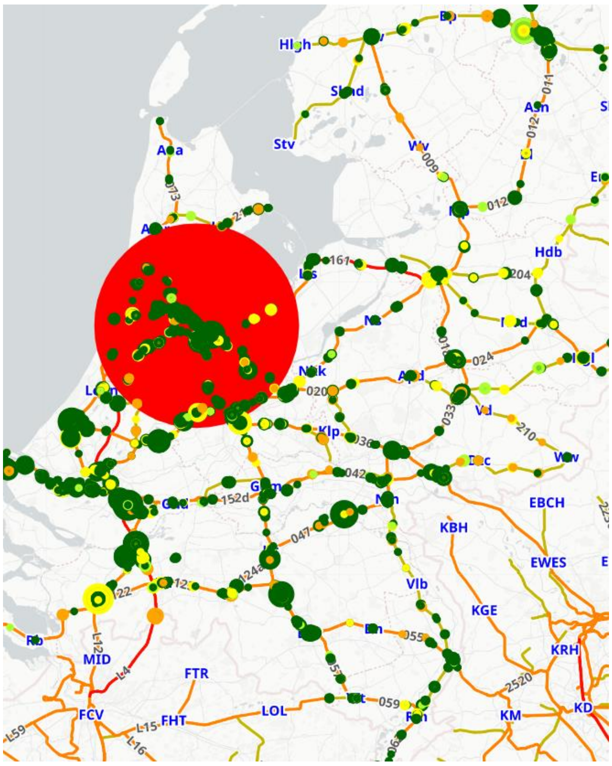

Figure 4.5: All switch failures with TIS code and number of occurrence.

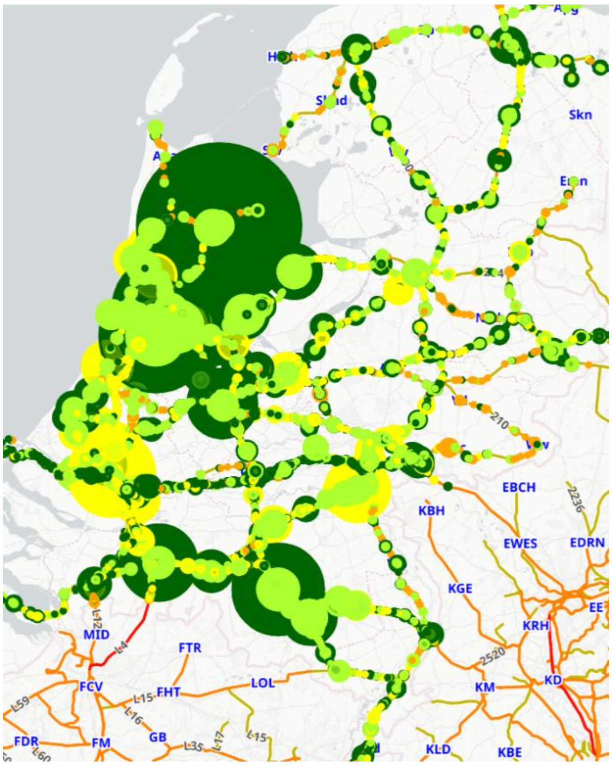

Figure 4.6: All broken trains with TIS code and number of occurrence.

By examining the two maps it can be concluded that disruptions on the side lines in the East and North of the country have more orange circles meaning that the disruption that takes place there have a higher TIS value and thus a higher impact. However, the impact on the number of passengers is less than when the same disruption takes place in the Randstad area, but there is no tap in tap out data available and therefore it is not possible to combine passenger numbers with the disruptions causes and TIS values. When a disruption occurs on one of the side lines, which contain mostly only one track, the impact for (only) that line is higher as train services is faster completely stopped. This is because the flexibility, the number of possibilities for enabling trains to change routes by switching from one track to another, is lower on lines with one track than on lines with multiple tracks, larger stations and more switches. The TIS .4 value is therefore more related to completely stopped train traffic (as stated in Table 4.1) and thus higher impact than on the number of passengers affected by the disruption. The number of passengers, nevertheless, is also related to the impact and for that, only lines in the Randstad area should be looked at since a disruption on a line in that area immediately affects many passengers. In Appendix B more maps like Figure 4.5 and Figure 4.6 but with different disruption causes can be found.

The very big circle with 192 times people were at, or very close to, the tracks in Vught as can be seen in Figure 4.7 is green, however it has had probably more impact on train services between Utrecht and Eindhoven than the colour shows, as this location also includes yellow, orange and possibly a few red TIS values. When zooming in on this map even more it can be seen that these persons near or at the tracks are not only in the station areas, but happen also often between stations and especially at railroad crossings and foot paths parallel to the tracks near larger stations.

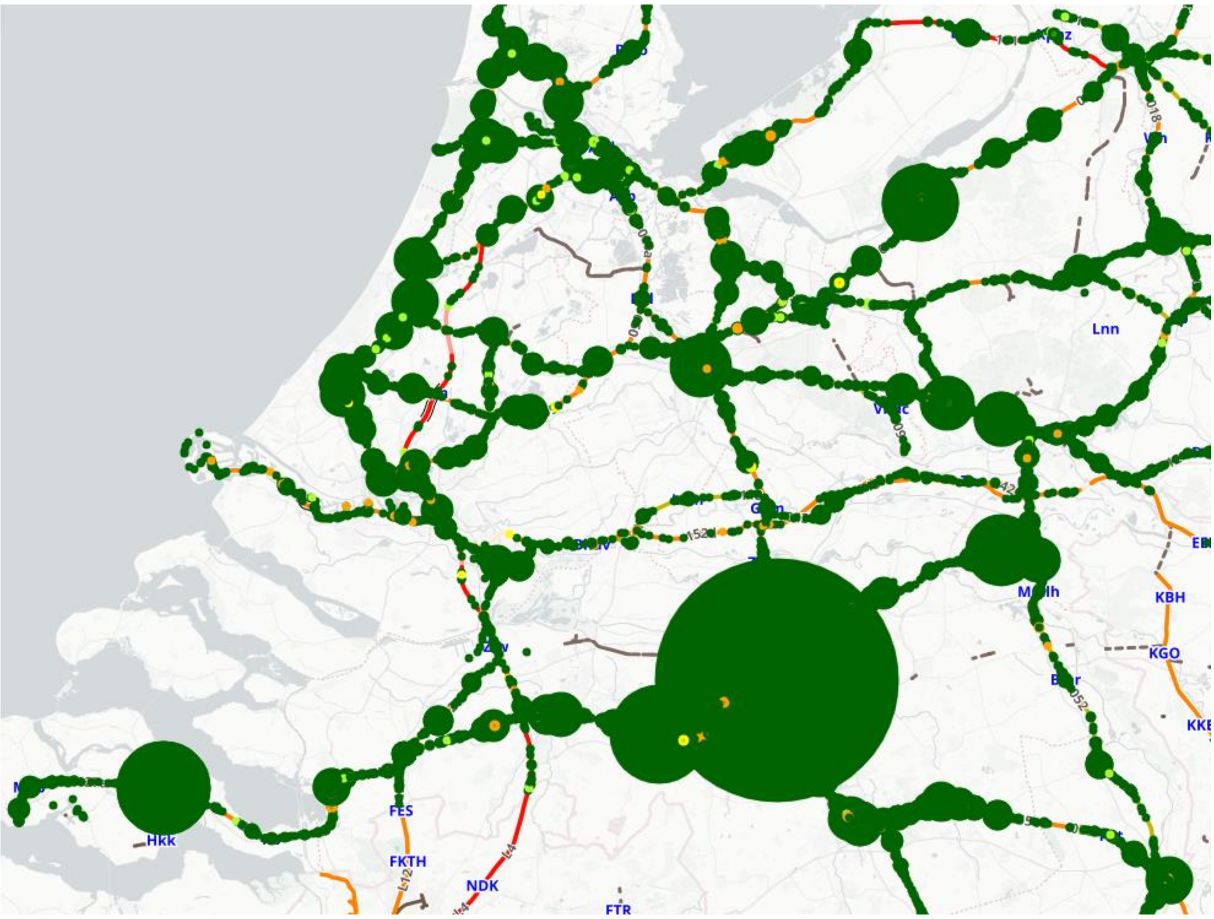

Figure 4.7: Persons near or at the tracks.

The database also contains information whether the railway line was completely or partially blocked which is shown in Figure 4.8, where red means a completely blocked and yellow partially blocked. Checking the area around Vught, which has a big green circle in Figure 4.7, the circle almost disappeared in Figure 4.8 concluding that probably most of these disruptions only caused small delays and not a lot of complete blockages of the railway line.

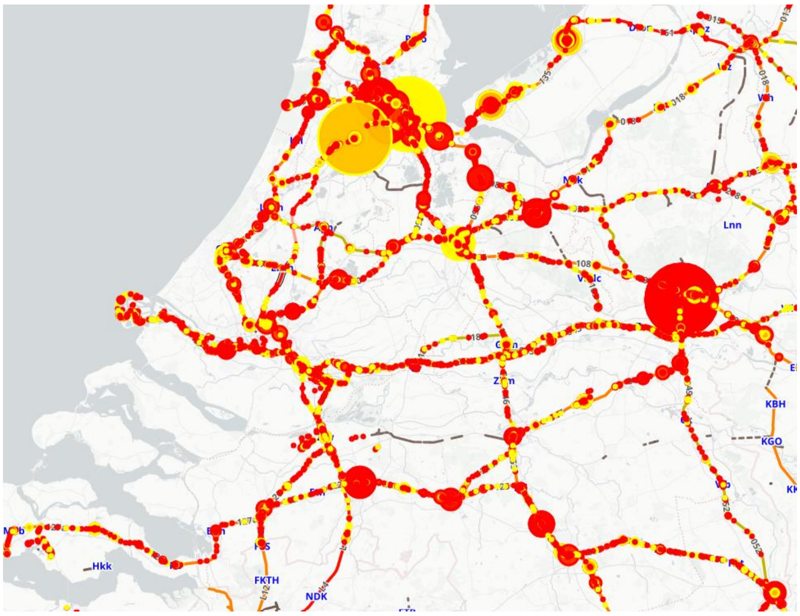

Figure 4.8: Map with blocked lines and number of occurrences. Red = completely blocked; yellow = partially blocked.

When zooming in into all lines to and from Utrecht Centraal the map can better be investigated as can be seen in Figure 4.9. Around Utrecht Centraal, Driebergen-Zeist, Breukelen and Den Dolder there appear to be more disruptions than on other stations.

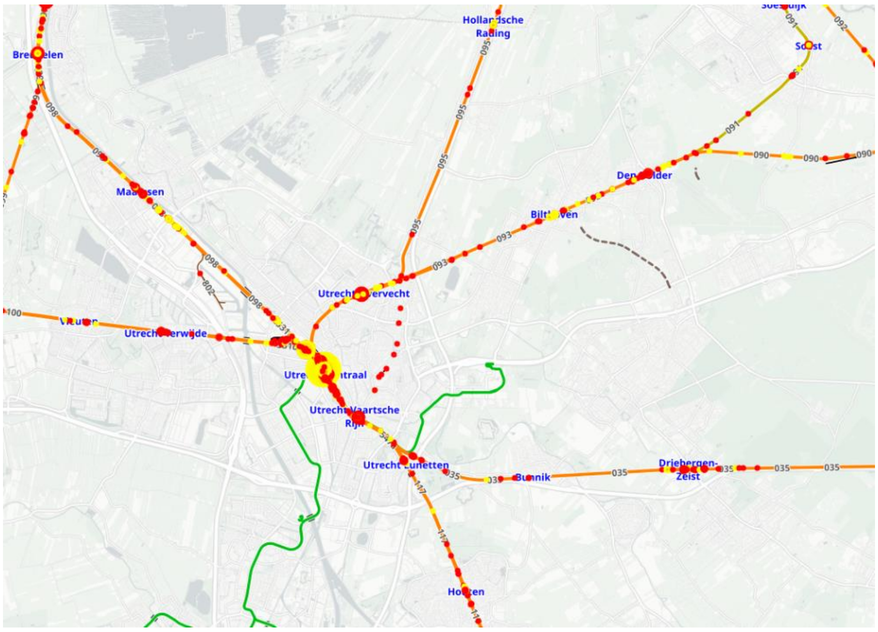

Figure 4.9: Map with (partially) blocked lines and number of occurrences zoomed in.

Some other locations where disruptions often have provided complete blockages are on the bridge over the Rhine between Arnhem and Nijmegen, in Hoorn Kersenboogerd and at four locations in Amsterdam. Other locations, also for partial blockages are at and near larger stations and junctions. Often the reason for these blockages is a broken train as can be seen in Figure 4.10, like the big green circle at Hoorn Kersenboogerd and also at three stations in Amsterdam: Schiphol Airport, Amsterdam Zuid and Amsterdam Sloterdijk. The fourth big circle in Figure 4.8 near Amsterdam is at Watergraafsmeer which is caused by one specific switch as can be seen in Figure 4.5 that failed for 172 days in total. Appendix B shows a zoomed in version of the map close to Amsterdam Watergraafsmeer.

As can be observed in Figure 4.10 broken trains appear everywhere on the network but it shows that trains break down way more frequent in stations than somewhere else. Especially, the large stations have bigger dots which can be derived from the fact that trains have a longer dwell time and for energy savings trains may be powered off which can sometimes lead to problems if the trains do not switch on again. Since the dots for a broken trains at stations are larger than the dots in between stations but the amount of dots between stations are more prevalent, it is estimated that around 75% of the broken trains occur at stations and 25% between stations.

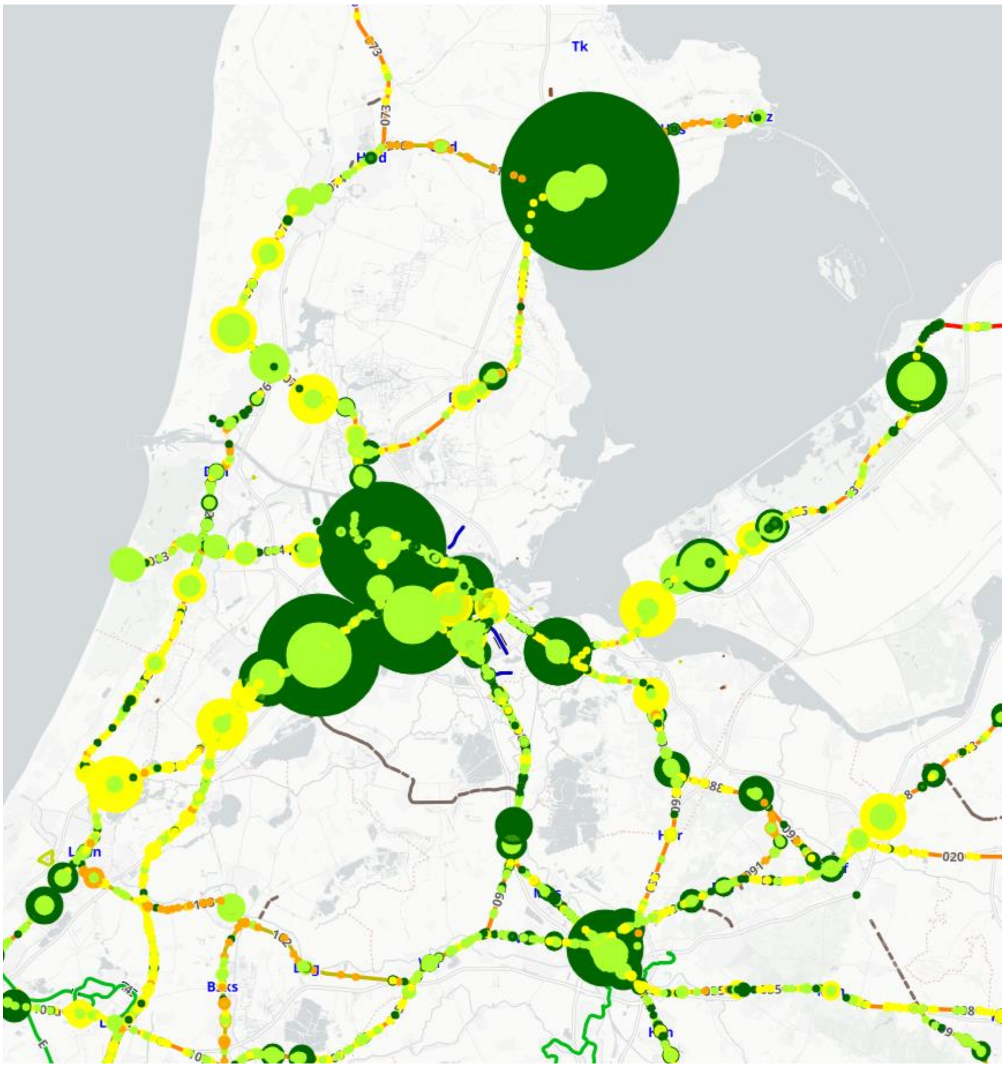

Figure 4.10: All broken trains with TIS codes and number of occurrences.

The high amount (170) of total blockages of the railway line between Arnhem and Nijmegen is caused by exactly 170 collisions with a person. It happened on the northern side of the railroad bridge Oosterbeek and impacted train traffic a lot. The amount is so high compared to all other collisions with persons that is causes doubts if this is not a mistake in the data as can be seen in Figure 4.11. When viewing the location in Google Maps using the coordinates it appears that there is no railway crossing, but only a small farm road next to the railway line. The exact location is already on the slope of the bridge, but people can possibly enter the tracks 110 meters from there by climbing a fence coming from the farm road. However, still the difference between the number of collisions near this bridge and at other locations is debatable, but when looking at the data there were exactly 305 days between the first and last 'collision'. The tracks were not 305 days closed because of 1 disruption so it is a mistake in the data or there was another problem with this bridge causing this many closures of it.

Figure 4.11: Collisions with persons.

4.4. Conclusions

As explained in section 4.1 three aspects should be derived from this disruption analysis. The first aspect is the railway line for the case study. A line with high frequent train service and many disruptions is interesting to investigate and especially to improve the locations of the switches to increase capacity during disruptions. However, since disruptions occur on all lines in the Netherlands but mostly in the Randstad area one of these lines will be chosen.

For the model that will be defined in chapter 6 it should be known where tracks should be blocked in the software indicating a disruption. The two most frequently occurring disruptions will be simulated and these are a broken train and people near or at the tracks. A broken train with an averaged duration of 1 hour will be simulated in the larger station and between two stations (Figure 4.10). People near or at the tracks will be simulated between two stations and will result in a total blockage of the line for two hours (Figure 4.7). This results in delays and cancellations since trains need to be rerouted or short turned which answers the second sub-question.

Disruptions take place near larger stations, junctions and more often at places where switches are located. For the latter, not always switch failures are the cause, but also signal failures and broken trains are common causes. Also, persons near or at tracks, the behaviour of passengers and to lesser extent collisions with people cause problems on the tracks and impact train service. Because of the big amount of data many conclusions can be drawn from this disruption analysis. This analysis can also be researched in more depth but that can be done in a follow-up study. It might be possible to adjust the infrastructure when a certain part breaks down often and if the reason for that can be deduced from the data. When looking at Figure 4.11 measurements can be taken to prevent any collisions with persons in the future at those locations. If the maps for all other causes of disruptions would be plotted similar conclusions could be drawn and the railway network could be improved leading to less disruptions.

5. Definition of key performance indicators to assess rail resilience

In literature, performance measures have been found how to measure resilience quantitatively as described in section 3.1.2. This chapter will answer sub-question 3: *Which key performance indicators can be used to quantitatively measure the resilience provided by a given switch location design configuration?.*

5.1. Key performance indicators

The key performance indicators derived from literature can be used to assess different variants of switch location configurations that are being simulated, but the overview with the available KPIs given in Table 3.2 shows some similarities between the KPIs. Infrastructure occupation, rate of actual departures and capacity all indicate in a different way how many trains run on the tracks causing biased results. To compare the number of trains during disruption and normal conditions it is chosen to use the inverse of rate of actual departures for the analysis which implies the rate of cancelled services including partial cancelled services. Infrastructure occupation is difficult as there are different maximum values for different kind of lines and capacity is difficult as it is not measured in a percentage. Also 'platform consistency' is included in the rate of actual departures as cancelled trains do not depart from their scheduled platform and therefore this KPI also gives partly the same results as rate of actual departures. For short turning, trains might depart from different platforms and this is annoying for passengers, but since passengers are out of scope for this research and the focus is on infrastructure the platform consistency will not be considered. Number of alternative routes is a KPI from road traffic, but is hard to compare different layouts (e.g. single track vs four track) regarding the number of alternative routes as a four track layout can have more alternative routes in case the switches are available. This KPI is therefore not chosen for further use in this research.

This implies that four key performance indicators are continuing and these are listed and explained in Table 5.1.

Table 5.1: Key performance indicators.

KPI ID	KPI name	KPI definition	KPI unit
1	**Costs of infrastructure**	The amount of costs for designing, constructing, building and maintaining new switches and crosses. Zero if no changes are made. This KPI is measured in the number of switches located in the configuration and not in a monetary unit. Costs are independent of the location. All switches cost the same amount of money. Horizontal and vertical alignment are out of scope.	# Switches
2	**Rate of cancelled services**	The number of cancelled services divided by the total number of scheduled arrivals. This is including partially cancelled services.	Percentage (%)
3	**Punctuality**	The number of trains that arrived maximum 5 minutes after arrival time divided by the total number of arrived trains (excluding cancelled trains).	Percentage (%)
4	**Time to recover**	The time between the delay of the system increasing above a small threshold value, and it returning below this threshold.	Minutes

For the calculation of the rate of cancelled services two types of cancellations should be taken into consideration. A train that is completely cancelled for the whole route is easy to calculate, but a partial cancellation is more difficult. In that case, the train is cancelled for i.e. 50 percent in case it did not arrive at 50 percent of the stations. The same applies to the punctuality which is calculated by looking at the arrival times of all trains at all stations. A train is considered to be not punctual if it arrives more than five minutes after scheduled arrival time. If a train arrives at 50 percent of the stations late at its route, this train has a punctuality of 50 percent. The summation of all trains gives the overall punctuality indicating the total number of delayed trains divided by the total number of train services during the disruption. The costs of building a 1:15 switch are around €255,000,- but to simplify the calculations the costs are measured in number of switches. The more switches the higher the costs for construction and maintenance (Royal HaskoningDHV, 2024). Time to recover is measured in minutes and this is the time between the system deviation increases above a threshold value until the deviation returns below the same threshold. In other words time to recover is the time between the start of the disruption and the time the downsized regular timetable has begun. The in chapter 3.1.1 introduced bathtub model contains a first chaotic phase and the duration of it is the time to recover.

5.2. Comparing different switch configurations with scores

There are several methods for comparing alternatives where some take more time and are more complex than others. A Cost Benefit Analysis is a tool to evaluate different alternatives against a single welfare criterion which is the net benefit (The Treasury, 2022). Since other criteria are also relevant this method is not chosen for evaluating the alternatives. Another method is the decision tree methodology which is a visual method where a diagram or a tree is drawn, and every alternative is a branch and all outcomes are a sub-branch. The most important steps at every node is to choose which branch to take and this can be done by asking a question where one of the KPIs can be used (Song & Lu, 2015). This method is complex and time consuming and does not really compare alternatives but makes the researcher choose an alternative based on yes or no questions (Linkedin, 2024). A method giving a score to each alternative which allows the researcher to compare and choose the best alternative is a multi criteria analysis (ipbes, 2024).

In a multi criteria analysis every key performance indicator or criterion should get a different weight and for this different methods exist. The weights can be determined by normalising pairwise comparisons in a matrix. These pairwise comparisons improve the reliability of the weights as expert preferences or opinions from the interviews will be applied which also boosts consistency amongst the various weights (Romeijn, Faggian, Diogo, & Sposito, 2016). If a certain criterion is more important than the other, it will get a number between 1 and 9. The more important a criterion is compared to the other the higher the number. The criteria that are less important will get the inverse of the score for the better alternative. If both criteria are equally important, both criteria get a 1 (Vidal, Marle, & Bocquet, 2010). The same applies for the sub-criteria (or sub-KPIs) which will be compared to one another by performing the same method (Nederveen, 2020). It is also possible to choose for only giving a 1 or a 0 to indicate that a KPI is more important (1) or less important (0) than the one it is compared with. Another method for determining the weights is using the Best-Worst Method which also uses pairwise comparisons in which first the best and worst criteria should be chosen. Then, all criteria will be compared to the best and are given a score between 1 and 9 where a 1 means that both criteria are of equal importance and a 9 means that the best criteria is absolutely more important than the given criteria. These comparisons are made between all criteria versus the best criteria and is finally also compared between the worst criteria and all other criteria. Using the Excel solver tool the weights for all criteria are calculated (Rezaei, 2016). The model will be further elaborated in chapter 6. The best-worst method described above is chosen because of its clear structure and reliable results as the weights are derived from pairwise comparisons that are based on expert opinions (1000minds, sd).

For comparing the alternatives, every alternative receives a score based on the values for the key performance indicators. These scores are calculated with Equation 3, 4 and 5. First, Equation 3 calculates the resilience of the alternative for the simulated disruption. The costs are calculated by multiplying the number of switches by the corresponding weight of the costs. The total score of an alternative can be calculated by subtracting the costs from the resilience.

$$R_{a,d} = P_{a,d} * w_P - RCS_{a,d} * w_{RCS} - T_{a,d} * w_T, \quad (3)$$

$$C_a = SW_a * w_C, \quad (4)$$

$$S_{a,d} = R_{a,d} - C_a, \quad (5)$$

where:

R = Resilience,
C = Costs [number of used switches in layout],
S = Score,
P = Punctuality [%],
RCS = Rate of cancelled services [%],
T = Time to recover [min],
SW = Number of switches,
w = weight,
a = alternative,
d = disruption.

In the interviews the weights for all key performance indicators have been found by performing the Best-Worst method. Table 5.2 shows the averaged weights. To make a trade-off between costs and resilience, costs is weighted 0.5 and the sum of the three resilience key performance indicators is 0.5 as well. The summarized results of the best-worst method and one calculation in more detail can be found in Appendix C.

Table 5.2: Weights for key performance indicators.

KPI	Costs (C)	Rate of cancelled services (RCS)	Punctuality (P)	Time to recover (T)	Sum
Weight	0.5	0.25	0.125	0.125	1

The higher the score of Equation 5, the better the alternative scores in terms of costs and resilience. If the costs increase (more switches) this number is multiplied with the high weight for costs (0.5) from Table 5.2 and this value is subtracted from the resilience value resulting in a lower total score. If punctuality increases, rate of cancelled services decreases and time to recover decreases the resilience improves resulting in a higher score.

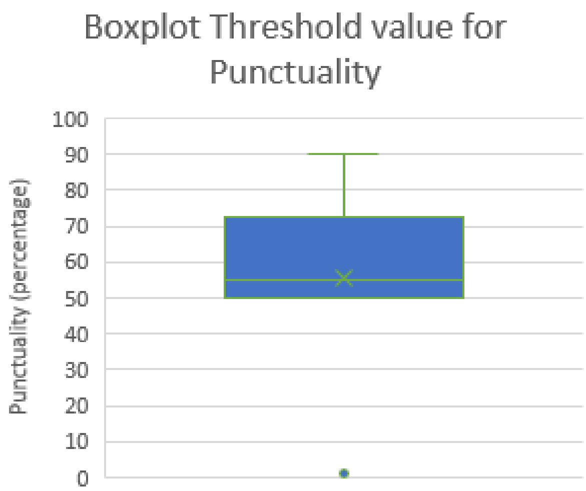

Figure 5.1: Boxplot threshold values for punctuality [%].

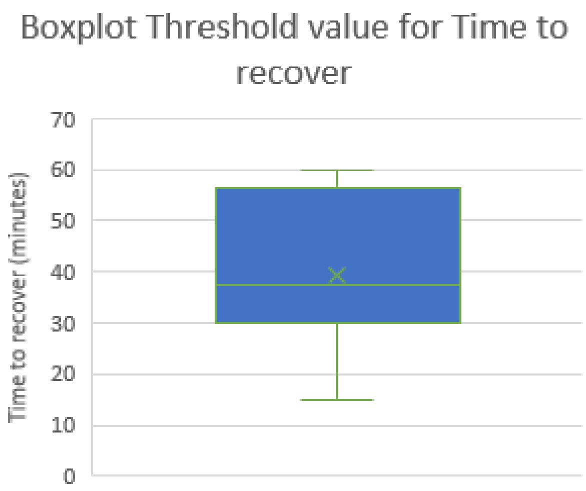

Figure 5.2: Boxplot threshold values for time to recover [min].

From the conducted interviews it also follows that during a disruption a maximum of 50 percent of the trains should be cancelled which was reported by all interviewees and that the punctuality should be at least 55 percent. The distribution of the responses for the threshold values for punctuality and time to recover are shown in Figure 5.1 and Figure 5.2. The left shows that one interviewee put the punctuality at 1% because this person attaches great importance to keeping trains running during disruptions, despite being late, rather than cancelling trains until all trains run on time again. As the model consists of iterations this MCA phase will return multiple times. An overview of all threshold values can be found in Table 5.3. If an alternative scores lower than the threshold value an iteration is required to improve the impact of the switch locations on train service. These iteration loops are visualised in Figure 2.1 in chapter 2. In chapter 6 the threshold values are used to calculate different scores to decide which iteration loop from Figure 2.1 should be used or in which case the corresponding layout already scores sufficient.

Table 5.3: Threshold values retrieved from the conducted interviews.

KPI	SW [# of switches]	RCS [%]	P [%]	T [min]
Threshold value	8	50	50	15

Equation 5 suggests multiple disruption scenarios that could be simulated for every alternative with each a different switch configuration. Since only the two most frequently occurring disruption causes will be simulated, as explained in chapter 4, even 85 more exist and the occurrence of both simulated causes is not equal, it is not possible to calculate the average of these scores. For this, a weighted average can be used in which percentages of occurrence of the corresponding disruption causes will be used.

However, since a broken train is simulated in two different situations: at a station and between two stations, the corresponding percentages are also required. Table 5.4 shows the percentages of each of the simulated disruptions that occur in the Netherlands based on the results from chapter 4. Equation 6 shows how the weighted average is calculated.

Table 5.4: Percentages of the different disruption causes.

Disruption cause	Occurrence [%]	Simulated disruption scenarios	p [%]
Broken train	26.3	Broken train at station	19.725
		Broken train between stations	6.575
Persons near or at the tracks	16.2	Persons near or at the tracks	16.2

$$\overline{S_a} = \frac{\sum_{k=1}^{n} S_{a,dk} \times p_{dk}}{\sum_{k=1}^{n} p_{dk}}, \qquad (6)$$

where:
$\bar{S}$ = Weighted average score,
S = Score,
a = alternative,
d = disruption scenario,
p = percentage a disruption occurs, see Table 5.4,
n = # of disruption scenarios, depending on number of tracks and will be explained in chapter 6.

These weighted averaged scores can be used to compare the results of multiple different infrastructure layouts in terms of costs and resilience. To answer the main research question a trade-off between costs and resilience should be used which therefore requires two different scores and not one score per layout as calculated in Equation 6. A weighted average for the resilience KPI should be calculated and since costs (number of switches) are constant for every disruption situation per layout no additional calculations are required for the costs. Finally, a graph can be made with the number of switches on the x-axis and the resilience on the y-axis. The different layouts are plotted in this scatter plot in which conclusions can be drawn which layouts score better in the trade-off. Equation 7 calculates the weighted average for the different simulated disruption scenarios per layout of the resilience KPI. These equations will be used in chapter 6.

$$\overline{R_a} = \frac{\sum_{k=1}^{n} R_{a,dk} \times p_{dk}}{\sum_{k=1}^{n} p_{dk}}, \qquad (7)$$

where:
$\bar{R}$ = Weighted average score for resilience,
R = Resilience.

6. Simulation-based assessment of switch location design on rail resilience

This chapter answers the fourth sub-question: *What is the relationship between switch location, costs and railway resilience under different disruption conditions?* This chapter introduces a set of multiple simplified infrastructure layouts with different combinations of tracks, converging/merging, junctions and platform tracks at stops. Although simplified, these fictious infrastructure layouts are based on real world layouts and intend to make the research more general. By varying the amount of switches as well as the locations of these, simulations can be performed and different switch configuration layouts can be compared to each other. Section 6.1 introduces the model and section 6.2 explains which simulation software has been chosen to use. The standardized infrastructure layouts are shown in section 6.3, while section 6.4 explains the operational characteristics. Section 6.5 gives the results that are interpreted in section 6.6 and being discussed in section 6.7.

6.1. Theoretical simulation model

In the model the impact of different switch location design configurations will be assessed considering traffic patterns (i.e. train categories, stopping patterns and departure sequence) of the current Dutch rail timetable. The considered traffic pattern features a periodic schedule with at least two Sprinter and two Intercity trains per hour per direction depending on the layout. Although the scenarios are fictious, the disruption analysis still can be used to come up to heavily plagued spots of disruptions by looking at similarities in infrastructure layout. Simulations will be fulfilled for the sake of acquiring the performance of the railway system with the chosen switch location configuration. The goal of this standardized model is to be able to apply the model not only for one case study in the Netherlands, but also for other locations in the Netherlands and for other countries. The different steps of the simulation and iteration process are described in this section. Switches are added and removed to different infrastructure layouts which is part of a sensitivity analysis that in general terms means that the goal is to investigate how a value of a given response value (the KPIs) changes with respect to a change in the model parameters (the switch locations) (Tortorelli & Michaleris, 1994).

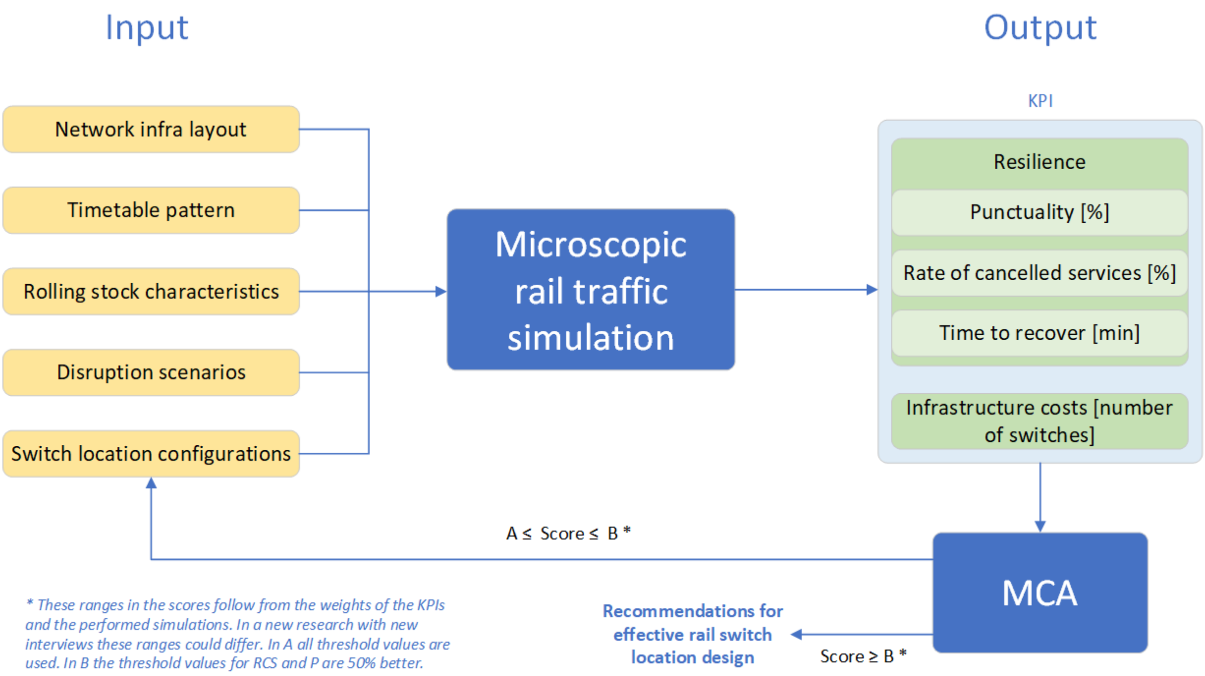

Figure 6.1: Model framework.

Figure 6.1 shows the model framework of the in chapter 2 indicated 'define model' box in the flow chart of the research methodology. The first step of the definition of the model is to investigate the different software packages for rail traffic simulations which is done in section 6.2. The next step is to decide the network infra layout. In this research it is chosen to simulate single track, double track and four track layouts which is shown in section 6.3. In the same section the length of the standardized layout is chosen, including the number of stations. This section also describes the characteristics related to the maximum speed on the line, specifies the angles of the subsequently added switches and defines other constraints. This is all summarized in the network infra layout box in Figure 6.1. The next step is to define some operational characteristics: the train types that will be used and the corresponding characteristics, the timetable and the disruptions which is described in section 6.4. Finally, switches are added, removed or located in a different configuration which is part of the sensitivity analysis and is visualised with the switch location configurations box. A new layout can arise immediately in case a different layout could provide additional insights for the research. New layouts might also be analysed after performing all simulations in case the results for the specific layout scored less than expected. Two iteration loops are visualised in Figure 6.1. If the score is higher than B the research can go to the next step which is the recommendations part. A lower score requires a new switch location configuration. These values for A and B will be further elaborated in section 6.6 where the results of the simulations are interpreted.

6.2. Microscopic rail traffic simulation model

Analysing rail traffic systems can be done by using microscopic and macroscopic simulations. This research will apply the microscopic simulations because these have a high level of detail for the infrastructure, e.g. exact station layouts, exact locations of switches and signals, and also a high level of detail for different types of trains (Johansson et al 2022). For the simulation there are different simulation software packages available. Soms examples are RailSys, Hacon and OpenTrack. An obstacle for RailSys is that initial (entry) delays are not supported which means that trains cannot run before their scheduled departure time. During disruptions where a temporary downsized timetable is used departure times could be slightly modified although that is not desired. Even though RailSys is a powerful and flexible simulation tool, it is not able to perform an accurate simulation of rail operations. These weaknesses are overcome by OpenTrack, but this requires longer simulation times. Nonetheless, this produces simulations in high detail in case all external components such as an external Traffic Management System are implemented correctly, which is however not easy (De Fabris et al, 2019). In OpenTrack rolling stock, infrastructure, timetables and disturbances are the input for the simulation as can be seen in Figure 6.2 which looks similar to Figure 6.1. Hacon is a relatively new software package that offers infrastructure operators and rail transport companies a wide range of flexible applications that help optimize processes. Live dispatching is possible and the software automatically determines the best possible dispatching measures (Hacon, sd). The convenience of adding disruptions and making adjustments in the infrastructure layout (i.e. adding or removing tracks and or switches) makes OpenTrack a good tool for this research despite the long running times (OpenTrack, sd).

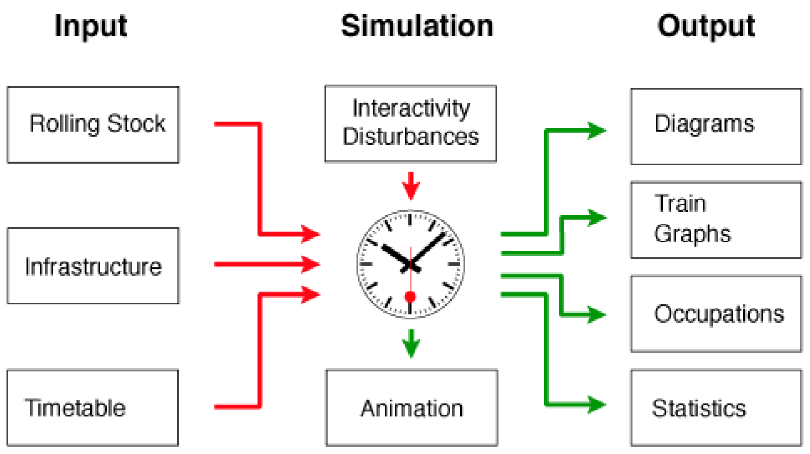

Figure 6.2: OpenTrack model framework (OpenTrack, sd).

The software will be used to obtain a set of what-if scenarios to assess the impact that a given switch location configuration has on delay propagation and on capacity for a disturbed traffic scenario. First this will be done with the simplified model and finally this will be done for a case study in the Netherlands. The new switches can easily be built in OpenTrack. The goal is to keep the rate of cancelled services low during the disruption since this follows from the interviews. Using the software in which the tracks can be blocked, the new switches can be added and some switches could also be removed when these are not necessarily needed. For the case study the complete Dutch infrastructure layout and timetable is included in the software as input from Royal HaskoningDHV and it can be modelled how many trains can still run during the disruption to come up to a better configuration than there is right now. After performing all iterations it is known where switches in the chosen case study should be located and not. Drawings of the tracks with the switches and their locations can be made and these can be delivered to ProRail as a recommendation to improve train traffic during disruptions.

6.3. Infrastructure layouts

The infrastructure layout can be divided into four main groups: single, double and four track and combinations. These layouts can be seen in Figure 6.3, Figure 6.4, Figure 6.5 and Figure 6.6 respectively. Some universal characteristics that apply to all layouts are listed below.

- The figures are not on scale which is to improve the visibility of the layouts. In Appendix F the whole line without switches can be found on scale.
- There are four stations: A, B, C and D.
- Sprinter trains stop at all stations and Intercity trains only at station B which may be modified during disruptions. To calculate the rate of cancelled services and punctuality in each station different weight are applied: 0.4 for the Intercity station and 0.2 for all other stations. This increases the impact of a delayed or cancelled train in the Intercity station which is realistic since Intercity trains are used by more passengers and since Intercity stations can also function as a transfer station to other trains or buses.
- The maximum speed on the railway line is 140 km/h based on the Dutch maximum speed.
- The minimum block length should be 1260 m based on a braking rate of 0.6 m/s^2 and a speed of 140 km/h.
- Block lengths of 1300 m are used; within the station area these are divided into two parts of 450 and 850 meters to locate signals for both directions at the same location. This means

that the distance between all stations will be 5.2 kilometres. In Appendix F a drawing is shown of the block lengths in a station area.

- All platforms have a length of 400 meters to accommodate the longest possible trains, i.e. two coupled VIRM-6 trains or two coupled SLT-6 trains in the Netherlands (NS, sd).
- The regular (undisturbed) timetable depends on the layout and is explained in section 6.4.1.
- All platform tracks at all stations contain turning facilities. Short turning between two stations is not possible.
- Trains run on the right track in undisturbed situations.
- In case of at least two tracks: it is not possible to leave the model via the left track which also applies to disrupted situations.
- In case of a single track at the border of the model: if a train leaves the model, a new train can enter the model after at least three minutes (ProRail, 2017).
- All switches are 1/15 and are allowed for 80 km/h (van Houwelingen, 1984). These switches can be placed at any location because physical constraints are not considered.
- A train can be cancelled completely (no appearance in the model) at least 20 minutes after the start of the disruption if this is needed to create a robust downsized timetable as quickly as possible.
- The number of trains entering and leaving the model on each side should be equal.
- Unlimited resources (crew and rolling stock) are available, however considering the previous bullet point.

Figure 6.3 shows the two variants of single track that are modelled. As explained in section 6.1 a layout starts with a line without switches. The first layout only received a limited amount of passing options: trains can only pass or overtake at station B. Layout 2 offers a second platform track at every station in the model. These layouts are not based on a specific railway line but examples in the Netherlands of layout 1 are IJlst – Stavoren in Friesland and Almelo – Mariënberg in Overijssel. Examples of layout 2 in which every station contains two tracks are Sneek – Leeuwarden in Friesland, Usquert – Winsum and Bedum – Appingedam in Groningen and Zwolle – Wierden in Overijssel.

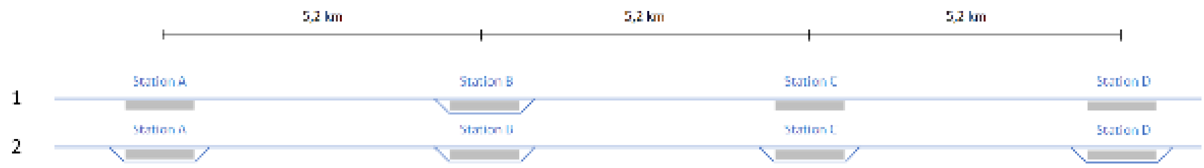

Figure 6.3: Single track infrastructure layouts.

Nine double tracks layouts are modelled and these are shown in Figure 6.4. Again these alternatives are designed by adding more switches in every layout or locating them differently which finally resulted in layout 9 where station B contains short turning tracks on both sides of the stations. Layout 3 only has a limited amount of four switches. These layouts are again not based on specific railway lines but some have some corresponding characteristics. However, the tail tracks in layout 9 are located in Driebergen-Zeist and Amsterdam Zuid, although only on one side of these stations. The stations of Schagen and Heerhugowaard which contain a third track is similar to layout 7 and the situation of Driebergen-Zeist is also similar to layout 8 having four tracks, despite the number of platforms is different. For all layouts similar real-world infrastructure layouts can be found, but two layouts are also designed as an iteration of another layout. This applies to layout 4.1 which is supposed to give other results compared to layout 4 since the switches are located differently and in layout 7.1 the switch configuration is different than in layout 7. Afterwards it was found out that layout 7.1 is the configuration of switches that is used in the renovated station of Ede-Wageningen.

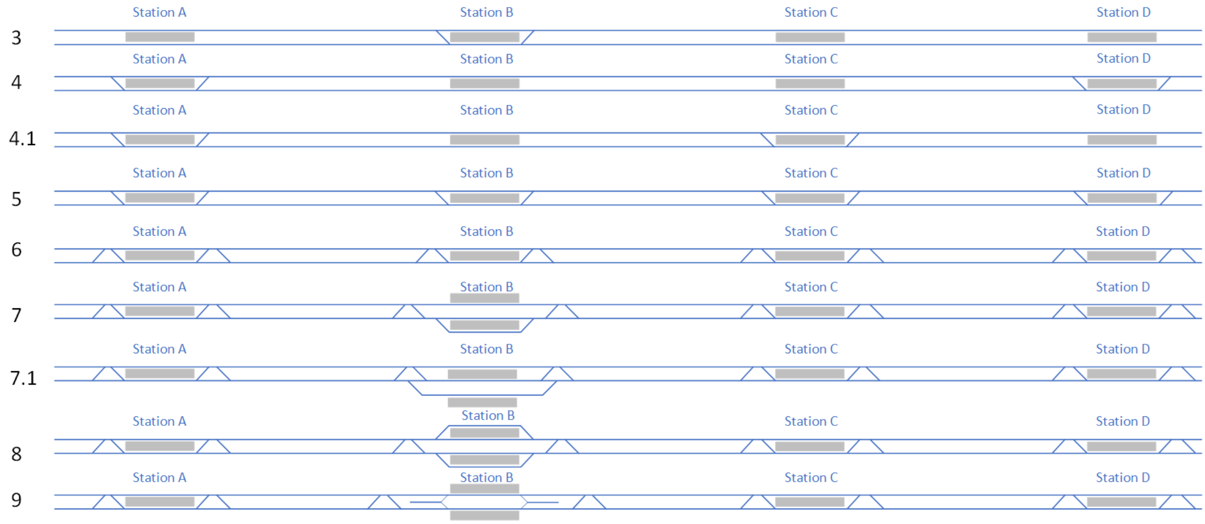

Figure 6.4: Double track infrastructure layouts.

The four layouts that contain four tracks also have different switch configurations. Layouts 10 and 11 have two types of tail tracks and are based on the stations of Breukelen and Lelystad in the Netherlands, while layouts 12 and 13 are based on Den Haag Mariahoeve (North side) and Schiedam Centrum (East side) (Sporenplan, 2023).

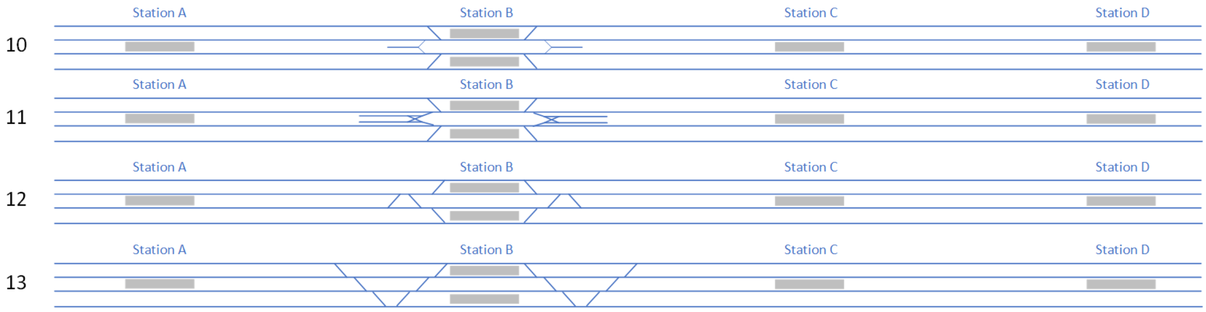

Figure 6.5: Four track infrastructure layouts.

Figure 6.6 gives a layout in which the number of tracks changes after station B. In the real world this happens at different stations in the Netherlands although having other layouts in terms of number of switches, (through) tracks and the locations of the switches. From two tracks between A and B there is only one track left between B and D. All these layouts are simulated and during modelling new layouts can be introduced if required as mentioned. In the sensitivity analysis switches will be added or removed in each layout and the performance of each layout will be evaluated by fulfilling a multi criteria analysis with the in chapter 4 introduced KPIs: costs, rate of cancelled services, punctuality and time to recover.

Figure 6.6: Change in number of tracks infrastructure layout.

Per layout the timetable and the disruptions will be simulated and it will be derived which switches could be removed, which switches are useful and where extra switches should be added. For the latter, the conducted interviews with rail experts are used, as these also gave hints where it might be convenient to add switches.

6.4. Operational characteristics

This section describes the different timetables and disruption characteristics for each of the infrastructure layouts that were discussed in the previous section.

6.4.1. Timetable

The four different categorized layouts have in total five different timetables for the undisturbed situation. This is because the capacity of a single track compared to the four track layouts is completely different. In layout 1 there are only two Sprinter trains per hour per direction and it would not be a difficult research to check if it would be possible to short turn or reroute these trains if the same timetable would be used in a four track layout. The exact arrival and departure times follow after the first simulation in OpenTrack. Layout 1 with only overtaking possibilities at station B offers two Sprinter trains per hour per direction, while layout 2 with two platform tracks at every station offers two Sprinter and two Intercity trains per hour per direction. The latter is possible because of the extra capacity resulting from the two tracks at all stations. In OpenTrack the actual arrival and departure times are in seconds, however in Table 6.1 these are rounded to minutes.

Table 6.1: Timetable layout 1 & 2.

Layout 1 Start → End					**Layout 2 Start → End**						
		SPR 1	SPR 3	...			IC 1	SPR 1	IC 3	SPR 3	...
Start	Dep.	6:00	6:30	...	Start	Dep.	5:55	6:00	6:25	6:30	...
Station A	Arr.	6:01	6:31	...	Station A	Arr.	|	6:01	|	6:31	...
Station B	Arr.	6:06	6:36	...	Station B	Arr.	5:59	6:07	6:29	6:37	...
Station B	Dep.	6:07	6:37	...	Station B	Dep.	6:00	6:08	6:30	6:38	...
Station C	Arr.	6:10	6:40	...	Station C	Arr.	|	6:12	|	6:42	...
Station D	Arr.	6:14	6:44	...	Station D	Arr.	|	6:16	|	6:46	...
End	Arr.	6:16	6:46	...	End	Arr.	6:06	6:18	6:36	6:48	...
Layout 1 End → Start					**Layout 2 End → Start**						
		SPR 2	SPR 4	...			IC 2	SPR 2	IC 4	SPR 4	...
End	Dep.	5:56	6:26	...	End	Dep.	5:52	5:56	6:22	6:26	...
Station D	Arr.	5:57	6:27	...	Station D	Arr.	|	5:57	|	6:27	...
Station C	Arr.	6:01	6:31	...	Station C	Arr.	|	6:01	|	6:31	...
Station B	Arr..	6:06	6:36	...	Station B	Arr..	5:58	6:07	6:28	6:37	...
Station B	Dep.	6:07	6:37	...	Station B	Dep.	6:00	6:08	6:30	6:38	...
Station A	Arr.	6:11	6:41	...	Station A	Arr.	|	6:12	|	6:42	...
Start	Arr.	6:12	6:42	...	Start	Arr.	6:04	6:14	6:34	6:44	...

For the double track layouts (L3-L9) the timetable will be doubled providing four Intercity and four Sprinter trains per hour per direction. In the layouts with four tracks (L10-L13) there will be four Sprinter and eight Intercity trains per hour per direction. Layout 14 will have two Sprinter and two Intercity trains per hour per direction on the whole line, but between the start of the model (on the left) via station A until station B the model also includes two more Sprinter and Intercity trains per hour per direction. This is chosen because of the infrastructure layout where between the start of the model and station B two tracks are available and between B and the end only one track without passing loops at stations C and D.

Table 6.2: Timetable double track layouts.

Layouts 3 – 9 Start → End										
		IC 1	SPR 1	IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	...
Start	Dep.	6:00	6:03	6:15	6:18	6:30	6:33	6:45	6:48	...
Station A	Arr.	|	6:04	|	6:19	|	6:34	|	6:49	...
Station B	Arr.	6:03	6:08	6:18	6:23	6:33	6:38	6:48	6:53	...
Station B	Dep.	6:04	6:09	6:19	6:24	6:34	6:39	6:49	6:54	...
Station C	Arr.	|	6:12	|	6:27	|	6:42	|	6:57	...
Station D	Arr.	|	6:16	|	6:31	|	6:46	|	7:01	...
End	Arr.	6:11	6:18	6:26	6:33	6:41	6:48	6:56	7:03	...

Layouts 3 – 9 End → Start										
		IC 2	SPR 2	IC 4	SPR 4	IC 6	SPR 6	IC 8	SPR 8	...
End	Dep.	6:00	6:03	6:15	6:18	6:30	6:33	6:45	6:48	...
Station D	Arr.	|	6:04	|	6:19	|	6:34	|	6:49	...
Station C	Arr.	|	6:08	|	6:23	|	6:38	|	6:53	...
Station B	Arr..	6:06	6:12	6:21	6:27	6:36	6:42	6:51	6:57	...
Station B	Dep.	6:07	6:13	6:22	6:28	6:37	6:43	6:52	6:58	...
Station A	Arr.	|	6:16	|	6:31	|	6:46	|	7:01	...
Start	Arr.	6:11	6:18	6:26	6:33	6:41	6:48	6:56	7:03	...

Table 6.3: Timetable four track layouts.

Layouts 10 – 13 Start → End														
		IC 1	SPR 1	IC 3	IC 5	SPR 3	IC 7	IC 9	SPR 5	IC 11	IC 13	SPR 7	IC 15	...
Start	Dep.	6:00	6:03	6:08	6:15	6:18	6:23	6:30	6:33	6:38	6:45	6:48	6:53	...
Station A	Arr.	|	6:04	|	|	6:19	|	|	6:34	|	|	6:49	|	...
Station B	Arr.	6:04	6:08	6:12	6:19	6:23	6:27	6:34	6:38	6:42	6:49	6:53	6:57	...
Station B	Dep.	6:05	6:09	6:13	6:20	6:24	6:28	6:35	6:39	6:43	6:50	6:54	6:58	...
Station C	Arr.	|	6:12	|	|	6:27	|	|	6:42	|	|	6:57	|	...
Station D	Arr.	|	6:16	|	|	6:31	|	|	6:46	|	|	7:01	|	...
End	Arr.	6:12	6:18	6:19	6:27	6:33	6:34	6:42	6:48	6:49	6:57	7:03	7:04	...

Layouts 10 – 13 End → Start														
		IC 2	SPR 2	IC 4	IC 6	SPR 4	IC 8	IC 10	SPR 6	IC 12	IC 14	SPR 8	IC 16	...
End	Dep.	6:00	6:03	6:07	6:15	6:18	6:22	6:30	6:33	6:37	6:45	6:48	6:52	...
Station D	Arr.	|	6:04	|	|	6:19	|	|	6:34	|	|	6:49	|	...
Station C	Arr.	|	6:08	|	|	6:23	|	|	6:38	|	|	6:53	|	...
Station B	Arr..	6:06	6:12	6:13	6:21	6:27	6:28	6:36	6:42	6:43	6:51	6:57	6:58	...
Station B	Dep.	6:07	6:13	6:14	6:22	6:28	6:29	6:37	6:43	6:44	6:52	6:58	6:59	...
Station A	Arr.	|	6:16	|	|	6:31	|	|	6:46	|	|	7:01	|	...
Start	Arr.	6:11	6:18	6:18	6:26	6:33	6:33	6:41	6:48	6:48	6:56	7:03	7:03	...

Table 6.4: Timetable layout 14.

Layout 14 Start → End										
		IC 1	SPR 1	IC 100	SPR 100	IC 5	SPR 5	IC 102	SPR 102	...
Start	Dep.	6:00	6:03	6:15	6:18	6:30	6:33	6:45	6:48	...
Station A	Arr.	|	6:04	|	6:19	|	6:34	|	6:49	...
Station B	Arr.	6:03	6:08	6:19	6:23	6:33	6:38	6:49	6:53	...
Station B	Dep.	6:04	6:09			6:34	6:39			...
Station C	Arr.	|	6:12			|	6:42			...
Station D	Arr.	|	6:16			|	6:46			...
End	Arr.	6:11	6:18			6:41	6:48			...

Layout 14 End → Start										
		IC 2	SPR 2	IC 98	SPR 98	IC 4	SPR 4	IC 100	SPR 102	...
End	Dep.	5:52	5:55			6:22	6:25			...
Station D	Arr.	|	5:56			|	6:26			...
Station C	Arr.	|	6:00			|	6:30			...
Station B	Arr..	5:58	6:04			6:28	6:34			...
Station B	Dep.	5:59	6:05	6:14	6:20	6:29	6:45	6:44	6:50	...
Station A	Arr.	|	6:08	|	6:23	|	6:48	|	6:53	...
Start	Arr.	6:03	6:10	6:18	6:25	6:33	6:50	6:48	6:55	...

6.4.2. Disruptions

Following from the disruption analysis in chapter 4 three types of disruptions will be modelled:

- A broken train at a platform of station B, because this is the largest station and from the analysis it can be concluded that a broken train by far happens the most at largest stations. This disruption will take one hour.
- A broken train between stations B and C, causing that one of the tracks is unavailable for one hour. Although this happens less often than the previous disruption it is interesting to see the performance of the layout when there is a partial blockage. Also, other causes of disruptions can cause a partial blockage, but the broken train happens the most.
- People near or at the tracks between stations B and C indicating a complete blockage of the line between B and C for two hours.

The exact locations of these three disruptions are visualised in Figure 6.7 and these will be modelled separately for each layout.

Figure 6.7: Tracks that are blocked during disruptions.

The location of the broken train at station B is always at track 1 (blue) and at track 2 (light blue in the layouts with four tracks). The same applies to the broken train between stations B and C (yellow and green). In case of the four track layout it creates a more difficult situation when track 2 is blocked, because it creates a divided situation where the layout can easily be seen as a three track layout in case of a broken train at track 1. Nonetheless, both broken trains are simulated for the four track layout and this is chosen because switches are only located at station B and trains cannot be rerouted outside of the model since it is unknown where switches are located. The disruption persons near or at the tracks between stations B and C is marked with a grey cross. The colours of the disruptions in Figure 6.7 match the colours of the graphs in Figure 6.9 and Figure 6.18 where the results of the different simulated disruptions can be compared to each other.

For every disruption scenario it is the goal to make the timetable conflict-free as fast as possible. This will be tested with real-time adjustments like retiming, reordering, rerouting, short turning and cancelling. These modifications are suggested and implemented by dispatchers relying on their knowledge, guidelines and rules of thumb (D'Ariano, 2008).

6.5. Results

This section will give a summary of the results from the simulations in the different layouts introduced in section 6.3 and is divided into four subsections. The detailed calculations are shown for one of the double track layouts. For all other layouts only the outcomes are visible which makes it easier to compare. The detailed calculations for all layouts are given in Appendix F.

6.5.1. Single track

The two single track layouts are difficult to compare because initially two different models for the timetable were used. Because of capacity limitations in layout 1, only two Sprinter trains per hour per direction were used for the disruption scenarios. Layout 2 however, offers multiple passing options wherefore a more extensive timetable was chosen including two Sprinter and two Intercity trains per hour per direction. In case of a disruption, the results from layout 1 are therefore better, because of the fewer number of trains running. The summarized results are given in Table 6.5 in which can be seen that layout 1 scores better on punctuality resulting in a higher average score for layout 1. A broken train between stations B and C and persons on the tracks between B and C show the same results which can be concluded by the fact that these are single track parts between B and C. Although the number of cancellations is higher during a two hour disruption (persons between B and C) than during the one hour broken train, the rate of cancelled services is calculated and the rate for a 1 and a 2 hour complete blockage is the same, where the same applies for punctuality.

Table 6.5: Summarized results single track layouts. SW = costs of infrastructure [# switches] , RCS = rate of cancelled services [%]. P = punctuality [%], T = time to recover [min], S = score, $\bar{S}$ = weighted averaged score.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	$\bar{R}$	S	$\bar{S}$
L1	Broken train B1	2	0	83	0	10.42		9.42	
	Broken train B-C	2	30	100	0	-2.50	3.19	4.00	6.51
	Persons B-C	2	30	100	0	-2.50		4.00	
L2	Broken train B1	8	0	58	0	7.29		3.29	
	Broken train B-C	8	30	90	0	-3.75	0.99	-0.25	1.39
	Persons B-C	8	30	90	0	-3.75		-0.25	

Both layouts have a time to recover of 0 minutes which indicates that after the beginning of the disruption, the downsized timetable immediately starts and there is therefore no chaotic phase. This can be caused by the fact that there are only few trains running on these single track layouts resulting in fast solutions: rerouting, retiming or short turning. The downsized timetable which is used during the different simulated disruptions as well as the calculations, the more detailed results and conclusions are given in Appendix F1.

6.5.2. Double track

For all double track layouts the same timetable is used which include four IC trains and four SPR trains per hour per direction which makes all alternatives good to compare. Without any disruption or delay the time-distance diagram for these layouts is visualised in Figure 6.8. The green lines indicate IC services while the blue lines represent the Sprinter trains that have a dwell time of 30 seconds at each station. In the model the stations A, B, C and D are used, but in the software these were translated to real stations starting with the letter indicated by the model. This is because the software contains a database of train stations which is convenient to use. Station A is therefore Amstetten (Ast), B is Bischofshofen (Bischo) both in Austria, C stands for Chiasso (Chias) in Switzerland and station D is represented by Delft Campus (Dtcp) in the Netherlands. The start (S) and end (E) of the model are named after Schwarzach-St. Veit in Austria and Emmeloord in the Netherlands.

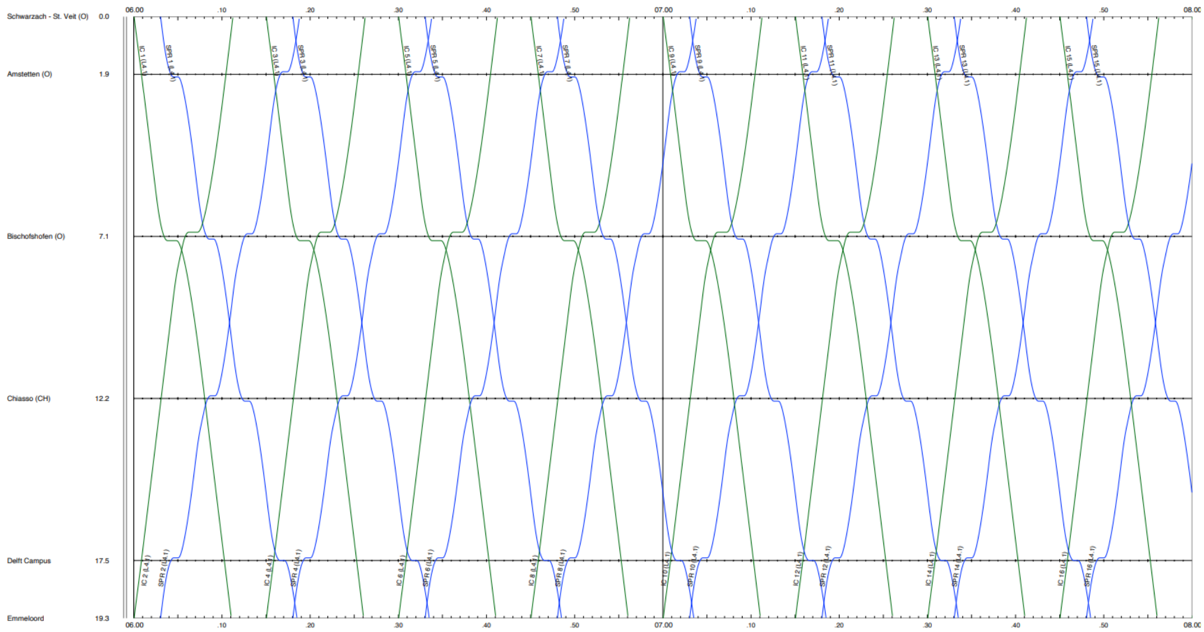

Figure 6.8: Time-distance diagram double track without disruptions.

All layouts have been simulated with the three disruptions and the results are given in Table 6.6. The values for all four key performance indicators are given, as well as the scores per disruption scenario and the weighted average score per layout. Figure 6.9 can be used to compare the results as this graph contains the scores for all disruptions in all double track layouts. Figure 6.10 shows a graph with all weighted averaged scores for these layouts to compare the different layouts. In section 6.6 the results of all scores will be interpreted. The score for a broken train at station B track 1 is for all layouts the highest of all except for layout 9. This can be concluded by the fact that layout 9 contains tail tracks on both sides of the station meaning that the switches are located further away from the platforms than in the other layouts that contained switches on both sides of station B. This results in longer waiting times, lower punctuality and even a rate of cancelled services of 23% for that disruption. Other conclusions are included in Appendix F. That layout also scores low in the trade-off between costs and resilience as can be seen in Figure 6.11. There it is also visible that layout 6 scores high relatively to layout 5 which is caused by the higher resilience and the same number of switches but a different configuration.

Table 6.6: Summarized results double track layouts.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L3	Broken train B1	4	0	88	0	11.00	-0.39	9.00	-2.92
	Broken train B-C	4	78	98	33	-30.61		-13.23	
	Persons B-C	4	78	98	33	-30.61		-13.23	
L4	Broken train B1	8	16	75	15	-0.74	0.88	-0.65	-1.93
	Broken train B-C	8	16	75	15	-0.74		-0.65	
	Persons B-C	8	45	90	0	-11.25		-4.00	
L4.1	Broken train B1	8	16	75	0	1.14	0.94	1.23	-1.79
	Broken train B-C	8	16	75	0	1.14		1.23	
	Persons B-C	8	60	99	0	-17.68		-6.68	
L5	Broken train B1	16	0	88	0	11.00	2.92	3.00	-1.13
	Broken train B-C	16	0	53	60	-0.88		-8.88	
	Persons B-C	16	30	100	0	-2.50		-3.00	
L6	Broken train B1	16	0	88	0	11.00	3.62	3.00	0.53
	Broken train B-C	16	0	78	15	7.86		-0.14	
	Persons B-C	16	26	99	0	-0.78		-2.22	
L7	Broken train B1	22	0	99	11	10.96	3.83	1.96	0.02
	Broken train B-C	22	0	89	0	11.17		2.17	
	Persons B-C	22	26	99	0	-0.78		-3.22	
L7.1	Broken train B1	18	0	100	0	12.50	3.96	3.50	0.32
	Broken train B-C	18	9	87	0	6.18		-0.47	
	Persons B-C	18	26	99	0	-0.78		-3.22	
L8	Broken train B1	20	0	100	0	12.50	3.92	2.50	-0.78
	Broken train B-C	20	0	78	15	7.86		-2.14	
	Persons B-C	20	26	99	0	-0.78		-4.22	
L9	Broken train B1	22	23	82	15	-3.26	2.20	-8.43	-5.83
	Broken train B-C	22	0	92	0	11.47		0.47	
	Persons B-C	22	0	99	0	-0.78		-5.22	

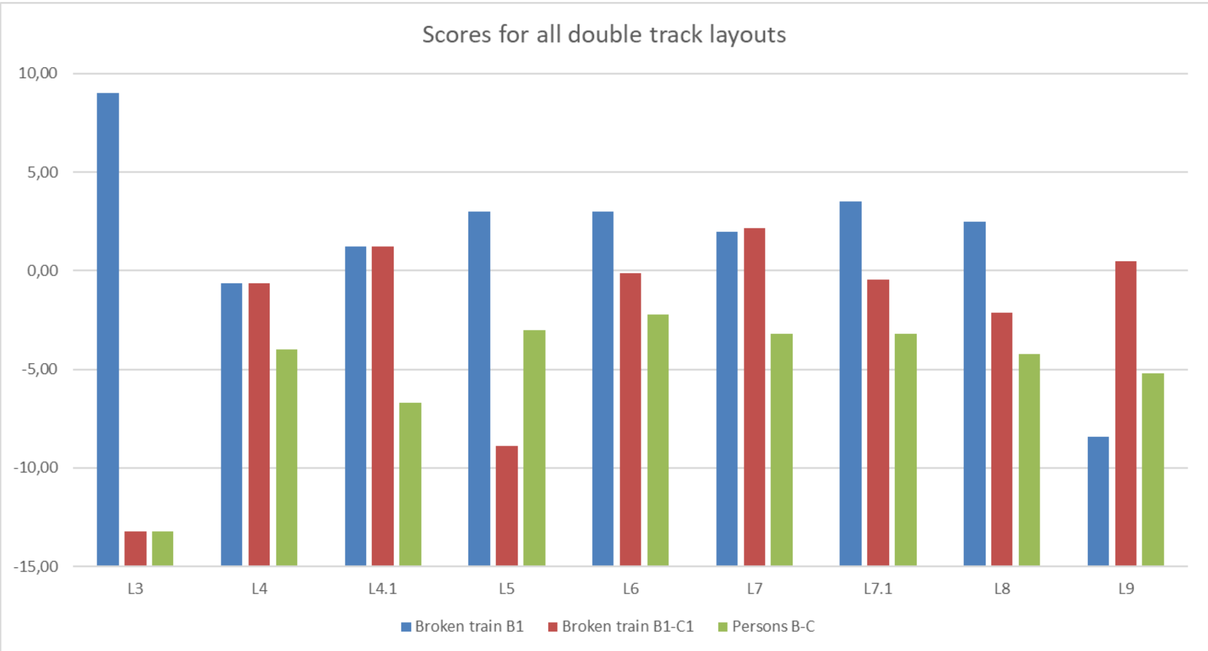

Figure 6.9: Scores for all double track layouts and all disruptions to compare.

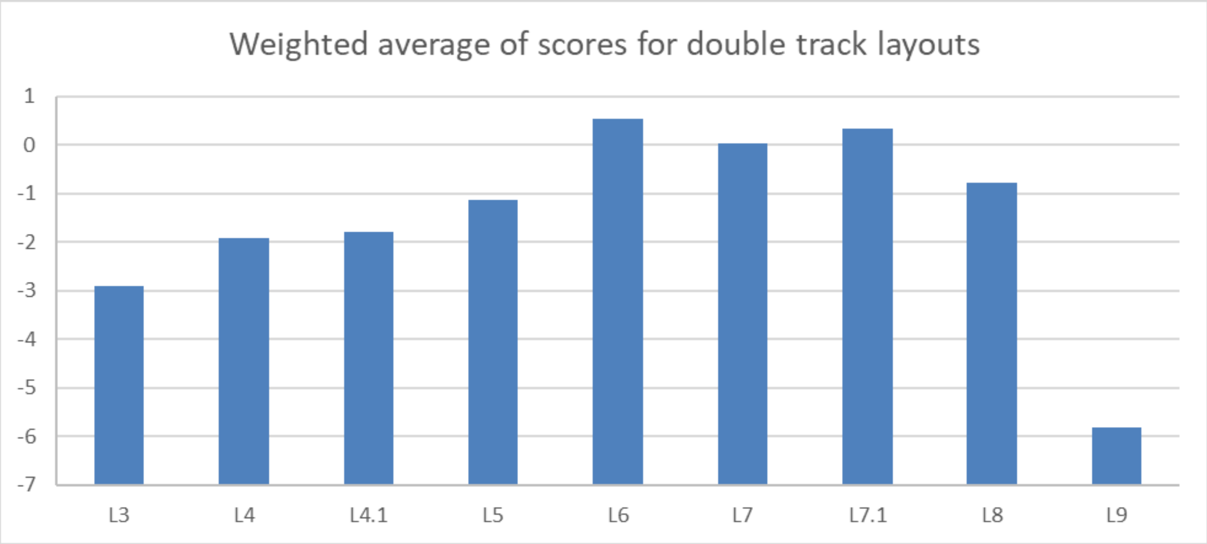

Figure 6.10: Weighted average of scores for double track layouts.

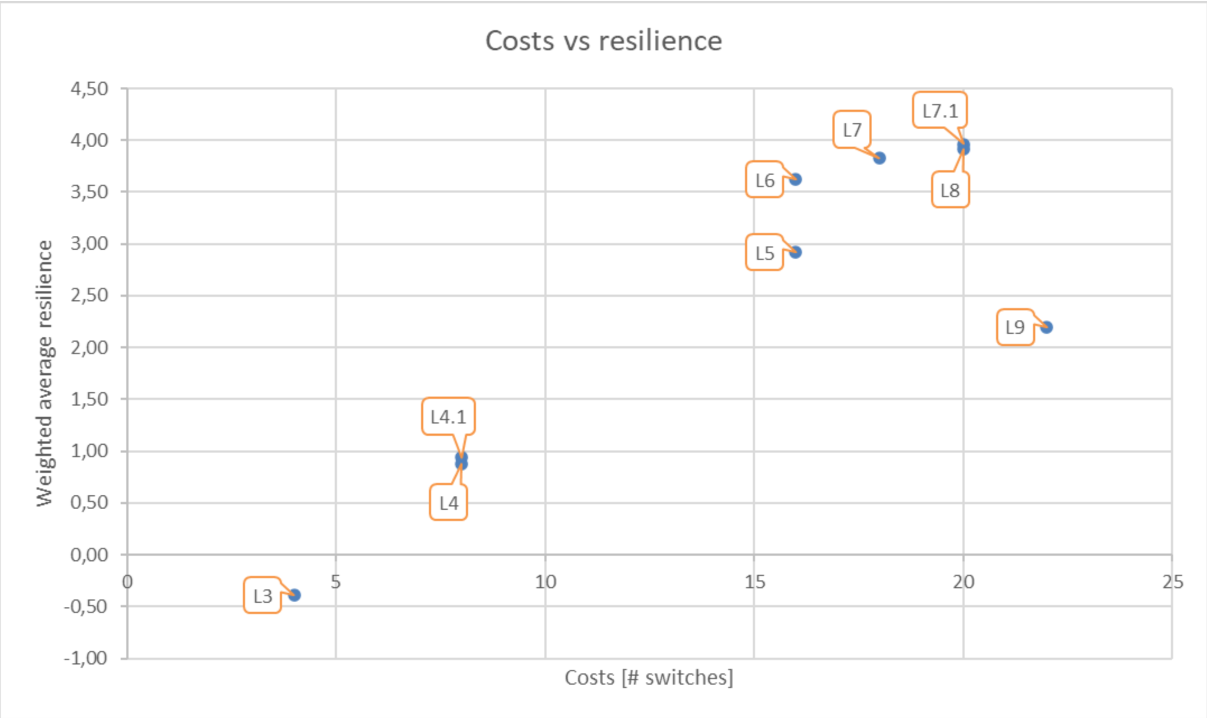

Figure 6.11: Trade-off between costs and resilience for the double track layouts.

Layout 5 (shown in Figure 6.12 again) will be explained in more detail because of the interesting rescheduling options during the different disruptions.

5

Figure 6.12: Layout 5.

Disruption 1: Broken train at track 1 of station B

If a train breaks down at station B1, trains can easily reroute via track B2 which also fits in the timetable. Trains from the left to the right run on time while trains from the right to the left are delayed by a maximum of 5 minutes at arrival in B. The timetable that is used during this disruption with a 1 hour broken train can be found in Table 6.7 in which all by a colour marked times are late arrivals. Late means 5 or more minutes later than originally planned. This rerouting is visualised with the yellow line in the upper layout of Figure 6.13.

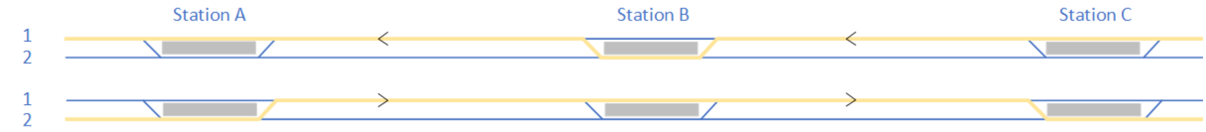

Figure 6.13: Rerouting at station B (layout 5).

If the broken train would be on track 2 instead of track 1 at station B, the situation will be different as can be seen in the bottom layout in Figure 6.13. There, trains are still able to bypass the broken train at track 2 of station B but this rerouting via track 1 takes more time as the distance of the single track would be longer (more than 10 kilometres instead of only 500 meters around station B) increasing delays and causing cancellations. The track numbering is also indicated in Figure 6.13.

Table 6.7: Timetable during broken train at track 1 of station B (layout 5).

Layout 5 Start → End												
		IC 1	*SPR 1*	***IC 3***	***SPR 3***	***IC 5***	***SPR 5***	***IC 7***	***SPR 7***	***IC 9***	*SPR 9*	*…*
Start	*Dep.*	*6:00*	*6:03*	*6:15*	*6:18*	*6:30*	*6:33*	*6:45*	*6:48*	*7:00*	*7:03*	
Station A	*Arr.*	*|*	*6:04*	*|*	*6:19*	*|*	*6:34*	*|*	*6:49*	*|*	*7:04*	
Station B	*Arr.*	*6:03*	*6:08*	*6:18*	*6:23*	*6:33*	*6:38*	*6:48*	*6:53*	*7:03*	*7:08*	
Station B	*Dep.*	*6:04*	*6:09*	*6:19*	*6:24*	*6:34*	*6:39*	*6:49*	*6:54*	*7:04*	*7:09*	
Station C	*Arr.*	*|*	*6:12*	*|*	*6:27*	*|*	*6:42*	*|*	*6:57*	*|*	*7:12*	
Station D	*Arr.*	*|*	*6:16*	*|*	*6:31*	*|*	*6:46*	*|*	*7:01*	*|*	*7:16*	
End	*Arr.*	*6:11*	*6:18*	*6:26*	*6:33*	*6:41*	*6:48*	*6:56*	*7:03*	*7:11*	*7:18*	
Layout 5 End → Start												
		IC 2	***SPR 2***	***IC 4***	***SPR 4***	***IC 6***	***SPR 6***	***IC 8***	***SPR 8***	***IC 10***	*SPR 10*	*…*
End	*Dep.*	*6:00*	*6:03*	*6:15*	*6:18*	*6:30*	*6:33*	*6:45*	*6:48*	*7:00*	*7:03*	
Station D	*Arr.*	*|*	*6:04*	*|*	*6:19*	*|*	*6:34*	*|*	*6:49*	*|*	*7:04*	
Station C	*Arr.*	*|*	*6:08*	*|*	*6:23*	*|*	*6:38*	*|*	*6:53*	*|*	*7:08*	
Station B	*Arr..*	*6:06*	*6:12*	*6:26*	*6:29*	*6:41*	*6:44*	*6:56*	*6:59*	*7:11*	*7:14*	
Station B	*Dep.*	*6:07*	*7:10*	*6:27*	*6:30*	*6:42*	*6:45*	*6:57*	*7:00*	*7:12*	*7:15*	
Station A	*Arr.*	*|*	*7:13*	*|*	*6:33*	*|*	*6:48*	*|*	*7:03*	*|*	*7:18*	
Start	*Arr.*	*6:11*	*7:15*	*6:31*	*6:35*	*6:46*	*6:50*	*7:01*	*7:05*	*7:16*	*7:20*	

The score for this disruption scenario is 3.00 and is calculated with Equation 5 introduced in chapter 5. As can be seen in Table 6.7, the rate of cancelled services is 0 percent. All in red marked arrival times are delayed arrivals giving a punctuality of 88 percent considering a sub weighting of 0.4 for late arrivals at station B and 0.2 for all other stations. There is no recovery time as the trains are immediately using this rescheduling and the total number of switches in use is 16 which can be explained after the other disruptions simulated for this layout. All these values are used to calculate the score.

Disruption 2: Broken train between stations B and C

As explained in section 6.4.2 the second disruption that is simulated is a broken train between stations B and C which causes a 1 hour single track between those stations. Also in this case there is a difference in results at which track the train breaks down, but for consistency track 1 is chosen again which will give in this case more delays than a broken train at track 2. This is because the distance that trains need to use the opposite track is shorter in the bottom rerouting as can be seen in Figure 6.14.

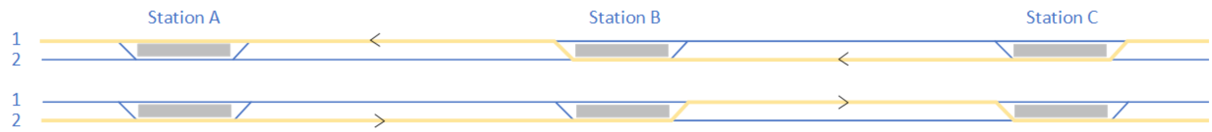

Figure 6.14: Rerouting to bypass broken train between stations B and C.

As shown in Table 6.6 the score for this disruption is -8.88. In both stations B and C only one track can be used which causes eleven trains delayed and therefore a punctuality of 53 percent for all trains which is slightly higher than the threshold value of 50 percent. Again zero trains are being cancelled which however increases the time to recover till 60 minutes since there is no regular timetable pattern: all trains still run and need to wait for each other. In the conducted interviews, experts mentioned that trains should not be cancelled as fast as it happens currently in the Netherlands, but run with limited delay to keep capacity high. This happens in this layout where punctuality remains above the threshold and all trains are still running.

Table 6.8: Timetable during broken train at track 1 between stations B and C (layout 5).

Layout 5 Start → End													
		IC 1	SPR 1	**IC 3**	**SPR 3**	**IC 5**	**SPR 5**	**IC 7**	**SPR 7**	**IC 9**	SPR 9	IC 11	SPR 11
Start	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18
Station A	Arr.	|	06:04	|	06:19	|	06:34	|	06:52	|	07:04	|	07:19
Station B	Arr.	06:03	06:08	06:18	06:23	06:39	06:42	06:59	07:02	07:04	07:08	07:18	07:23
Station B	Dep.	06:04	06:09	06:19	06:24	06:40	06:43	07:00	07:02	07:05	07:09	07:19	07:24
Station C	Arr.	|	06:12	|	06:27	|	06:46	|	07:06	|	07:12	|	07:27
Station D	Arr.	|	06:16	|	06:31	|	06:50	|	07:10	|	07:16	|	07:31
End	Arr.	06:11	06:18	06:26	06:33	06:47	06:52	07:06	07:11	07:13	07:18	07:26	07:33
Layout 5 End → Start													
		IC 2	**SPR 2**	**IC 4**	**SPR 4**	**IC 6**	**SPR 6**	**IC 8**	**SPR 8**	**IC 10**	SPR 10	IC 12	SPR 12
End	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:47	06:50	07:06	07:09	07:15	07:18
Station D	Arr.	|	06:04	|	06:29	|	06:48	|	07:07	|	07:12	|	07:19
Station C	Arr.	|	06:08	|	06:33	|	06:52	|	07:11	|	07:17	|	07:23
Station B	Arr..	06:06	07:07	06:33	06:37	06:52	06:56	07:12	07:16	07:18	07:21	07:23	07:27
Station B	Dep.	06:07	07:07	06:34	06:37	06:53	06:57	07:13	07:16	07:19	07:22	07:24	07:28
Station A	Arr.	|	07:11	|	06:41	|	07:00	|	07:20	|	07:25	|	07:31
Start	Arr.	06:11	07:13	06:38	06:43	06:57	07:02	07:17	07:22	07:23	07:27	07:28	07:33

Disruption 3: Persons on the tracks between stations B and C

The third and final disruption that is simulated in layout 5 is the complete blockage of the line between stations B an C. The switch configuration in layout 5 enables short turning at stations B and C for all trains in case there are persons on the tracks between these two stations. Figure 6.15 shows which tracks an Intercity and a Sprinter use to short turn at station B. Sprinters are using the upper track between stations A and B for both directions which is possible because of the shorter time it takes to short turn a Sprinter (5 minutes) compared to an Intercity (9 minutes) considering that these trains run every 15 minutes.

Figure 6.15: Short turning at station B (layout 5).

Figure 6.16 shows the time-distance diagram of all trains that are being short turned at stations B and C. The time to recover is 0 minutes since this rescheduling immediately starts. There is however a difference in delay by looking at the arriving IC trains into the model. From the start towards station B all trains can enter the model and arrive on time at station B. On the other side, IC trains coming from E (the end) towards station C need to slow down and arrive two minutes late at station C which can be seen in Figure 6.16. These delays can be explained by looking at Figure 6.17 where it becomes obvious that the upper track (1) is now used by the Sprinter on its way back to the end while the next Intercity already enters the model. This was not a problem in Figure 6.15, because trains that were short turned all used the upper track back to the start of the model while new trains towards station B entered the model via the bottom track (2). Fortunately, delays are not stacking which causes a time to recover of 0 minutes.

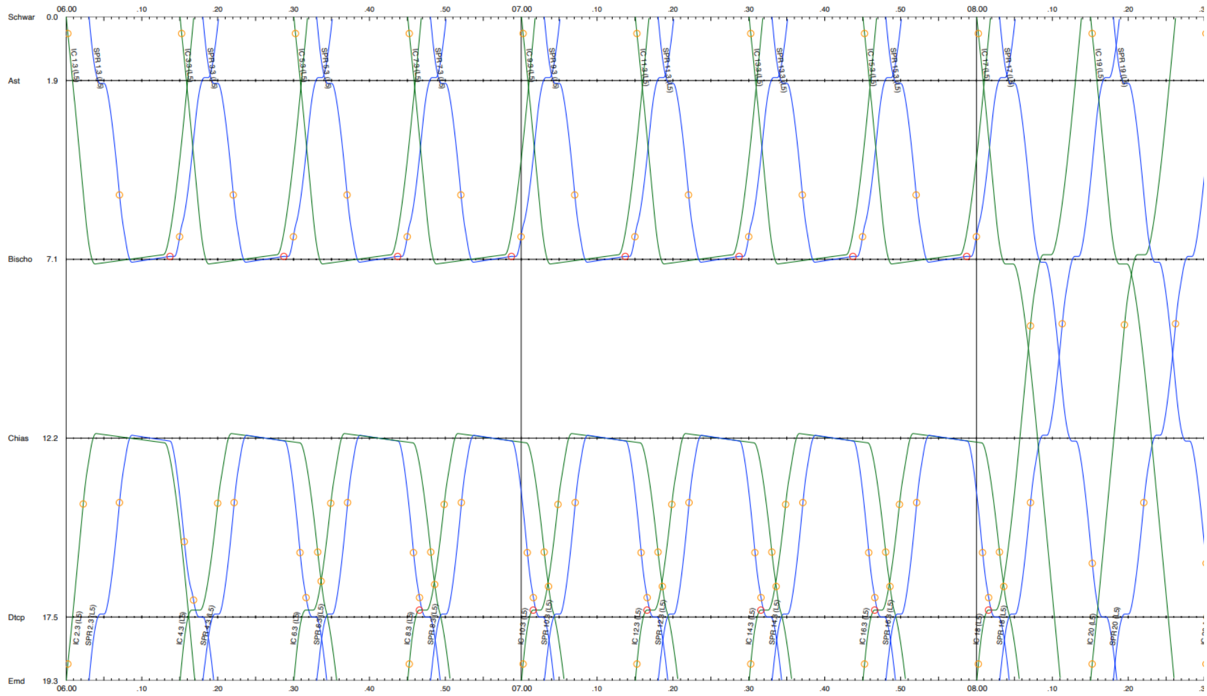

Figure 6.16: Time-distance diagram persons on tracks between stations B and C (layout 5).

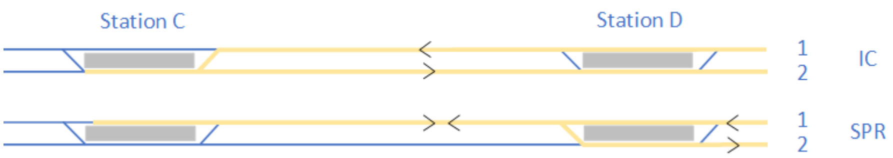

Figure 6.17: Short turning at station C (layout 5).

The timetable during the two hour closure is periodic and the first hour is visualised in Table 6.9 in which there are for the odd train numbers no departures at B and no arrivals at C and for the even train numbers no arrivals at station B. As example: IC 1 arrives on time at station B, becomes IC 2 as indicated and departs at station B at 6:12 which is 5 minutes later than IC 2 should depart, because it takes 9 minutes to short turn the train.

Table 6.9: Timetable during persons on tracks between stations B and C (layout 5).

Layout 5 Start → End												
		IC 1	***SPR 1***	***IC 3***	***SPR 3***	***IC 5***	***SPR 5***	***IC 7***	***SPR 7***	***IC 9***	***SPR 9***
Start	*Dep.*	*06:00*	*06:03*	*06:15*	*06:18*	*06:30*	*06:33*	*06:45*	*06:48*	*07:00*	*07:03*
Station A	*Arr.*		*06:04*		*06:19*		*06:34*		*06:49*		*07:04*
Station B	*Arr.*	*06:03*	*06:08*	*06:18*	*06:23*	*06:33*	*06:38*	*06:48*	*06:53*	*07:03*	*07:08*
Station B	*Dep.*	*to IC 2*	*to S 2*	*to IC 4*	*to S 4*	*to IC 6*	*to S 6*	*to IC 8*	*to S 8*	*to IC 10*	*to S 10*
Station C	*Arr.*										
Station D	*Arr.*		*06:17*		*06:32*		*06:47*		*07:02*		*07:17*
End	*Arr.*	*06:17*	*06:19*	*06:36*	*06:34*	*06:51*	*06:49*	*07:06*	*07:04*	*07:21*	*07:19*
Layout 5 End → Start											
		IC 2	***SPR 2***	***IC 4***	***SPR 4***	***IC 6***	***SPR 6***	***IC 8***	***SPR 8***	***IC 10***	***SPR 10***
End	*Dep.*	*06:00*	*06:03*	*06:15*	*06:18*	*06:30*	*06:33*	*06:45*	*06:48*	*07:00*	*07:03*
Station D	*Arr.*		*06:04*		*06:19*		*06:34*		*06:49*		*07:04*
Station C	*Arr.*	*06:06*	*06:08*	*06:21*	*06:23*	*06:36*	*06:38*	*06:51*	*06:53*	*07:06*	*07:08*
Station B	*Arr..*	*to IC 1*	*to S1*	*to IC 3*	*to S 3*	*to IC 5*	*to S 5*	*to IC 7*	*to S 7*	*to IC 9*	*to S 9*
Station B	*Dep.*	*06:12*	*06:14*	*06:27*	*06:29*	*06:42*	*06:44*	*06:57*	*06:59*	*07:12*	*07:14*
Station A	*Arr.*		*06:18*		*06:33*		*06:48*		*07:03*		*07:18*
Start	*Arr.*	*06:17*	*06:20*	*06:32*	*06:35*	*06:47*	*06:50*	*07:02*	*07:05*	*07:17*	*07:20*

The punctuality for this disruption is 100 percent which is because cancelled trains are not included. However, as can be seen in Table 6.9, all even IC numbers depart late at station B after being short turned and also leave the model (at the start) late. These delays are also not included as only arrival delays are counted and not departure delays. The rate of cancelled services is 30 percent, having 16 trains not having arrived at station B (weight 0.4), also 16 at station C (weight 0.2) and a total number of 32 services during the 2 hour disruption. The score for the alternative with the complete blockage is -3.00. A disadvantage for the situation in Figure 6.17 is that Sprinter trains leave the model right before the Intercity which is not wished for. Otherwise, the Sprinter needs to wait a couple minutes longer and depart after the Intercity, but this will result in a delayed arrival of the next Intercity. Figure 6.9 enables comparisons between all layouts by looking at the minimum and maximum values each layout scores for the simulated disruptions. The scores for the three simulated disruptions are calculated in the next four lines and the differences in scores can be seen.

$$S_{a,d} = R_{a,d} - C_a = P_{a,d} * w_P - RCS_{a,d} * w_{RCS} - T_{a,d} * w_T - NS_a * w_C \quad (6)$$

$$S_{5,1} = 88 * 0.125 - 0 * 0.25 - 0 * 0.125 - 16 * 0.5 = 3.00$$

$$S_{5,2} = 53 * 0.125 - 0 * 0.25 - 60 * 0.125 - 16 * 0.5 = -8.88$$

$$S_{5,3} = 100 * 0.125 - 30 * 0.25 - 0 * 0.125 - 16 * 0.5 = -3.00$$

The weighted average of these three simulated disruptions is -1.13 which is the fifth highest score for the double track layouts. Layouts 6, 7, 7.1 and 8 all score higher as can be seen in Figure 6.10. These scores for all layouts indicate that higher costs (more switches) results in higher resilience which is however not for all situations the case. It depends on how switches are located: having tail tracks decreases resilience again despite the higher costs. Therefore switch location, costs and resilience are related to each other and this already answers the sub-question which will be explained in more detail in the upcoming sections.

6.5.3. Four tracks

There is a difference in scores between the layouts that consist of four tracks. With more switches around station B there are more rerouting possibilities as well as higher short turning capacity. The latter is especially notable during the persons on the tracks between stations B and C where layout 13 scores significantly higher than the other layouts. Table 6.10 shows all results and Figure 6.18 enables easy comparisons between these layouts based on their scores.

Table 6.10: Summarized results four track layouts.

Line	Disruption	C [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L10	Broken train B1	14	0	100	0	12.50		5.50	
	Broken train B2	14	31	100	0	-2.88		-2.19	
	Broken train B-C (1)	14	29	100	0	-2.05	3.12	-1.77	-2.65
	Broken train B-C (2)	14	31	100	0	-2.88		-2.19	
	Persons B-C	14	47	97	50	-17.70		-12.90	
L11	Broken train B1	18	0	100	0	12.50		3.50	
	Broken train B2	18	31	100	0	-2.88		-4.19	
	Broken train B-C (1)	18	29	100	0	-2.05	3.90	-3.77	-3.03
	Broken train B-C (2)	18	31	100	0	-2.88		-4.19	
	Persons B-C	18	39	97	27	-10.88		-10.08	
L12	Broken train B1	16	25	100	0	0.19		-1.65	
	Broken train B2	16	0	99	0	12.40		4.40	
	Broken train B-C (1)	16	25	100	0	0.19	4.10	-1.65	-2.13
	Broken train B-C (2)	16	31	98	0	-3.17		-3.48	
	Persons B-C	16	39	100	37	-3.90		-9.93	
L13	Broken train B1	20	0	100	0	12.50		2.50	
	Broken train B2	20	0	100	0	12.50		2.50	
	Broken train B-C (1)	20	25	100	0	0.19	6.34	-3.65	-0.96
	Broken train B-C (2)	20	31	98	0	-3.17		-5.48	
	Persons B-C	20	33	100	0	-3.90		-5.70	

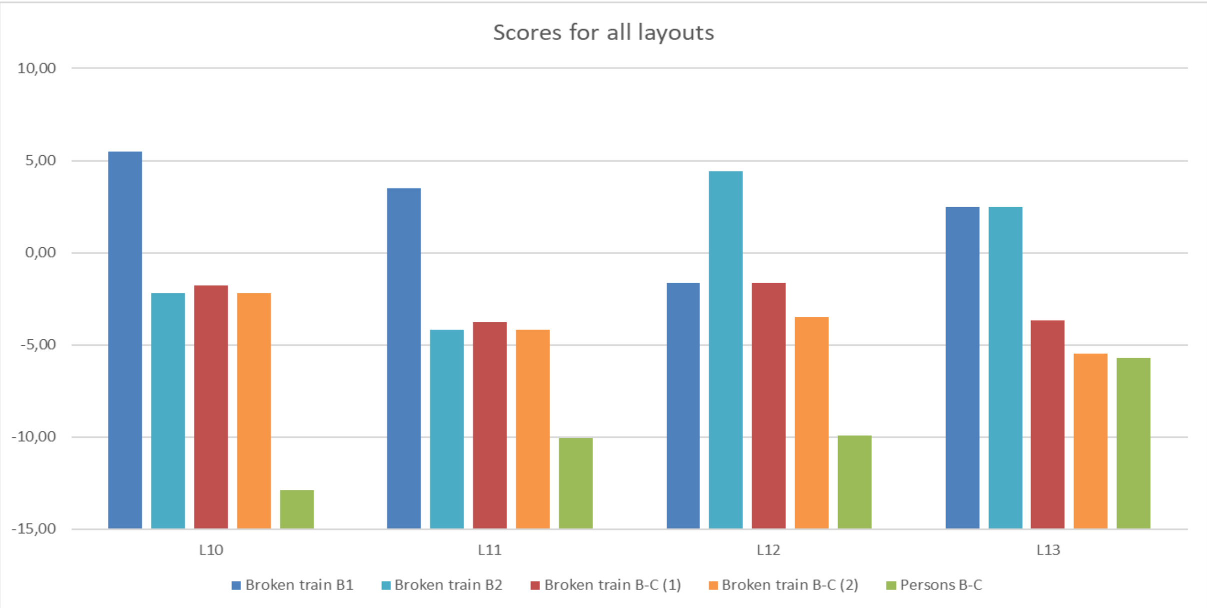

Figure 6.18: Scores for all four track layouts and all disruptions to compare.

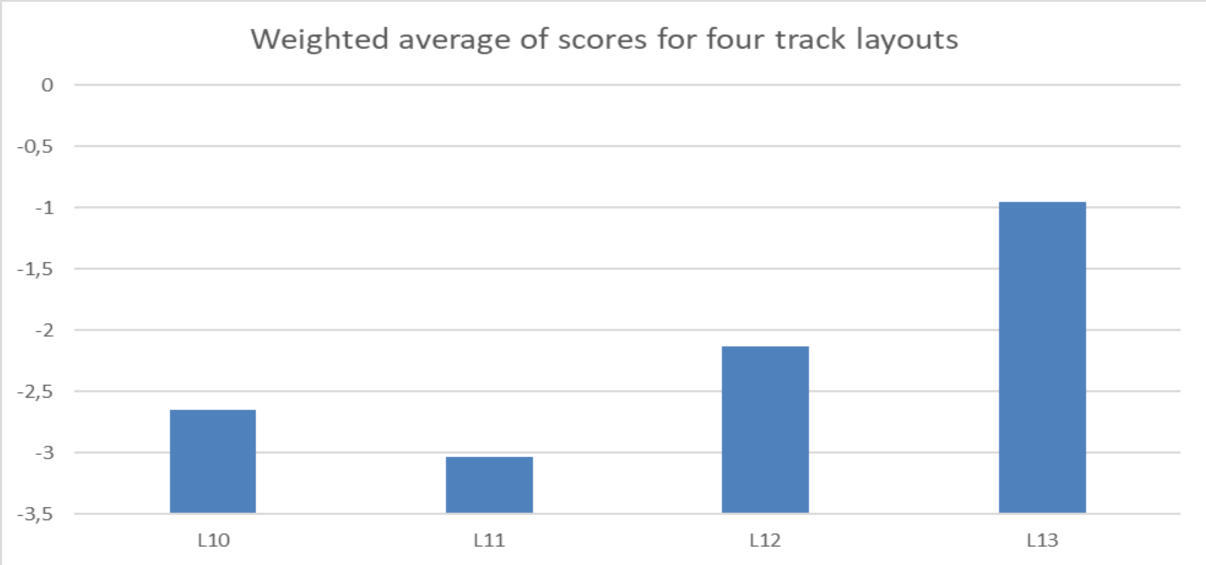

Figure 6.19: Weighted average of scores for four track layouts.

As can be seen in Figure 6.18 the scores for a broken train at track 1 or track 2 does matter for the different alternatives and this is highly dependent on the corresponding switch layout configuration. The difference in results is caused by the fact if the switches are from the Intercity towards the Sprinter tracks or the other way around. Layout 13 scores the best, but this is also due to the highest amount of switches. Layout 12 seems to score slightly better than layout 11 despite having two switches less. This can be explained by the fact that, despite having less Sprinter trains running in the timetable, these however have more station arrivals which means that these are also counting significantly. Detailed results for the four track layouts can be found in Appendix F. The averaged scores are visible in Figure 6.19 in which can be seen that Layout 13 scores best in the trade-off between costs and resilience, despite the fact containing the most switches of all. However, this layout which contains switches providing three short turning tracks for both the Intercity and Sprinter track scores high on all resilience key performance indicators resulting in a good trade-off which can also be seen in the graph in Figure 6.20. This shows an increase in score from approximately 4 to 6.5 by only adding two switches (layout 11 versus layout 13).

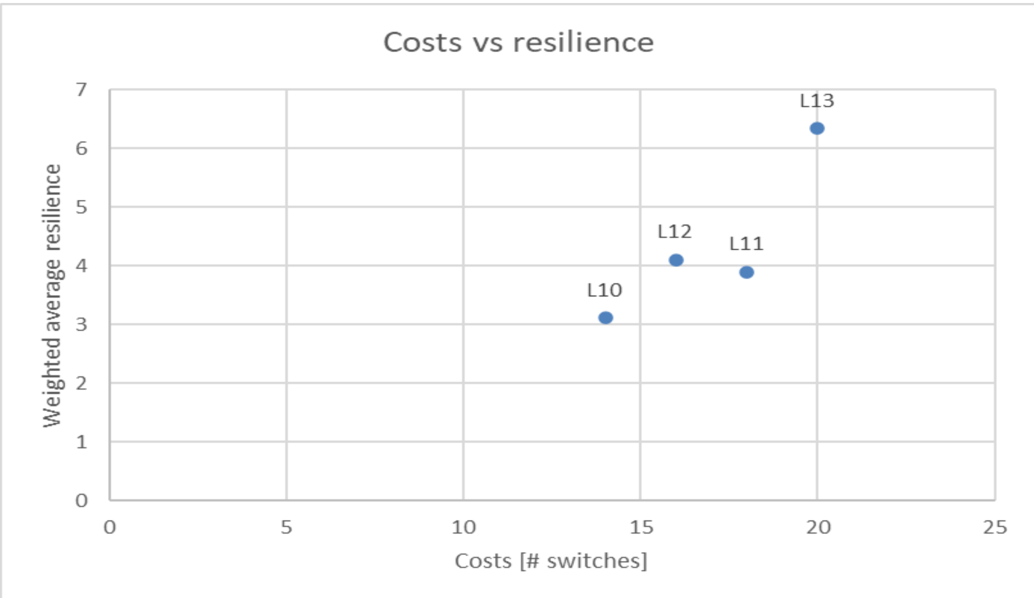

Figure 6.20: Trade-off between costs and resilience for the four track layouts.

6.5.4. Combinations

The detailed results for layout 14 are given in Appendix F but the summarized results are shown in Table 6.11. For all simulated disruptions the scores appear to be high relative to the scores found for the double and four track layouts. This was also expected since layout 14 is on the left side similar to layout 8 and on the right side similar to layout 1 where both layouts score individually also well.

Table 6.11: Summarized results layout 14.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L14	Broken train B1	9	0	99	0	12.36	6.29	7.86	3.85
	Broken train B2	9	0	96	15	10.17		5.67	
	Broken train B-C	9	12	94	5	5.10		3.63	
	Persons B-C	9	12	94	5	5.10		3.63	

Table 6.5, Table 6.6, Table 6.10 and Table 6.11 show a difference in the costs and the original costs because not all switches that were proposed in the first design have been used since those were not necessary. Figure 6.21 shows an overview of which switches are useful (black) or not (blue).

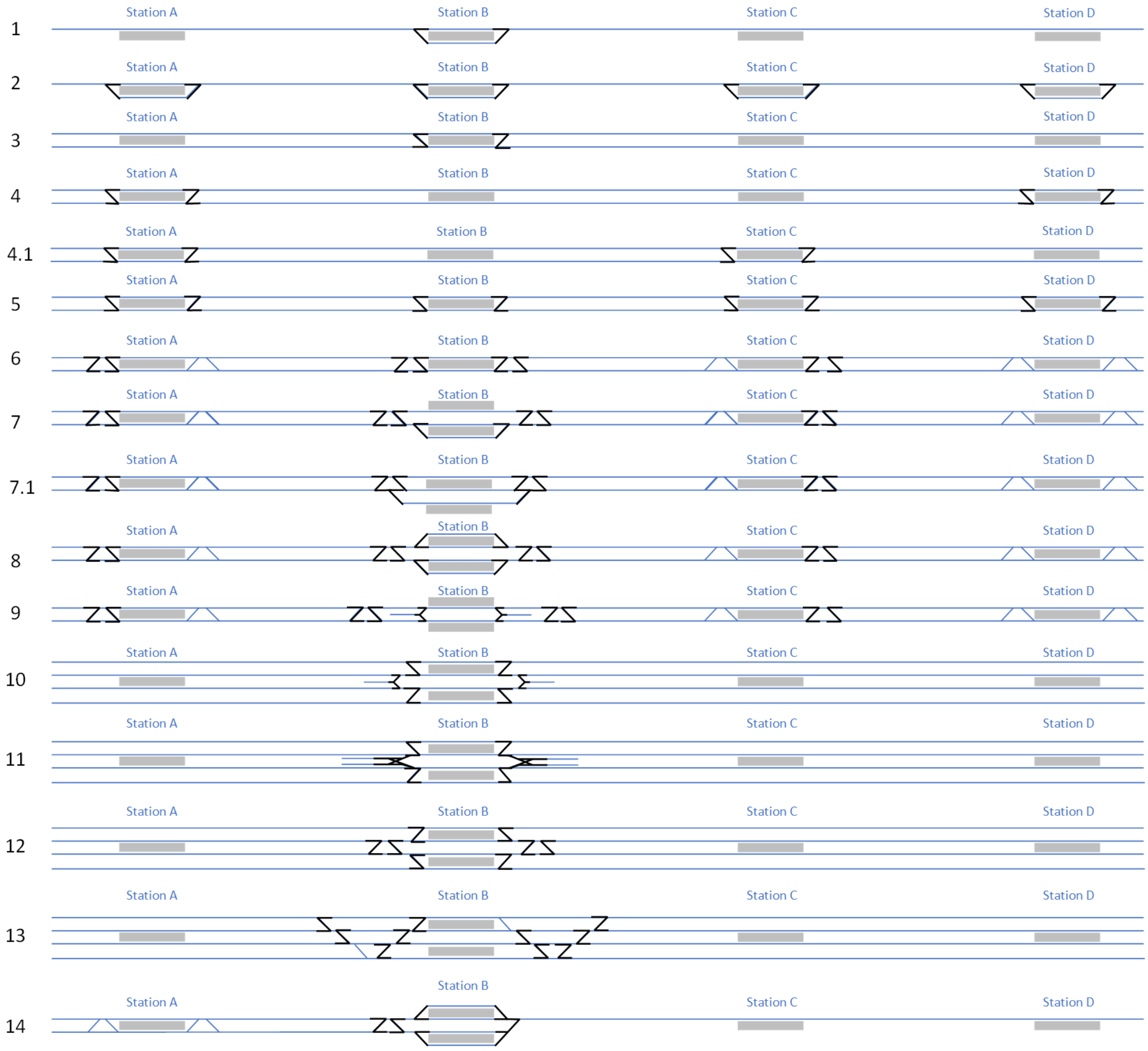

Figure 6.21: Overview of switches that are used in simulations (marked in black); the blue switches are not used.

Not all switches that are highlighted have been used in simulations but for symmetry reasons the corresponding switches were still highlighted. As example for this, layout 6 is looked at in which the black switches at station C are used for short turning in case of a disruption between B and C. Although the same disruption is not simulated between A and B, the switches west of A are still highlighted. Something else to notice is that the switches at station D in case of a double track layout are not necessary, at least for the layouts that score high. Also the switches at both smaller stations A and C on the side of station B are not necessarily needed since these could only function in case of a single track blockage. The switches on the other sides of stations A and C, however, have short turn functionality as well as the possibility to reroute trains to the other tracks in case of a single track blockage.

6.6. Interpretation of the results

The results of the model are described in section 6.5 in detail for layout 5 and in Appendix F for all other layouts. The weighted average scores are ranging between 6.51 (layout 1: single track) and -5.83 (layout 9: double track with tail tracks at station B). However, the highest score can be achieved by having no disruption at all and is 12.5. The lowest possible score is negative infinite since the number of switches and the time to recover can be theoretically infinite. Having a punctuality of 0% and all trains cancelled 100% the score already is -25. Although the fact that cancelled trains are not counted as a delayed trains, punctuality still is 0% if all trains are cancelled since zero trains are running on time. In the same situation but with a time to recover of one hour and a situation with 22 switches which is the highest amount of switches in a layout of the described model the lowest possible score would become -43.5.

The question now is where the difference between a good and a bad score lies. The threshold values given by the experts in the interviews could help, but since the calculated scores for punctuality and rate of cancelled services are almost never coming close to those values, these should actually be redefined. The average of the rate of cancelled services for all layouts after simulating appears to be 20% and for punctuality it is 93% where both distributions can be seen in the boxplots in Figure 6.22 and Figure 6.23. These average values could be used in a follow-up study as new threshold values to make an even better layout since the score S should in that case be higher than that value. Using these averaged values for rate of cancelled services and punctuality and a minimum number of switches for a double track layout (eight) giving both directions the possibility of rerouting to the other track and going back to the planned track, the minimum score S of 0.75 is calculated.

Figure 6.22: Boxplot for rate of cancelled services [%].

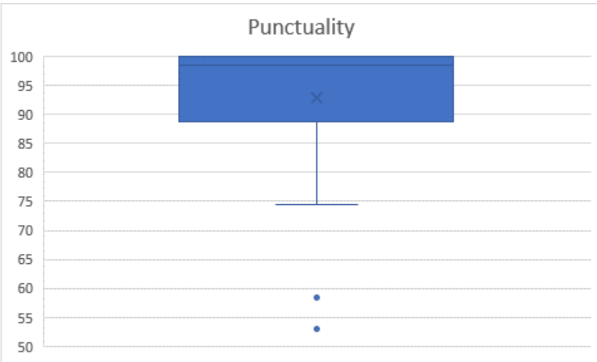

Figure 6.23: Boxplot for punctuality [%].

As can be seen in Figure 6.22 one disruption scenario had almost 80% of the trains being cancelled. This was the double track layout 3 in which only four switches were included and short turn capacity was low. Figure 6.23 shows high punctuality for almost all layouts. With a threshold value of 50% all simulated layouts therefore suffice, however, there were two layouts that had scores between 50 and

60. The lowest value for punctuality was achieved by layout 5 which was explained in more detail in section 6.5.2

The score in case all threshold values (SW ≤ 8, RCS ≤ 50%, P ≥ 50% and T ≤ 15 min) are used, becomes -12.125. Given the fact that all layouts (except layout 3) score higher than -12.125 as can be seen in section 6.5, the threshold values for rate of cancelled services and punctuality are both made 50% better: rate of cancelled services: 25% and punctuality: 75%. Using these values a score of -2.75 is achieved which is a score that appears to be a good division for if a score is sufficient or not, since not all layouts score higher than this score as will be explained below.

Given these scores, there are three possible outcomes for new simulations: a score higher than -2.75 (and lower or equal than the maximum score of 12.5), a score between -12.125 and -2.75 and a score lower than -12.125. If a layout scores higher than -2.75 for all simulated disruptions, the layout with the corresponding switch configuration is sufficient in terms of offering enough capacity, providing high punctuality and short time to recover. This value is represented by the 'B' in Figure 6.1. In this situation this layout can be put into the recommendations section as stated by the arrow in Figure 6.1 in section 6.1. In case the score is between -12.125 and -2.75 (between 'A' and 'B') the layout should be adapted by performing the sensitivity analysis where switches will be added or removed or will be placed in a different configuration. If the score is below -12.125 the layout does not suffice at all which can be fixed by changing the operational characteristics and afterwards changing the layout again in a sensitivity analysis. Figure 6.1 also gives an arrow to the input for the general characteristics which can be followed in case after ten iterations for one layout the results still not suffice. Using this formulation only layouts L1, L2, L6 and L14 can be marked as layouts that are acceptable. These layouts all offer enough rerouting possibilities and short turn capacity. These are both single track layouts, only one double track layout containing switches on both sides of the Intercity station and switches on one side of both neighbouring (smaller) stations. Layout 3 with only four switches received two scores of -13.23 is the only layout that receives a score lower than the threshold score. By looking at the weighted averaged scores for all layouts, more layouts will pass the -2.75 threshold score. Besides the already explained layouts, all double track layouts (except L3 with only limited number of switches and L9 with the tail tracks) suffice. From the four track layouts, L10, L12 and L13 suffice which means that the layout having two tail tracks (L11) scores worse than the layout having only one tail track (L10). Although values for all resilience KPIs are better in L11, the costs are higher giving it a total lower score.

In chapter 7 a case study will be performed in which a railway line in the Netherlands will be used and where the current track layout will be simulated with the same disruption scenarios. Knowing the results of the model which layout scores the best in which situation new switch configurations could be tested in the case study to check and validate the model.

6.7. Discussion of the results

Interesting results have been gathered in section 6.5 and in Appendix F but this model should also function for other case studies in the Netherlands and for similar studies in Germany, Belgium and other countries. Although doing this research for a case study in a different country the model should be redefined. Also new disruption data should be obtained as in other countries other disruption causes and locations might occur more often. Nevertheless, the used locations in this research are generalised: one track at the largest station that is out of use for one hour, one track between a big and a small station out of use for one hour and the whole line between a big and small station out of use for two hours. This thesis named these disruptions to the names that belong to these disruptions in the Netherlands, but a partially blocked line could also be caused by a signal failure which might be occurring more often in other countries. Furthermore, in other countries other threshold values could be applicable which means that new interviews with rail experts of that specific country are required.

It should be emphasised that the ‘optimal’ switch location configuration is not compared to the real situation, but instead is compared to a modelled version of the existing rail network in the Netherlands. As the Dutch rail model is used and the real Dutch timetable is used, it can be assumed that the modelled version of the existing network is equivalent to the real network. However, in the model, switches can be located on every location. In the real world this is not the case. Switches cannot be located in curves or on slopes in the Netherlands. In Germany for example this is possible as they design switches for every location separately. In the Netherlands switches are standardized in design to reduce maintenance costs which means that the results from the model need to be checked if the locations also fit in the real-world case concerning vertical and horizontal alignment.

During constructing of the model many assumptions have been made in order to obtain a functioning model. These assumptions and limitations can however be taken into discussion as these have influenced the model results. The discussion of the results is divided into four groups that are related to each other. Firstly, the general characteristics that are explained in section 6.3 are taken into discussion.

- **Block lengths**: a maximum speed of 140 km/h is used to calculate the block length. This is done by using a braking rate of 0.6 m/s^2 which belongs to the worst braking train in the Netherlands. Modern trains can brake faster and in future the maximum speed might be higher. With shorter blocks trains can follow-up each other faster which increases capacity and will therefore result in higher scores. Calculating block lengths and locating signals is, however, out of scope for this research and is therefore based on rules of thumbs and short calculations together with some experts from Royal HaskoningDHV and TU Delft.
- **Distance between stations**: for generalisation it is chosen to locate all stations on equal distances from each other. If the model would have been a bit longer in terms of total length more stations could have been added where the distance between stations near the large station could have been shorter since this assumes to be the central station of a bigger city. The distance of 5.2 km between the stations is chosen because of the fact designing exactly four blocks of 1.3 km between the stations. Increasing the distance between the stations would make the results, especially for the single track part in case of a partial blockage, worse. Decreasing the distance would make the results for these partial blockages better, but to find an optimal solution between costs and resilience switches should not be located to close to each other. In case of decreasing the distance between the stations new switch configurations could therefore arise.
- **Left riding**: in the Netherlands trains run on the right track. There are other countries, like Belgium and Switzerland, where trains run on the left. For the model it is chosen that trains run on the right because of the Dutch situation. Results will assumably not change a lot, but it might be interesting to research since not all layouts are completely symmetric. For symmetric layouts there will not change anything. One of the limitations in the model is that trains are not allowed to enter or leave the model on the left track because the infrastructure layout outside the model is not known. If trains however are allowed to enter or leave the model using the left track, results will change, but is difficult to say if the scores increase or decrease. This is because more trains can enter or leave the model at the same time and less switches are required in case of short turning, however, if a train leaves the model, the next train can enter the model using the same track after three minutes which could cause delays and also requires switches directly outside the model.

- **Short turning in between two stations during disruptions**: for short turning trains specific signals are required to facilitate safe train passings. All stations are equipped with exit signals and therefore allow trains to short turn, which is however in real world not always the case, see chapter 7. If trains also have the opportunity to short turn in between two stations this will impact capacity and punctuality in a positive sense resulting in a higher score. The costs are higher, but these are not taken into account in the model since the costs are specified as the number of switches.
- **Switch angle ratio**: the so-called 1/15 switches are used in this model which allow safe passings of 80 km/h in the curved direction. The results will change if other types of switches are used which means a higher or lower speed.

The operational characteristics described in section 6.4 also influence the results of the model. These assumptions and limitations are described below.

- **Length and type of trains**: in the model two train types have been used. For an Intercity the Dutch double-decker VIRM has been used and as a regional train the Dutch Sprinter SLT. Both trains have a length of 10 carriages resulting in a length of 270 m and 170 m respectively. These trains are typically used during peak hour. During off-peak hours trains in the Netherlands are shorter as this is more cost-efficient as can be read in Appendix E. Shorter trains means faster accelerations and also faster braking resulting in shorter travel times. Although, since trains are overcrowded often and also because in other countries (e.g. Switzerland) trains are always running in peak hour length, this assumption is made. Coupling trains making them even longer is not possible in the model because of the maximum platform length.
- **Timetable**: for the double track layouts four Intercity and four Sprinter trains per hour per direction are used. Results in terms of rate of cancelled services, punctuality and time to recover would be worse in case the frequency is even higher. Furthermore, if the moments the trains are entering the model would be slightly different this would also influence the results in case of the situation with a partial blockage since trains need to wait shorter or longer on each other. Finally, the pattern of the timetable can influence the results. The pattern now is: first an Intercity and than a Sprinter which is logical because a Sprinter has more travel time because of all the stops. If this would be the other way around, which does not make sense, it would also affect the results. The downsized timetables during disruptions could also have minor changes which can affect the results but this will not result in major changes in score since in these downsized timetables as many trains as possible are still running (low rate of cancelled services) and only punctuality could change slightly in case some trains are, e.g., retimed or reordered.
- **Disruptions**: the locations of the disruptions follow from the disruption analysis carried out in chapter 4. Other locations with a disruption are also possible to simulate. For example between two smaller stations (C and D) since at these kinds of locations also disruptions occur which followed from the disruption analysis carried out in chapter 4. However, only the most heavily plagued spots have been used for this research.

There are also some limitations in the way the KPIs are calculated. These limitations are described below.

- **Sub-weightings for different stations**: cancelling one Sprinter train is approximately two times worse by means of the score than cancelling one Intercity train. This is caused by the number of arrivals in the model. An Intercity only dwells at station B while a Sprinter has four stops. The rate of cancelled services and the punctuality are both calculated by looking at the arrivals at each stations. The arrival time at station B has a weight of 0.4 and the other three stations have a weight of 0.2. This is done to increase the importance of the Intercity since it is used by more passengers and also by the fact that at larger stations passengers could change to other trains or other modes of transport from which this station B should be made more important than the other stations. Also, by using these weights the Sprinter trains are more important in the scores. This could be changed by giving also a weight for an Intercity and a Sprinter separately, e.g. 1 and 0.5, but this would be interesting for future research.

- **Average score**: currently, the scores for each layout are a weighted average of the simulated disruption scenarios. However, by significantly expanding the disruption analysis and using more causes and again taking into account how often each failure occurs, it is possible to calculate an average score which would make the results more realistic since 85 disruption causes have been left out and only the two most occurring are used. These two most occurring causes are 42.5% of all disruptions from the last 7.5 years, but still more than 50% is missing.
- **Short turning IC trains at station B**: in case of a total blockage of the line between B and C, Intercity trains are short turned at B. These trains mostly arrive on time and if not, the train will be counted as late which will be used in the calculations. After being short turned, these Intercity trains are riding a different course and mostly, these depart late at B which means that these trains also leave the model late. Since, only arrival punctuality is used in this research, these delayed trains, after being short turned, are not used in the calculations since because they do not stop anymore after departure at B and leaving the model at the start of the model (left side, upper track)
- **Other simulation software**: OpenTrack is chosen as software package for the reasons mentioned in section 6.2 and because of the availability of the software on the laptops. By using other simulation tools the results could be different.

The last assumptions and limitations that have influenced the model results are in the category 'others' and are listed below.

- **ERTMS**: the Dutch train detection system ATB is included in the OpenTrack software and is used for the simulations. ERTMS is the train detection system for the future resulting in safer and faster trains (ProRail, 2024). This means that the timetable can include more trains. ERTMS is still only on very few lines in the Netherlands which also applies for foreign countries. How ERTMS works is not part of this research, but it might be interesting how the application of ERTMS into the scenarios would affect the results because of higher speeds, more trains and new signalling systems.
- **Interviews**: eight interviews have been carried out. Four with rail advisors at Royal HaskoningDHV, two train drivers of NS, one cargo train driver and one person from ProRail. The results between ProRail and on the other side the people from Royal HaskoningDHV and the train drivers differed. For a more complete overview also for the weightings of the KPIs it would be good to conduct more interviews and that all companies are represented multiple times.
- **Number of passengers**: this research looks at the number of trains cancelled and the number of trains being late. Results will change if not the trains are looked at but the passengers as a key performance indicator. How many passengers are stranded and how many passengers are late at their destination or missed their connecting train or bus? And how can the locations of switches influence these results? This would be an interesting research but requires sensitive tap in and tap out personal data that should be provided by NS.

7. Case study

The simulated model in chapter 6 is validated by performing a case study. The considered area is the Dutch railway line Utrecht Centraal – Arnhem Centraal with the side line to Rhenen. In this area multiple Intercity stations are located that have different switch layout configurations which are also similar to some of the layouts simulated in chapter 6. Figure 7.1 shows a map of the railway line on scale and Figure 7.2 shows the same line with all available infrastructure and the distances between all the stations.

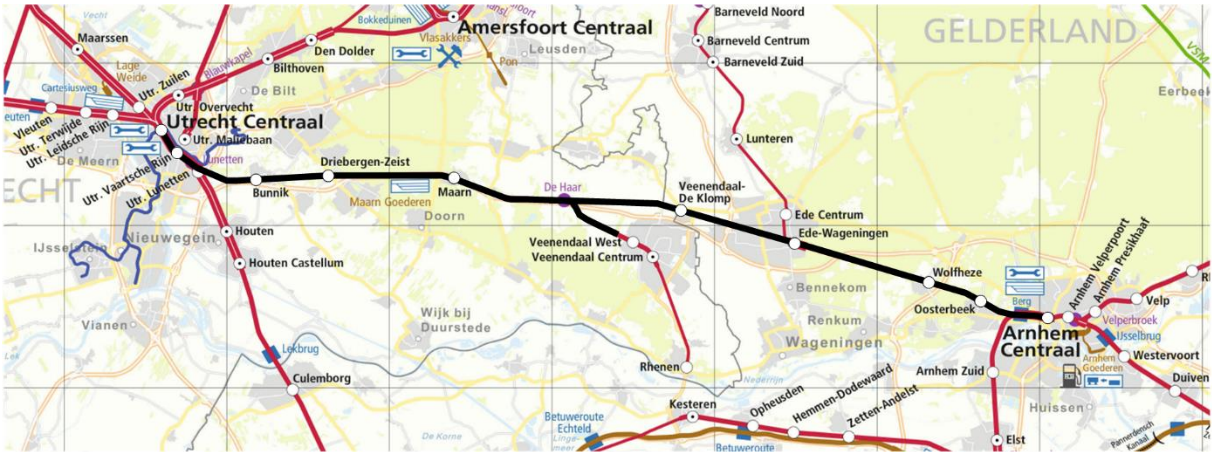

Figure 7.1: The line Utrecht Centraal - Arnhem Centraal on scale with all intermediate stations (ProRail, 2020).

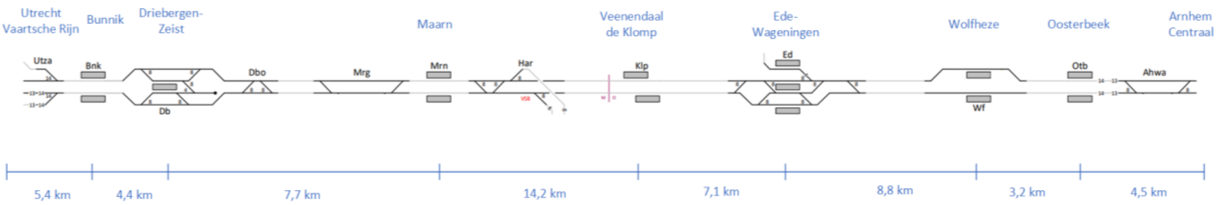

Figure 7.2: Switch configuration Utrecht Centraal - Arnhem Centraal (Hofstra, 2022).

At the start of the case study no switches will be added or removed but the current infrastructure will be tested as the layouts of stations Driebergen-Zeist and Ede-Wageningen are similar to layouts 9 and 7.1 respectively. Several disruptions are simulated and the results are compared with the model results. A new switch location configuration could then be proposed to increase capacity during a disruption or a different train rescheduling as trains are currently cancelled too fast and to far away from the disruption in the Netherlands. In case of a complete blockage of the route between Driebergen-Zeist and Ede-Wageningen trains coming from Nijmegen are cancelled at Arnhem and trains coming from Utrecht are sometimes not even arriving in Utrecht because of limited short turning capacity due to the low amount of switches.

7.1. Timetable

All train services operating on the line Utrecht Centraal to Arnhem Centraal are included in the model and are listed below. The bold stations are included in the case study while the other stations are the origin and destination of each train service and some important intermediate stations like Amsterdam Centraal or Schiphol Airport.

- IC 3000: Den Helder – Amsterdam Centraal – **Utrecht Centraal – Driebergen-Zeist – Ede-Wageningen – Arnhem Centraal** – Nijmegen

- IC 3100: Den Haag Centraal – Leiden Centraal – Schiphol Airport – **Utrecht Centraal – Ede-Wageningen – Arnhem Centraal** – Nijmegen
- IC 3200: Rotterdam Centraal – Leiden Centraal – Schiphol Airport – **Utrecht Centraal – Veenendaal de Klomp – Ede-Wageningen – Arnhem Centraal**
- SPR 7300: Breukelen – **Utrecht Centraal – Utrecht Vaartsche Rijn – Bunnik – Driebergen-Zeist – Maarn – Veenendaal West – Veenendaal Centrum – Rhenen**
- SPR 7400: Uitgeest – Amsterdam Centraal – **Utrecht Centraal – Utrecht Vaartsche Rijn – Bunnik – Driebergen-Zeist – Maarn – Veenendaal West – Veenendaal Centrum**
- SPR 7500: **Arnhem Centraal – Oosterbeek – Wolfheze – Ede-Wageningen**

Also the next four lines are included as these are using the same tracks between Utrecht and Amsterdam or because it gives a complete impression of all train services at Ede-Wageningen although does not interfere with all other train services there.

- IC 800: Schagen – Amsterdam Centraal – **Utrecht Centraal** – Eindhoven Centraal – Maastricht
- IC 3500: Dordrecht – Rotterdam Centraal – Leiden Centraal – Schiphol Airport – **Utrecht Centraal** – Eindhoven Centraal – Venlo
- IC 3900: Enkhuizen – Amsterdam Centraal – **Utrecht Centraal** – Eindhoven Centraal – Heerlen
- RS 31300: **Ede-Wageningen** – Barneveld – Amersfoort Centraal

In the model the Intercity station received a weighting of 0.4 and all other stations a weighting of 0.2 resulting in a sum of 1. Since there are more stations in this case study the weights should be distributed over all stations on the line Utrecht – Arnhem again and the more important stations should get a higher weighting. A difference between the model and the case study is that the borders of the case study are two very large stations: Utrecht Centraal and Arnhem Centraal, while in the model these borders were just the open track. Utrecht Centraal and Arnhem Centraal will both get a weighting of 0.2 because of the impact on many connecting trains. The two larger Intercity stations Driebergen-Zeist and Ede-Wageningen both get a 0.1 weighting as these stations offer many regional bus connections. All other stations along the line are weighted 0.067.

7.2. Disruptions

The line Utrecht Centraal - Arnhem Centraal has a total length of 57 kilometres which is approximately three times the length of the line in the model which has a length of 19.3 kilometres. In the model three different disruptions were simulated which were all located at or near the Intercity stations. The observed line of this case study consists of three Intercity stations where two of those stations contain switches: Driebergen-Zeist and Ede-Wageningen. 9 different disruptions are simulated and are listed below.

- Broken train at Driebergen-Zeist track 1 and 2 – 1 hour
- Broken train at Ede-Wageningen track 3,4 and 5 – all 1 hour
- Broken train between Driebergen-Zeist and Ede-Wageningen (at Veenendaal de Klomp) – 1 hour
- Broken train at Bunnik track 1 – 1 hour
- Broken train at Oosterbeek track 1 – 1 hour
- Persons on the tracks near Bunnik – 2 hours

7.3. Results and comparison with model

The summarized results for all nine simulated disruptions are given in Table 7.1 and as can be seen the only negative score is for a broken train at Bunnik. A broken train at one of the two Intercity stations still scores relatively high: approximately -5. A broken train at de Klomp or Oosterbeek or even a complete blockage at Bunnik scores in a range between -9.78 till -8.10, but a broken train, meaning single track, between Utrecht Centraal and Driebergen-Zeist scores poor with -13.78. Therefore new switch layout configurations based on gained knowledge from the model are proposed in this section and these new configurations are also simulated and the results are compared at the end of this section. The scores for these simulated disruption scenarios are lower than in the model which can be deduced from the fact that the considered line in this case study is three times longer in terms of length than the model line and it therefore consists of around three times as many switches. These switches have a high influence in the score since the costs, the number of switches times the weighting factor of 0.5, are deducted from the score which results in a lower score than in the model.

Table 7.1: Results case study. For SW (the number of switches) all switches on the route are used, also the switches that are not used in the simulations.

Disruption cause and location	SW [# of switches]	RCS [%]	P [%]	T [min]	R	$\bar{R}$	S	$\bar{S}$
Broken train Driebergen-Zeist track 1	33	2.40	99.20	0	11.80		-4.70	
Broken train Driebergen-Zeist track 2	33	2.40	100	0	11.90		-4.60	
Broken train Ede-Wageningen track 3	33	3.46	98.80	0	11.49		-5.02	
Broken train Ede-Wageningen track 4	33	3.46	98.27	0	11.42		-5.08	
Broken train Ede-Wageningen track 5	33	3.46	98.67	0	11.47	10.38	-5.03	-6.12
Broken train Bunnik track 1	33	14.6	85.87	35	2.71		-13.78	
Broken train de Klomp track 1	33	7.47	93.73	25	6.72		-9.78	
Broken train Oosterbeek track 1	33	14.93	98.8	5	7.99		-8.51	
Persons on tracks Bunnik	33	13.8	99.8	5	8.40		-8.10	

This train line between Utrecht Centraal and Driebergen-Zeist has similar characteristics as layout 3 of the model since the number of switches is low and only few rerouting possibilities exist. Although at Driebergen-Zeist it is not possible to change tracks at the left side of the station, in Utrecht it is possible to change tracks close by the station, but only at the Sprinter tracks. These switches are visible in Figure 7.3. The rate of cancelled services is high and punctuality is low which can be explained by the fact that there is a 11.5 km single track which will decrease capacity even more since the single track parts in the model were shorter. Also, there are only four signals between both large stations for trains running on the opposite track which increases follow-up times and decreases capacity during disruptions significantly.

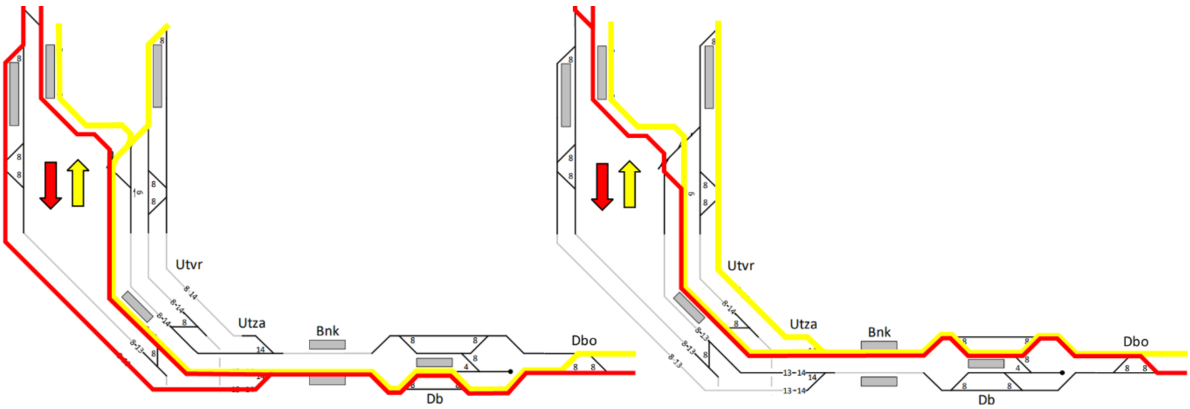

Figure 7.3: Rerouting options with broken train at Bunnik track 1 (left) and track 2 (right).

Furthermore, the model and the case study use different timetables: the case study consist of only 6 Intercity and 4 Sprinter trains per hour per direction instead of 8 and 4 respectively. From the model it follows that before and after each Intercity station switches are useful to increase capacity during a disruption as the score increased from -2.92 (Layout 3 with four switches around the largest station) till 0.52 (Layout 6 with 16 switches). Therefore 8 switches will be added between Utrecht Centraal and Driebergen-Zeist. A drawing of the new situation can be found in Figure 7.4 and the results of the current and new situation can be compared to each other in Table 7.2. An intermediate version with only new switches on the west side of Driebergen-Zeist is also simulated, because in that case, trains can take the Sprinter tracks in Utrecht and can use their regular platform tracks at Driebergen-Zeist increasing the score from -13.78 till -11.61 as can be seen in Table 7.2. If the in Figure 7.4 depicted switches in red are also included the score increases till -12.01.

Table 7.2: Comparison of results case study broken train at Bunnik track 1 with current and new switch configuration layouts. The last two rows show the results from the two proposed switch location configurations.

Disruption	Used switches (Figure 7.4)	C [# of switches]	RCS [%]	P [%]	T [min]	R	$\bar{R}$	S	$\bar{S}$
Broken train Bunnik Track 1	Black – current situation	33	15	85	35	2.71	10.38	-13.78	-6.12
	Current + green switches	37	11	84	7	6.88	10.58	-11.61	-6.02
	Current + green & red switches	41	8	91	7	8.50	10.66	-12.01	-6.31

The relatively low rate of cancelled services can be explained by the fact that the considered line of the case study is three times as long as the line in the model and despite the disruption in Bunnik in this example trains between Ede-Wageningen and Arnhem Centraal are still running as usual. Also Intercity trains from Arnhem can short turn at Driebergen-Zeist and are therefore only cancelled at Utrecht which means that these trains are only cancelled for 20%. By reducing the area, e.g. only looking at the line between Utrecht Centraal and Driebergen-Zeist, differences will be even clearer. However, despite the fact that the differences in RCS and P are small, the scores do show major differences from which can be concluded that the addition of four switches between Utrecht and Driebergen-Zeist provides better scores in case of a disruption.

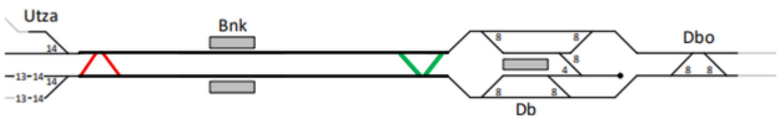

Figure 7.4: Proposed switch configuration layouts between Utrecht and Driebergen-Zeist.

As can be seen in the results in Table 7.2 adding four switches at Driebergen-Zeist increases the score by 2.17, but adding also the four switches near Utrecht decreases the score again with 0.4. From this it can be concluded that the switches on the west side of Driebergen-Zeist (green in Figure 7.4) have positive impact and switches on the east side of Utrecht Centraal (red in Figure 7.4) do have negative impact on the score. This can be explained by the fact that the Intercity trains in Utrecht can also use the Sprinter tracks and use the already existing switches close by the station Utrecht Centraal. The values for $\bar{R}$ and $\bar{S}$ did not increase as fast as the values for R and S which can be explained because all other eight simulated disruptions from Table 7.1 did not change. It would be better to decrease the area of the case study to see bigger differences in scores. However, it can still be seen that proposed solution with the addition of the green switches in Figure 7.4, score higher than the current situation and that the addition of the red switches decreases the score again.

In this research only disruptions between Utrecht and Arnhem are simulated and these switches marked in red can also have an important function in case a disruption between Utrecht and Amsterdam occurs. Intercity trains are easily cancelled (Section 3.2) already in Arnhem, Eindhoven or ‘s-Hertogenbosch and by adding these four red switches trains can short turn at tracks 5/7 and 18/19, next to having some opportunities on the tracks in between although these short turn movements also influence train traffic on other corridors which is not wished for.

The block lengths for trains running on the opposite track are long as mentioned earlier this chapter and this is also visible in Figure 7.6 between Utrecht Centraal and Driebergen-Zeist. Trains towards Arnhem are running with a short headway while trains towards Utrecht need to wait at Driebergen-Zeist until the previous train passed 'Utrecht zuidzijde aansluiting' (Utza). Figure 7.5 shows the time-distance diagram without any changes in the infrastructure where the results are shown in Table 7.2 (only the black switches). This results in low capacity and delays: Intercity trains towards Utrecht need to wait at Maarn Goederen since there is only one track available at Driebergen-Zeist. Between Utrecht Centraal and Driebergen-Zeist there is only space for two Intercity trains per hour per direction. By adding the switches on the east side of Utrecht Centraal as well, the amount of trains between both stations can be doubled. The time-distance diagrams for the variants with extra switches at Driebergen-Zeist and Utrecht Centraal can be found in Figure 7.6 and Figure 7.7.

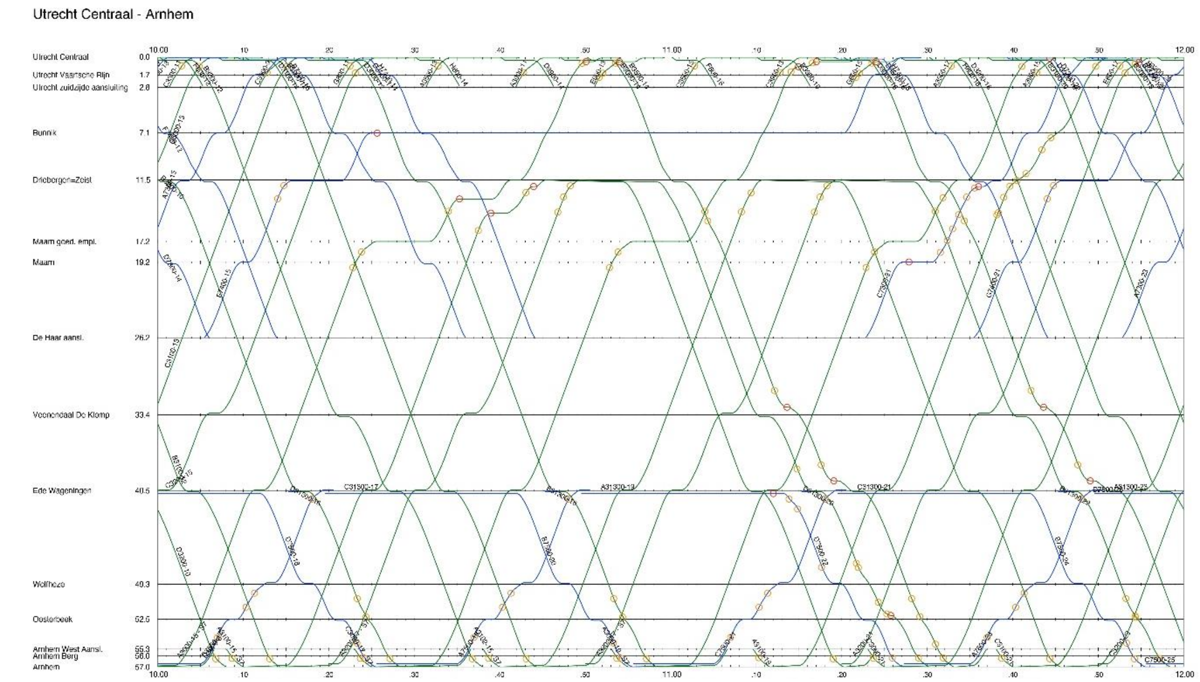

Figure 7.5: Time-distance diagram of a broken train in Bunnik without changes in infrastructure.

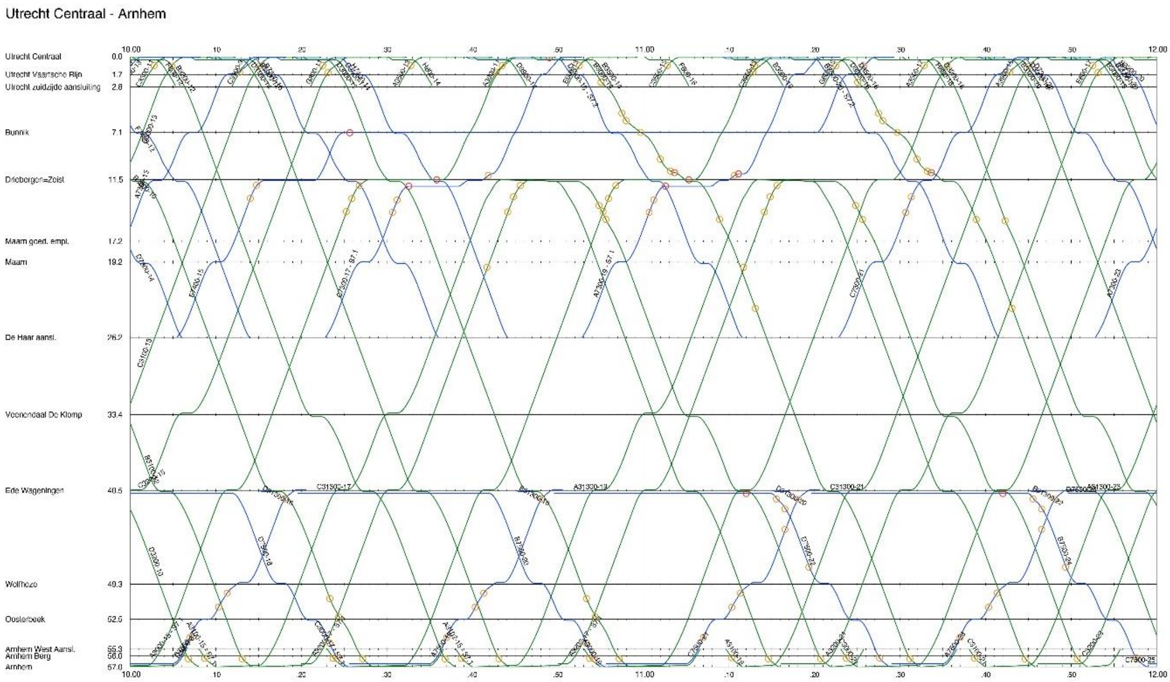

Figure 7.6: Time-distance diagram of a broken train in Bunnik with new switches on the west side of Driebergen-Zeist.

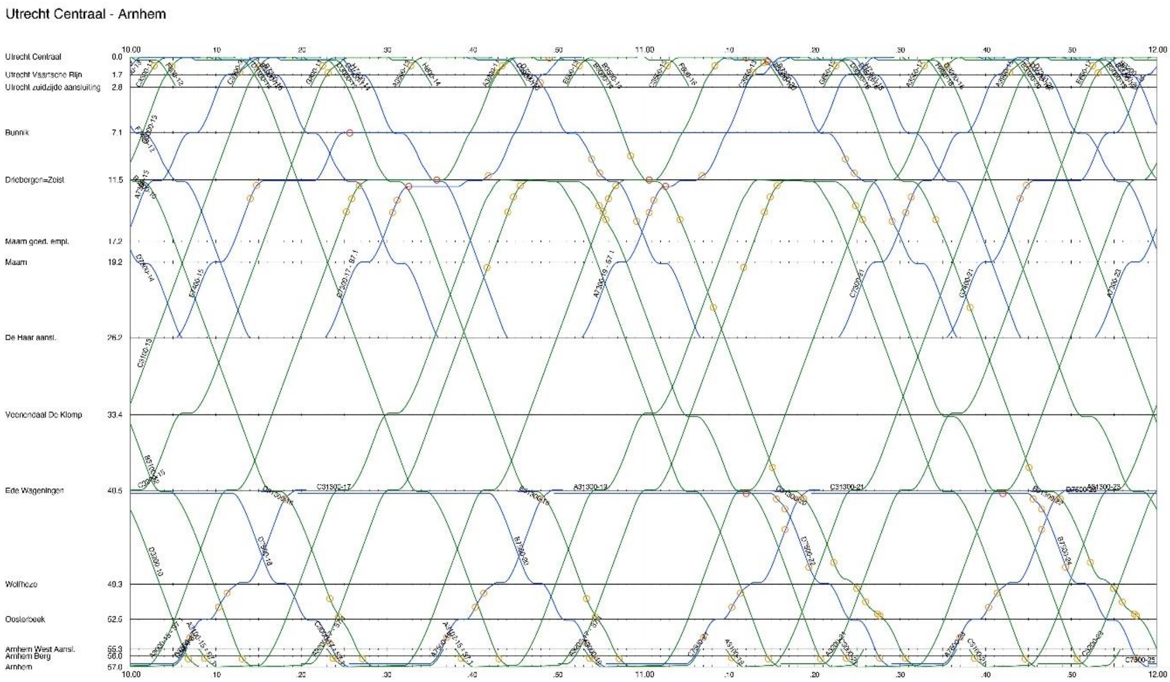

Figure 7.7: Time-distance diagram of a broken train in Bunnik with new switches on west side of Driebergen-Zeist and east side of Utrecht Vaartsche Rijn.

Figure 7.3 showed how all trains are being rerouted in case of a broken train at Bunnik track 1 or track 2. For all calculations it is chosen to use the broken train at track 1 and for both new switch configurations the rerouting options of all trains are shown in Figure 7.8. The left side shows rerouted trains in case of the extra switches on the west side of Driebergen-Zeist and the right side shows the trains if also switches are being constructed on the east side of Utrecht Vaartsche Rijn, east of the junction with the line towards ‘s-Hertogenbosch.

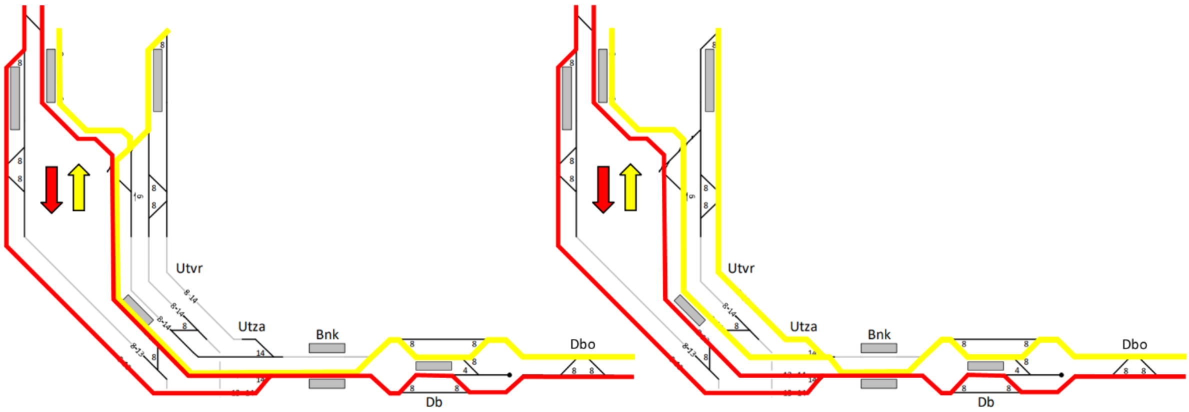

Figure 7.8: Rerouting options with broken train at Bunnik track 1. New switches Driebergen West (left), new switches Driebergen East and Utrecht East (right).

The additional switches on the west side of Driebergen-Zeist can also function for short turning trains in case of a complete blockage of the route east of Driebergen-Zeist. The tail track on the east has only limited length and cannot accommodate the longest Intercity trains of NS, but this tail track has also limited capacity as it takes 9 minutes to short turn a VIRM-10 in case it would fit. Extending the tail track and building a second parallel track just like in Houten Castellum would increase capacity. Otherwise constructing the four switches west of Driebergen-Zeist and possibly even adding two platforms on the two outer track will increase capacity even more during disruptions. These outer platforms can also be used in case of a broken train on one of the platforms or in case of a full blockage towards Utrecht since there are already four switches on the east of Driebergen-Zeist.

Nowadays, if there is a disruption between Utrecht and Arnhem, trains are already cancelled at Amsterdam and do not even arrive at Utrecht because of limited short turning capacity and since both corridors (5/7 to Amsterdam and 18/19 to Arnhem/Eindhoven) are far away from each other. In the current situation Driebergen-Zeist is not able to short turn 10 trains per hour coming from Utrecht (6 Intercity and 4 Sprinter trains) which results in cancellations between Utrecht and Amsterdam. The tail tracks at both Driebergen-Zeist and Houten Castellum however could be useful in case of a disruption. If trains cannot continue east of Driebergen-Zeist trains should all be short turned there and at Houten Castellum, which will not decrease capacity between Amsterdam and Utrecht. Two Intercity trains and all four Sprinter trains can short turn at Driebergen-Zeist, two Intercity trains can be short turned at Utrecht Centraal track 14/15 and two Intercity trains per hour can be rerouted from Utrecht Centraal track 19 to Houten Castellum where they can use the two tail tracks that are planned to be built or use the currently available four switches to change tracks between the two tracks of Houten Castellum. From the model in chapter 6 it could be concluded that double track layouts with a tail track are not good alternatives, because of the low scores in the trade-off between costs and resilience which was explained by the fact that the capacity of a tail track is low. The layout with the tail tracks scored -5.83 and the same layout without these two tail tracks and for the rest the same switch configuration scored 0.53 which is a significant difference. However, the tail track is already present at Driebergen-Zeist and can therefore be used which also applies to Houten Castellum. To increase the score and have a better costs resilience trade-off adding four switches to the west of Driebergen-Zeist would be better since short turn capacity is higher with adding these four switches compared to the adding of three switches and the corresponding tail track. The same principle should also be applied in case of a disruption between Utrecht and 's-Hertogenbosch where Intercity trains cannot be short turned all at Utrecht Centraal. Four Intercity trains per hour can be rerouted to Driebergen-Zeist, the Sprinter trains can be short turned at Houten Castellum and the remaining two Intercity trains can be short turned at Utrecht Centraal track 14/15.

8. Conclusions and recommendations

In summary, this report shows the development of a model in which a simulation-based assessment is performed for optimal rail switch location design to identify the best trade-off between network resilience and costs. The model provides valuable insights into the interactions and relationships between a certain switch configuration and the rate of cancelled trains, the punctuality and the time to recover. Moreover, the results demonstrate that adding switches on both sides of Intercity stations would increase resilience as the rail system can more quickly recover from disrupted events. A case study of the railway line Utrecht Centraal – Arnhem Centraal confirms these results. The model introduced in this study addresses the literature gap by combining simulation experiments with different switch layout configurations and defining four relevant key performance indicators that can be used to quantitatively measure resilience. Interviews with rail experts are conducted to come up with different weights for all criteria and by combining the four criteria, scores were applied to each alternative. By using a trade-off between costs and resilience the different alternatives can be compared to each other.

This chapter presents the answers to the four sub-questions and the main research question in section 8.1. Finally, in section 8.2 recommendations for future research resulting from the work in this thesis will be given.

8.1. Answers to the research questions

This thesis investigated where switches should be located to have a balance between high operational resilience and low (maintenance) costs. The location of the switches has been examined by performing a data analysis where disruptions in the past 10 years on the Dutch railway network took place. All four sub-questions are answered separately.

What is the state-of-the-art on switch location design to improve resilience of the railway network?

In literature many articles are found about the impact of a disruption or how to optimize train rescheduling during a disruption. Some papers studied how trains are short turned optimally or how train service can be optimized by flexible stopping patterns, retiming, reordering and cancelling trains (Zhu & Goverde, 2019). All papers that did research into these rescheduling of trains make use of the current available infrastructure and did not suppose to make changes to improve resilience based on switch location.

Research has also been conducted into reports more focused on practice. Functional Integral System Designs show how tracks are designed and why certain decisions are made for locations of switches and signals. The location designs are depending i.e. on the proposed timetable, speed, available space, vertical alignment and costs (Wildschut, Bos, & Tigchelaar, 2021). Another important aspect of the location design is that certain platform tracks still can be reached from certain directions. However, no direct relationship between switch location design and resilience has been found.

How can different types of railway disruption affect railway operations related to switch locations?

A data analysis has been carried out in which all disruptions on the Dutch railway network from the past seven years are included. The cause, duration, location and impact are included in the data set and different maps are made where specific disruptions are plotted with dots on the correct locations. The colour and size of the dots give more information about the impact of the disruption(s) that occurred on that location. Disruptions take place near larger stations, junctions and more often at places where switches are located. For the latter, not always switch failures are the cause, but also signal failures and broken trains are common causes. A broken train and people near or at the tracks are actually the two most common causes of disruptions. A broken train affects the railway system with one track that is blocked for an hour and this occurs mostly in the larger stations where trains are powered off for energy savings but while switching on again trains can break down but more causes for a broken train exist. Fortunately, larger stations mostly contain a couple of switches meaning that rerouting trains to other tracks is a good alternative. A broken train between two stations causes more problems as trains now have to be rerouted and trains running in the two opposite directions use only one track for multiple kilometres since switches are not located every on every blade of grass. Persons near or at the tracks have, however, even higher impact on the resilience of the railway system since the whole line is closed and trains thus cannot run between the two stations closed by where the persons are on the tracks. Especially on the lines with many trains running a line closure for two hours has huge impact since trains need to short turn at specific stations if capacity is high enough and passengers will take other routes that will then lead to overcrowded trains on those routes. Due to the big amount of data many more conclusions can be drawn and the analysis can be done in more depth. However by looking at the two most frequently occurring disruptions and its locations which are at or near the larger stations enough information was gathered for as input for the model.

Which key performance indicators can be used to quantitatively measure the resilience provided by a given switch location design configuration?

To quantitatively measure the resilience of a railway network specific indicators are required and these key performance indicators have been found in literature. In the first place nine indicators were found, but this number has been reduced to four. The indicators that were removed from the list are the infrastructure occupation, platform consistency, timetable feasibility and the number of alternative routes. These indicators were somehow correlated to others resulting in biased scores or these were not focused enough on railways but more on road traffic. By virtue of that correlation only four considered key performance indicators which were independent from each other are considered. The four key performance indicators that are used to quantitatively measure a given switch location design configuration are:

- Costs of infrastructure [# of switches]
- Rate of cancelled services [%]
- Punctuality [%]
- Time to recover [min]

The weights for the indicators are the results from a best-worst method which is performed with eight rail experts. The interviewees mentioned that the rate of cancelled services is the most important, meaning that during a disruption it is more important to keep trains running as much as possible than downsize the timetable to a minimum and keeping punctuality high which is the current strategy in the Netherlands. The time to recover is the time it takes to start with the downsized timetable after the beginning of the disruption and there is a link between not only the number of but also the location of the switches and this time to recover. Since a trade-off is made between costs and resilience both get a weight of 0.5. Costs are therefore weighted 0.5 and the three resilience KPIs are weighted based on the results from the interviews: rate of cancelled services 0.25, punctuality 0.125 and time to recover 0.125.

What is the relationship between switch location, costs and railway resilience under different disruption conditions?

In the model different layouts all with a different switch configuration have been simulated. All these variants obtained a score by using the key performance indicators including the corresponding weights. The main research question suggests that a trade-off between costs and resilience should be found. To calculate scores for different switch location configurations costs and resilience are both weighted 0.5. Costs are defined as the used number of the switches in the layout and resilience contains of rate of cancelled services, punctuality and time to recover. Adding more switches, increases the (maintenance) costs and chance of switch failures, but trains can more easily be rerouted during disruptions since flexibility increases.

From the model it follows that the layouts with more switches included also get higher scores and score higher in the trade-off between costs and resilience. However, the double track layout with the most switches does not score the highest. It follows that if a larger station contains a tail track on both sides the score is lower than if the larger station has four switches on each side of the station to be able to switch from and to both tracks. This can be concluded by the fact that one tail track has only limited capacity due to long short turning times: 9 minutes for the VIRM-10 Intercity and 5 minutes for the SLT-10 Sprinter. By having four switches on both sides of the station, trains can be short turned on both platform tracks resulting in higher capacity.

The layouts where the Intercity station contains four switches on each side score the highest. There is a difference in switch configuration between the two layouts that have three platform tracks at the Intercity station. One layout (7.1) scores higher for a broken train on any platform since the middle track at the Intercity station in this layout is connected to both outer tracks and trains can separately use tracks 1 and 2, 1 and 3 or 2 and 3 for both directions which does not apply for the other layout (7) where the third track is one of the outer tracks. The Intercity station with the third track as side track, however, offers a higher short turn capacity in case of a complete blockage of the line, but the station with the third track in the middle also suffices since the four Intercity and four Sprinter trains can be short turned on two tracks and these trains can leave the station on time before the next train arrives that should be short turned. The best double track layout in the trade-off between costs and resilience is a layout with four switches on both sides of the Intercity station and four switches for short turning at the stations approximately 5 km from the Intercity station (layout 6), That layout scores better than the other layouts, because of the lesser amount of switches than the layouts with more tracks at the Intercity station.

For the layouts with four tracks it is interesting to see that a layout (12) having two switches less than layout 11 can score almost 1 point higher for resilience. From this can be explained that tail tracks at the larger stations also do not score high which is the same for the double track layouts. The configuration that scores the highest has only four additional switches and even doubles the resilience score compared to a layout (12) providing Sprinter trains to use all tracks and Intercity trains use only their own platform. This highest ranked layout scores high because of the more short turning tracks for the eight Intercity trains per hour for which two tracks are needed. The layout with one tail track scores poor as this only offers low short turn capacity and having two tail tracks only decreases the rate of cancelled services slightly and increases the score for resilience with 0.8 (Figure 6.20). The weighted average of the total score with costs and resilience both included is even lower for the layout with two tail tracks versus one tail track which is caused by the amount of switches which has a negative influence on the score (Figure 6.19).

Based on the answers to these four sub-questions, an answer to the main research question can now be formulated:

What is the impact of rail switch locations on the trade-off between railway network resilience and costs?

As answer to the main research question, switches have significant influence on train traffic and can help keeping capacity high during disruptions by rerouting and short turning trains. A balance between the number of switches and high resilience is needed since switches also fail regularly in case they are not maintained properly and maintenance costs are high. From the conducted interviews it follows that the number of trains running during a disruption is more important than the costs for building and maintaining the switches. The results from the interviews might be biased since only one person from ProRail is interviewed and ProRail have only limited financial resources for the infrastructure. All other interviewees are from NS and engineering firm Royal HaskoningDHV and mentioned the number of trains still running to be more important since they are not required to keep ProRail's budget under control. From the model and also the case study it however follows that at least at the most important railway lines in the Netherlands, switches should be located on both sides of the larger stations and also on one side of the nearby smaller station (located approximately 5 km from the larger station). This enables a capacity of eight trains per hour per direction on a single track in case of a partial blockage and also offers enough short turning capacity which therefore increases resilience in terms of lower time to recover and rate of cancelled services. Nine different double track layouts have been simulated and in the trade-off between costs and resilience differences in scores were clearly visible. An Intercity station with two tracks and tail tracks for short turning scores low (-5.83) while the same layout with four switches on both sides of the Intercity station and four more switches on each of the nearby stations scores highest (0.53). The higher the costs (number of switches) the higher the possible resilience which was visualised in Figure 6.11.

8.2. Discussion

In this thesis a model is developed that a simulation-based assessment has performed for rail switch location design. The limitations and assumptions made in this study to delineate the scope will be addressed in this section. The impact of these limitations on the results will be discussed and these will suggest areas for future research which will be explained in section 8.4. Limitations and assumptions that have been made in the model and influenced the model results are discussed in section 6.7.

8.2.1. Costs

Firstly, the cost key performance indicator which was defined as: the amount of costs for designing, constructing, building and maintaining new switches and crosses. This KPI is measured in terms of the number of switches. The number of switches, however, cannot represent all the costs. If a new switch is added, not only the costs of building the switch should be taken into account, but also the costs for designing, constructing and in a later phase maintaining. By using Euros as unit the costs can be calculated in more detail resulting in more realistic scores. For the removal of switches no negative costs are used in the model and the case study. The removal of switches also cost money, but this will save money after a certain period since there are fewer maintenance costs. This will also be further elaborated in section 8.4.

8.2.2. Switches

Also the angle of the switches will change the results. The 1:15 switch is used in the model which was already discussed in section 6.7 but is mentioned in this section again, because this limitation is made for generalisation reasons. These switches allow trains to ride 80 km/h in the curved direction but require more space than, e.g., a 1:9 switch (40 km/h). The land use of switches and the horizontal alignment were however out of scope for this research. In the model this was no problem at all since it is a simplified representation of the real world and there are no buildings nearby the tracks that hinder a potential additional track. Furthermore, the model is assumed to be flat and therefore the vertical alignment is also not looked at in the case study. Switches may not be located on slopes in the Netherlands, but since in the case study only switches were added between Utrecht and Driebergen-Zeist this would not be a problem. If switches would have been added between Driebergen-Zeist and Arnhem the vertical alignment could have been research since the Utrechtse Heuvelrug and the Veluwe both have some small hills which would probably not have been a problem as these hills are not as steep as certain train lines in, e.g., the Alps.

8.2.3. Train types

In the model only two types of trains are considered: an Intercity (the Dutch VIRM-10) and a Sprinter (the Dutch SLT-10). Having more train types with all different stopping patterns, speeds and frequencies, the timetable will become messier. This limitation was chosen because of the Dutch situation where NS only offers these two train types and therefore also made comparisons between model and case study possible since the case study also a Dutch train line was. In other countries there are more train types and for a more general approach, the model could be adapted with more train types. Cargo trains are also left out since these are rare on Dutch main lines (Rijksoverheid, sd) and these mainly use train lines that are specially built for cargo trains like the Betuweroute. In case of a disruption these cargo trains will also not short turn, but will most likely wait till the end of the disruption and then continue their journey (ProRail, 2014).

8.2.4. Calculation of the scores

There is also a difference in the calculation of the scores between the model and the case study. In the model only the used number of switches (inclusive the ones required based on symmetry reasons) have been counted and are used in the equation. However, in the case study all existing switches between Utrecht and Arnhem are counted, also the switches that are not used in the simulated disruption scenarios. A reason for this is also another point of discussion: the model and the case study have a different length. The case study is approximately three times longer which makes it hard to compare the scores of model versus case study, especially when the number of switches are counted differently. Nonetheless, the scores between different layouts in the model are possible to compare and this applies for the different disruption scenarios within the case study as well.

8.2.5. Literature study and interviews

In the literature study 28 publications are used in the main text. The first part of the literature study was an impact assessment in which the impact of a disruption on train traffic is researched. In the second section the goal was to find papers about researches in which different switch locations are proposed but these were not found. That section, however, also introduced the key performance indicators. The third part explained disruption management strategies in the Netherlands. By adding more publications these three parts could have resulted in better results for the analysis, but for keeping the overview over all publications a balance between better results and the amount of work had to be found. A more diverse list, by not only using Google Scholar, Scopus and ScienceDirect, other results could have been gathered. Also, mainly English papers were searched for, but other languages like German and Dutch could have played a bigger role and this could have been useful in the literature study. There is a mix between recent and older papers. More recent publications may be better because of the latest findings and innovations but since no papers were found about switch location design this is inapplicable.

The conducted interviews are performed with rail experts from four different companies: Royal HaskoningDHV (4), NS (2), RailExperts (1) and ProRail (1). The amount of people per company is not equally distributed as shown in brackets. This can give biased results, especially since ProRail is the only company that should pay for the infrastructure for example. By interviewing more people and also from other companies like the Ministry of Infrastructure and Water Management this could give more and better results since more experts and people who make decisions are included in the interviews. Another group of people that could have been asked are TU Delft Transport & Planning students or train travellers of different age groups. The most important is that all groups are equally often interviewed and also multiple persons per company to get the best results. Due to the amount of time, it was chosen to conduct eight interviews with the in total four different companies.

8.3. Recommendation for effective rail switch location design

This section provides recommendations on a general level independent on the location of the analysed case study. These recommendations are based on the set of experiments performed in this thesis. Finally, some recommendations will be given specifically for the considered case study.

- Stations which are used by Intercity trains should have four switches on both sides of the stations. This enables rerouting possibilities from both directions to the other track in case of a broken train as well as a high short turn capacity from both sides in case there is a complete track blockage on one of the lines towards that station. In the trade-off between costs and resilience layouts score with these switches as described above approximately 1.5 points higher than a layout with only two switches on both sides of the larger station.

- Since the second most occurring disruption cause (persons near or at the tracks) happens often between a larger station and a station close by, which is a 5.2 km distance in the model, trains should have short turning possibilities at other stations as well. At the larger station this is possible by locating the switches as described in the previous bullet point, but trains coming from the other direction should be short turned at a different station. That could be outside of the model, in a different Intercity station, but since the infrastructure outside the model is not known, the stations located in the model are used. These smaller stations should have four switches in total but these should be located on the opposite side of the large station, in order to offer trains the possibility to short turn. In the model these stations are located 5.2 km from the large station but in a real-world situation this distance can be shorter or longer. If the distance is longer, it will influence the resilience in case of a single track usage of the line between these two stations since capacity will be lower. Most important to investigate in each specific case study is to determine which smaller stations should have these short turn possibilities as well. It does not make sense when all trains are running until a very small train stop and passengers get stranded since there are no possibilities to travel further by, e.g., bus or tram. In those cases a bit larger station further away should be chosen as short turn station in case of a disruption.

- Tail tracks score poor in the trade-off between costs and resilience. This is the case for the double track layout with a tail track on both sides of the larger station and for the four track layouts with one and two tail tracks as well. The layouts as described in the previous bullet points scores approximately three points for resilience higher, even with six switches less which is a big difference compared to other scores and layouts. The same applies for the four track layouts: a layout with having two switches less scores slightly higher than the layout with the tail tracks. Compared to the layout with two tail tracks (having 18 switches), adding two more switches and changing the configuration can increase the score with 2.5. This offers for both Intercity and Sprinter trains three tracks for short turning.

The next five recommendations can be given to ProRail for the considered case study Utrecht Centraal – Arnhem Centraal.

- The part of the case study between Utrecht Centraal and Driebergen-Zeist scores significantly lower than other parts of the case study for the same types of disruptions. This lower scores was caused by the fact that there are no switches on the west side of Driebergen-Zeist , a tail track on the east of Driebergen-Zeist meaning that the four switches on the east side are far away from the station (from the model it follows that this results in a low score) and only four switches on the east of Utrecht Centraal for the Sprinter tracks. Therefore this location was chosen to make some proposed new switch location designs. Adding a few switches at smartly chosen locations on the west side of Driebergen-Zeist increases the score in case of a single track disruption near Bunnik significantly. Four switches are added which increased the score with more than two points. Adding another four switches on the east of Utrecht Centraal let the score decrease again. The addition of these four extra switches apparently decreased the trade-off between costs and resilience since the resilience only increased slightly (due to the existing switches at the Sprinter tracks) but the costs increased with four switches. The addition of the four switches west of Driebergen-Zeist can also increase short turn capacity in case of a total blockage of the line towards Arnhem and prevent cancellations between Utrecht and Amsterdam.

- From the interviews it follows that trains in the Netherlands are cancelled too quickly and many passengers experience inconvenience during a disruption. It should not happen that trains are cancelled between Amsterdam and Utrecht if there is a disruption near Veenendaal (line to Arnhem) or Geldermalsen (line to Eindhoven) as this Amsterdam - Utrecht line is one of the most important lines where many passengers travel. The interviewed experts in rail mentioned that during a disruption keeping the rate of cancellation as low as possible is more important than keeping punctuality high. Since NS is examined on punctuality and not on rate of cancelled services, NS cancels trains during disruptions to keep punctuality high. During a disruption many passengers are stranded on a certain station and as a passenger the most important thing is to be able to travel again as fast as possible and preferably with a seat. The worst scenario is that many trains are cancelled and the trains that are running are so overcrowded that a part of the passengers even miss their train and need to wait even longer. Punctuality during a disruption is for passengers therefore less important and NS could offer more trains during a disruption by more smartly thinking in options where trains can be short turned. For the case study Utrecht – Arnhem trains can use the Sprinter tracks 14/15 at Utrecht Centraal, the tail track at Driebergen-Zeist and trains can even use Houten Castellum in case of a disruption between Driebergen-Zeist and Arnhem. This solution without changes in the infrastructure is not considered yet since NS is examined on punctuality. In case of a disruption close to Utrecht Centraal, like on the 30th of May 2024 in Utrecht Vaartsche Rijn where a cargo train was leaking a dangerous good, the whole train traffic to the east and south were disturbed, but also again between Amsterdam and Utrecht (Amelsbeek, 2024). Since all tracks were closed at Vaartsche Rijn, the proposed solution of short turning at Driebergen-Zeist and Houten Castellum are not possible. Trains, however, should all be short turned at tracks 14/15 that cannot accommodate all Intercity and Sprinter trains coming from Amsterdam. In this scenario, trains should partly be short turned at Breukelen and 50% of the Intercity trains should be using tracks 14/15 in Utrecht Centraal. If the disruption is further on the line towards Arnhem or Eindhoven the proposed solution of short turning at Driebergen-Zeist, Houten Castellum and a small part at tracks 14/15 is again a possibility.

- Other options that can be considered are adding two platforms on the two outer tracks at Driebergen-Zeist besides the switches on the west. These two platforms can ensure that all trains on the route between Utrecht and Arnhem can be short turned at Driebergen-Zeist from both directions. By bringing through passengers from Arnhem and Nijmegen towards Utrecht and Amsterdam closer to the disruption (instead of cancelling trains at Arnhem or maybe Ede-Wageningen) people can be moved by the regional buses towards Utrecht Centraal. Possibly adding extra buses by NS in case of a longer blockage of the line would also benefit from the changes at Driebergen-Zeist as the distance between Driebergen-Zeist and Utrecht Centraal is shorter than to Ede-Wageningen or even Arnhem Centraal meaning that less buses are required.

- Adding switches at Utrecht Centraal is more difficult since certain corridors are located far away from each other but the other contingency plans where trains are rerouted towards Driebergen-Zeist or Houten Castellum should make it possible to keep capacity between Amsterdam Centraal / Schiphol Airport, Amsterdam Zuid and Utrecht Centraal high.

- Finally, it can be beneficial to shorten the block distance on the lines to and from the biggest cities. This will raise the costs, but decreases the follow-up times of trains and thus will increase capacity in case a train suddenly needs to use the tracks that is in normal conditions only used by trains in the opposite direction. A combination of the last three solutions would increase resilience, but will be interesting for future research considering the costs: shorter block distance, the addition of switches on the west of Driebergen-Zeist and increasing short turn capacity in Driebergen-Zeist by adding two platforms on the two outer tracks which can also function in case of a disruption on one of the tracks at the island platform.

8.4. Future research

This section highlights the most important future research possibilities within switch location design and disruption management to increase capacity during a disruption in general.

- Firstly, after the analysis of disruption events executed in chapter 4 only two disruption causes were taken into account in the model. These were a broken train and persons near or at the tracks. From that analysis it followed that there were 85 other causes of disruption and some only occurred a few times as can be seen in Appendix B, but despite having a relatively low occurrence these are also interesting to investigate. A signal failure which comes in third place and a switch failure on fourth place could possibly change the results. This thesis was about relocating switches but does not include the fact that switches can fail themselves which means that other switches are required to change tracks.
- Also, this disruption analysis could be executed in more depth. Many more conclusions can be drawn and this is a separate research worth. As a simple example: Figure 4.7 and Figure 4.11 in chapter 4 showed maps with persons near or at the tracks and collisions with people respectively. Based on these results ProRail could take measurements to, e.g., reduce the amount of these disruptions since preventing is better than solving. This could also be done for other disruption causes and filters can be applied to investigate whether certain days of the week a specific cause occurred more or less and if relationships can be found with events with many people, weather conditions and so on.

- Furthermore, the scores are calculated with the equation given in chapter 4 and these are averaged with a weighted average since only two disruption causes are included representing almost 50% of all disruptions. By looking at more disruption causes and the impact on the system (partly or completely blocked lines per cause) and the number of occurrences per cause which can be found in Appendix B, all these disruptions can be simulated. This would give much better results but is very time consuming where computer programming possibly could save time.
- The length of the blocks and where signals are located was actually out of scope for this research but while constructing the model some basic calculations were performed to come up to a block length of 1300 m. It could be interesting to research how much different block lengths and locations of signals also influence capacity during a disruptions. In the model all layouts contain signals for both directions on all tracks. This can be realistic and is applied on certain lines, but looking at the case study this is not even the case on an important line between two big cities. The application of ERTMS can also influence the results because shorter blocks are usual. This is also part of the discussion of the model results in section 6.7.
- Moreover, the key performance indicator costs is measured in the number of switches. To make the research more realistic, the costs can also be measured in euros where the costs of building extra signals should also be included.
- Short turning, rerouting, reordering and cancelling are some of the train rescheduling methods that have been used to come up to a solution to keep trains running during a disruption. In future research this can be taken into account in more depth and investigating the influence of a switch configuration together with these methods, e.g., by looking which method scores best in different switch configurations.
- The best locations for switches should also be checked if these fit in terms of vertical and horizontal alignment. This was out of scope for this research but is an interesting follow-up research worth. For the model a flat surface was used which means that vertical alignment was no problem. The horizontal alignment was also no problem since the model only consist of railway tracks and no surrounding buildings etc. For a case study these questions are however interesting.
- ProRail has a limited budget, but also NS is optimizing all schedules to save money. NS is, e.g., optimizing train lengths to save on energy costs based on expected amount of passengers which requires many shunting movements with coupling and decoupling. This takes time and extra personnel and NS should think whether it might be better to use these train drivers for the current train driver shortage and run more often with longer trains than necessary which is also done in Switzerland following from the interviews. So for NS it could be interesting to also include rolling stock and crew management in the trade-off in a follow-up study.
- In this research only trains are looked at and the number of passengers are completely left out of scope. For future research this might be interesting to investigate whether these influence the results. Now there is a difference between an Intercity and a Sprinter but these should be given different weights based on the number of passengers that they can transport.
- Finally, two interesting challenges for NS during a disruption are crew rescheduling and bringing information to passengers via the app and the announcements at the platforms. Both are out of scope for this thesis but are interesting to further investigate to improve the overall experience for passengers during a disruption.

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Appendix A. Overview of literature

A1: Survey methodology of the literature review

In this section the survey methodology of the literature review is performed. The literature review is done by using websites as Google Scholar, Scopus, ScienceDirect and ResearchGate to retrieve relevant papers. Also, the TU Delft repository containing other Master theses that are similar to this project is useful. Finally, the regular Google search engine is used to find relevant new articles on the topic. When using the different websites to get scientific articles about railway infrastructure and timetables specific search terms and keywords will be used. By using multiple keywords, the number of results will be lower and will be more specific. If Boolean operators like 'AND', 'OR' and 'NOT' are used to combine the different keywords the results of the search will be even better. The first task after entering the search terms is to look at the title. If the title of the paper seems relevant the next step is to read the summary of the article and if the article still is good for this thesis, a certain chapter or even the whole paper or article should be read and will be included in this literature review. The findings that are relevant to this research will be given in a structured way and will be summarised which can help answering the sub questions. The keywords that are used are visible in Table A.1. This table also provides the number of relevant papers that were found by using the keywords in Scopus.

Table A.1: Search queries and keywords including filtering steps.

Query	Keywords	Number of search results in Scopus	Number of relevant papers within first 20 search results	Why some papers are not relevant
1	Switch AND optimisation	16840	0	These are not railway related.
2	Railway AND switch AND optimisation	125	1	Papers are about how to decrease switch failures and not about the switch locations.
3	Railway AND switch AND optimisation AND location	11	3 (of which 1 the same as in the previous query)	Not about switch location configuration.
4	Railway AND switch AND design AND location	0	0	Inapplicable.
4	Railway AND disruption	940	10	These papers were about vehicle onboard monitoring railway tracks and safety or about predicting disruptions for example.
5	Railway AND disruption AND management	271	12 (of which 4 the same as in the previous query)	Some about human science for railways, railway track quality or digitalisation for example.
6	Railway AND disruption AND management AND Netherlands	26	14 (of which 6 the same as in the previous query)	These papers were mainly about rolling stock rescheduling.
7	Railway AND disruption AND management AND Austria OR Germany OR	7	5 (of which 3 the same as in one of the previous	The ones that are not relevant are about a flood damage model or weather impact on

	Switzerland		queries)	freight railways.
8	Railway AND disruption AND management AND England OR Britain	9	2 (of which 1 the same as in one of the previous queries)	About risks of slope instability and also about tunnelling opportunities.
9	Railway AND switch AND flexibility	33	1	The papers were about passenger behaviour.
10	Railway AND flexibility OR resilience	13	1	The topics of these papers were about risks and not about switches.
11	Rail AND resilience AND indicator	39	1	Some about resilience in the context of COVID-19, no same kind of disruptions or methods to measure resilience by using demand and passengers numbers which is out of scope for this research.
12	Rail AND resilience AND indicator AND punctuality	0	0	Inapplicable.
13	Rail AND resilience AND indicator AND recovery	7	1	About passenger flows
14	Rail AND resilience AND indicator AND disruption	10	1 (which is the same as in the previous query)	About passenger flows or how to make the materials of the infrastructure more resilient
15	Resilience AND indicator AND disruption AND punctuality	2	2	Both were focussing on trucks and logistics, but are interesting to compare with rail resilience

As can be seen in Table A.1 there are three types of topics for which was searched. The first three queries were about switch location optimisation. By only using the terms “switch” and “optimisation” there were too many results and most of them were not railway related. Therefore, it is chosen to use the term “railway” from now on in every query. Rather than ‘optimisation’ also ‘design’ was searched for, but this gave no results in Scopus, but it did in other search engines. The second topic is about disruption management in different countries where especially from the Netherlands there were way more papers available than from Great Britain, Germany, Austria and Switzerland combined. For the last topic about flexibility and resilience less papers were available unfortunately. However, changing the input towards indicators and by logically coupling keywords together interesting results are found. Some key performance indicators about the resilience of trucks where punctuality, which is often used term in railways, also come into place and has other impact since a late delivery of goods has impact on many other deliveries, shops and costumers (Li, Chen, Govindan, & Jin, 2018). A delayed train also could have major impact in case it is on one of the busier lines of the country.

Also by using Google Scholar, ScienceDirect and ResearchGate papers have been found about resilience and how to assess this quantitatively. The results from the literature study are given in Chapter 3.

A2: Disruption management in other countries

Section 3.1.3.2 described how disruptions are being solved in the Netherlands and how thee contingency plans work. It is however interesting to compare the different disruption management strategies for different countries. Some literature has been found for this topic and will be discussed in this sub-section. Disruption management strategies for Germany, Austria, Switzerland and England have been researched.

Germany

The railways in Germany are completely different compared to the Netherlands. One of the biggest differences comes from the fact that Germany is almost nine times as big in square meters than the Netherlands (Index Mundi, 2020). Germany has a total length of 39.200 kilometres of railway tracks where regional trains and the highspeed Intercity Express (ICE) are using the same tracks for a lot of railway lines (Allianz pro Schiene, sd) (DB Netze; ÖBB Infra, 2020). The country is located in Central Europe and therefore 6 out of 9 European freight corridors are running through the country and on all these corridors the freight transport volumes are quite high (Gerrits & Schipper, 2018).

The German railway network is at many line already close or even over capacity and furthermore, the state of the tracks, signals, switches etcetera is sometimes really bad and not good maintained (Allianz pro Schiene, sd) (Partridge, 2023). Deutsche Bahn (DB), the national rail operator, does not perform well in terms of punctuality, especially the long-distance trains (Deutsche Bahn, 2023). Due to the bad condition of the infrastructure there a many disruptions and therefore also many (big) delays although not all disruptions are caused by the bad infrastructure and or the Deutsche Bahn as main operator (Business Insider, 2019). Most of the delays come from DB Fernverkehr which is the long-distance train service including i.e. ICE, Intercity and Eurocity. The other subsidiaries of Deutsche Bahn are DB Regio (regional train traffic) and DB Cargo (freight). Passenger satisfaction in Germany is not high compared to neighbouring countries and this is caused by the many delays (European Commission, 2018). In case of delays train-path managers can give advise to dispatchers to alter sequences of trains with the goal to improve punctuality and efficiency. In some main stations that enables passengers to use cross platform changes like in Köln Hbf (Cologne) and Mannheim Hbf. Trains are waiting for each other when in case the connection cannot be reached. Although this waiting time is only 5 minutes between trains from DB Fernverkehr this can lead to a big snowball effect at the next main stations (Jacobs, 2003). Some simple solutions in case of a delay are mentioned below.

- Time of a stop is extended; delayed faster train can overtake the regional train
- Other routes in stations; use another track at the station, but, if possible, the same platform to decrease passenger inconvenience
- Relocation of an overtake stop; if there are switches available at other stations this would decrease the combined delay of fast and regional train
- Extend travel time; to prevent conflicts it is possible to slow trains down
- Cancellation: in case of big delays, it is possible to cancel the train or short turn it before its destination to prevent a delay in the next trip of the train (Jacobs, 2003)

These decisions are mainly made at a regional level. Conflicts are managed with the help of predefined dispatching rules and during a disruption train dispatchers take the first measurements by isolating the location of the disruption by using their traffic management system LeiDis-NK which is an abbreviation of ‘Leitsystem zur Netzdisposition Kunde’ (DB Netze, 2020).

Austria

In mountainous area the kind of disruptions may differ as well as the occurrence of certain causes. In the Alps extreme weather events are more likely to happen than in a country like the Netherlands. This includes heavy precipitation and floods, snow fall, avalanches and rockslides (Dörnenburg, et al., 2022). In these areas there are not a lot of possibilities to reroute trains because there are no other train lines available when a train line crosses a mountain. The Arlbergbahn between Bludenz in Vorarlberg and Innsbruck in Tirol has also faced a lot of total closures for multiple days because of the danger of getting avalanches (Kolp, 2021). During these kinds of disruptions there are only three options for passengers. They can cancel their journey; they can take a train via a route that takes significantly more time (which will not be applicable for each location), or these passengers take the by the railway operator arranged rail-replacement bus service. The same applies for the Brenner line between Innsbruck in Austria and Bozen in Italy. This is a particularly important route for passengers and cargo and of utmost importance to reduce the number of cars using the Brenner highway. The Brenner Pass is due to its location within the Alps a crucial connection to the whole region as alternative routes are costly in terms of time and also a huge amount of business that are dependent on this route (Fikar, Hirsch, Posset, & Gronalt, 2016). With the construction of the Brenner Base Tunnel, it will be the longest underground railway connection in the world with a length of 64 kilometres (Raimondi, 2023). The currently used Brenner Line, however, will not be demolished. The tunnel will be used by the cargo trains and the highspeed Railjet trains between München (Germany), Innsbruck (Austria) and Verona (Italy). The old line will be used for regional trains between Innsbruck, Brenner and Bozen (Neue Brennerachse, sd). When in future scenario one of the two lines is closed for several hours due to some kind of disruption a good strategy is just to operate all trains via the other route. Only for regional trains using the tunnel this would not make sense as there are no regional train stations inside the tunnel. In case of a disruption in the tunnel, all cargo and high-speed trains can be operated via the old route.

If a disruption on a more regular line occurs, the ÖBB have pre-made contingency plans developed. These are for the most common disruptions and are detailed and numerous. In practice, it is always depending on the situation and will be an on-the-spot decision-making to find the best solution to still operate as many trains as possible (Gerrits & Schipper, 2018). When a certain track is blocked most of the time it is decided to cancel a couple of train lines and still operate the rest. In this case the timetable during the disruption has far lower capacity but is reliable at least: the trains that are announced to run, are running (Newsdesk Heute, 2023).

The ÖBB designed Aramis which is a real-time train monitoring system. It stands for 'Advanced Railway Automation Management Information System' and it provides train monitoring for railway undertakings and infrastructure managers in real time (ÖBB, sd). In case of potential conflicts and disruptions the system automatically generates operational solutions. Routes including switches and signals are automatically changed and passenger information is automatically adjusted in the app, on the monitor screens at the platforms and through the announcements in the stations (ÖBB Infrastruktur, 2023).

Switzerland

The Swiss have the highest-performing railway system of Europe. The network is used intensively by passenger trains and cargo, and it also receives good ratings for safety and quality of service (Ari, 2018). Although the train network in Switzerland has the highest capacity utilization in Europe, the trains are still very punctual (SBB, sd). However, also the Swiss train network experiences disruptions due to, among other things, switch failures, delayed inbound internationals trains, landslides and animals on the tracks (Matsch, 2022). Approximately a third of all disruptions has an external cause, again a third is due to the infrastructure and the last part is because of problems with the trains. The SBB, the ‘Schweizerische Bundesbahnen’ or in Englisch Swiss federal railways, however, do not talk about disruptions (Störungen) but about events (Ereignisse). The SBB have made a communication tool called RCS ALEA. RCS ALEA means ‘Rail Control System Alarm- und Ereignisassistent’ which can be translated to Rail Control System Alarm and Event assistant where ‘event’ can be read as a disruption. The tool is used in the case of having technical problems or unforeseen incidents during operations and can help choose the right disruption management system and construct an adapted timetable (SBB, sd). Disruptions can therefore be solved quickly which means that 80 percent of all disruptions is solved within 30 minutes (Saheb, 2017). If the disruption cannot be solved within 30 minutes plan B is ready which exists of 900 variants with the goal to minimize the consequences for the passengers. These variants are for total blockages of tracks and for disruptions where only one track cannot be used. The Swiss have a thought-out system when the events occur and how to solve the events to go back to the normal timetable as soon as possible.

England

England is a country in which extreme weather are regular, there are more tornadoes by area than in any other country in the world (Ritchie, 2023). This will cause big problems, because most of the infrastructure in the United Kingdom is not able to withstand the amount of rainfall, heatwaves and storms (Harvy, 2021). Passengers are complaining about the delays and cancellations, they even leave their homes one hour earlier than they actually should leave just to hope they make it on time to their jobs (Fagg & Unia, 2023). The impact of harsh weather on train traffic has been researched in 2015 where a case study of the intense storms of 28 June 2012 were used as a case study. These storms caused ten thousand minutes of delays throughout the whole country and a lot of track blockages because of floodings and landslips. Railway lines are then closed being repaired as fast as possible and then opened again. This means that trains need to be short turned at stations nearby and capacity is decreased, because capacity of short turning is lower than the capacity of the line without a disruption (Jaroszweski, Hooper, Baker, Chapman, & Quinn, 2014). Also, in the future there are concerns about bad weather that will lead to major disruptions which will even increase due to climate change. The UK have under invested in their transport operations and its infrastructure for decades which means that there will be many more big line closures in the future (Dawson, Shaw, & Gehrels, 2016). Network Rail, the national UK rail operator has just like all other countries premade contingency plans ready if a disruption takes place at a certain location. This is to reduce the ‘knock-on’ delays, which were previously called oil slick effect or snowball effect. Some of the actions that are taken by Network Rail are mentioned below (Network Rail, 2023).

- Trains with few passengers may be cancelled so that there is space on the tracks for delayed trains to complete their journey and decrease the delay.
- Stops could be missed out to make up time or added to keep services moving.
- If a line closes, trains may have to be diverted onto other routes or lines.
- Short turning to carry out checks and cleaning faster and avoid further delays on the next journey of the train.
- Cancellation might be a solution to decrease the total delay and get trains running on time again as quickly as possible.

Appendix B. Disruption analysis

This Appendix shows more detailed information of the analysis of disrupted events based on a database from ProRail. Section B1 shows a small part of the Excel file that contains the data. Then, section B2 gives the complete code that was constructed to make the maps that were shown in Chapter 5. In B3, a list of all disruption causes will be given included the number of occurrences. Finally, B4 show some more maps with other disruption causes.

B1: Data

Figure B.1 shows a part of the dataset that is filtered on switch failures and broken trains. Although this is not the sensitive part of the data, the coordinates, the date and time of beginning and ending of the disruption have been made invisible.

1	incidentLabel	latitu	longi	geocod	tis	datumT	datumT	logistiekebeperki	logistiekebeperkingGe	infrabeperkingstatus	prorailbedieningge	IEP_dat		IEP_C_Locatie
14	Wisselstoring / defect	######	54.233	001	1.0	########	########	Max 5 min vertraging	Harlingen Haven - Leeuwar	Gedeeltelijk versperd	Leeuwarden - Harlingen Haven		##	Wissel
19	Defect materieel	######	######	535	1.0	########	########	Geen		Gedeeltelijk versperd	Amsterdam Bijlmer ArenA		Am	Dienstregelpunte
24	Wisselstoring / defect	######	######	508	1.3	########	########	Geen treinverkeer	Arnhem	Versperd	Arnhem Berg	########	91!	Wissel
34	Wisselstoring / defect	######	######	161	1.1	########	########	Structurele vertraging	Lelystad Industrieterrein - H	Normaal	Kampen Zuid		##	Wissel
35	Wisselstoring / defect	######	######	508	1.2	########	########	Beperkt treinverkeer		Normaal	Arnhem Berg		95:	Wissel
38	Wisselstoring / defect	######	######	052	1.0	########	########	Beperkt treinverkeer	Beugen - Blerick	Gedeeltelijk versperd	Boxmeer		84	Wissel
42	Wisselstoring / defect	######	######	624	1.0	########	########	Max 5 min vertraging	Gouda	Gedeeltelijk versperd	Gouda		15:	Wissel
48	Defect materieel	######	######	082	1.0	########	########	Max 5 min vertraging	Haarlem - Santpoort Noord	Normaal	Santpoort Noord - Haarlem		Blc	Dienstregelpunte
51	Wisselstoring / defect	######	######	600	1.0	########	########	Max 5 min vertraging	Sauwerd	Normaal	Sauwerd		10:	Wissel

Figure B.1: Example of the dataset (ProRail, 2023).

B2: Python code

Importing all programs:

In [1]:

```
%matplotlib notebook
import matplotlib.pyplot as plt
import pandas as pd
import numpy as np
import seaborn as sns
import folium as fl
from folium import GeoJson
from folium import plugins
import ipywidgets as widgets
from IPython.display import display
from selenium import webdriver
from selenium.webdriver.chrome.options import Options
import time
import io
from PIL import Image
from collections import defaultdict
```

Importing the data:

In [2]:

```
data = pd.read_csv('Spoorweb_merged.csv', delimiter=';',
                   parse_dates = ['datumTijdVoorval', 'datumTijdEindeIncident', 'IEP_datumtijdEindeIncidentICB'],
                   low_memory=False)
data
```

Date and time:

```
In [4]: #Add column with day of the week

        data['day_of_week'] = data['datumTijdVoorval'].dt.dayofweek
```

```
In [5]: data['day_of_week'] = data['day_of_week'].map({
            0: 'Monday',
            1: 'Tuesday',
            2: 'Wednesday',
            3: 'Thursday',
            4: 'Friday',
            5: 'Saturday',
            6: 'Sunday'
        })
```

```
In [6]: #Add column with duration of disruption

        data['duration'] = (data.datumTijdEindeIncident - data.datumTijdVoorval) / pd.Timedelta(hours=1)
```

```
In [7]: # number of disruptions per day  18 June 2017 - 6 December 2023

        data_number = data['day_of_week'].unique()
        for i in data_number:
            day_counts = len(data[data.day_of_week == i])
            #print(day_counts)
```

```
In [8]: plt.figure()
        data_number = data['day_of_week'].unique()

        # Count occurrences of each day
        day_counts = [len(data[data.day_of_week == day]) for day in data_number]

        # Create a bar plot using seaborn
        sns.barplot(x=data_number, y=day_counts, color='skyblue')

        plt.xlabel('Day of the Week')
        plt.ylabel('Count')
        plt.title('Number of disruptions per weekday since June 2017')

        # Show the plot
        plt.show()
```

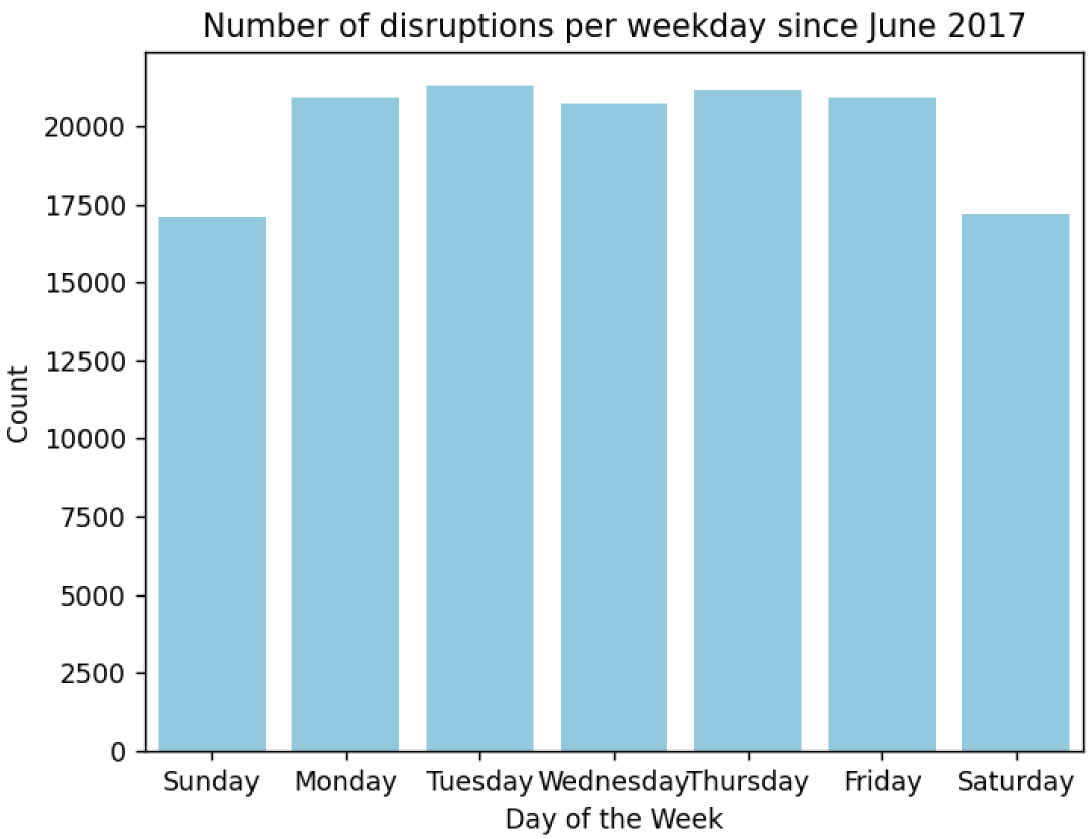


Figure B.2: Number of disruptions per weekday since June 2017.

In [9]:
```
#Zelfde als hierboven maar nu het gemiddeld aantal storingen per dag

#plt.figure()

verschil = int((data.datumTijdVoorval[len(data)-1] - data.datumTijdVoorval[0]) / np.timedelta64(1,'D'))
print(f'Number of days in database = {round(verschil, 0)}')
```

```
Number of days in database = 2362
```

In [10]:
```
plt.figure()
day_countsNEW = []
for number in day_counts:
    day_countsNEW.append(number / verschil * 7)
print(day_countsNEW)

# Create a bar plot using seaborn
sns.barplot(x=data_number, y=day_countsNEW, color='skyblue')

plt.xlabel('Day of the Week')
plt.ylabel('Count')
plt.title('Average number of disruptions per weekday since June 2017')

plt.show()
```

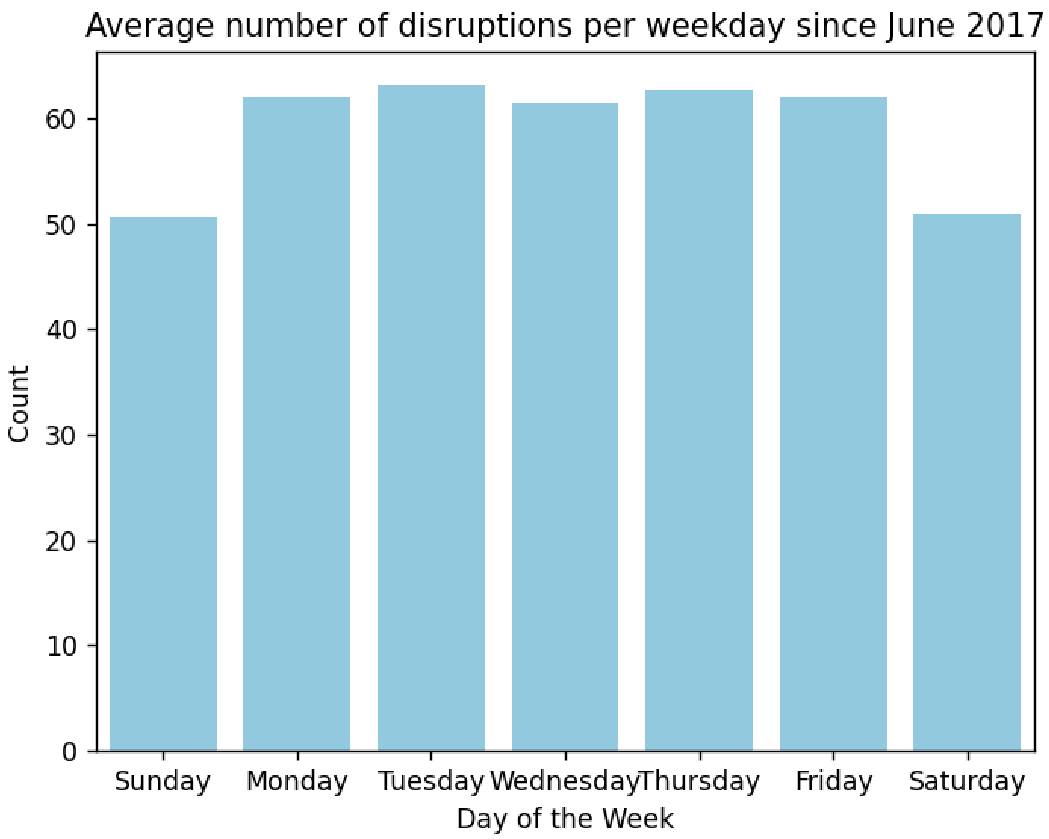


Figure B.3: Average number of disruptions per weekday since June 2017.

Number of occurrences per disruption cause:

```
In [11]: smoes_tellingen = data['incidentLabel'].value_counts()

         print("Cause of disruption; number of occurences:")
         for smoes, telling in smoes_tellingen.items():
             print(f"{smoes}; {telling}")
```

The output for this can be found in Appendix B3.

First step of creating the maps: filtering the data:

All coordinates that are not available will be removed from the dataset.

```
In [14]: data = data[data['latitude'].notna()]
         data = data[data['longitude'].notna()]
         data.to_csv('Spoorweb_aangepast.csv')
```

```
In [15]: datanew = pd.read_csv('Spoorweb_aangepast.csv', delimiter=',',
                             parse_dates = ['datumTijdVoorval', 'datumTijdEindeIncident', 'IEP_datumtijdEindeIncidentICB'],
                             low_memory=False)
         datanew.drop(['Unnamed: 0'], axis=1, inplace=True)
         datanew
```

First map with all disruptions plotted:

```
In [16]: map1 = fl.Map(location=(52.12,5.16),
              zoom_start=7.5,
              width='60%',
              height='100%',
              tiles="https://{s}.basemaps.cartocdn.com/light_nolabels/{z}/{x}/{y}{r}.png",
              attr="Mapbox attribution",
          )
         fl.TileLayer("https://{s}.tiles.openrailwaymap.org/standard/{z}/{x}/{y}.png?access_token=mytoken", attr="Mapbox attribution").add_to(map1)

         #smoeskaart1 = datanew[datanew.incidentLabel == 'Wisselstoring / defect']

         for i in range(len(datanew)):

             fl.CircleMarker(location=(datanew.latitude[i], datanew.longitude[i]), radius=1, color='black').add_to(map1)

         map1.save('map1.html')
         map1
```

Figure B.4: All disruptions in the Netherlands (June 2017 – December 2023) (ProRail, 2023), same as Figure 4.4.

Map with only switch failures:

```
In [17]: # Voorbeeld van een DataFrame met coördinaten en een kolom met waarden
data = {
    'Latitude': datanew.latitude,
    'Longitude': datanew.longitude,
    'Smoes': datanew.incidentLabel,
    'TIS': datanew.tis,
    'Infrabeperking': datanew.infrabeperkingstatus
}

df = pd.DataFrame(data)

# Creëer een folium kaart
map2 = fl.Map(location=(52.12, 5.16),
              zoom_start=7.5,
              width='60%',
              height='100%',
              tiles="https://{s}.basemaps.cartocdn.com/light_nolabels/{z}/{x}/{y}{r}.png",
              attr="Mapbox attribution",
             )

# Voeg een TileLayer toe aan de kaart
fl.TileLayer("https://{s}.tiles.openrailwaymap.org/standard/{z}/{x}/{y}.png?access_token=mytoken",
             attr="Mapbox attribution"
            ).add_to(map2)

# Filter de DataFrame op basis van de waarde in de 'Waarde'-kolom
df_filtered = df[df['Smoes'] == 'Wisselstoring / defect']

# Loop door de rijen van het gefilterde DataFrame en voeg cirkelmarkers toe aan de kaart
for index, row in df_filtered.iterrows():
    # Voeg een cirkelmarker toe aan de kaart
    fl.CircleMarker(
        location=[row['Latitude'], row['Longitude']],
        radius=2,  # Pas de grootte van de cirkelmarker aan indien nodig
        color='black',
        fill=True,
        fill_color='black',
        fill_opacity=0.7,
        popup=f"Oorzaak: {row['Smoes']}, {row['Latitude']}, {row['Longitude']}, TIS: {row['TIS']}"
    ).add_to(map2)

# Toon de kaart
map2.save('map2.html')
map2
```

Figure B.5: Map with all switch failures in the Netherlands (June 2017 – December 2023) (ProRail, 2023).

Creating a pie chart and a bar plot, see also **Figure 4.1** and **Figure 4.2**:

```
In [19]: # Simuleer een dataset (vervang dit door je eigen dataset)
plt.figure()
data2 = datanew.incidentLabel
df = pd.DataFrame(data2)

# Bepaal de kolom waarvan je de frequenties wilt berekenen
kolom_naam = 'incidentLabel'

# Bereken de frequenties van de woorden in de kolom
incidentLabel_frequenties = df[kolom_naam].value_counts()

# Stel een drempelwaarde in voor het tonen van woorden
drempelwaarde = 2000  # Stel deze waarde in op basis van je eigen criteria

# Filter woorden die minder vaak voorkomen dan de drempelwaarde
veel_voorkomende_woorden = incidentLabel_frequenties[incidentLabel_frequenties >= drempelwaarde]
overige_woorden = incidentLabel_frequenties[incidentLabel_frequenties < drempelwaarde]

# Voeg de rest samen in een enkel item genaamd 'Overige'
overige_count = overige_woorden.sum()
veel_voorkomende_woorden['Overige'] = overige_count

# Maak een pie chart
labels = veel_voorkomende_woorden.index
sizes = veel_voorkomende_woorden.values
colors = plt.cm.Paired(range(len(labels)))

plt.pie(sizes, labels=labels, colors=colors, autopct='%1.1f%%', startangle=90, counterclock=False)
plt.axis('equal')  # Zorgt ervoor dat de pie chart een cirkel is.
plt.title(f'# Specific disruptions causes with occurrence of at least {drempelwaarde}')
plt.show()
plt.savefig('myfile.png', bbox_inches="tight")
```

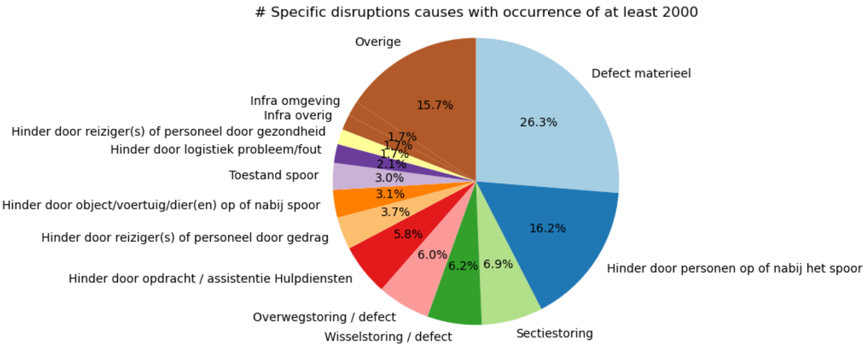


Figure B.6: Disruption causes in percentages (ProRail, 2023).

```
In [20]: plt.figure()
plt.bar(x= labels, height=sizes, color=colors)
plt.xticks(rotation=45, ha='right')
plt.title('# Specific disruptions')
plt.savefig('Bar.png', bbox_inches="tight")
```

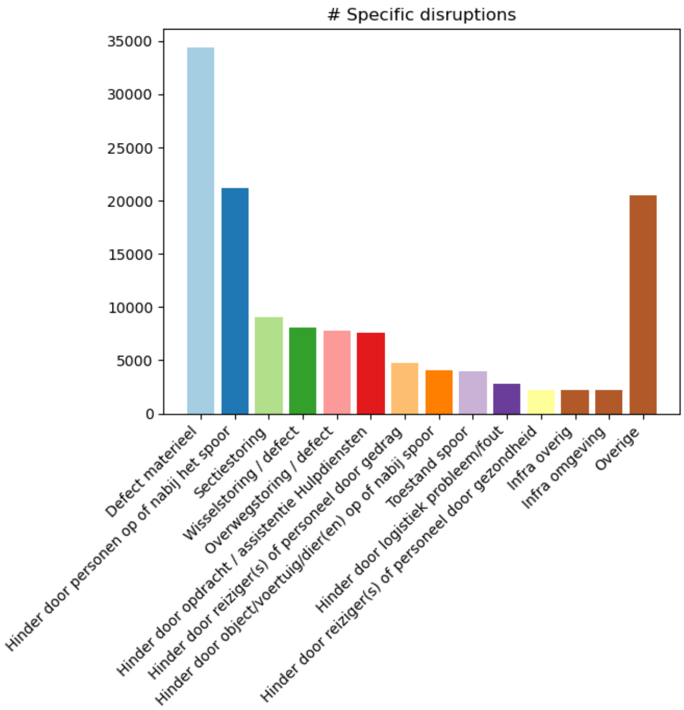


Figure B.7: Disruption causes in absolute numbers (ProRail, 2023).

Function in Python with colours without radius

```
In [21]: def Map(filter_smoes):

    data = {
        'Latitude': datanew.latitude,
        'Longitude': datanew.longitude,
        'Smoes': datanew.incidentLabel,
        'TIS': datanew.tis,
        'Infrabeperking': datanew.infrabeperkingstatus,
        'Datum': datanew.datumTijdVoorval
    }

    df = pd.DataFrame(data)

    df_filtered = df[df['Smoes'] == filter_smoes]

    mymap = fl.Map(location=[52.12, 5.16], zoom_start=7.5, width='60%', height='100%',
                   tiles="https://{s}.basemaps.cartocdn.com/light_nolabels/{z}/{x}/{y}{r}.png",
                   attr="Mapbox attribution")

    fl.TileLayer("https://{s}.tiles.openrailwaymap.org/standard/{z}/{x}/{y}.png?access_token=mytoken",
                 attr="Mapbox attribution").add_to(mymap)

    for index, row in df_filtered.iterrows():
        tis_value = int(str(row['TIS']).split('.')[1])
        color = {
            0: 'darkgreen',
            1: 'greenyellow',
            2: 'yellow',
            3: 'orange',
            4: 'red'
        }.get(tis_value, 'black')

        fl.CircleMarker(
            location=[row['Latitude'], row['Longitude']],
            radius=2,
            color=color,
            fill=True,
            fill_color=color,
            fill_opacity=0.7,
            popup=f"Datum: {row['Datum']}, {row['Smoes']}, {row['Latitude']}, {row['Longitude']}, TIS: {row['TIS']}, Infrabeperking: {row['Infrabeperking']}"
        ).add_to(mymap)

    map_filename = f"map_{filter_smoes}.html"
    mymap.save(map_filename)

    fl.Map(location=[52.12, 5.16], zoom_start=7.5, width='60%', height='100%',
           tiles=map_filename, attr="Mapbox attribution")
    return mymap
```

```
In [22]: Map('Hinder door reiziger(s) of personeel door gedrag')
```

Figure B.8: Hindrance due to passengers or personnel due to behaviour.

Figure B.9: Tunnel failures.

Function with colour and radius change; colour based on most frequent one:

```
In [24]: def MapRadius2(filter_smoes):
    data = {
        'Latitude': datanew.latitude,
        'Longitude': datanew.longitude,
        'Smoes': datanew.incidentLabel,
        'TIS': datanew.tis,
        'Infrabeperking': datanew.infrabeperkingstatus,
        'Datum': datanew.datumTijdVoorval
    }

    df = pd.DataFrame(data)

    df_filtered = df[df['Smoes'] == filter_smoes]

    mymap = fl.Map(location=[52.12, 5.16], zoom_start=7.5, width='60%', height='100%',
                   tiles="https://{s}.basemaps.cartocdn.com/light_nolabels/{z}/{x}/{y}{r}.png",
                   attr="Mapbox attribution")

    fl.TileLayer("https://{s}.tiles.openrailwaymap.org/standard/{z}/{x}/{y}.png?access_token=mytoken",
                 attr="Mapbox attribution").add_to(mymap)

    coord_counter = defaultdict(int)
    color_counter = defaultdict(lambda: defaultdict(int))


    for index, row in df_filtered.iterrows():
        current_coords = (row['Latitude'], row['Longitude'])
        tis_value = int(str(row['TIS']).split('.')[-1])
        color_counter[current_coords][tis_value] += 1
        most_common_tis_value = max(color_counter[current_coords], key=color_counter[current_coords].get)
        color = {
            0: 'darkgreen',
            1: 'greenyellow',
            2: 'yellow',
            3: 'orange',
            4: 'red'
        }.get(most_common_tis_value, 'black')  # Als het getal niet overeenkomt met 0, 1, 2, 3 of 4, gebruik dan zwart


        radius = 2 + coord_counter[current_coords] * 0.5


        fl.CircleMarker(
            location=[row['Latitude'], row['Longitude']],
            radius=radius,
            color=color,
            fill=True,
            fill_color=color,
            fill_opacity=0.7,
            popup=f"Aantal keer {row['Smoes']}: {coord_counter[current_coords]+1}, Datum: {row['Datum']}, Coordinates: {row['Latitude']}, {row['Longitude']}, TIS: {row['TIS']}, Infrabeperking: {row['Infrabeperking']}"
        ).add_to(mymap)


        coord_counter[current_coords] += 1

    name = filter_smoes.replace('/', '')
    map_filename = f"map_{name}.html"
    mymap.save(map_filename)

    return mymap
```

Figure B.10: Slippery tracks with colour based on TIS code and radius based on occurrence.

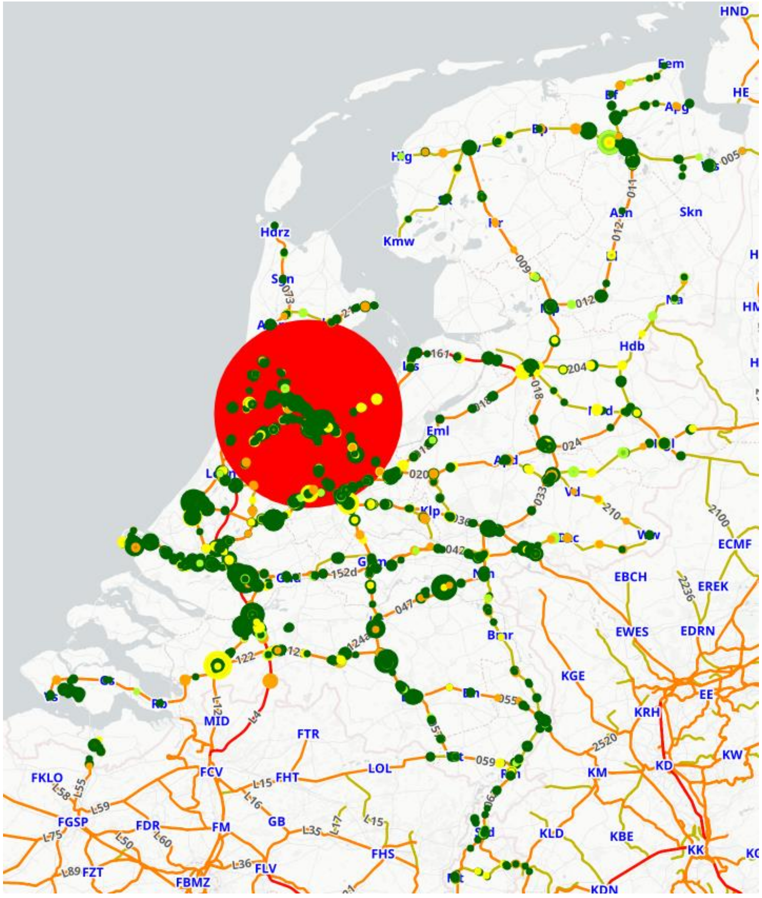


Figure B.11: All switch failures with colour based on TIS code and radius based on occurrence.

Figure B.12: Collision with a person with colour based on TIS code and radius based on occurrence.

Function with completely or partially blocked tracks:

```
In [28]: def MapRadius3():
    data = {
        'Latitude': datanew.latitude,
        'Longitude': datanew.longitude,
        'Smoes': datanew.incidentLabel,
        'TIS': datanew.tis,
        'Infrabeperking': datanew.infrabeperkingstatus,
        'Datum': datanew.datumTijdVoorval
    }

    df = pd.DataFrame(data)

    df_filtered = df[df['Infrabeperking'].isin(['Versperd', 'Gedeeltelijk versperd'])]

    mymap = fl.Map(location=[52.12, 5.16], zoom_start=7.5, width='60%', height='100%',
                   tiles="https://{s}.basemaps.cartocdn.com/light_nolabels/{z}/{x}/{y}{r}.png",
                   attr="Mapbox attribution")

    fl.TileLayer("https://{s}.tiles.openrailwaymap.org/standard/{z}/{x}/{y}.png?access_token=mytoken",
                 attr="Mapbox attribution").add_to(mymap)

    coord_counter = defaultdict(int)
    color_counter = defaultdict(lambda: defaultdict(int))

    for index, row in df_filtered.iterrows():
        current_coords = (row['Latitude'], row['Longitude'])
        tis_value = int(str(row['TIS']).split('.')[-1])
        color_counter[current_coords][tis_value] += 1
        most_common_tis_value = max(color_counter[current_coords], key=color_counter[current_coords].get)

        if row['Infrabeperking'] == 'Versperd':
            color = 'red'
        elif row['Infrabeperking'] == 'Gedeeltelijk versperd':
            color = 'yellow'
        #else:
        #    color = 'black'  # Onbekende waarde, gebruik zwarte marker

        radius = 2 + coord_counter[current_coords] * 0.25

        fl.CircleMarker(
            location=[row['Latitude'], row['Longitude']],
            radius=radius,
            color=color,
            fill=True,
            fill_color=color,
            fill_opacity=0.7,
            popup=f"Aantal keer: {coord_counter[current_coords]+1}, Cause: {row['Smoes']}, Coordinates: {row['Latitude']}, {row['Longitude']}, Infrabeperking: {row['Infrabeperking']}"
        ).add_to(mymap)

        coord_counter[current_coords] += 1

    name = '(Gedeeltelijk)'
    map_filename = f"map_{name}.html"
    mymap.save(map_filename)

    return mymap
```

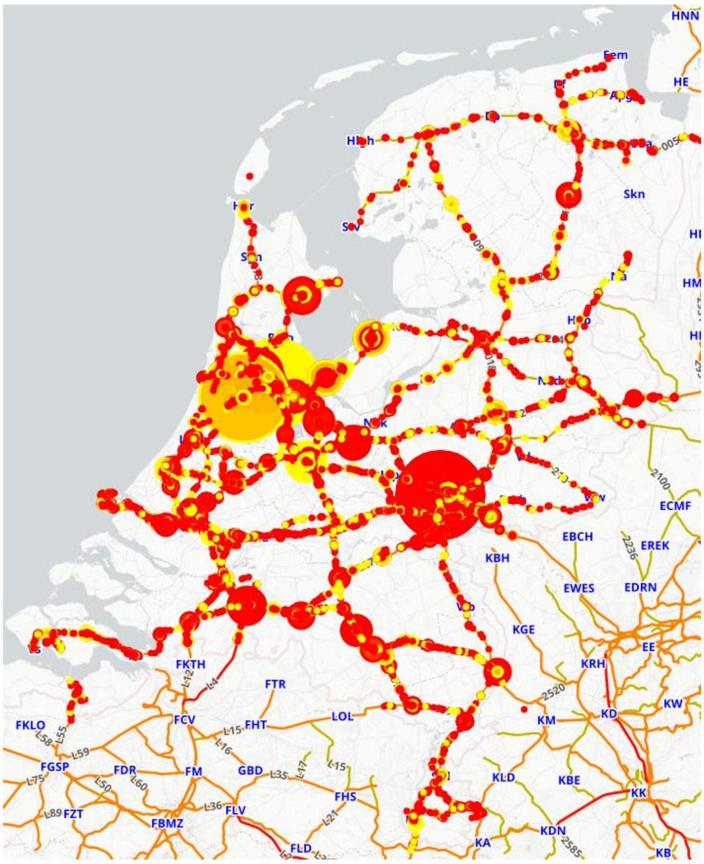


Figure B.13: Map with (partly) blocked lines and number of occurrences. Red means completely blocked, yellow means partially blocked – same as Figure 4.8.

Function with all disruptions only TIS .3 and .4

```
In [30]: def MapRadius4():
    data = {
        'Latitude': datanew.latitude,
        'Longitude': datanew.longitude,
        'Smoes': datanew.incidentLabel,
        'TIS': datanew.tis,
        'Infrabeperking': datanew.infrabeperkingstatus,
        'Datum': datanew.datumTijdVoorval
    }

    df = pd.DataFrame(data)

    mymap = fl.Map(location=[52.12, 5.16], zoom_start=7.5, width='60%', height='100%',
                   tiles="https://{s}.basemaps.cartocdn.com/light_nolabels/{z}/{x}/{y}{r}.png",
                   attr="Mapbox attribution")


    fl.TileLayer("https://{s}.tiles.openrailwaymap.org/standard/{z}/{x}/{y}.png?access_token=mytoken",
                 attr="Mapbox attribution").add_to(mymap)


    coord_counter = defaultdict(int)
    color_counter = defaultdict(lambda: defaultdict(int))


    for index, row in df.iterrows():

        last_digit_tis = int(str(row['TIS'])[-1])

        if last_digit_tis in [3, 4]:

            current_coords = (row['Latitude'], row['Longitude'])
            color_counter[current_coords][last_digit_tis] += 1
            most_common_tis_value = max(color_counter[current_coords], key=color_counter[current_coords].get)
            color = {
                0: 'darkgreen',
                1: 'greenyellow',
                2: 'yellow',
                3: 'brown',
                4: 'red'
            }.get(most_common_tis_value, 'black')

            radius = 2 + coord_counter[current_coords] * 0.5


            fl.CircleMarker(
                location=[row['Latitude'], row['Longitude']],
                radius=radius,
                color=color,
                fill=True,
                fill_color=color,
                fill_opacity=0.7,
                popup=f"Aantal keer {row['Smoes']}: {coord_counter[current_coords]+1}, Datum: {row['Datum']}, Coordinates: {row['Latitude']}, {row['Longitude']}, TIS: {row['TIS']}, Infrabeperking: {row['Infrabeperking']}"
            ).add_to(mymap)


            coord_counter[current_coords] += 1


    map_filename = "map_filtered.html"
    mymap.save(map_filename)

    return mymap

MapRadius4()
```

Figure B.14: All disruptions with TIS .3 and .4.

Function with only TIS .2, .3 and .4 including filtering for the cause of the disruption:

```
In [31]: #Alleen bepaalde TIS waardes en met filtering voor smoes

def MapRadius5(filter_smoes):
    data = {
        'Latitude': datanew.latitude,
        'Longitude': datanew.longitude,
        'Smoes': datanew.incidentLabel,
        'TIS': datanew.tis,
        'Infrabeperking': datanew.infrabeperkingstatus,
        'Datum': datanew.datumTijdVoorval
    }

    df = pd.DataFrame(data)

    df_filtered = df[df['Smoes'] == filter_smoes]

    mymap = fl.Map(location=[52.12, 5.16], zoom_start=7.5, width='60%', height='100%',
                   tiles="https://{s}.basemaps.cartocdn.com/light_nolabels/{z}/{x}/{y}{r}.png",
                   attr="Mapbox attribution")

    fl.TileLayer("https://{s}.tiles.openrailwaymap.org/standard/{z}/{x}/{y}.png?access_token=mytoken",
                 attr="Mapbox attribution").add_to(mymap)


    coord_counter = defaultdict(int)
    color_counter = defaultdict(lambda: defaultdict(int))


    for index, row in df_filtered.iterrows():

        last_digit_tis = int(str(row['TIS'])[-1])

        if last_digit_tis in [2, 3, 4]:
            current_coords = (row['Latitude'], row['Longitude'])
            color_counter[current_coords][last_digit_tis] += 1
            most_common_tis_value = max(color_counter[current_coords], key=color_counter[current_coords].get)
            color = {
                0: 'darkgreen',
                1: 'greenyellow',
                2: 'yellow',
                3: 'brown',
                4: 'red'
            }.get(most_common_tis_value, 'black')
            radius = 2 + coord_counter[current_coords] * 0.5


            fl.CircleMarker(
                location=[row['Latitude'], row['Longitude']],
                radius=radius,
                color=color,
                fill=True,
                fill_color=color,
                fill_opacity=0.7,
                popup=f"Aantal keer {row['Smoes']}: {coord_counter[current_coords]+1}, Datum: {row['Datum']}, Coordinates: {row['Latitude']}, {row['Longitude']}, TIS: {row['TIS']}, Infrabeperking: {row['Infrabeperking']}"
            ).add_to(mymap)

            coord_counter[current_coords] += 1

    name = filter_smoes.replace('/', '')
    map_filename = f"map_{name}2.html"
    mymap.save(map_filename)

    return mymap
```

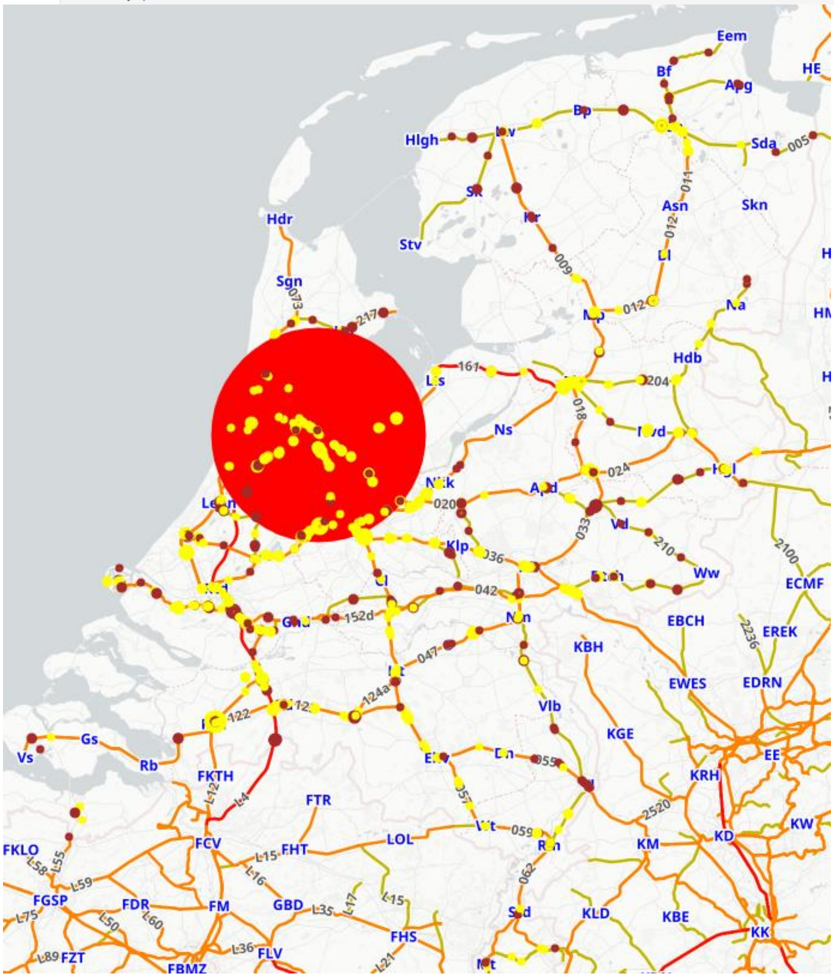


Figure B.15: Only TIS .2, .3 and .4 and only switch failures.

B3: Disruption causes

Table B.1: Disruption causes.

Cause of disruption	Number of occurrences:
Defect materieel	34461
Hinder door personen op of nabij het spoor	21175
Sectiestoring	9046
Wisselstoring / defect	8101
Overwegstoring / defect	7823
Hinder door opdracht / assistentie Hulpdiensten	7625
Hinder door reiziger(s) of personeel door gedrag	4799
Hinder door object/voertuig/dier(en) op of nabij spoor	4090
Toestand spoor	3959
Hinder door logistiek probleem/fout	3366
Overig	2688
(dreigende) Storing ICT systemen	2515
Gladde sporen	2341
Infra overig	2339
Infra omgeving	2265
Hinder door reiziger(s) of personeel door gezondheid	2252
Aanrijding (infra)object/voorwerp	1787
Bijna aanrijding	1743
Aanrijding persoon	1729
Hinder door calamiteit in buitenland	1590
Seinstoring	1507
Bovenleiding defect en/of spanningsloos	1211
Brugstoring of defect	1203
Stoptonend sein passage geen gevaarzetting - trein rijdt zonder toestemming	1158
Uitloop werkzaamheden	718
Stroomstoring	663
Infra ATB	651
Hinder door vandalisme of diefstal	560
Defecte infrastructuur	446
Rijrichtingstoring	428
Aanrijding of aanvaring verkeer met brug of viaduct	403
Overige veiligheidsincidenten	363
Brand- of rook(melding) in berm	355
Lekkende of stinkende wagen	338
Storing besturings- communicatiesystemen	281
Smeulende biels / wisselbrand	273
Storing beveiligingssystemen	265
Harde wind	221
GSM-R / Inttel storing	178
Tunnelstoring	167
Ontsporing (zonder slachtoffers)	152
Aanrijding klein wegvoertuig	146
Brand- of rook(melding) in materieel	137
Stoptonend sein passage - trein rijdt zonder toestemming	136
Brand- of rook(melding) Tunnel	120
Detectie storing/problemen	116
Aanrijding groot dier	107
Storing heuvelsysteem	104
Bomvinding of verdacht voorwerp	82
Dringende herstelwerkzaamheden	78

Brand- of rook(melding) Station(sgebouw)	73
Brand- of rook(melding) in infra	64
Milieuschade op spoorterrein	61
Brand- of rook(melding) onder materieel	58
Lage temperaturen	53
Stoptonend sein passage met gevaarzetting - trein rijdt zonder toestemming	52
Stoptonend sein passage - trein rijdt zonder toestemming zonder gevaarzetting	51
Hoge temperaturen	46
Aanrijding groot wegvoertuig	45
Botsing stootjuk	41
Signaleringstoring	41
Botsing rangeerdelen onderling	36
Verdacht voorwerp of bomvinding	34
Tunnelalarm door treinstilstand of (automatische) brandmelding	34
Winterse neerslag	34
Uitval walapparatuur GSM-Rail	30
Gaslekkage buiten spoorterrein	28
Aanrijding (motor- of brom)fietser	28
Hoog water	26
Bommelding of verdacht gedrag	24
Verdacht gedrag of bommelding	23
Bomvinding NGCE	21
Blikseminslag	19
Postuitval	18
Gaslekkage op spoorterrein	17
Brand- of rook(melding) in overige ProRail gebouwen	15
(Bom)explosie	9
Botsing treinen onderling	6
Stoptonend sein passage - trein rijdt zonder toestemming met gevaarzetting	5
Ontsporing (slachtoffers onbekend)	4
Tunnelalarm door gasdetectie (LEL)	3
Aardbeving	3
Tunnelalarm door melding hoog vloeistofniveau	2
Brand- of rook(melding) in post-T	2
Treinstilstand zonder spraakcontact in tunnel	1
Extreme droogte	1
Ontsporing (met slachtoffers)	1

B4: Other visualisations

Figure B.16 shows all switch failures including the impact of each where the colours are based on the last number of the TIS code and these can be found in the top line of Table 4.1. The dark green colours in the map are applied for a TIS code of 1.0 which means that the impact is less than considering a TIS of 1.1. These maps can be made for every cause of disruption, like in Figure B.17 where all broken trains are visualized. Broken trains can be on every location on the network, but regarding the switches the locations match with real switch locations as expected. A problem with a broken train on the Betuweroute (only cargo trains) appears to be much faster solved than on regular railway lines as can be seen in Figure B.17.

Figure B.16: All switch failures with TIS codes.

Figure B.17: All broken trains with TIS codes.

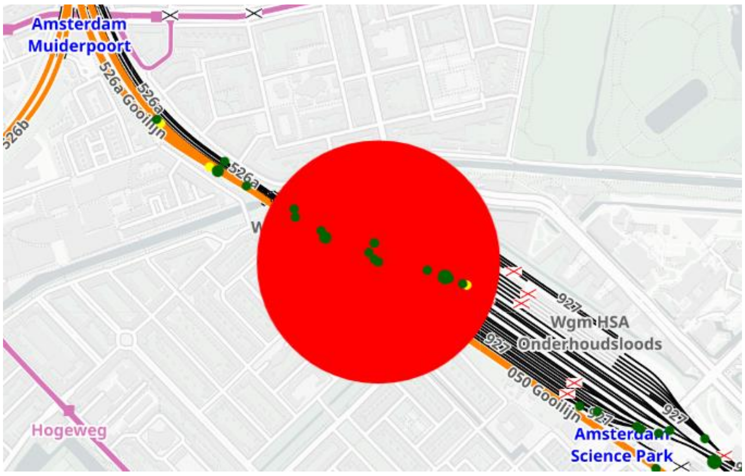


Figure B.18: Broken switches near Amsterdam Watergraafsmeer zoomed in.

Appendix C. Key performance indicators

This appendix gives all key performance indicators introduced in chapter 5 with all references.

Table C.1: KPIs with references.

KPI name	KPI definition	KPI unit
Costs of infrastructure	The amount of costs for designing, constructing, building and maintaining new switches, crosses, signals. Zero if no changes are made. This KPI is measured in the number of switches located in the configuration and not in a monetary unit. Costs are independent of the location. All switches cost the same amount of money. Horizontal and vertical alignment are out of scope (Ling, 2005) (Vitásek & Měšťanová, 2017) (ProRail, sd).	# of switches
Infrastructure occupation	The share of time required to operate trains on a given railway infrastructure according to a given timetable pattern and can be computed using the timetable compression method. Maximum 75% for mixed traffic or high-speed lines, maximum 85% for suburban lines. Both during peak hours which is part of the topic of this research (Goverde & Hansen, 2012).	Percentage (%)
Platform consistency	The sum of the total number of trains that did arrive at the planned platform and the planned track divided by the total number of arrived trains. This KPI can be divided in two parts: the first will be the consistency compared between normal and disrupted timetable and the second part will be the platform consistency during the downsized timetable. Goal is to keep the consistency high, if possible above 75% for both sub-KPIs (Lo, Pluyter, & Meijer, 2015).	Percentage (%)
Rate of actual departures*	The number of actual departures divided by the total number of departures. This value is supposed to be higher than 95% (ProRail, 2024). During a disruption it is still the goal to have a reliable timetable, nevertheless downsized to at least 50% of the trains still running (Hofman, Madsen, Groth, Clausen, & Larsen, 2006).	Percentage (%)
Punctuality	The number of trains that arrived maximum 5 minutes after arrival time divided by the total number of arrived trains (including cancelled trains). This value is aimed to be higher than 91.5% (ProRail, 2023) (Nicholson, Kirkwood, Roberts, & Schmid, 2015) (Goverde & Hansen, 2012).	Percentage (%)
Timetable feasibility	The amount of scheduled train paths conflicts with a norm of zero conflicts (Goverde & Hansen, 2012).	# conflicts
Capacity*	It is the maximum possible number of trains per direction which can cross a certain section (Goverde & Hansen, 2012) (Calvert & Snelder, 2017) (Nicholson, Kirkwood, Roberts, & Schmid, 2015).	# trains per direction
Number of alternative routes	The number of available alternative routes (on a line or at a station) in case of a disruption, where a higher redundancy is better (Calvert & Snelder, 2017).	# alternative routes
Time to recover	The time between the delay of the system increasing above a small threshold value, and it returning below this threshold (Nicholson, Kirkwood, Roberts, & Schmid, 2015).	Minutes

Four of these key performance indicators have been chosen to use in the model. These four are shown in Table C.2 and an explanation can be found in chapter 5. In chapter 5 a method was introduced how the different alternatives were scored by using a formula. Another option to score all alternatives is described below.

For comparing the alternatives, a weighed-sum model could also be used. Each alternative will get a score for each criterion and for every criterion a linear progression of the score is invented between 0 and 10. Does an alternative score poor it will get 0 points and does the alternative score excellent it gets 10 points (Thokala, et al., 2016). Table C.2 shows when a certain alternative gets a score (0-10) for the corresponding key performance indicator.

Table C.2: Score for every key performance indicator.

ID	KPI name: Score →	0	1	2	3	4	5	6	7	8	9	10
1	**Costs of infrastructure**	≥ 19	18	16	14	12	10	8	6	4	2	0
2	**Rate of cancelled services [%]**	100	90	80	70	60	50	40	30	20	10	0
3	**Punctuality [%]**	0	10	20	30	40	50	60	70	**80**	90	100
4	**Time to recover**	≥ 75	67.5	60	52.5	45	32.5	30	22.5	15	7.5	0

This method is used during the simulations but a new method, described in chapter 5 has been used to calculate the final scores for each alternative. The two light blue marked cells indicate a threshold value which comes from the interviews. The scores for all layouts can be calculated with Equations 7 and 8 (Rezaei, 2022).

$$V_i = \sum_{j=1}^{n} w_j p_{ij} \tag{7}$$

$$w_j \geq 0, \qquad \sum w_j = 1 \tag{8}$$

where:

V = total score of alternative
w = weight of criterion
p = score of alternative
n = number of criteria
i = alternative
j = criterion

This method is not used for the final calculations of the scores for the alternatives. Chapter 5 shows how the scores are calculated.

Appendix D. Ethics

To be able to conduct the interviews conducted in chapter 3.2 it was needed to get permission from TU Delft's Human Research Ethics Committee (HREC) before data collection begins. Three additional forms were needed: Human Research Ethics Checklist for Human Research (HREC), informed consent and a Data Management Plan (DMP). The informed consent can be read below:

Informed consent

The potential participants will be informed in three instances for the consent on a few things. In the first mail or WhatsApp message they will be informed about my research, the goal of the interview and if they want to participate under the stated conditions.

A couple of days in advance of the interview the interviewees will be asked three important questions. These are about the recordings, adding the conclusions to the report and if the name of the interviewee can be mentioned or if it should be anonymised. The participants will be mainly or all Dutch so the text below is given in Dutch, but a translated version is given in English.

First mail for contact

Dutch:

Beste [mogelijke deelnemer],

Ik ben Jesse Zegeling en ik ben master student Transport & Planning (Civiele Techniek) aan de TU Delft. Op dit moment ben ik bezig met mijn afstudeeropdracht bij Royal HaskoningDHV en ik doe onderzoek naar de optimale plaatsing van bijsturingswissels. Als onderdeel van dit onderzoek zou ik graag een aantal experts op het gebied van wissels en storingsmanagement willen interviewen. De mensen die ik wil interviewen zijn voornamelijk werkzaam bij NS, ProRail en Royal HaskoningDHV.

Om deze reden neem ik contact op met u. [Uitleg hoe ik bij de deelnemer terecht ben gekomen]. Ik zou u dus willen vragen of u openstaat om enkele vragen te willen beantwoorden in een gesprek dat maximaal 30 minuten zal duren. Uw antwoorden zullen worden gebruikt bij het onderzoek naar de plaatsing van wissels en om hiermee de capaciteit tijdens storingen op het spoor te verhogen. Uiteindelijk zal de Master Thesis gepubliceerd worden in de openbaar toegankelijke TU Delft Education Repository. Dit is verplicht voor het afronden van de Master Thesis.

Als u voor een interview openstaat, zou ik graag een keer met u willen afspreken voor het interview. Het interview kan plaatsvinden bij u [kantoor deelnemer], op een kantoor van Royal HaskoningDHV of op de TU Delft. Uiteraard is het ook mogelijk om het interview online af te nemen.

Bij vragen over het onderzoek en/of het interview hoor ik het uiteraard graag van u.

Alvast bedankt voor uw reactie.

Met vriendelijke groet,

Jesse Zegeling

English:

Dear [potential participant],

My name is Jesse Zegeling and I am a master student Transport & Planning (Civil Engineering) at Delft University of Technology. At this moment I am doing my Master Thesis at Royal HaskoningDHV and I am analysing rail switch locations versus network resilience under disrupted train operations. As a part of my research I want to speak with some experts on these topics and conduct some interviews. The people that I want to interview are mainly working at NS, ProRail and Royal HaskoningDHV.

For this reason I am contacting you. [Explanation how I come up to the participant]. I would like to ask if you are willing to answer some questions in a conversation with a duration of maximum 30 minutes. Your answers will be used for the research into switch location configurations to improve capacity during disruptions. Finally, the Master Thesis will be published in the public TU Delft Education Repository. This is mandatory for finishing the Master Thesis.

If you are open for an interview, I would like to arrange a moment with you for the interview. The interview can take place at the office of [office of participant], at one of the offices of Royal HaskoningDHV or at the TU Delft campus. Of course, it is also possible to arrange an online meeting.

If you have any questions regarding the research or the interview I would like to hear this from you.

Thank you in advance for your response.

Best regards,

Jesse Zegeling

j.j.zegeling@student.tudelft.nl

Prior to the interview

Dutch:

Voor mijn Master Thesis ben ik dus onderzoek aan het doen naar de plaatsing van wissels en het verband te leggen met resilience en hiervoor stel ik u graag een aantal vragen. Er zijn geen vragen tot in detail uitgewerkt en er is geen vaste structuur voor het interview, maar het moet vooral een gesprek worden over de onderwerpen die besproken zijn in de vorige mail. Uitgebreide antwoorden worden gewaardeerd. Het interview zal ongeveer 30 minuten duren. Als u het goed vindt, zou ik graag het interview opnemen. Dit heeft twee redenen: ten eerste maakt dat de verwerking en analyse achteraf makkelijker voor mij en ten tweede kan ik tijdens het gesprek mezelf meer richten op het gesprek zelf in plaats van op het maken van aantekeningen. De opname zal gebruikt worden om een transcriptie te maken en zal daarna worden verwijderd. Ik zal de transcriptie naar u mailen, zodat u indien u dat wil de tekst kan controleren, waarna eventueel nog aanpassingen en aanvullingen aan de tekst gedaan kunnen worden.

Uw antwoorden zullen worden gebruikt voor de analyse in mijn onderzoek en daarnaast zou ik ze na uw goedkeuring graag meenemen als bijlage van mijn onderzoek. Dit kan natuurlijk met vermelding van uw naam en functie, of volledig geanonimiseerd indien u dat wilt. Hierbij moet ik vermelden dat de uiteindelijke versie van het onderzoek verplicht gepubliceerd wordt in de TU Delft Education Repository waarbij de thesis vrij te downloaden is.

Vragen:

Gaat u akkoord met de opname van het gesprek onder de genoemde voorwaarden?

- Als er niet akkoord wordt gegaan met de opname, zal ik aantekeningen maken op papier of in een Word bestand

Gaat u akkoord met het als bijlage toevoegen van het interview aan de publicatie van de thesis?

- Als er niet akkoord wordt gegaan met het als bijlage toevoegen, zal ik de antwoorden alleen gebruiken in het onderzoek en dus niet toevoegen aan de bijlage.

Gaat u akkoord met het vermelden van uw naam en uw functie bij de antwoorden die worden vermeld in de thesis?

- Als er niet akkoord wordt gegaan, zal ik het interview bijvoegen met een geanonimiseerde vermelding.

English:

For my Master Thesis I am doing research into the optimal location of switches to improve resilience and improve capacity during disruptions and for this I would like to ask you some questions. The questions are not worked out in detail and there is no on beforehand made structure, but it will be a conversation about the topics mentioned in the previous email. Long answers with a lot of detail are appreciated. The interview will take around 30 minutes. If you are okay, I would like to record the meeting. This has two reasons: first of all, this will make the analysis afterwards easier and secondly, I can more focus on the interview and the corresponding questions instead of writing the whole time. The recording will be used to make a transcript and after the research is finished these recordings will be deleted. I will email you the transcript in order for you to be able to check the text and make some adjustments and additions if needed.

Your answers will be used for the analysis in my research and I would like to get the permission to use the answers in the appendix of my thesis. This is possible with stating you name and position, but completely anonymised is of course also possible. I would like to mention again that the final version of the thesis will be published in the public TU Delft Education Repository which is freely accessible for anyone.

Questions:

Do you agree with the recording of the interview under the stated conditions?

- If you do not agree with the recording, I will make notes on a paper or in a Word file.

Do you agree to include the interview as appendix to the thesis?

- If you do not agree I will only use the answers for the analysis and not add the answers to the appendix.

Do you agree with mentioning your name and position together with your answers?

- If you do not agree, I will append the interview with an anonymised statement.

Mail after the interview

Dutch:

Beste [deelnemer],

Bedankt dat ik u heb mogen interviewen voor mijn afstudeeronderzoek. Zoals afgesproken is hier de transcriptie van het interview ter controle. Zou u het willen doorlezen en mij kunnen vermelden of u nog aanpassingen en of aanvulling wenst aan de tekst?

Daarnaast wil ik nu nog eens vragen of u akkoord gaat met het toevoegen van het interview aan de appendix van de thesis en met het vermelden van uw naam en functie of dat u wilt dat ik het anoniem gebruik.

Als u de transcriptie goedkeurt, geeft u ook gelijk toestemming voor het gebruik van de antwoorden voor de analyse in mijn onderzoek. De informatie zal alleen worden gebruikt voor dit onderzoek en niet voor andere onderzoeken van de TU Delft en Royal HaskoningDHV. De Master Thesis zal wel worden gepubliceerd in de vrij toegankelijke TU Delft Education Repository.

Alvast bedankt voor uw reactie.

Met vriendelijke groet,

Jesse Zegeling

j.j.zegeling@student.tudelft.nl

English:

Dear [participant],

Thank you for allowing me to interview you for my Master Thesis. As agreed, attached to this email you can find the transcript of the interview to check. Would you like to read and review it and could you tell me if you would like any adjustments and or additions to the text?

Also, I would like to ask you again if you agree to adding the interview to the appendix of the final thesis report and if you agree to mentioning your name and position or if you want me to use it anonymised?

If you agree with the transcript, you are also agreeing that I will use the answers for analysing purposes of my research. The information will only be used for this research and not for any other researches of TU Delft and Royal HaskoningDHV. The Master Thesis will however as mentioned, be published in the public TU Delft Education Repository.

Thank you in advance for your answer.

Best regards,

Jesse Zegeling

j.j.zegeling@student.tudelft.nl

Appendix E. Interviews

This appendix gives a summary of the transcripts of each of the conducted interviews. All questions are not literally asked as it seems in the transcripts below. The interviews were open conversations and the mentioned topics were discussed. Section E4 shows some results of the best-worst method that is applied to get the weights for the key performance indicators.

E1: Royal HaskoningDHV

E1.1: Interview (#1) with Advisor Rail Traffic Technology (Adviseur Railverkeerstechniek) 1:

Een aantal jaren terug is Utrecht flink verbouwd. Wat zijn in jouw ogen de positieve en negatieve effecten van de verbouwing?

Ja, zoals de meeste mensen hier denk ik wel zullen zeggen, zijn die er allebei. Er is nu een corridorwerking, dus als deze kant verstoord is, blijft de andere corridor onaangeroerd. Als de verstoring op en vervelend punt plaatsvindt, geeft het je echter geen doorwisselmogelijkheden meer waardoor ook echt je hele lijn stil komt te liggen en je echt geen kant meer op kan. Het keren van Intercity's op de Amsterdam Utrecht Den Bosch / Arnhem corridor is ook erg lastig aangezien de sporen 5 7 en 18 19 ver van elkaar liggen. Er zijn wel mogelijkheden via de Sprinter sporen 14 en 15 maar de capaciteit is daar wel lager en het beïnvloedt de Sprinters tussen Breukelen en Rhenen. Vaak zie je in de huidige versperringsmaatregelen dat ze er dus zeker twee series direct volledig uit halen, want vaak zijn er op tussengelegen stops ook geen keermogelijkheden. Treinen die al onderweg zijn op het moment dat de storing net begonnen is leveren wat chaos op. Dit zal niet verdwijnen, maar als de duur terug kan naar een kwartiertje dan is dat te overzien voor de reizigers.

Kijkende naar de bijsturing in Nederland in het algemeen. Wat valt er op en wat zou er volgens jou beter kunnen?

NS en ProRail willen graag naar een hoge voorspelbaarheid. Ik heb hier een probleem en ik moet van A naar B. Daar is een ding verstoord, dus BAM, nu gaan we dit uitvoeren. En die en die scenario's, die zijn allemaal van tevoren uitgewerkt. Nu kijken we van oké, ik heb hier nu een verstoring. Wat kan er nog wel? Dus wat kan ik nog wel rijden daar? Dat hebben ze volledig losgelaten. Daar zijn ze vanaf gestapt. Ze hebben nu echt van die kant en klare scenario's van oké, als dit gebeurt, dan hebben we scenario 23. En dat maakt wel de voorspelbaarheid voor personeel van de vervoerder veel duidelijker. Ik denk dat het voor de reiziger niet zo heel veel uit maakt omdat die daar niet zoveel van merkt als die op het perron staat. Ik heb dat natuurlijk beter, omdat ik meer achtergrond heb, maar ik denk dat de reizigers om mij heen dat die nou echt geen idee hebben of een trein naar Maastricht opgeheven wordt of naar Heerlen of Venlo opgeheven wordt als er een verstoring is. De meeste reizigers gaan naar Den Bosch of Eindhoven en welke van die 3 treinseries nu rijdt, dat zal ze eigenlijk een worst zijn. Voor de mensen die verder dan Eindhoven zouden reizen, wordt er dan vanaf daar de oorspronkelijke trein wel weer verder opgepakt. Het is alleen dan de kunst om in Eindhoven te komen.

In het geval van een gedeeltelijke versperring (één van de twee sporen is bezet) heb je dan liever zoveel mogelijk treinen die op tijd rijden met wat uitgevallen treinen of juist zoveel mogelijk treinen / hoge capaciteit waarbij er misschien soms twee treinen kort achter elkaar aan rijden en dan met wat vertraging?

Dat laatste ben ik eigenlijk meer voorstander van en het is helaas zo dat in die concessie met NS echt puur de afspraken gemaakt zijn om op tijd te rijden. Bij Arriva bijvoorbeeld zijn er juist afspraken over aantal treinen en minder over punctualiteit. Daar zul je dus ook veel minder zien dat treinen worden opgeheven bij verstoringen en die willen dan alsnog de treinen laten rijden, want die worden afgerekend op de hoeveelheid treinen die zij gereden hebben en daarmee vervoerscapaciteit. Ja, je moet de mensen van A naar B brengen en daar heb je materieel voor nodig en NS, die wordt daar niet op afgerekend. NS wordt afgerekend op tijdrijden en dat reizigers vervolgens allemaal als haringen In de ton zitten of staan, zal NS minder een zorg zijn als die trein op tijd heeft gereden.

Een trein die uitvalt, wordt ook niet meegenomen bij de vertraagde treinen. Voor NS is dat dus beter. Kijk als NS 20 treinen op tijd hebben gereden, dan is dat voor hun goed. Of ze er eigenlijk 35 hadden moeten rijden, dat doet niet terzake. Uiteindelijk krijgen ze daar ook wel op hun donder voor van: jullie bieden te weinig treinen aan voor het aantal mensen wat je wil. Maar het hoofddoel is dus op tijd rijden.

In Duitsland gaat het anders. Daar laten ze alles gewoon doorrijden wat grote vertraging als gevolg heeft die ook ver in het netwerk doorwerken. Eigenlijk zou er een soort van balans gevonden moeten worden tussen het Nederlandse en Duitse systeem in de zin van dat treinen minder snel uit moeten vallen zoals in Nederland, maar als de chaos te groot wordt (Duitsland) dan moeten er toch acties worden ondernomen

Om die chaos te omzeilen zijn dan weer wissels nodig en daar zijn er de afgelopen jaren een heleboel van verdwenen.

Hoe meer wissels, hoe meer flexibiliteit. Maar goed, meer wissels neerleggen daar zit ook weer een kostenplaatje aan en onderhoud. De storingsgevoeligheid valt nog wel mee. Het is beter geworden. Een tijd lang is het onderhoud onder de maat geweest en dat kwam door de onderhoudsvorm die ProRail had met de verschillende aannemers. Dat waren PGO contracten; prestatie gericht onderhoud en in de eerste contractvormen daarvan zaten gewoon gaten. Die aannemer zei dan vaak: ja dat staat niet in mijn contract, dat hoef ik niet te doen. Tenzij er extra door ProRail betaald zou worden. In de loop der jaren (vanaf 2009 ongeveer) is dat wel weer meer opgelost in de nieuwere contracten. De storingsgevoeligheid is dus verbeterd door betere contracten en dus beter onderhoud. Voor elke wissel gaan ze gewoon bekijken: hoeveel wordt dit wissel bereden in stand links of rechts en hoeveel hebben we eigenlijk nodig en waar is het voor? Op die manier is er vaak bevonden dat wissels gesaneerd konden worden en dan gingen vervoerders bezwaar indienen maar kon ProRail wel aangeven dat dat wissel vrijwel helemaal niet gebruikt werd. Die werden dan alleen 's nachts één keertje gebruikt om roest te rijden en verder alleen in verstoorde situaties. De vraag is dan of er voor die situaties echt wissels moeten liggen of dat dat dan zonde is.

Even terugkomend op Utrecht Centraal. Je bent echt een mega knooppunt dat ook super belangrijk is voor de algemene treindienst in het hele land dat je misschien toch niet ergens een overloop hebt laten liggen. Iedereen is het er mee eens dat de hoeveelheid die er lag veel te veel was, maar er zijn nu complete tussenverbindingen ertussenuit gehaald en dat is achteraf gezien niet zo handig.

E1.2: Interview (#3) with Advisor Rail Traffic Technology (Adviseur Railverkeerstechniek) 2:

Een aantal jaren terug is Utrecht flink verbouwd. Wat zijn in jouw ogen de positieve en negatieve effecten van de verbouwing?

De wisselstraten zijn natuurlijk zo omgebouwd dat je nu met hogere snelheden kan rijden dus de perronopvolgingen en de wisselstraatbezettingen zijn natuurlijk veel korter omdat je met hogere snelheden kan opvolgen. Daarvoor zijn natuurlijk een hoop mogelijkheden opgeofferd. ProRail heeft bij dit project wel het idee gehad om echt tot het gaatje te gaan en er zijn wel een aantal mogelijkheden die ontbreken waarvan ik vind dat het niet heel handig is dat ze die hebben weggelaten. Dat zorgt dat je met situaties waar nu nog niet over nagedacht is, dat je daar eigenlijk niks mee kan. En dat zijn verbindingen die nu nog niet bestaan, de zeer veel voorkomende werkzaamheden, naja eigenlijk de geplande en ongeplande stremmingen waardoor je wil keren en dat eigenlijk heel lastig wordt gemaakt. Als er bijvoorbeeld richting Gouda een storing is, dan moeten alle IC’s vanuit Amersfoort op spoor 9 keren. Of je moet vanaf Blauwkapel heel lang tegen het verkeer in rijden en dan kunnen er wel meer sporen gebruikt worden in Utrecht. Maar eigenlijk is het zo dat 11 en 12 daar kom je niet vanuit Amersfoort en 8 kom je niet naar Amersfoort op het normale spoor, zeg maar. Bij ongeplande stremmingen is het vaak dat er eerst een paar treinen vastlopen en de rest komt er achteraan. Je weet wel dat je die achteraan komende treinen wil gaan keren, maar zolang de eerder vastgelopen treinen nog niet opgeruimd zijn, loopt de hele boel vast. Of je schiet jezelf in de voet door een trein binnen te nemen op een spoor waar je eigenlijk niet goed weg kunt. Je hoeft niet de mogelijkheid te hebben om van elke richting op elk spoor te komen, maar als je in ieder geval aan beide kanten een uitwijkmogelijkheid hebt naar links en naar rechts dan zou dat toch wel erg handig zijn waardoor de kans kleiner wordt dat je je helemaal vast manoeuvreert. Zeker met die grote hoeveelheden treinen die we graag willen rijden. Voor de IC’s Amsterdam – Arnhem / Eindhoven is het ook lastig met keren aangezien deze corridors in beide richtingen heel ver uit elkaar liggen. Keren moet dan via de Sprinter sporen 14 15, maar of dat nou zo handig is, weet ik ook niet. Een overloopwissel ergens zou misschien al een hoop schelen. De keerspoortjes op Houten Castellum en Driebergen-Zeist zouden inderdaad mooie opties zijn. De grap van Driebergen-Zeist is dat ze dat spoortje precies op een Sprinter lengte hebben gebouwd en niet op een Intercity lengte van een werkelijk verbijsterende gebrek aan vooruitziend vermogen. Kijk een wissel is duur, maar 50 meter spoor… Dat keerspoortje zou in de toekomst ook nog best gebruikt kunnen worden voor een route Amersfoort – Utrecht – Driebergen-Zeist als je een beetje ondernemend bent voor een spitstrein of Driebergen-Zeist – Bunnik – Vaartsche Rijn en vanaf Centraal als IC naar Den Haag Centraal.

Oke en de huidige bijstuurmaatregelen. Denk je dat die vooraf gemaakte plannen goed zijn?

Ik denk wel dat het een voordeel van die plannen is dat er van tevoren heel goed over nagedacht kan worden wat er mogelijk is en wat niet dus ik denk dat die plannen wel vrij redelijk zijn. In de huidige dienstregeling zitten ook wel heel veel marges dus bij een bepaalde mogelijke verbetering die mogelijk tot wat krapte leidt, wordt dan niet gedaan want ze zeggen van ja, dit zouden we normaal nooit doen in de gewenste dienstregeling en dus doen ze dan die storing situatie ook niet. Ja er wordt dan ook heel goed volgens plan gereden, maar daar wordt dus niet alles uitgehaald naar mijn mening. Maar als je daar een grote puinhoop van maakt zoals ze in Duitsland doen, dan word je daar ook niet blij van. Daar worden treinen omgeleid via andere routes waardoor dat daar voor vertragingen en andere grote chaos zorgt. De normale dienstregeling in Duitsland die slaat zeker nog wel ergens op, maar als het rommel is, dan geldt gewoon de wet van proppen; alles moet doorrijden en de vertraging doet er dan minder toe.

Heb je liever veel treinen tijdens een storing met vertraging of minder treinen die wel op tijd rijden zoveel als mogelijk?

Het is contextafhankelijk, maar het zou mooi zijn om zo weinig mogelijk te cancelen en zoveel directe verbindingen aan te bieden als mogelijk. Dit kan dan in gebundelde setjes om er zoveel mogelijk over het beschikbare spoor heen te pompen en dat levert dan wel vertraging op, maar dat zullen reizigers liever hebben dan wanneer hun trein niet rijdt of wanneer ze moeten overstappen. Echter, tussen een Utrecht en Amsterdam Bijlmer zou ik misschien zeggen dat er iets verzonnen moet worden dat zoveel mogelijk op tijd rijdt en ook zoveel mogelijk capaciteit biedt en dan moeten mensen maar gaan overstappen op die stations. Dan zou je kunnen gaan pendelen tussen die twee stations en eventueel één rechtstreekse trein per half uur erdoorheen sturen. Treinen combineren om meer capaciteit te bieden is uiteraard ook een optie. Tussen twee grotere stations is het dus eventueel een optie om te gaan pendelen en te keren juist ook om de punctualiteit ver weg van de stremming hoog te houden. Maar het is lastig, want het hangt ook van spits of dal af en het keren zal ook tot chaos leiden.

Meer of minder wissels, ook kijkende naar de kosten en de storingsgevoeligheid?

Het verhaal dat meer wissels meer storingen veroorzaken is wel hoog spreadsheet management gehalte en ja ze zijn storingsgevoelig maar als je ze goed onderhoudt dan zullen ze minder storen. Door allerlei maatregelingen is hete onderhoud wel flink verslechterd. Het Koningswissel in Utrecht Centraal vanuit Amsterdam Centraal komend ging na twee weken al stuk en dat is dus het wissel dat vanaf het IC spoor de sporen 18 en 19 bereikbaar maakt en toen konden er geen IC's rijden. ProRail zei vervolgens dat het een Koningswissel is en dat de effecten heel groot zijn als dat kapot gaat. Iedereen zei toen, dus ja je moet dat wissel meer onderhoud geven dan andere wissels. Als je minder wissels hebt, dan heb je minder uitwijkmogelijkheden dus dan moet je in ieder geval zorgen dat die rotzooi het doet; misschien wel met een dagelijks onderhoudsbeurtje. Dus ik zou zeggen hoe minder wissels hoe duurder elk individueel wissel moet zijn eigenlijk. Meer of minder hangt ook weer af van de locatie. Er is natuurlijk een verschil tussen een wissel in Utrecht Centraal en eentje in Krabbendijke. Een wissel in Utrecht mag best wat kosten kijkende naar het aantal mensen dat het station gebruiken.

Over het onderhoud weet ik dat ze in Zwitserland in een van de tunnels een wissel hebben dat met 180 kilometer per uur bereden kan worden en die is elke dag 15 minuten buiten dienst voor een onderhoudsbeurt en dan gaan ze met een doekje elk stofje weghalen onder andere. Met dat soort checks kan je al in een heel vroeg stadium afwijkingen constateren en storingen verhelpen voordat ze ontstaan. In Nederland hoor je vaak dat er een puntstuk kapot is in wissel x y z, klein voorbehoud want ik loop niet in heet onderhoud, maar dat dat als een donderslag bij heldere hemel komt, vind ik heel gek. Je zou op zijn minst moeten zeggen dit wissel ligt al een half jaar te klapperen dus het gaat een keer mis. Wees dus voorzichtig met de aanname meer wissels is meer wisselstoringen, want dat is alleen bij gelijkblijvend onderhoud.

E1.3: Interview (#5) with Advisor Rail Capacity studies (Adviseur Netwerkstudies):

Een aantal jaren terug is Utrecht flink verbouwd. Wat zijn in jouw ogen de positieve en negatieve effecten van de verbouwing?

Ik zal proberen om het kort en bondig te houden, maar over het algemeen ben ik wel redelijk positief. Ik zie vooral, niet per se in de wisselsaneringen maar wel in de ombouw van Utrecht Centraal een enorme verbetering in reistijd want je kan met 80 km/h wegrijden en dat kan straks in Amersfoort ook en daar win je echt tijd mee. Ik denk zelfs dat je daar meer mee wint, dan het verhogen van de snelheden op baanvakken van 140 naar 160. Persoonlijk denk ik wel zo van zolang het past houd zoveel mogelijk opties open, want dan ben je flexibel in de dienstregeling en kan je na een aantal jaren een andere lijnvoering gaan rijden als daar de wens voor is maar ook bij bijsturing. In de beginjaren bij Utrecht Centraal was het zelfs heel moeilijk en hebben ze teveel gesaneerd en zo kon je van Utrecht niet naar 15 komen (vanaf het IC spoor) en dat is nu wel weer teruggebouwd. Het voordeel van de mindere wissels is het in corridor denken dat een vertraging op een corridor niet overspringt op een andere corridor. Je kan extra overloopwissels bouwen dat een trein tijdens een storing op een ander perronspoor aan kan komen, maar dan wordt een andere corridor opgehouden. Wat ook erg jammer is dat er bij Overvecht wissels zijn weggehaald waardoor een omleiding via Hilversum naar Amersfoort ook lastiger is geworden. Maar als dat soort opties niet gebruikt hoeven te worden, is het misschien ook zonde van het geld. Maar goed, doorgaans wel positief want het schijnt ook dat het aantal storingen op Utrecht Centraal echt significant is afgenomen.

Maar als er dan een storing plaatsvindt, is het ook gelijk hommeles in Utrecht.

Nou, in principe zou die storing dan beperkt moeten blijven tot één corridor. Dat was laatst inderdaad niet het geval maar toen waren er op meerdere corridors tegelijkertijd storingen en lag heel Utrecht Centraal plat. Dat lag ook weer aan de materieel- en of de personeelsplanning van NS. Als er een storing richting Den Bosch is dan wordt nu vaak die hele trein vanaf Amsterdam eruit gehaald omdat er in Utrecht niet tot nauwelijks gekeerd kan worden.

Kijkende naar die situatie en er is inderdaad tussen Utrecht en Den Bosch een storing; vind jij dat dan de beste oplossing dat er treinen worden uitgehaald of kan dat ook anders in de bijsturing?

Omrijden is wel lastig richting Den Bosch. Stel dat ze wel een omreisoptie hebben bij Geldermalsen dan zou ik zeker zeggen zoveel mogelijk rijden. Als er tussen Utrecht en Driebergen een storing is, zou het wel beter zijn om die treinen zover mogelijk door te laten rijden. Stel dat de hele lijn gestremd is, kunnen reizigers alsnog met het streekvervoer vanaf Driebergen naar Utrecht. Dat is vanaf Ede of Arnhem niet mogelijk. De vraag blijft wel of heet streekvervoer dat aan kan en er genoeg bus capaciteit is, maar je biedt de reizigers in ieder geval wel een extra optie aan. Arnhem Utrecht is niet een verbinding waar maar een paar passagiers overheen reizen dus als je dan aankomt met een volle intercity in Driebergen, zou je misschien in Driebergen een heel groot probleem gaan creëren.

Bij een gedeeltelijke stremming wil je dan veel treinen die rijden of de treinen die rijden dat die op tijd rijden?

Dat is wel een heel leuk dilemma. Ik denk zelf wel zoveel mogelijk streven naar op tijd rijden. Want als je met vertraging gaat rijden, halen mensen hun aansluitingen niet, ben je alsnog langer onderweg. Ik denk ook als je gewoon goede protocollen klaar hebt liggen dat je tijdens storingen er meer uit kan halen als je gewoon zegt dat die en die treinseries niet rijden. Stel je hebt een heel erg geïsoleerde lijn zoals Zwolle Emmen wat overigens weer lastig is omdat het enkelspoor is, maar stel je hebt een lijn met maar weinig interactie met andere lijnen; de Zeeuwse lijn bijvoorbeeld. Als je daar zorgt dat alles gewoon rijdt tijdens een gedeeltelijke stremming… de IC's naar Amsterdam probeer je dan zoveel mogelijk op tijd te laten rijden en de IC's naar Vlissingen mogen vertraging hebben omdat dat verder niet heel veel uitmaakt. Maar wacht, als we kijken naar een spits situatie dan is het wel heel irritant voor reizigers als mensen moeten staan of als er een trein uitvalt. Wat misschien wel mooi is, is om dan in de spitsrichting iets meer te laten rijden, maar dat wordt misschien wel heel lastig in de materieel planning. Ik zou wel zeggen van probeer zoveel mogelijk echt te kijken van welke treinen moet ik echt hebben qua reizigersaantallen. Dus ga niet zeggen van nou ik wil altijd op Maarn Driebergen en Bunnik stoppen. Voor reizigersaantallen is het misschien beter om de IC's wel te laten rijden en de Sprinters eventjes niet of in ieder geval minder dan de IC's, omdat IC's meer impact hebben als ze uitvallen. Met een beetje creativiteit kan je wel een IC extra laten stoppen, maar wat vooral belangrijk is, is om de capaciteit per trein te verhogen. Misschien kunnen treinen worden samengevoegd en later voorbij de storing weer worden ontkoppeld.

E1.4: Interview (#6) with Advisor Rail Capacity studies / Rail Traffic Technology (Adviseur Netwerkstudies / Railverkeerstechniek):

Wat zijn jouw bevindingen van Utrecht Centraal in het algemeen?

Ja ik ken het oude Utrecht Centraal niet heel goed dus dat is voor mij moeilijk te zeggen maar het is wel zo sinds Utrecht Centraal af is dat de vertragingen flink zijn afgenomen sinds de verbouwing en dat Utrecht Centraal niet meer de bottleneck is. Je merkt ook dat je heel snel het station binnenkomt als je het vergelijkt met andere stations. Vertragingen worden ook ingehaald, maar dat komt dan ook misschien deels door het langere stilstaan door sommige treinen wat je net aangaf. Of er te weinig of genoeg wissels in Utrecht zijn, hangt een beetje af waar de storing plaatsvindt. Maar wat je nu in Utrecht ziet, is dat wanneer er een storing plaatsvindt in de buurt van Utrecht dat je een opeenstapeling krijgt van treinen en dat het heel moeilijk is voor de bijsturing om die treinen weg te rijden tot dat het een keer helemaal om valt. Treinen moeten weg, maar wachten nog op een machinist die er dan nog niet is vanwege die storing en zo wordt dat dan een chaos. Ik ga niet zeggen dat dat komt door te weinig wissels maar ook de afhandeling van Utrecht, Utrecht heeft veel treinen en relatief weinig perronsporen wat ervoor zorgt dat de capaciteit beperkt is en je snel een file krijgt. Veel sporen kunnen ook maar één kant bereden worden. Spoor 8 kan je bijvoorbeeld niet keren richting Amersfoort en daardoor ontstaat er tijdens verstoringen of werkzaamheden een kunstmatige of zelf gecreëerde krapte. Een overloopwissel bij Overvecht had al wat kunnen verhelpen en datzelfde geldt ook richting Gouda waar de IC's nu over de binnensporen rijden. Als 20 21 gestremd is, kunnen er over het hele stuk geen Sprinters rijden omdat er geen alternatief is. Dus op de toeleggende baanvakken zouden een paar extra overloopwissels wel kunnen helpen om wat redundantie te creëren.

Storingen in het algemeen. Bij een gedeeltelijke stremming zou je dan veel treinen willen laten rijden met vertraging of minder zonder vertraging?

Hangt van de situatie af en vooral van de duur van de storing. Tijdens geplande werkzaamheden of een langere storing zou ik zeggen dat alles op tijd moet rijden en dat het dan niet erg is als er een aantal treinen uitvallen. Als de storing kortstondig is dan willen mensen vooral naar huis en zou ik gewoon zoveel mogelijk laten rijden en erdoorheen proppen. Voor storingen van max 2 uur die jij gaat simuleren, zou ik dus zeggen zoveel mogelijk proppen als past. De vertragingen moeten echter niet teveel oplopen. Als je een kwartier vertraging krijgt en je rijdt kwartierdienst dan kan je misschien wel wat laten uitvallen. Voor 5 minuten zou ik dat niet per se doen. Wel zou ik een goede balans vinden tussen IC's en Sprinters zodat alle stations nog steeds bediend worden. Pendelen is ook nog een optie, want iets is beter dan niets.

E2: Train drivers

E2.1: Interview (#2) with NS train driver 1:

Mijn thesis gaat dus over de optimale locaties zoeken voor bijsturingswissels, want er gebeuren op het Nederlandse spoor veel storingen voor.

Voor mij moet er eigenlijk veel meer aandacht besteed worden aan het voorkomen van storingen. Als we door de jaarcijfers van NS bladeren die vandaag gepubliceerd zijn dan zie je veel treinstoringen, slechte punctualiteit, veel storingen. Daar moet als eerste aan gewerkt worden eigenlijk. Bijsturen is eigenlijk symptoombestrijding. Als het onderhoud gewoon op orde is, dan gaan het aantal storingen ook omlaag, maar nu is het onderhoud gewoon slecht. Er is ook geen aannemer die zijn nee uitsteekt, want over drie jaar hebben ze een ander die er met een contract vandaar gaat in die regio en hebben ze eigenlijk het werk voor een ander gedaan dus dat doen ze niet en dat zie je op alle kanten terug. We moeten met zijn allen en ook de directie van allerlei vervoerders veel meer gas geven richting richting Den Haag dat de trein veel belangrijker moet worden en dat er veel meer geld naar het spoor moet. Twee weken geleden op een treinrondreis door Zwitserland dan is het gewoon bizar hoe goed de Zwitsers het voor elkaar hebben. Daar gaat ook wel veel meer geld naar het spoor, maar alles klopt wel gewoon: dienstverlening, dienstregeling, reizen, alles. En dan trek je heel veel reizigers, bijna de helft van de bevolking heeft ook een kortingskaart – dat zegt al genoeg, er worden veel meer lange afstandsreizen per trein gemaakt dan met de auto en dat is veelzeggend. Met alleen meer geld in Nederland is het probleem niet opgelost. De kwaliteit van de infrastructuur moet omhoog en er moet ook op belangrijke plekken gewoon infrastructuur bij. Kijk wat je nu al jaren ziet gebeuren, is dat alle vervoerders treinpaden aanvragen en dat ProRail die als onafhankelijke partij die capaciteit moet verdelen. Wat je nu continu ziet is dat er een compromis gemaakt wordt tussen alle vervoerders als er ergens niet genoeg capaciteit is. Alleen gaat er geen infra bijgebouwd worden. Alleen na jaren wordt een lijn overbelast verklaard en dan moeten ze ineens iets gaan doen. Voordat de nieuwe infra er is, ben je echter ook weer 5 tot 10 jaar verder. Dat is dus misschien al 15 jaar verder en in tegenstelling tot de Zwitsers: daar gaat het allemaal anders. Zij zien dat er ergens te weinig capaciteit is, bouwen er bij en gaan dan pas meer rijden. In Nederland zijn we nu heel veel meer aan het proberen te rijden, tot de grenzen van wat mogelijk is. Het Zwitserse netwerk is ongeveer even groot als het Nederlandse spoornetwerk, ze hebben alleen drie keer zoveel wissels, veel meer seinen en de prestaties zijn veel beter. Er rijden 20 tot 25 procent meer treinen per kilometer spoor in Zwitserland dan in Nederland en eigenlijk is dat netwerk dus een mooi streven voor Nederland. Daarnaast hebben ze al meer reizigers dan voor Corona en dat is in Nederland nog niet het geval. Ook in de daluren krijgen ze hun treinen vol en dat doen wij niet goed. Wij hebben 10.000 verschillende flexpassen, kortingen en van alles en nog wat, app, OV Chipkaart, er is geen touw aan vast te knopen en er wordt niet goed gewerkt om het makkelijk te maken om reizigers de trein in te lokken. Ook daar kunnen we van de Zwitsers nog heel veel leren.

Wat is jouw mening over het nieuwe Utrecht Centraal en alle bijbehorende wisselsaneringen?

Ja kijk, Utrecht Centraal is gebouwd op basis van een dienstregelingmodel en dat is nooit slim. Vroeg of laat ga of wil je met een ander dienstregelingmodel rijden en dan zit je met de problemen. Vanuit Arnhem Nijmegen, een van de grotere knooppunten van het land is er bijvoorbeeld geen rechtstreekse verbinding met de westelijke Randstad, het is gewoon niet mogelijk. Wat je ook heel veel ziet in Nederland en wat de Zwitsers juist niet doen, is dat wij voor of na de spits heel veel treinen gaan combineren en splitsen. In Utrecht moet dat dan grotendeels via de Cartesiusweg gebeuren en dat kan dan alleen nog via spoortjes 20 en 21 waar al 6 treinen per uur per richting rijden en dan moet er ook gereden worden van en naar de opstelsporen. Dat wordt gewoon lastig. En er hoeft maar dit te gebeuren, de boel loopt in de soep daar en de treinen stapelen zich daar op.

Moeten we dan gaan splitsen en combineren op andere stations?

Nee, we zouden het eigenlijk moeten minimaliseren. Weer kijkende naar de Zwitsers, die rijden de hele dag met dezelfde treinen op spitsbezetting en toch krijgen ze hun treinen vol, hebben ze nog steeds een goede zitplaatskans voor reizigers en een hoge punctualiteit. En goed, NS zegt dat je dan wel meer materieelkilometers krijgt wat ook klopt uiteraard en daar zit het probleem want ze hebben te weinig techneuten die het onderhoud moeten doen. Daarom wordt er bijna de hele dag op de zitplaats nauwkeurig gepland en zijn de treinen altijd precies pas voor het verwachte aantal reizigers. Nu met die 10 minuten IC's, daar heb je treinen die sneller achter elkaar aankomen, maar de hoeveelheid zitplaatsen gaat echt niet omhoog. De treinen worden per stuk korter en je hebt er ook nog eens meer personeel voor nodig. En we willen met z'n allen snelle IC's, maar die staan nu 8 minuten in Utrecht te wachten om maar een overstap te kunnen creëren terwijl we allemaal vlot, veilig en voordelig openbaar vervoer willen hebben en dan moet je niet 8 minuten gaan stilstaan op een knooppunt station, dat gaat helemaal nergens over. Dit probleem is ook in Hoorn waar treinen moeten wachten zodat ze in Zaandam mooi in het rijtje gezet kunnen worden. Tussen Arnhem en Schiphol wordt er gezegd er zijn 6 treinen per uur. Daarvan zijn er echter maar 2 rechtstreeks en de snelste verbinding is nota bene die met een overstap in Utrecht. Rij dan beter 4 keer 6 bakken ipv 6 keer vier bakken. In Zwitserland rijden ze gewoon met 16 bakken dubbeldekkers en buiten de spits wordt er dan één retourtje misschien één stel van 8 bakken afgehaald, maar dat is nogal een verschil met wat hier allemaal gebeurt. In de jaarcijfers staat er ook dat we langere treinen willen laten rijden, maar de IC perrons zijn de afgelopen jaren door ProRail juist allemaal ingekort van 15 naar 12 rijtuigen en hoe vaak zien we überhaupt nog 12 rijtuigen rijden? Naast bijsturing voorkomen, moet ook het proces eenvoudiger worden gemaakt. Ons proces is elke dag anders. Er zijn geen twee dagen achter elkaar dat de dienstregeling hetzelfde is, ja en ook in Zwitserland rijden ze maandag tot en met zondag hetzelfde. Ook op zondag kan je om 5:30 's ochtends met de trein. Je hebt daar gewoon elke dag hetzelfde materieel, dezelfde vertrektijden en bij ons is altijd alles elke dag anders en dat komt door dat continue maatwerk. En de kosten rijzen de pan uit dus dan is het logisch en makkelijk om te denken aan bezuinigen, maar het is beter om meer inkomsten te genereren en dat is natuurlijk wel moeilijker, maar dat is uiteindelijk wel het doel. Er moeten gewoon meer mensen de trein in en daar gaan die ingewikkelde tariefsystemen niet bij helpen en al helemaal niet dat gedoe over die samenreiskorting. Ongekend ingewikkeld en onvriendelijk en eigenlijk zou die hele samenreiskorting gewoon helemaal afgeschaft moeten worden. De prijs van de rit moet bepaald worden aan de hand van in- en uitchecktijd. Het Duitse systeem is voor Nederland ook weer niet goed. Kortingen zouden eventueel automatisch verrekend kunnen worden met de tijd waarop men in- en uitcheckt: voor, na, tijdens de spits.

Welke van de vier genoemde KPI's vind jij het belangrijkste?

Naja kosten niet. De kwaliteit moet omhoog en uiteindelijk trek je daar meer reizigers mee naar de trein toe. Er moeten voldoende lange treinen aangeboden worden. Met die wissels in je model moet je er eigenlijk voor zorgen met de afstanden tussen de stations en de bijbehorende wissels dat je kunt overlopen binnen 14 minuten want dan kan er elk half uur nog gereden worden. En dit is wel interessant want als we kijken naar Hoogeveen waar er wissels zijn weggehaald en daar kunnen we met moeite net een halfuursdienst rijden tijdens een storing. En een voorbeeld uit Oostenrijk, daar konden ze tijdens werkzaamheden vervolgens op het resterende enkelspoor nog met 6 treinen per uur per richting rijden en gewoon omdat ze genoeg wissels hadden om over te lopen.

Als je maar één spoortje beschikbaar hebt, heb ik (en reizigers) liever dat er veel treinen alsnog rijden met wat vertraging. Reizigers hebben namelijk liever dat ze wel kunnen aankomen op hun bestemming weliswaar met 15 minuten vertraging in plaats van niet kunnen aankomen of met een flinke omreis. Dus in dat geval is de rate of actual departures wel het belangrijkste ja. Kosten zijn het minder belangrijk, maar tuurlijk moet er wel op gelet worden waar bepaalde wissels niet nodig zijn. Plekken waar geen alternatieve routes zijn, moet juist extra aandacht besteed aan worden en minder wissels worden gesaneerd. Maar blijven rijden is het belangrijkste, want je kan beter tegen mensen zeggen je trein rijdt, maar komt 10 minuten later aan vanwege dit probleem, dan zeggen dat hij niet rijdt. Punctualiteit is dus het minst belangrijk.

Voor de kosten van de wissels is het niet alleen het beton en ijzer. Ook de plaatsing, de planning, de buitendienstelling, alternatief vervoer, dienstregelingwijzigingen kosten geld en misschien nog wel veel meer. Bij onderhoud van de wissels repareren ze in Nederland ook alleen het kapotte gedeelte, maar dan blijft het een slecht wissel. In Nederland is misschien wel een kwart van alle wissels verzakt en een gerepareerd onderdeel is dus zo weer kapot. Als je Zwitserland binnenrijdt, dan is dat niet het geval, maar daar is het onderhoud ook veel beter geregeld.

Wat is een drempelwaarde voor de rate of actual departures en punctualiteit tijdens een storing?

Dat hangt van de normale dienstregeling af, maar als je bij bijvoorbeeld die tweesporige baanvakken ervan uitgaat dat er 4 SPR en 4 IC's per uur per richting rijden dan moet je minstens de helft over houden wat voor storing het ook is. Je mag tot 50% halveren, zolang je nooit onder een uursdienst uitkomt. Voor punctualiteit maakt de drempelwaarde niet uit. Aankomen is veel belangrijker dan op tijd aankomen. Punctualiteit kan dus op 1% gezet worden. Late aansluitingen garanderen is wel een belangrijk puntje.

Daarnaast is het ook handig als er zoals de Zwitsers het noemen een Ersatzzug gereed staat. Die kan in het pad van een andere gecancelde of te late trein verder rijden of terug rijden. Dat gebeurt bij de Zwitsers vaak in Basel en in Brig als er treinen te laat uit Duitsland of Italië binnenkomen en dan worden die gewoon in het internationale pad gezet en even later wordt de te late internationale trein op een binnenlands pad gezet om de vertragingen te beperken. Er kunnen best wissels weg gehaald worden die niet nodig zijn, maar zeker de grotere stations moeten meer keervoorzieningen krijgen. Zeker kijkende naar de wisselsaneringen op de kaart die je net liet zien, dan is het echt van belang dat er op de juiste plekken wel nog keervoorzieningen en vooral genoeg aanwezig zijn.

Concluderend als je de reiziger op 1 wil zetten dan is het als eerste ellende voorkomen en als dat niet lukt, dan is het noodzakelijk dat er wel op handige plekken voldoende gekeerd kan worden. In Utrecht vanuit Den Bosch moeten treinen dus al keren in Dn Bosch als er een storing is richting Amsterdam en dat is gewoon te gek voor woorden. Er moet of gekeerd kunnen worden in Utrecht op 14 15. De andere kant op zou je moeten kunnen keren met IC's in Driebergen of Houten Castellum of natuurlijk Geldermalsen zolang de keersporen daar lang genoeg zijn. Pendelen op één spoortje is uiteraard ook een goede optie. Of de andere kant op tot Vaartsche Rijn of Lunetten en dat mensen vanaf daar kunnen pendelen naar Centraal of eventueel met ander OV doorkunnen. Eensporig doorrijden gebeurt helaas te weinig. Bij een aanrijding op een viersporig traject helemaal op het buitenste spoor, dan moet heet gewoon afgeschermd worden en dan rijden de treinen op twee sporen door, de twee sporen ver van de aanrijding af.

De treinen zijn zoals gezegd ook te kort, dat door dat maatwerk komt. Als de treinen nou langer zijn en minder vaak rijden hoeft er ook minder bijgestuurd te worden. We hebben hier in Zwolle heel veel werk met al dat combineren en splitsen en zitten hier soms met 30 man per dag en dat is niet efficiënt.

E2.2: Interview (#8) with NS train driver 2:

Met deze machinist is er een hele dienst meegereden. Het interview vond plaats tijdens het rijden en ook in de pauzes. Vanwege de duur van de dienst (14:35-22:59) is er geen audio opname gemaakt en is er dus geen samenvatting van de transcriptie. Na afloop van het interview is deze compacte samenvatting hieronder geschreven. Tijdens de dienst ging het niet alleen over Utrecht Centraal, bijsturing in het algemeen en de key performance indicators, maar werd er ook heel veel geleerd over blokken, seinen, borden, beveiliging, bovenleiding, treincabines en nog veel meer.

De dienst begon in Amsterdam Centraal met de Intercity naar Vlissingen. Er werd tot Roosendaal meegereden en gelijk na het verlaten van het in ombouw zijnde Amsterdam Centraal volgden er een aantal wisselbewegingen bij aansluiting Overbakelpolder. Deze voor 80 km/h geschikte wissels werden uiteraard met maximaal 80 km/h bereden en pas na het volledig passeren van de trein wat gecheckt kan worden door de bovenleidingsportalen te tellen, kon er gas (eigenlijk tractie) worden gegeven tot 130 km/h wat eigenlijk al direct na de wissels aangegeven was met een bordje aangegeven. Tussen Amsterdam Sloterdijk en Haarlem lagen er aan beide spoorzijdes inhaalsporen. De machinist gaf aan dat deze spoortjes weggehaald zullen worden door ProRail en dus het spoor minder flexibel zal maken in geval van verstoringen. Een defecte trein kan er immers makkelijk aan de kant gezet worden en zal hierdoor het overige treinverkeer niet tot last zijn. De machinist heeft hier echter nooit stil gestaan met een kapotte trein en snapt dan ook dat de sporen weggehaald worden. Na het passeren van Leiden Centraal werd er naast de Intercity naar Den Haag Centraal een tijdje gereden en werden onder andere de wissels bij Den Haag Mariahoeve gepasseerd die onderdeel zijn van een van de layouts in het model. De wisselstraat vlak voor Den Haag Hollands Spoor was vanuit de cabine thesis-voorpagina-waardig, maar helaas is er geen foto van gemaakt. Het traject tussen Den Haag en Rotterdam was om meerdere redenen interessant. Natuurlijk omdat het traject veel bereden wordt door de student in kwestie, maar ook vanwege de tunnel in Delft die binnenkort naar 4 sporen wordt uitgebreid en alle wissels die er op dit moment nog aan Den Haagse zijde liggen. In Rotterdam werd er een treinstel afgekoppeld om vervolgens met 4 bakken VIRM door te rijden richting Roosendaal. In Roosendaal liggen er op dit moment nog heel veel wissels en een groot deel daarvan zal in 2025 worden weggehaald. Ondanks dat dit in de beoogde dienstregeling moet passen, daalt de flexibiliteit en belemmert het toekomstige wijzigingen in de dienstregeling in de vorm van andere lijnvoering e.d.

In de pauze in Roosendaal werd er in de cabine van VIRM 9417 uitleg gegeven over de key performance indicators en deze werden vervolgens door de machinist ten opzichte van elkaar gewogen met behulp van de best-worst method. Hieruit volgde dat het tijdens een storing verreweg het belangrijkste is dat er in ieder geval gereden wordt. Er moeten zo weinig mogelijk treinen uitvallen. Vertragingen moeten uiteraard beperkt blijven maar als er met een 5 minuten norm gewerkt wordt, moet er toch wel minimaal 50 procent op tijd rijden. Beter is misschien zelfs om met een 15 minuten norm te werken waarvan 90 procent op tijd zou moeten rijden. Dit werd aanbevolen door de machinist en is zeer interessant om mee te nemen in het onderzoek. Als treinen namelijk meer dan 15 minuten te laat zijn, komen ze al snel in het pad van hun opvolger (dezelfde trein van 15 of 30 minuten later) en dan kan die misschien wel beter worden opgeheven. Over het algemeen is het wel zo dat machinisten vinden dat er gewoon zoveel mogelijk gereden moet worden, want dat is uiteindelijk het doel van NS: reizigers van A naar B brengen. De kosten van de infra werden het minst belangrijk gezet. Natuurlijk is het wel belangrijk om de financiën in de gaten te houden, maar eigenlijk zou er gewoon structureel meer geld moeten naar het spoor.

Eenmaal vertrokken werd er tussen Roosendaal en Breda uitleg gegeven over linker spoor beveiliging. Er zijn in Nederland meerdere trajecten met op het linker spoor in beide richtingen maar één aanwezig blok. Dit wil zeggen dat er bij een storing waarbij er op één spoor doorgereden moet worden in één richting maar één trein tegelijkertijd op het hele traject kan zijn. Dit heeft grote gevolgen voor de capaciteit. Daar waar er wel elke +- 1500 meter een blok is op beide sporen, kan er bij enkelspoor rijden tijdens een storing wel meer overheen in beide richtingen. In het gemaakte model zijn er op alle sporen seinen aan beide zijden wat dus wil zeggen dat dit de capaciteit verhoogt als er linker spoor moet worden gereden in geval van de defecte trein tussen stations B en C.

Bij stations Tilburg en ’s-Hertogenbosch werd er verteld over de toekomstige aanpassingen aan het spoor. In Tilburg wordt er een vierde perronspoor bijgebouwd en verdwijnen er veel wissels. Door het slim plaatsen van de wissels kunnen er zowel vanuit oost als west nog op twee sporen per richting treinen keren indien er een storing is aan de andere kant van het station. De capaciteit en de dienstregeling planning wordt in ’s-Hertogenbosch ook makkelijker gemaakt doordat de treinen vanuit Tilburg niet meer het druk bereden spoor Utrecht – Eindhoven in beide richtingen hoeven te kruisen. De brug over de Maas bij Ravenstein is een stukje enkelspoor en wordt door middel van twee ‘y-wissels’ aan weerszijden aangesloten op de tweesporigheid. Doordat het in de dienstregeling maar net past kruisen treinen elkaar vlak voor en vlak na de brug. Bij een kleine vertraging van trein 1, is trein 2 dus ook al snel te laat. Verder keren er Sprinters in zowel Oss als Wijchen. Als de brug tweesporig wordt, kunnen deze Sprinter lijntjes aan elkaar gekoppeld worden. Bij binnenkomst in Nijmegen werd er gesproken over de toekomstige verbouwing en het nieuwe PHS Nijmegen waar er een extra perron wordt gebouwd waardoor er in de toekomst meer treinen kunnen rijden. Die extra capaciteit is ook nodig want tussen Arnhem en Nijmegen rijden er nu al heel veel treinen en dat was ook te merken in de cabine met al het tegenverkeer.

Bij Zutphen is de dienstregeling ook erg krap voor de Intercity want er wordt voor beide richtingen één spoor gebruikt en de treinen zitten kort achter elkaar. Het station van Zutphen dient verder als startstation van verschillende regionale lijntjes van verschillende vervoerder. Eenmaal aangekomen in Zwolle was het donker en na een pauze ging de reis verder met de SNG Sprinter naar Utrecht Centraal. Er werd iets te laat vertrokken want de Intercity’s naar Rotterdam en Den Haag waren iets te laat en hadden voorrang. Een logische keuze, want anders had een van de twee de Sprinter alleen maar in de nek gezeten. Tussen Zwolle en Amersfoort zijn er nog wel heel veel inhaalsporen en overloopwissels aanwezig. Als de IC meer vertraging had gehad, was het best mogelijk dat de Sprinter wel voor mocht, maar even later op een van de flexibele stukken van dit traject even aan de kant werd gezet. In Utrecht kwamen we aan op spoor 1 en werd er enigszins haast gemaakt om een bijgestuurde DDZ naar Amersfoort te besturen. Door een defecte trein bij Gouda keerde de IC uit het noorden in Utrecht op spoor 9, het enige spoor dat in Utrecht geschikt is om een IC op die manier te keren zonder heel lang linker spoor te moeten rijden. Over Utrecht werd er nog gezegd dat het doorstroomstation iets te geoptimaliseerd is en dat het eigenlijk niet moet kunnen dat treinen in Amsterdam of ’s-Hertogenbosch of soms zelfs al in Eindhoven moeten keren omdat er ergens voorbij Utrecht een storing is. Het zou mooi zijn als daar een oplossing voor zou komen. In Amersfoort werd er vervolgens overgestapt op een ICM naar Amsterdam Centraal. De doorloopkoppen werden laten zien, de remmen werden getest, inclusief de noodrem en uiteindelijk werd er met een minuutje vertraging vertrokken naar Hilversum en Amsterdam. Er was weinig speling in de dienstregeling en door het kruisen van een ICE vlak voor Amsterdam kwamen we nog eventjes voor een rood sein te wachten. Bij aankomst in Amsterdam was de dag klaar na 8.5 uur en 500 kilometer cabinerit.

E2.3: Interview (#7) with RailExperts international cargo train driver:

In de afgelopen jaren zijn er een heleboel wissels gesaneerd en is de flexibiliteit op het Nederlandse spoor daardoor afgenomen. Hoe kijk jij als goederenmachinist daar naar?

Nou er zijn genoeg voorbeelden te verzinnen waar er wissels zijn weggehaald en wij met onze goederentrein moeten wachten op het overige treinverkeer om onze lok naar de andere kant te rijden. Dan denk ik soms bij mezelf van welke ****** heeft dat verzonnen? Waarom? Ja je kan niks meer. Het is ontworpen door iemand die totaal niet weet waarvoor die iets aan het ontwerpen is. Mooi voorbeeld, Oudewater, alle vervoerders inclusief NS waren tegen. Wat doen ze? Het moet weg, waarom weet niemand, naja het scheelt ze weer 8 wissels. Planmatig werd het niet gebruikt, maar wel in geval van verstoringen en zeker met goederentreinen en werktreinen die richting Utrecht moesten. Want zeker als je vanaf Rotterdam richting Utrecht ging met een goederentrein ging je standaard aan de kant. Een kwartiertje tot 20 minuten en ja nu gaat dat niet meer. Nu staan we bijna 50 minuten op Rotterdam Noord te wachten en dan denk ik waarom? Uiteindelijk worden de kosten alleen maar hoger. Wij komen minder op tijd aan, goederen worden misschien dus niet op tijd geleverd en de tarieven van de extra rijtijden zijn ook flink. We willen een modal shift, we willen dus meer goederen op het spoor, maar we breken wel de infra af in Nederland en het wordt omgebouwd tot metronet enkel en alleen voor NS. Het is niet meer mogelijk om straks met een goederentrein te rijden tussen het andere treinverkeer door. Waar ProRail naar kijkt is, wat zit er in de jaardienst, wat is er gepland en voor de rest mag NS alles plannen. Alles wordt volgebouwd met NS treinen waar niemand blij mee is, want niks sluit op elkaar aan tegenwoordig. En er wordt niet meer gekeken naar problemen, want in die ideale wereld van ProRail werkt alles perfect. Ook momenteel bij Schiphol, moeten ze ineens roestrijden. Het ontbreekt kennis bij ProRail.

Kijk, goederen is niet planmatig en kan niet planmatig. Je moet altijd mogelijkheden hebben voor uitbreiding en zeker in deze tijd, je wil duurzaam verkeer. Nou spoor is altijd nog de ideale of tenminste de groenste manier van transport. En wat je ook ziet het is alleen maar wegverkeer en het binnenlandse (goederen)treinverkeer wordt alleen maar minder en puur en alleen omdat het niet meer loont. Lineas reed een containertrein naar Tilburg maar die stond een paar dagen opgesteld in Rotterdam en die tarieven zijn verleden jaar met 800% omhoog gegaan. Dan loont het niet meer. Dan ga je kijken hoe beroerd de infra erbij ligt in de Rotterdamse haven. Ze hebben de ene storing na de andere en dan wordt er door de CEO van ProRail gezegd ‘nee hoor, we hebben geen achterstallig onderhoud, alleen in de Rotterdamse haven’

Jij reed ook goederentreinen door Duitsland, wat is het verschil met Nederland?

Naja Duitsland moeten we het eigenlijk niet over hebben. Eind vorige eeuw is er in de infra in de voormalige DDR flink geïnvesteerd om die up to date te krijgen. Dat is aardig goed gelukt, maar wat je nu in het westen ziet, is dat daar alles in elkaar stort. Maar er is wel een heel groot voordeel in Duitsland, je hebt heel veel omleidingsroutes en ook nog heel veel overloopwissels liggen dat we weer een stuk linker spoor kunnen rijden. Dat is in Nederland niet meer het geval, want hier moet alles weg, want een wissel zou wellicht ooit een storing kunnen geven. Dat sommige wissels weg worden gehaald zoals in Helmond dat is prima dat was een kort spoortje, dat snap ik. Maar Oudewater, kom op zeg. Op de Zeeuwse lijn zijn ook alle zijsporen weggehaald en sindsdien is het een en al storing. Alleen in Goes kan je nog aan de kant.

Mooi voorbeeld, Utrecht Centraal, dat was het eerste doorstroomstation dat ze gebouwd hebben en ik moest toevallig afgelopen september een ICNG ophalen van de Cartesiusweg naar de Alstom Raildagen. Naja kijk, vanaf Cartesiusweg kan je alleen maar via één spoortje terug naar Utrecht Centraal (15) en als daar net een defecte trein staat kan je geen kant op. Hoe verzin je het? Kijk als het allemaal planmatig is, oke. Maar als er iets is dat niet planmatig is, wat wel eens voorkomt, dan is het allemaal leuk dat die wissels weggaan, maar eentje in de storing en alles ligt plat.

Mooi voorbeeld, Apeldoorn, daar hebben ze spoor 5 opengebroken en op spoor 6 liggen grendels op om de losplaats te komen om bij de Veluwse stoomtrein maatschappij te komen maar het wordt gebruikt voor werktreinen te laden en te lossen. Wij moesten daar een werktrein ophalen die 's avonds naar een buitendienststelling moest. Wat was er nou gebeurd; er was een goederentrein gestrand en die hadden ze op spoor 6 neergezet en het gevolg was dat wij er niet heen konden. Apeldoorn spoor 1, als daar een defecte trein staat en het is al een paar keer gebeurd dan kan je ook niks meer. Wat ik echt denk van ProRail dat er mensen werken die totaal niet weten wat ze doen, niet met de trein reizen, ze kunnen zich niet inleven in de vervoerder en ze zouden zich meer moeten verdiepen in de werktreinen bijvoorbeeld.

Mooi voorbeeld ook van Den Helder. Iemand van een ander ingenieursbureau zei ook dat er voor werktreinen binnenkort twee loks nodig zijn, omdat we niet meer kunnen omlopen en dat ga je in de kosten merken.

Heb jij tijdens een gedeeltelijke stremming liever meer capaciteit of hogere punctualiteit?

Ja kijk, ik ben van mening dat er in Nederland een groot probleem is met die 10 minuten dienstregeling. Haal er eentje uit en maak de andere langer. NS gooit op dit moment alles eruit, goederen rijdt wel door, maar de bijsturing bij NS is op dit moment ook niet heel erg bijster. Ok, nou, kijk het moet ook kunnen trouwens hè, want je hebt ook baanvakken met beveiligd linker spoor zoals tussen Gouda en Woerden. Daar is de blokafstand op stationsafstand, dus zijn de blokken de ene kant veel groter, dus het duurt veel langer voordat een trein een blok uit is. Zo'n Utrecht Amsterdam zou het heel goed kunnen denk ik en dan met een halfuursdienst met IC's. Dan kan je in ieder geval gewoon doorrijden en moeten de treinen ook wel zo lang mogelijk zijn. Maar dat is een probleem want dan klopt het materieel allemaal weer niet. Bij een storing van 2 à 3 uur is dat koppelen wellicht wel lastig en niet de moeite waard. Nu zegt NS vaak oke die trein is een paar minuten te laat dus hij rijdt niet meer verder en ik vind dat kan je niet maken naar de klant. Want ja, busvervoer is ook niet zomaar geregeld. Laat op z'n minst de belangrijkste treinen rijden.

E3: ProRail

E3.1: Interview (#4) with Advisor Traffic Control / Planning & Infra (Adviseur Afdeling Plan & Infra):

In Utrecht Centraal is er een aantal jaar geleden flink wat veranderd. Hoe kijk jij naar de verbouwing?

Utrecht Centraal is het knooppunt in het midden van Nederland en dat was vroeger een knooppunt met heel veel wissels waardoor er ook heel veel bijstuurmogelijkheden waren. Echter, de punctualiteit was heel erg laag en er werden vaak analyses gedaan welke knopen de grootste negatieve bijdrage hadden aan de landelijke punctualiteit en Utrecht had hier altijd de meeste invloed op. Hiervoor waren verschillende oorzaken en één van die oorzaken was het aantal wissels die wel eens konden storen waardoor dat dan veel hinder geeft voor de hele treinenloop en er veel bijgestuurd moet worden. Er waren wel veel wissels en dus waren er genoeg opties om een kapotte wissel te omzeilen wat dan weer een voordeel was. Alleen is het treinverkeer dusdanig druk dat je ook andere treinen beïnvloed als je bijstuurt en die dan ook weer minder punctueel worden. Ook zijn er rondom Utrecht Centraal een aantal opstelterreinen die voor de verbouwing vanaf vrijwel elk perronspoor bereikt konden worden. Dat is nu heel anders en dit maakt het moeilijker om treinen weg te rijden en voor te brengen indien nodig. Al die wissels rondom Utrecht Centraal zorgden ook voor relatief lage snelheden waarmee treinen het station konden binnenrijden en omdat de seinen ver voor het station stonden moest er over een lang stuk 40 kilometer per uur gereden worden.

De filosofie van het nieuwe Utrecht Centraal is dat de snelheden verhoogd moesten worden. Dit gebeurde deels door de wissels dichter bij het stations te leggen en dus die '40 kilometer per uur zone' te verkorten. Minder wissels betekent natuurlijk ook minder bijstuurmogelijkheden en minder mogelijkheden als het gaat om materieel rijden van en naar de opstelterreinen. Een groot voordeel van het nieuwe Utrecht Centraal is de verbeterde punctualiteit en daar was het ook voornamelijk om te doen. Evenals de verhoogde reissnelheid en het feit dat er in Utrecht nu vaak vertragingen worden ingelopen in plaats van worden veroorzaakt. Minder wissels rondom Utrecht betekent ook dat er minder wisselstoringen zijn.

De beperktere bijstuurmogelijkheden zijn vooral van invloed tijdens een storing. Treinen kunnen moeilijk keren omdat verschillende heen en terug richting ver uit elkaar liggen (bijvoorbeeld Amsterdam-Eindhoven/Arnhem in de twee verschillende richtingen). Tijdens de ontwerpfase is er wel goed rekening gehouden dat er tijdens storing X toch een vooraf bepaald minimaal aantal treinen gereden kan worden. Echter, vooral de eerste fase van de storing, de ongecontroleerde fase, is vaak zoals de naam het al aangeeft erg chaotisch: treinen moeten weg maar er zijn beperkte afvoermogelijkheden. Ook zijn er nog allemaal treinen onderweg richting de storing. Zeker als er meerdere storingen tegelijkertijd plaatsvinden, kan dit voor grote problemen zorgen. Als de duur van deze fase verkort kan worden, zou dat mooi zijn, maar het is lastig om alle treinen die op het spoor zijn ineens allemaal van richting te veranderen.

Er worden op veel plekken wissels verwijderd. Dit heeft als gevolg dat de flexibiliteit afneemt. Waar is de balans hiertussen?

ProRail heeft een budget van het ministerie waar alles van betaald moet worden en daar moet efficiënt mee worden omgegaan. Meer wissels kost nou eenmaal ook meer geld voor de bouw en het onderhoud en als het geld er niet is, dan is het als ProRail zijnde lastig om meer uit te geven aan infra.

ProRail haalt overigens niet alleen wissels weg; er zijn bijvoorbeeld aan de Schiphol-zijde van station Amsterdam Zuid recent vier wissels bijgeplaatst. Die wissels zijn straks nodig voor het uitvoeren van de dienstregeling, maar zijn ook nuttig voor de bijsturing. Overigens zijn niet alleen wissels nodig voor goede bijsturing, ook de beveiliging/seinen moet aan bepaalde voorwaarden voldoen. Als er een storing is tussen Amsterdam Bijlmer en Utrecht dan is het straks wenselijk Intercity's naar Utrecht te keren in Amsterdam Zuid. Dat is met de huidige infra niet goed mogelijk aangezien er aan de oostzijde van de perrons op Amsterdam zuid geen bediende seinen staan. Op dit moment komen de IC naar Utrecht vanaf Schiphol en is het onnodig om deze Intercity van Schiphol naar Amsterdam Zuid te rijden en dan weer terug. In de nieuwe dienstregeling 2025 komen die IC's echter uit Den Haag of Rotterdam. Een storing tussen Bijlmer en Utrecht zorgt er dan voor dat treinen al in Leiden moeten keren wat niet de bedoeling zou moeten zijn. Investeren in nieuwe infra rondom Amsterdam Zuid is echter zonde van de kosten aangezien Amsterdam Zuid in een aantal jaren grootschalig aangepast gaat worden en ook een nieuw beveiligingssysteem geïntroduceerd gaat worden (ERTMS).

Een ander soort probleem is er tussen Utrecht en Arnhem bij Driebergen-Zeist waar er een (kort) keerspoor ligt en Sprinters vanuit Utrecht kunnen keren. Bij een storing tussen Driebergen en Ede kunnen IC's vanuit Utrecht niet op Driebergen keren, omdat die niet op het keerspoor passen, en er geen wissels aan de westzijde van Driebergen liggen. Is er een storing tussen Utrecht en Driebergen, dan kunnen IC's uit Ede/Arnhem wel keren op Driebergen langs het perron en via de wissels aan de oostzijde van Driebergen wisselen van spoor.

Tijdens een storing is de veiligheid overigens een heel belangrijk aspect. Soms is het noodzakelijk om dan tijdens de storing iets minder treinen te laten rijden dan er gewoon maar zoveel als mogelijk koste wat het kost te laten rijden. Ook zijn de kosten voor ProRail erg belangrijk aangezien er een bepaald budget vanuit het ministerie is. Tijdens een storing moeten de treinen die rijden conflictvrij (veiligheid) en op tijd (betrouwbaar) kunnen rijden. Dat is belangrijker dan zoveel mogelijk treinen laten rijden die allemaal te laat rijden. Een laatste belangrijk punt is dat de punctualiteit waar in dit onderzoek mee gewerkt wordt de trein punctualiteit is en bij ProRail en NS werken we met de reizigers punctualiteit. Kan allebei maar de getallen zullen anders zijn.

E4: Best-worst method

The best-worst method is used in the interviews to get the weights for the different key performance indicators that can be used to calculate the scores for different switch configurations. All four KPIs are weighted against each other. The best or most and the worst or least important KPI were chosen and filled in in the Excel form in Figure E.1. The next step is to give a number for the three KPIs from 1 till 9 for the comparison with the best KPI. A '1' will indicate that the other KPI is also really important and a '9' indicates that the corresponding KPI is not important compared to the best KPI. This same procedure is also used to compare with the worst KPI. By using the Excel solver tool and the already built-in equations the weights are calculated (Rezaei, 2016) which are shown in yellow.

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Cost of infra	Rate of cancelled services	Punctuality	Time to recover

Select the Best	Rate of cancelled

Select the Worst	Cost of infra

Best to Others	Cost of infra	Rate of cancelled services	Punctuality	Time to recover
Rate of cancelled	8	1	2	7

Others to the Worst	Cost of infra
Cost of infra	1
Rate of cancelled	7
Punctuality	6
Time to recover	2

Weights	Cost of infra	Rate of cancelled services	Punctuality	Time to recover
	0,065116279	0,537209302	0,309302326	0,088372093

Input-Based CR	0,107142857	The pairwise comparison consistency level is acceptable
Associated Threshold	0,2521	

Figure E.1: Best-worst method.

The person that is interviewed in Figure E.1 thinks the rate of cancelled services is most important and thinks that costs are least important. From this it can be concluded that these results are not from ProRail but from one of the other seven interviews. The interviewee thinks that punctuality is also important as he/she applies the number 2 in the comparison with the best KPI. Both time to recover and costs of infra are not that important to this person, although time to recover scores slightly higher. This best-worst method is performed with all eight interviewees and these values are averaged which can be found in Table E.1.

Table E.1: Results best-worst method.

KPI	Costs (C)	Rate of cancelled services (RCS)	Punctuality (P)	Time to recover (T)	Sum
Weight	0.1236	0.4709	0.2025	0.2030	1

Since a trade-off between costs and resilience (RCS, P and T) is supposed to be made according to the main research question, the weights will be adapted. Costs and resilience will both get 0.5 as weighting. However, the results from the best-worst method are still used in terms of difference in importance in between the three different resilience KPIs: rate of cancelled services is twice as important as punctuality and time to recover following from Table E.1. This leads to the following weights that are shown in Table E.2.

Table E.2: Weights key performance indicators.

KPI	Costs (C)	Rate of cancelled services (RCS)	Punctuality (P)	Time to recover (T)	Sum
Weight	0.5	0.25	0.125	0.125	1

Appendix F. Model

Figure F.2 shows the model with the distances between the stations and the lengths of the platforms (400 meters) on scale. The width of the platforms is not on scale. In Figure F.1 one block is visualized including the locations of the signals. All stations are located in the middle of the blocks and all stations have exit signals.

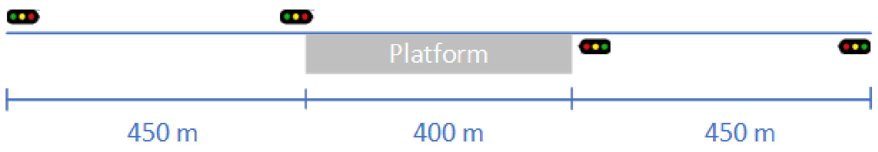


Figure F.1: Locations of platforms within the block.

To calculate the rate of cancelled services and punctuality sub-weightings are required. The weightings for the four stations should sum up to 1. It is chosen to make the Intercity station B more important in the weighting and give it a 0.4 and give all other three stations a weighting of 0.2. This is chosen because the Intercity station could also be more important in terms of connecting trains or it could function as a regional hub for buses or trams and therefore a delayed or cancelled train at station B should be weighted heavier. The sub-weightings are also shown in Figure F.4 which shows the designed Excel tool to calculate the scores for the alternatives.

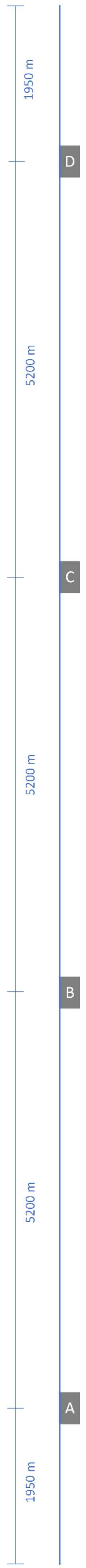


Figure F.2: Model on scale.

F1: Layout 1

Layout 1 only has a second track at station B. The results for a broken train at station B track 1 are shown in Table F.1, Figure F.4 and Figure F.6. The arrival times in red are arrival times more than five minutes later than planned. Layout 1 is again shown in Figure F.3. For this Appendix: all switches in black, like in Figure F.3, are the one that are used. The other switches in blue are not used in the simulations.

Figure F.3: Layout 1.

Table F.1: Timetable layout 1 broken train at B1.

Layout 1 Start → End												
		SPR 1	SPR 3.1	SPR 5	SPR 7	SPR 9	SPR 11	SPR 13	SPR 15	SPR 17	SPR 19	...
Start	*Dep.*	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	
Station A	*Arr.*	06:01	06:31	07:01	07:31	08:01	08:31	09:01	09:31	10:01	10:31	
Station B	*Arr.*	06:06	06:36	07:06	07:36	08:06	08:36	09:06	09:36	10:06	10:36	
Station B	*Dep.*	06:07	06:48	07:09	07:37	08:07	08:37	09:07	09:37	10:07	10:37	
Station C	*Arr.*	06:10	06:51	07:12	07:40	08:10	08:40	09:10	09:40	10:10	10:40	
Station D	*Arr.*	06:14	06:55	07:16	07:44	08:14	08:44	09:14	09:44	10:14	10:44	
End	*Arr.*	06:16	06:57	07:18	07:46	08:16	08:46	09:16	09:46	10:16	10:46	
Layout 1 End → Start												
		SPR 2	SPR 4.1	SPR 6	SPR 8	SPR 10	SPR 12	SPR 14	SPR 16	SPR 18	SPR 20	...
End	*Dep.*	05:56	06:26	06:57	07:26	07:56	08:26	08:56	09:26	09:56	10:26	
Station D	*Arr.*	05:57	06:27	06:59	07:27	07:57	08:27	08:57	09:27	09:57	10:27	
Station C	*Arr.*	06:01	06:31	07:03	07:31	08:01	08:31	09:01	09:31	10:01	10:31	
Station B	*Arr..*	06:06	06:43	07:08	07:36	08:06	08:36	09:06	09:36	10:06	10:36	
Station B	*Dep.*	07:07	06:40	07:09	07:37	08:07	08:37	09:07	09:37	10:07	10:37	
Station A	*Arr.*	07:11	06:44	07:13	07:41	08:11	08:41	09:11	09:41	10:11	10:41	
Start	*Arr.*	07:12	06:45	07:15	07:42	08:12	08:42	09:12	09:42	10:12	10:42	

The timetable is input in Excel and follows from the performed simulations. The number of late trains (#te laat) in Figure F.4 is calculated automatically by Excel by checking every arrival time at all stations for all trains and comparing it with the planned arrival time in the case there is no disruption. The used formula is shown in 5.2. That equation uses the two timetable given in Figure F.5 in which the upper one is the timetable in the undisturbed situation and the bottom one is the timetable during the disruption. The equation calculates the difference between the arrival times and if this difference is more or equal than five minutes (a value which is located in cell AD1) this will be counted as a late arrival. These late arrivals are summed and from this the punctuality can be calculated.

$$= SOM(--(ABS(S17{:}AB17 - S36{:}AB36) \geq \$AD\$1) * (S36{:}AB36 <> "") * (S23{:}AB23 <> ""))) + SOM(--((ABS(S4{:}AB4 - S23{:}AB23) \geq \$AD\$1) * (S4{:}AB4 <>) * (S23{:}AB23 <>))) \quad (9)$$

Disruption 1: Broken train at station B - 1 hour													
	De KPI die de hoogste weging heeft, wordt vetgedrukt oid												
	Cost of infra	Rate of cancalled services					Punctuality					Time to recove	**Score of alternative**
			A	B	C	D		A	B	C	D		
Iteration 1	2	#gecancelled	0	0	0	0	#te laat	1	1	1	1	0	9,25
		Rate of canca	0	0	0	0	Punctuality	83,333333	83,33333	83,33333	83,33333		
subweightings	n/a		0,2	0,4	0,2	0,2		0,2	0,4	0,2	0,2	n/a	
subscores	2		0					83,333333				0	Score of alternative
weightings	0,5	0,25					0,125					0,125	9,42
score 1-10	9	10					8					10	
scores mca (incl weg.)	4,5	2,5					1					1,25	
thres check		0,00					83,33						
threshold values	nvt	50					55,25					39,375	
top threshold check		27											

Figure F.4: Calculation tool in Excel.

Timetable											
		SPR 1	SPR 3	SPR 5	SPR 7	SPR 9	SPR 11	SPR 13	SPR 15	SPR 17	SPR 19
Start	dep	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30
A	arr	06:01	06:31	07:01	07:31	08:01	08:31	09:01	09:31	10:01	10:31
B	arr	06:06	06:36	07:06	07:36	08:06	08:36	09:06	09:36	10:06	10:36
B	dep	06:07	06:37	07:07	07:37	08:07	08:37	09:07	09:37	10:07	10:37
C	arr	06:10	06:40	07:10	07:40	08:10	08:40	09:10	09:40	10:10	10:40
D	arr	06:14	06:44	07:14	07:44	08:14	08:44	09:14	09:44	10:14	10:44
End	arr	06:16	06:46	07:16	07:46	08:16	08:46	09:16	09:46	10:16	10:46
		SPR 2	SPR 4	SPR 6	SPR 8	SPR 10	SPR 12	SPR 14	SPR 16	SPR 18	SPR 20
End	dep	05:56	06:26	06:56	07:26	07:56	08:26	08:56	09:26	09:56	10:26
D	arr	05:57	06:27	06:57	07:27	07:57	08:27	08:57	09:27	09:57	10:27
C	arr	06:01	06:31	07:01	07:31	08:01	08:31	09:01	09:31	10:01	10:31
B	arr	06:06	06:36	07:06	07:36	08:06	08:36	09:06	09:36	10:06	10:36
B	dep	06:07	06:37	07:07	07:37	08:07	08:37	09:07	09:37	10:07	10:37
A	arr	06:11	06:41	07:11	07:41	08:11	08:41	09:11	09:41	10:11	10:41
Start	arr	06:12	06:42	07:12	07:42	08:12	08:42	09:12	09:42	10:12	10:42
		SPR 1	SPR 3.1	SPR 5	SPR 7	SPR 9	SPR 11	SPR 13	SPR 15	SPR 17	SPR 19
Start	dep	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30
A	arr	06:01	06:31	07:01	07:31	08:01	08:31	09:01	09:31	10:01	10:31
B	arr	06:06	06:36	07:06	07:36	08:06	08:36	09:06	09:36	10:06	10:36
B	dep	06:07	06:48	07:09	07:37	08:07	08:37	09:07	09:37	10:07	10:37
C	arr	06:10	06:51	07:12	07:40	08:10	08:40	09:10	09:40	10:10	10:40
D	arr	06:14	06:55	07:16	07:44	08:14	08:44	09:14	09:44	10:14	10:44
End	arr	06:16	06:57	07:18	07:46	08:16	08:46	09:16	09:46	10:16	10:46
		SPR 2	SPR 4.1	SPR 6	SPR 8	SPR 10	SPR 12	SPR 14	SPR 16	SPR 18	SPR 20
End	dep	05:56	06:26	06:57	07:26	07:56	08:26	08:56	09:26	09:56	10:26
D	arr	05:57	06:27	06:59	07:27	07:57	08:27	08:57	09:27	09:57	10:27
C	arr	06:01	06:31	07:03	07:31	08:01	08:31	09:01	09:31	10:01	10:31
B	arr	06:06	06:43	07:08	07:36	08:06	08:36	09:06	09:36	10:06	10:36
B	dep	07:07	06:40	07:09	07:37	08:07	08:37	09:07	09:37	10:07	10:37
A	arr	07:11	06:44	07:13	07:41	08:11	08:41	09:11	09:41	10:11	10:41
Start	arr	07:12	06:45	07:15	07:42	08:12	08:42	09:12	09:42	10:12	10:42

Figure F.5: Timetable calculation in Excel.

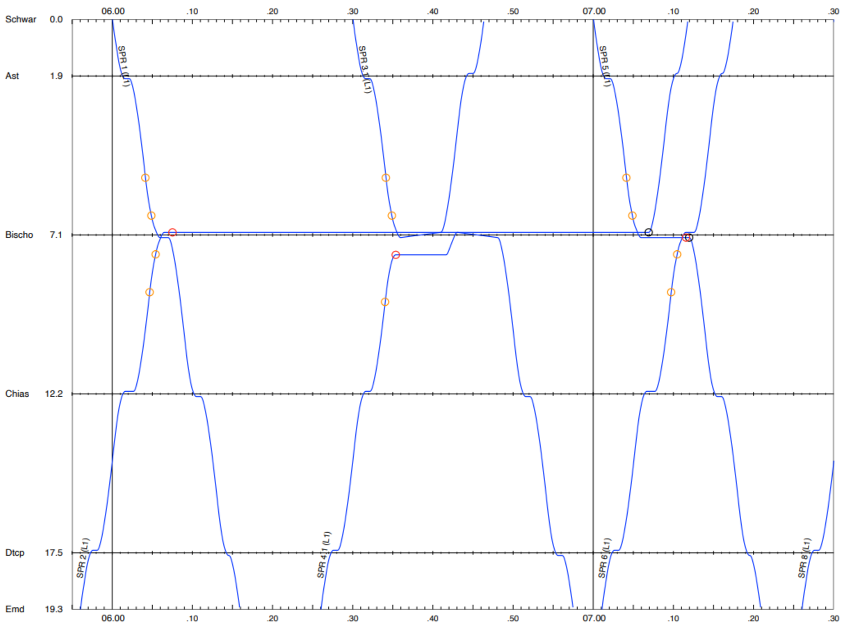


Figure F.6: Time-distance diagram layout 1 with broken train at B1.

The results for the second disruption are given in Table F.2 and Figure F.7. A broken train between B and C is not simulated as this would have the same effect as the 2 hour disruption that is simulated now on this single track line. Trains are being short turned at stations B and C since there is a full line blockage between both stations and this is visible in Figure F.7.

Table F.2: Timetable layout 1 persons on tracks between B and C.

Layout 1 Start → End												
		SPR 1	SPR 3.2	SPR 5.2	SPR 7.2	SPR 9.2	SPR 11	SPR 13	SPR 15	SPR 17	SPR 19	...
Start	*Dep.*	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	
Station A	*Arr.*	06:01	06:31	07:01	07:31	08:01	08:31	09:01	09:31	10:01	10:31	
Station B	*Arr.*	06:06	06:36	07:06	07:36	08:06	08:36	09:06	09:36	10:06	10:36	
Station B	*Dep.*	06:07					08:37	09:07	09:37	10:07	10:37	
Station C	*Arr.*	06:10					08:40	09:10	09:40	10:10	10:40	
Station D	*Arr.*	06:14	06:44	07:14	07:44	08:14	08:44	09:14	09:44	10:14	10:44	
End	*Arr.*	06:16	06:46	07:18	07:46	08:16	08:46	09:16	09:46	10:16	10:46	
Layout 1 End → Start												
		SPR 2	SPR 4.2	SPR 6.2	SPR 8.2	SPR 10.2	SPR 12	SPR 14	SPR 16	SPR 18	SPR 20	...
End	*Dep.*	05:56	06:26	06:57	07:26	07:56	08:26	08:56	09:26	09:56	10:26	
Station D	*Arr.*	05:57	06:27	06:57	07:27	07:57	08:27	08:57	09:27	09:57	10:27	
Station C	*Arr.*	06:01	06:31	07:01	07:31	08:01	08:31	09:01	09:31	10:01	10:31	
Station B	*Arr..*	06:06					08:36	09:06	09:36	10:06	10:36	
Station B	*Dep.*	06:07	*06:41*	*07:11*	*07:41*	*08:11*	08:37	09:07	09:37	10:07	10:37	
Station A	*Arr.*	06:11	*06:44*	*07:14*	*07:44*	*08:14*	08:41	09:11	09:41	10:11	10:41	
Start	*Arr.*	06:12	*06:46*	*07:16*	*07:46*	*08:16*	08:42	09:12	09:42	10:12	10:42	

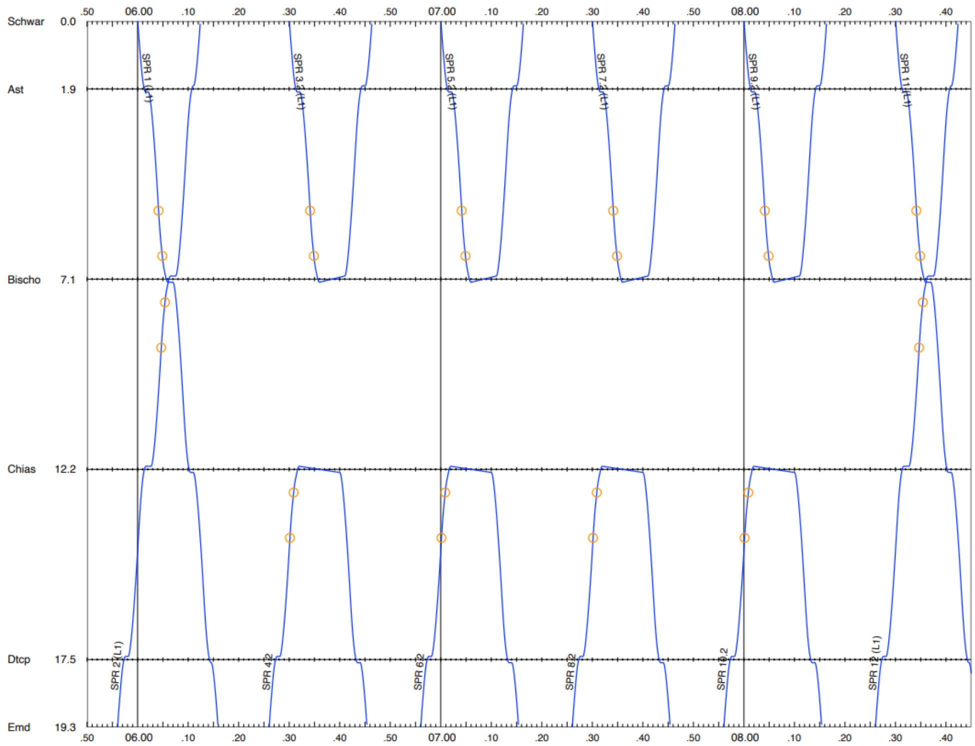


Figure F.7: Time-distance diagram layout 1 with persons on tracks between B and C.

Table F.3 shows the key performance indicators and the corresponding values for the simulated disruptions in layout 1.

Table F.3: Results layout 1 for all simulated disruptions.

Line	**Disruption**	**SW [# of switches]**	**RCS [%]**	**P [%]**	**T [min]**	**R**	**R̄**	**S**	**S̄**
L1	Broken train B1	2	0	83	0	10.42		9.42	
	Broken train B-C	2	30	100	0	-2.50	3.19	4.00	6.51
	Persons B-C	2	30	100	0	-2.50		4.00	

F2: Layout 2

Although layout 1 and 2 both are single track railway lines the timetable is different. This is because in layout 2 there was space to add an Intercity. This makes it however more difficult to compare the results from the calculations for both layouts. Table F.4 and Figure F.9 show the results for a broken train at track 1 of station B for this layout. SPR 2 is the broken train as can be seen in the table, the other trains are retimed since the crossing of trains should take place at other stations than station B. In normal conditions the crossing of trains of the same category takes place in station B which is now moved to station C. The crossing of trains of two different categories took place in stations A and C which is now moved to stations A and D. An overview of layout 2 can be found in Figure F.8.

2

Figure F.8: Layout 2.

Table F.4: Timetable layout 2 with a broken train at B1.

Start → End												
		IC 1	SPR 1	IC 3.1	SPR 3.1	IC 5.1	SPR 5.1	IC 7	SPR 7	IC 9	SPR 9	...
Start	Dep.	05:55	06:00	06:25	06:30	06:55	07:00	07:25	07:30	07:55	08:00	
Station A	Arr.		06:01		06:31		07:02		07:32		08:01	
Station B	Arr.	05:59	06:07	06:29	06:46	07:04	07:15	07:32	07:40	07:59	08:07	
Station B	Dep.	06:00	06:08	06:30	06:47	07:05	07:16	07:33	07:41	08:00	08:08	
Station C	Arr.		06:12		06:51		07:19		07:45		08:12	
Station D	Arr.		06:16		06:55		07:23		07:49		08:16	
End	Arr.	06:06	06:18	06:40	06:57	07:12	07:25	07:40	07:51	08:06	08:18	
End → Start												
		IC 2	SPR 2	IC 4.1	SPR 4.1	IC 6.1	SPR 6.1	IC 8	SPR 8	IC 10	SPR 10	...
End	Dep.	05:52	05:56	06:22	06:26	06:52	06:56	07:22	07:26	07:52	07:56	
Station D	Arr.		05:57		06:27		06:59		07:27		07:57	
Station C	Arr.		06:01		06:36		07:15		07:31		08:01	
Station B	Arr..	05:58	06:07	06:38	06:55	07:13	07:23	07:30	07:41	07:58	08:07	
Station B	Dep.	06:00	07:08	06:39	06:56	07:15	07:24	07:33	07:42	08:00	08:08	
Station A	Arr.		07:11		07:00		07:28		07:45		08:12	
Start	Arr.	06:04	07:12	06:43	07:04	07:19	07:30	07:37	07:47	08:04	08:14	

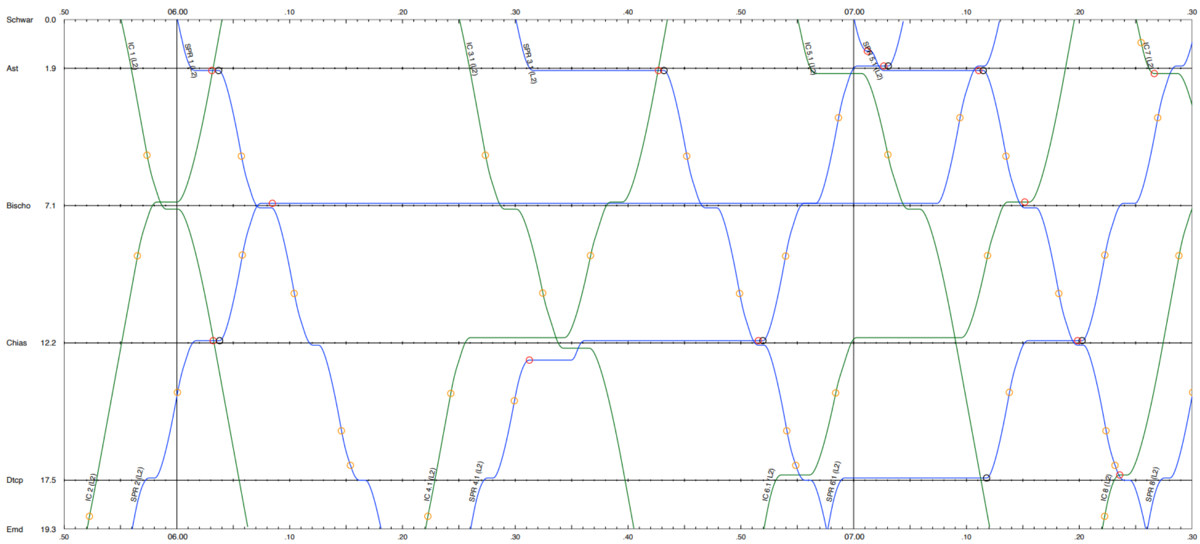


Figure F.9: Time-distance diagram layout 2 with broken train at B1.

Again, a broken train between stations B and C and persons on the tracks between B and C will give the same results and therefore only the latter is simulated.

Table F.5: Timetable layout 2 with persons near or at the tracks between stations B and C.

Start → End												
		IC 1	SPR 1.2	IC 3.2	SPR 3.2	IC 5.2	SPR 5.2	IC 7.2	SPR 7.2	IC 9	SPR 9	...
Start	Dep.	05:55	06:00	06:25	06:30	06:55	07:00	07:25	07:30	07:55	08:00	
Station A	Arr.		06:01		06:31		07:01		07:31		08:01	
Station B	Arr.	05:59	06:07	06:29	06:35	06:59	07:07	07:29	07:37	07:59	08:11	
Station B	Dep.	06:00								08:03	08:12	
Station C	Arr.										08:16	
Station D	Arr.		06:16		06:46		07:16		07:46		08:20	
End	Arr.	06:06	06:18	06:36	06:48	07:06	07:18	07:36	07:48	08:09	08:22	
End → Start												
		IC 2	SPR 2.2	IC 4.2	SPR 4.2	IC 6.2	SPR 6.2	IC 8.2	SPR 8.2	IC 10	SPR 10	...
End	Dep.	05:52	05:56	06:22	06:26	06:52	06:56	07:22	07:26	07:52	07:56	
Station D	Arr.		05:57		06:27		06:57		07:27		07:57	
Station C	Arr.		06:01	06:26	06:31	06:56	07:01	07:26	07:31		08:01	
Station B	Arr..	05:58								08:03	08:11	
Station B	Dep.	06:00	06:12	06:35	06:40	07:05	07:12	07:35	07:42	08:04	08:12	
Station A	Arr.		06:16		06:44		07:16		07:46		08:15	
Start	Arr.	06:04	*06:17*	*06:41*	*06:46*	*07:11*	07:17	07:41	06:47	08:08	08:17	

As can be seen in Figure F.5 the Intercity trains are making an extra stop at station C and are being short turned back to the 'End' because of the total blockage of the line between stations B and C. Actually, all trains are being short turned at station B or station C depending from which direction the trains came. Figure F.10 shows corresponding the time-distance diagram where it can be seen that all scheduled train service returns after two hours of disruption.

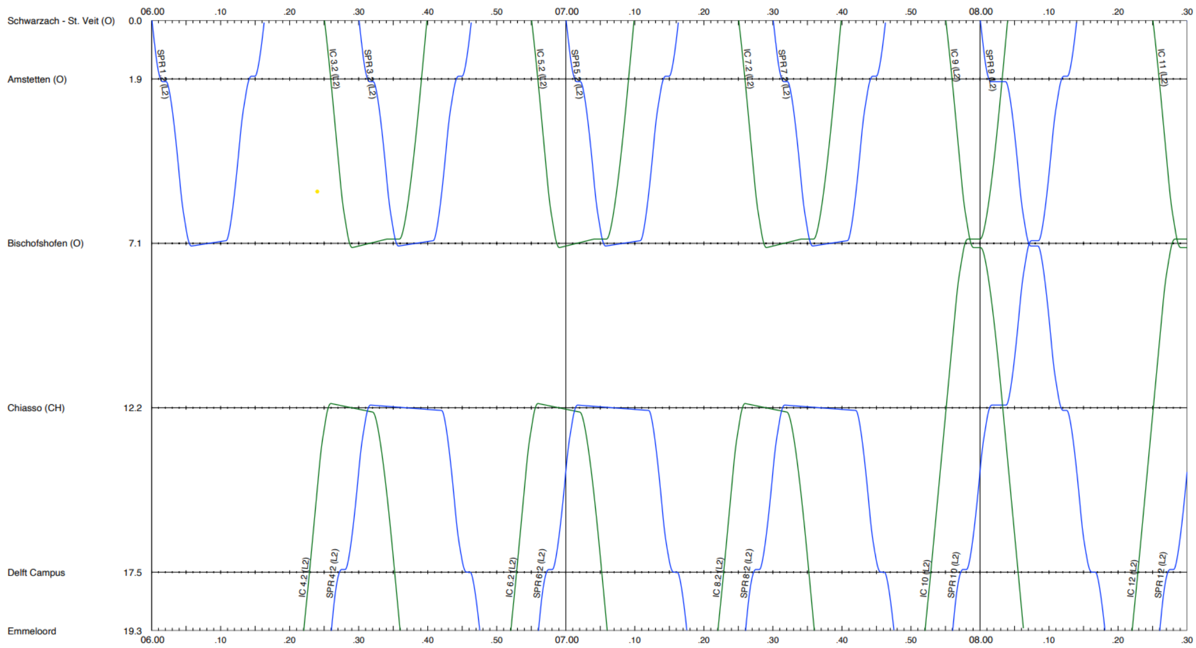


Figure F.10: Time-distance diagram of layout 2 with persons near or at the tracks between stations B and C.

The scores for both disruptions are shown in Table F.6 indicating the values for all key performance indicators as well.

Table F.6: Results layout 2 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L2	Broken train B1	8	0	58	0	7.29		3.29	
	Broken train B-C	8	30	90	0	-3.75	0.99	-0.25	1.39
	Persons B-C	8	30	90	0	-3.75		-0.25	

F3: Layout 3

Starting from layout 3 there are multiple double track layouts increasing the number of switches. Figure F.11 shows the layout in which only switches can be seen at station B. This complicates the process of rerouting and short turning as one of the constraint for the model is that trains cannot enter or leave the model via the 'wrong' track which means that trains can only enter the model on the right track and leave the model only by using the left track. Short turning at station B is therefore possible via the bottom track looking from both directions but rerouting from left to right via the upper track in station B is not possible. The other way around if there is a broken train at track 1 in station B is however very easy to get trains rerouted.

3 

Figure F.11: Layout 3.

For this research again a train at track 1 of station B is simulated to be broken. The results of the new timetable and the time-distance diagram can be found in Figure F.12 and Table F.7.

Table F.7: Timetable layout 3 with a broken train at track 1 of station B.

Start → End												
		IC 1	SPR 1	IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	…
Start	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station A	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station B	*Arr.*	06:03	06:08	06:18	06:23	06:33	06:38	06:48	06:53	07:03	07:08	
Station B	*Dep.*	06:04	06:09	06:19	06:24	06:34	06:39	06:49	06:54	07:04	07:09	
Station C	*Arr.*		06:12		06:27		06:42		06:57		07:12	
Station D	*Arr.*		06:16		06:31		06:46		07:01		07:16	
End	*Arr.*	06:11	06:18	06:26	06:33	06:41	06:48	06:56	07:03	07:11	07:18	
End → Start												
		IC 2	SPR 2	IC 4.1	SPR 4.1	IC 6.1	SPR 6.1	IC 8.1	SPR 8.1	IC 10.1	SPR 10	…
End	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station D	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station C	*Arr.*		06:08		06:23		06:38		06:53		07:08	
Station B	*Arr..*	06:06	06:12	06:26	06:29	06:41	06:44	06:56	06:59	07:11	07:12	
Station B	*Dep.*	06:07	07:10	06:27	06:30	06:42	06:45	06:57	07:00	07:12	07:13	
Station A	*Arr.*		07:13		06:33		06:48		07:03		07:17	
Start	*Arr.*	06:11	07:15	06:31	06:35	06:46	06:50	07:01	07:05	07:16	07:19	

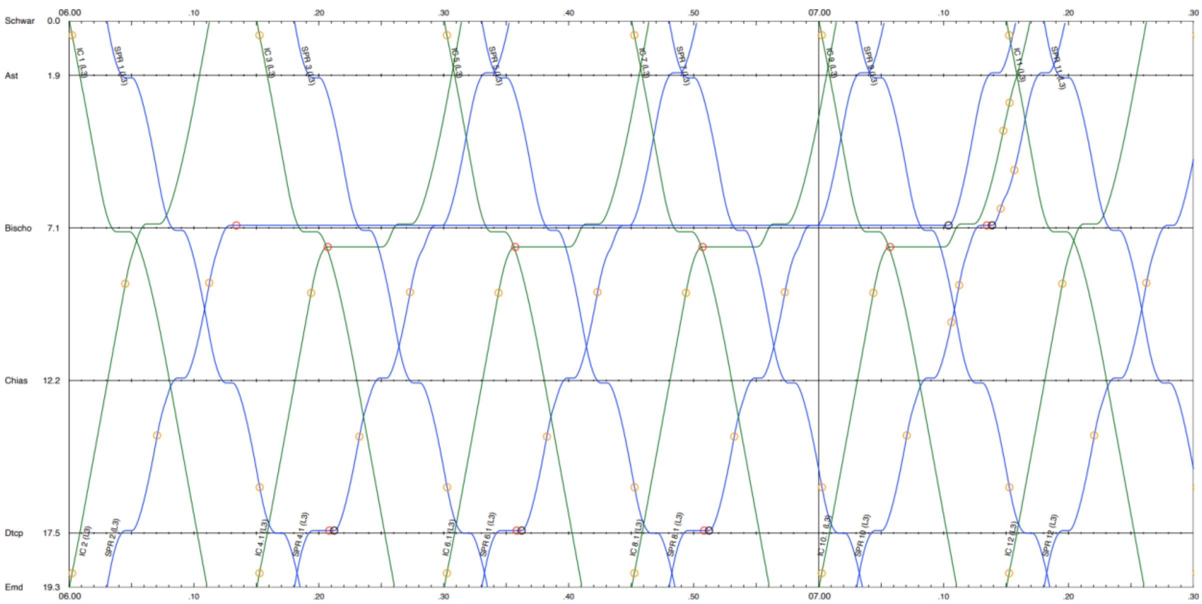


Figure F.12: Time-distance diagram layout 3 with broken train at track 1 of station B.

Due to the explained problem with the location of the switches in the beginning of this Appendix F3 a problem arises in case there is a broken train between stations B and C or if there are persons near or at the track between those two stations. All trains coming from the right are cancelled completely. Trains from the left only run for 50% meaning that half of the trains is cancelled outside of the model. This is because of the limited short turning capacity at station B which only offers one track to short turn the trains. Table F.8 shows the timetable for the first hour of the disruption and Figure F.13 shows the complete time-distance diagram.

Table F.8: Timetable layout 3 with persons near or at the tracks between B and C.

Start → End												
		IC 1	SPR 1	IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	...
Start	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station A	Arr.		06:04		06:19		06:34		06:49		07:04	
Station B	Arr.	06:03	06:15	06:22	06:23	06:33	06:38	06:48	06:53	07:03	07:08	
Station B	Dep.											
Station C	Arr.											
Station D	Arr.											
End	Arr.											
End → Start												
		IC 2	SPR 2	IC 4	SPR 4	IC 6	SPR 6	IC 8	SPR 8	IC 10	SPR 10	...
End	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station D	Arr.		06:04		06:19		06:34		06:49		07:04	
Station C	Arr.		06:08		06:23		06:38		06:53		07:08	
Station B	Arr..	06:06	06:12	06:21	06:27	06:36	06:42	06:51	06:57	07:06	07:12	
Station B	Dep.	06:12	06:19	06:31	06:28	06:37	06:43	06:58	06:58	07:13	07:13	
Station A	Arr.		06:23		06:31		06:46		07:01		07:16	
Start	Arr.	06:17	06:25	06:35	06:33	06:41	06:48	07:02	07:03	07:17	07:18	

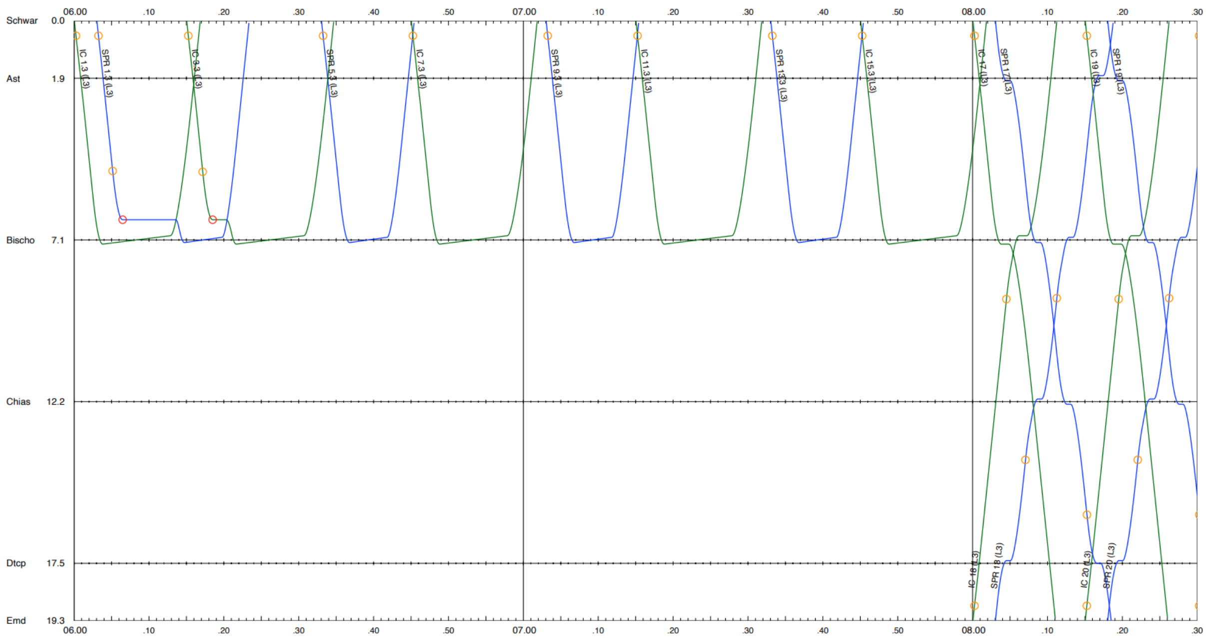


Figure F.13: Time-distance diagram layout 3 with persons near or at the tracks between stations B and C.

Table F.9: Results layout 3 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L3	Broken train B1	4	0	88	0	11.00		9.00	
	Broken train B-C	4	78	98	33	-30.61	-0.39	-13.23	-2.92
	Persons B-C	4	78	98	33	-30.61		-13.23	

Table F.9 presents the results for all simulated disruptions in layout 3. The range of the scores varies from -13.23 till 9.00 which is extremely high. With a rate of cancelled services of 78% this layout is not good. A broken train at B1 scores actually really good, but as mentioned before, if the broken train is located at B2 this layout has a big problem since trains cannot be rerouted then.

Also it has been investigated what happens if literally all trains are waiting for the termination of the disruption. This is visualised in Figure F.14. Without train rescheduling in case of a complete blockage of the route between B and C trains are waiting for two hours and it takes approximately an hour to remove all delayed trains out of the model. The punctuality is only 45 percent if trains are called 'late' if it arrives more than 5 minutes late. For the 15 minute norm, which calls a train late if it arrives more than 15 minutes late, the punctuality is also 45 percent and therefore rescheduling is necessary.

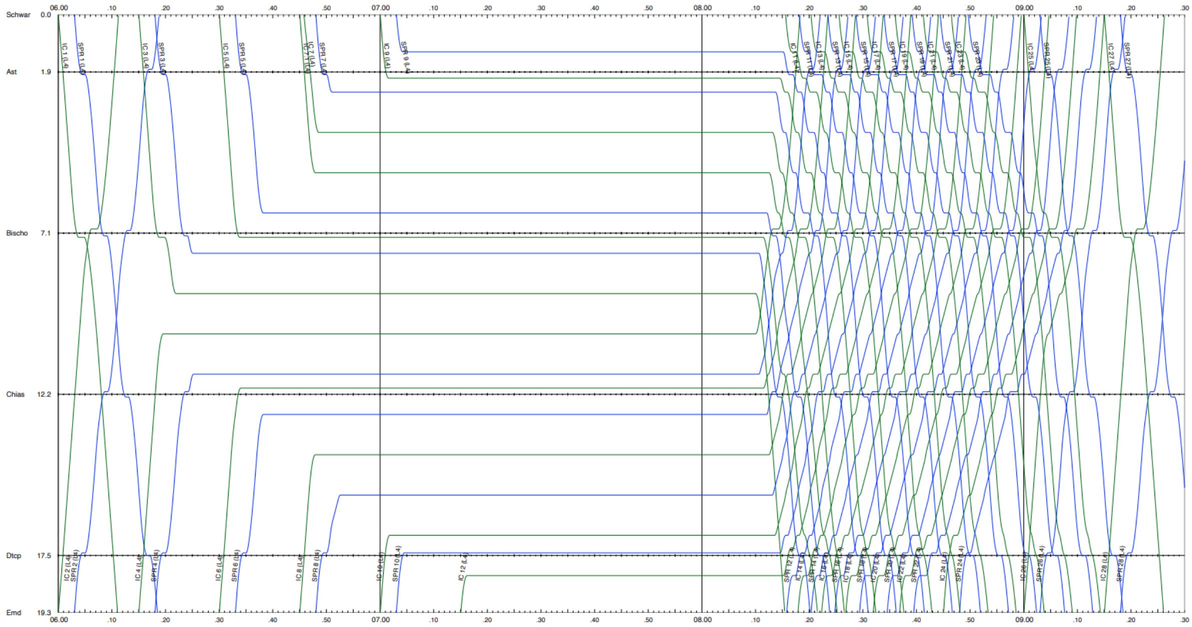


Figure F.14: Time-distance diagram double track layout where all trains are waiting for the end of the disruption.

F4: Layout 4

This layout contains double the amount of switches of layout 3 but these are located at the smaller stations A and D and this can be seen in Figure F.15.

Figure F.15: Layout 4.

A broken train at B1 means that trains from the right are being rerouted via the bottom track D2, C2, B2 and A2 and after station A these trains can move to their scheduled track again. This is a single track part of more than 15 km which will definitely impact capacity since 4 IC and 4 SPR trains are running currently per direction on this line.

The results of a broken train at B1 are given in Figure F.16 and Table F.10. Due to the decreased capacity all SPR trains are short turned at stations A track 2 and C track 1 and it is chosen to keep all IC trains running as these can accommodate more passengers. The single track part is long and therefore trains are delayed significantly which results in bundling two IC trains in the same direction with minimum headway. The time-distance diagram shows that after the end of the disruption delays are propagating and it takes until approximately 7:30 when the trains are running on scheduled times again.

Table F.10: Timetable layout 4 with broken train at station B track 1.

Start → End												
		IC 1	SPR 1	IC 3.1	SPR 3.1	IC 5.1	SPR 5.1	IC 7.1	SPR 7.1	IC 9.1	SPR 9.1	...
Start	*Dep.*	06:00	06:03	06:15	06:18	06:40	06:41	06:45	06:49	07:10	07:12	
Station A	*Arr.*		06:04		06:19		06:43		06:51		07:14	
Station B	*Arr.*	06:03	06:08	06:18		06:44		06:52		07:16	07:19	
Station B	*Dep.*	06:04	06:09	06:19		06:45		06:53		07:17	07:19	
Station C	*Arr.*		06:12								07:23	
Station D	*Arr.*		06:16		06:40		06:53		07:14		07:27	
End	*Arr.*	06:11	06:18	06:25	06:42	06:51	06:54	06:59	07:16	07:23	07:29	
End → Start												
		IC 2	SPR 2	IC 4.1	SPR 4.1	IC 6.1	SPR 6.1	IC 8.1	SPR 8.1	IC 10.1	SPR 10	...
End	*Dep.*	06:00	06:03	06:25	06:26	06:30	06:33	06:59	07:00	07:01	07:03	
Station D	*Arr.*		06:04		06:28		06:34		07:02		07:04	
Station C	*Arr.*		06:08		06:32		06:44		07:06		07:18	
Station B	*Arr..*	06:06	06:12	06:31		06:36		07:05		07:08	07:19	
Station B	*Dep.*	06:07	07:10	06:32		06:36		07:06		07:08	07:22	
Station A	*Arr.*		07:13								07:26	
Start	*Arr.*	06:11	07:15	06:36	06:25	06:40	06:49	07:10	06:57	07:12	07:28	

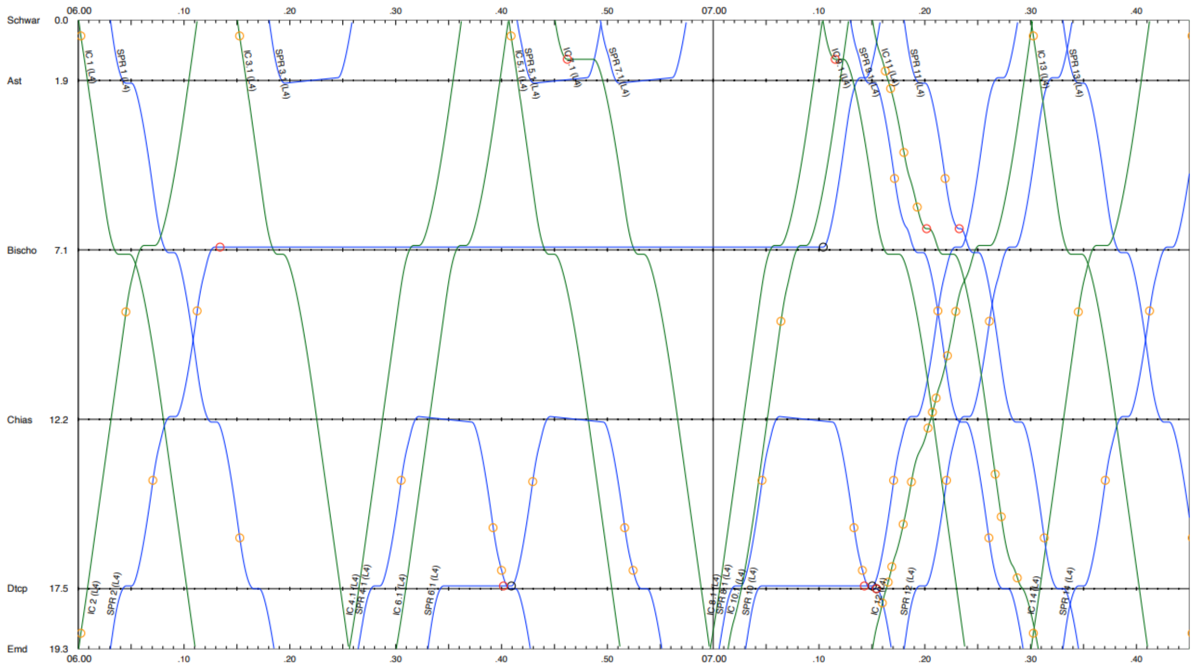


Figure F.16: Time-distance diagram layout 4 with broken train at B1.

In case of persons near or at the tracks trains should be short turned again at stations B and C. The results can be found in Table F.11 and Figure F.17.

Table F.11: Timetable layout 4 persons near or at the tracks between stations B and C.

Start → End												
		IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	IC 11	SPR 11	...
Start	*Dep.*	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18	
Station A	*Arr.*		06:19		06:34		06:49		07:04		07:19	
Station B	*Arr.*	06:18		06:33		06:48		07:03		07:18		
Station B	*Dep.*											
Station C	*Arr.*											
Station D	*Arr.*		06:24		06:39		06:54		07:09		07:24	
End	*Arr.*	06:35	06:26	06:50	06:41	07:05	06:56	07:20	07:11	07:35	07:26	

End → Start												
		IC 4	SPR 4	IC 6	SPR 6	IC 8	SPR 8	IC 10	SPR 10	IC 12	SPR 12	...
End	*Dep.*	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18	
Station D	*Arr.*		06:20		06:35		06:50		07:05		07:20	
Station C	*Arr.*	06:18		06:33		06:48		07:03		07:18		
Station B	*Arr..*											
Station B	*Dep.*	06:30		06:45		07:00		07:15		07:30		
Station A	*Arr.*		06:24		06:39		06:54		07:09		07:24	
Start	*Arr.*	06:35	06:26	06:50	06:41	07:05	06:56	07:20	07:11	07:35	07:24	

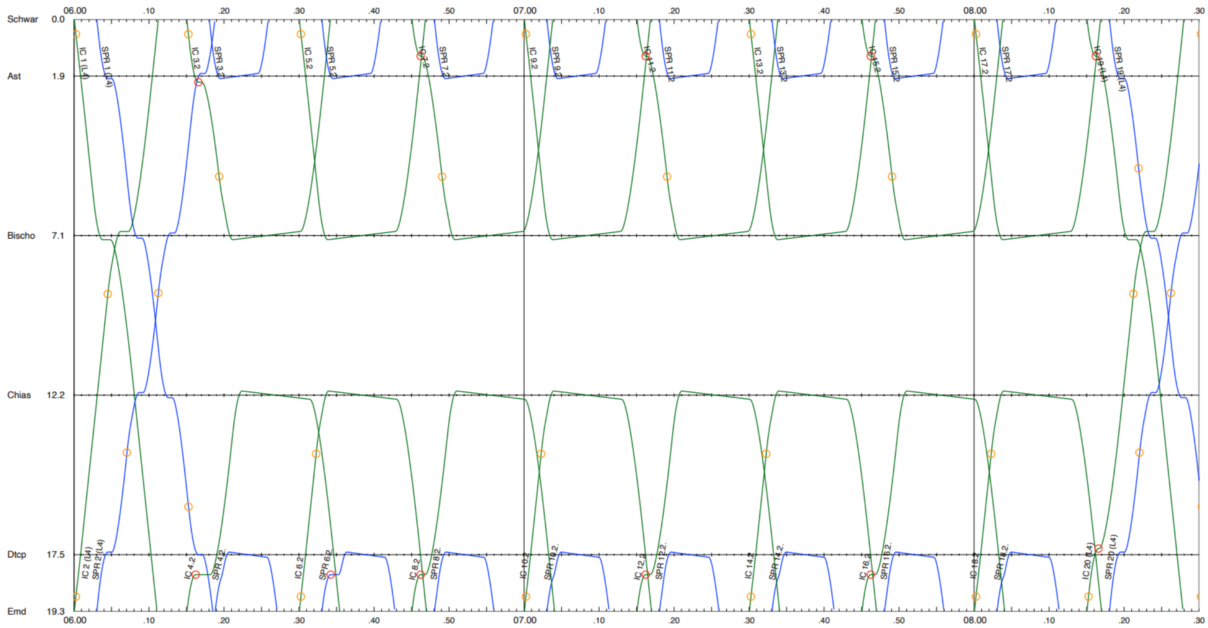


Figure F.17: Time-distance diagram layout 4 with persons near or at the tracks between stations B and C.

The results of the key performance indicators are given in Table F.12 and compared to layout 3 the range of the scores is smaller and also the threshold values for both rate of cancelled services and punctuality have been achieved.

Table F.12: Results layout 4 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L4	Broken train B1	8	16	75	15	-0.74		-0.65	
	Broken train B-C	8	16	75	15	-0.74	0.88	-0.65	-1.93
	Persons B-C	8	45	90	0	-11.25		-4.00	

F5: Layout 4.1

This layout was constructed with the thought to improve the scores of layout 4 by changing the locations of the switches from A and D to A and C and thus to the two small stations closest to the Intercity station. The layout can be seen in Figure F.18.

Figure F.18: Layout 4.1.

If a broken train is located at track 1 (upper track) in station B the distance of the single track part is smaller as this single track part is now only between stations A and C (about 10 km) instead of between stations A and D (about 15 km) as in layout 4.

Table F.13: Timetable layout 4.1 with a broken train at station B track 1.

Start → End												
		IC 1	SPR 1	IC 3.1	SPR 3.1	IC 5.1	SPR 5.1	IC 7.1	SPR 7.1	IC 9.1	SPR 9.1	...
Start	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:50	06:51	07:07	07:08	
Station A	*Arr.*		06:04		06:19		06:34		06:52		07:10	
Station B	*Arr.*	06:03	06:08	06:18		06:36		06:54		07:11	07:14	
Station B	*Dep.*	06:04	06:09	06:19		06:37		06:55		07:12	07:15	
Station C	*Arr.*		06:12								07:18	
Station D	*Arr.*		06:16		06:39		06:56		07:14		07:22	
End	*Arr.*	06:11	06:18	06:26	06:41	06:43	06:58	07:01	07:16	07:19	07:24	
End → Start												
		IC 2	SPR 2	IC 4.1	SPR 4.1	IC 6.1	SPR 6.1	IC 8.1	SPR 8.1	IC 10.1	SPR 10.1	...
End	*Dep.*	06:00	06:03	06:15	06:21	06:30	06:39	06:45	06:56	07:00	07:03	
Station D	*Arr.*		06:04		06:23		06:40		06:58		07:12	
Station C	*Arr.*		06:08		06:27		06:45		07:02		07:16	
Station B	*Arr..*	06:06	06:12	06:27		06:45		07:02		07:17	07:20	
Station B	*Dep.*	06:07	07:10	06:28		06:46		07:03		07:18	07:21	
Station A	*Arr.*		07:14								07:25	
Start	*Arr.*	06:11	07:15	06:32	06:29	06:50	06:45	07:07	07:03	07:22	07:26	

Again Sprinter trains are short turned at stations A and C just as in layout 4, but there is a difference in the time-distance diagrams where the one of layout 4.1 in Figure F.19 looks less messy compared to the one of layout 4. The corresponding timetable can be seen in Table F.13.

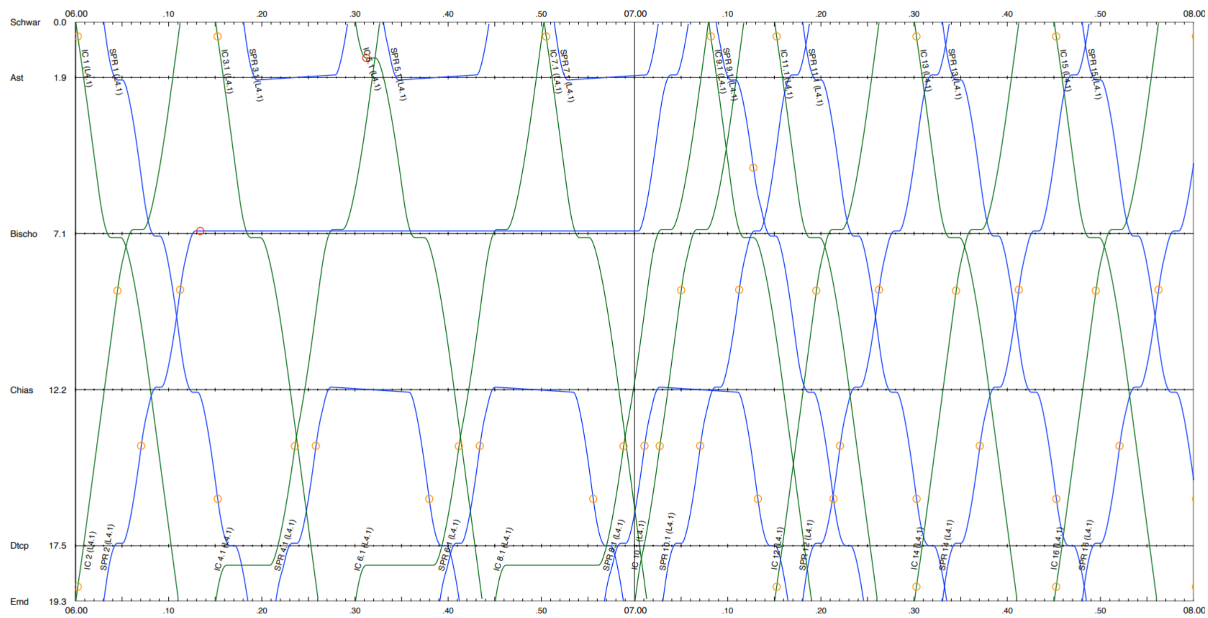


Figure F.19: Time-distance diagram layout 4.1 with broken train at station B track 1.

Because of the layout of the switches the results for a broken train at B1 and between B and C on track 1 will be the same. Therefore the next simulated disruption is again the one with the persons near or at the tracks between stations B and C. Trains from the right are cancelled for 50% outside of the model and trains from the left are short turning at B1 and B2 (for the IC trains) and A2 for the Sprinter trains. The results for this layout are given in Table F.14 and Figure F.20.

Table F.14: Timetable layout 4.1 with persons near or at the tracks between stations B and C.

Start → End												
		IC 3.2	SPR 3.2	IC 5.2	SPR 5.2	IC 7.2	SPR 7.2	IC 9.2	SPR 9.2	IC 11.2	SPR 11.2	...
Start	*Dep.*	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18	
Station A	*Arr.*		06:19		06:34		06:49		07:04		07:19	
Station B	*Arr.*	06:18		06:35		06:48		07:05		07:18		
Station B	*Dep.*											
Station C	*Arr.*											
Station D	*Arr.*				06:47				07:17			
End	*Arr.*	06:32			06:49	07:02			07:19	07:32		
End → Start												
		IC 4.2	SPR 4.2	IC 6.2	SPR 6.2	IC 8.2	SPR 8.2	IC 10.2	SPR 10.2	IC 12.2	SPR 12.2	...
End	*Dep.*	06:15			06:33	06:45			07:03	07:15		
Station D	*Arr.*				06:34				07:04			
Station C	*Arr.*	06:18			06:38	06:48			07:08	07:18		
Station B	*Arr..*											
Station B	*Dep.*	06:27		06:44		06:57		07:14		07:27		
Station A	*Arr.*											
Start	*Arr.*	06:32	06:18	06:49	06:41	07:02	06:56	07:19	07:11	07:32	07:26	

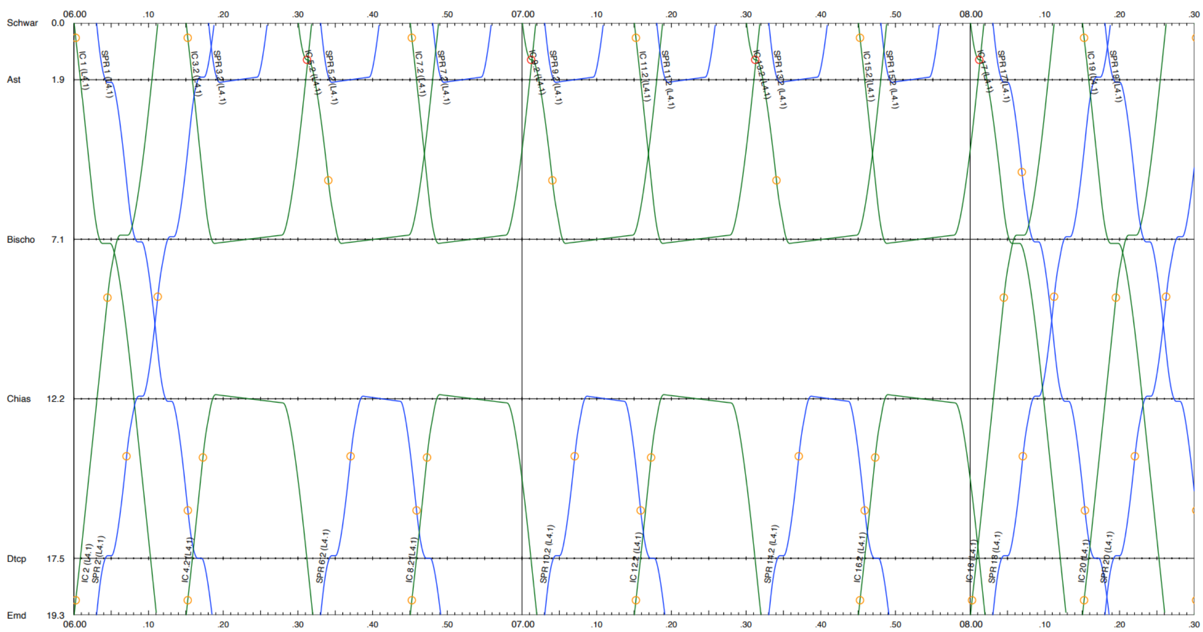


Figure F.20: Time-distance diagram layout 4.1 with persons near or at the tracks between stations B and C.

The overall results for this layout are given Table F.15 and are in the same table able to be compared with the results from layout 4 as layout 4.1 was supposed to be a better version of layout 4.

Table F.15: Results layout 4.1 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L4	Broken train B1	8	16	75	15	-0.74		-0.65	
	Broken train B-C	8	16	75	15	-0.74	0.88	-0.65	-1.93
	Persons B-C	8	45	90	0	-11.25		-4.00	
L4.1	Broken train B1	8	16	75	0	1.14		1.23	
	Broken train B-C	8	16	75	0	1.14	0.94	1.23	-1.79
	Persons B-C	8	60	99	0	-17.68		-6.68	

As a conclusion, the range of the scores for layout 4.1 is larger than for layout 3. The highest score which is for the broken train at B1 is almost 2 points higher than a broken train in layout 4, but if there is a full blockage of the line between two stations the score drops with almost 3 points compared to layout 4. This has to do with the much higher rate of cancelled services which is caused by the fact that trains coming from the right can now only use one track at station C to short turn while layout 4 offered two tracks at station C to short turn. Because of the 60% cancelled services layout 4.1 does not suffice.

F6: Layout 5

The results of layout 5 can also be found in the main report in section 6.5.2 but will be given here as well. The schematic view of this layout can however be found in Figure F.21 where it can be seen that all stations have switches on both sides.

Figure F.21: Layout 5.

Disruption 1: Broken train at track 1 of station B

If a train breaks down at station B1, trains can easily reroute via track B2 which also fits in the timetable. Trains from the left to the right run on time while trains from the right to the left are delayed by a maximum of 5 minutes at arrival in B. The timetable that is used during this disruption with a 1 hour broken train can be found in Table F.16 in which all by a colour marked times are late arrivals. Late means 5 or more minutes later than originally planned. This rerouting is visualised with the yellow line in the upper layout of Figure F.22.

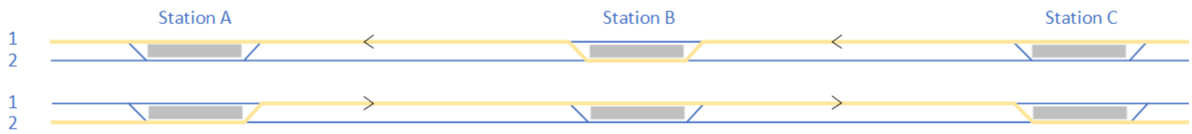


Figure F.22: Rerouting at station B (layout 5).

If the broken train would be on track 2 instead of track 1 at station B, the situation will be different as can be seen in the bottom layout in Figure F.22. There, trains are still able to bypass the broken train at track 2 of station B but this rerouting via track 1 takes more time as the distance of the single track would be longer (more than 10 kilometres instead of only 500 meters around station B) increasing delays and causing cancellations. The track numbering is indicated in Figure F.22.

Table F.16: Timetable during broken train at track 1 of station B (layout 5).

Layout 5 Start → End											
		IC 1	SPR 1	IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	...
Start	Dep.	6:00	6:03	6:15	6:18	6:30	6:33	6:45	6:48	7:00	7:03	
Station A	Arr.	|	6:04	|	6:19	|	6:34	|	6:49	|	7:04	
Station B	Arr.	6:03	6:08	6:18	6:23	6:33	6:38	6:48	6:53	7:03	7:08	
Station B	Dep.	6:04	6:09	6:19	6:24	6:34	6:39	6:49	6:54	7:04	7:09	
Station C	Arr.	|	6:12	|	6:27	|	6:42	|	6:57	|	7:12	
Station D	Arr.	|	6:16	|	6:31	|	6:46	|	7:01	|	7:16	
End	Arr.	6:11	6:18	6:26	6:33	6:41	6:48	6:56	7:03	7:11	7:18	
Layout 5 End → Start												
		IC 2	SPR 2	IC 4	SPR 4	IC 6	SPR 6	IC 8	SPR 8	IC 10	SPR 10	...
End	Dep.	6:00	6:03	6:15	6:18	6:30	6:33	6:45	6:48	7:00	7:03	
Station D	Arr.	|	6:04	|	6:19	|	6:34	|	6:49	|	7:04	
Station C	Arr.	|	6:08	|	6:23	|	6:38	|	6:53	|	7:08	
Station B	Arr..	6:06	6:12	6:26	6:29	6:41	6:44	6:56	6:59	7:11	7:14	
Station B	Dep.	6:07	7:10	6:27	6:30	6:42	6:45	6:57	7:00	7:12	7:15	
Station A	Arr.	|	7:13	|	6:33	|	6:48	|	7:03	|	7:18	
Start	Arr.	6:11	7:15	6:31	6:35	6:46	6:50	7:01	7:05	7:16	7:20	

The score for this disruption scenario is 3.00 and is calculated with Equation 5 introduced in chapter 5. As can be seen in Table 6.7, the rate of cancelled services is 0 percent. All in red marked arrival times are delayed arrivals giving a punctuality of 88 percent considering a sub weighting of 0.4 for late arrivals at station B and 0.2 for all other stations. There is no recovery time as the trains are immediately using this rescheduling and the total number of switches in use is 16 which can be explained after the other disruptions simulated for this layout. All these values are used to calculate the score.

Disruption 2: Broken train between stations B and C

As explained in section 6.4.2 the second disruption that is simulated is a broken train between stations B and C which causes a 1 hour single track between those stations. Also in this case there is a difference in results at which track the train breaks down, but for consistency track 1 is chosen again which will give in this case more delays than a broken train at track 2 since the distance trains need to use the opposite track is shorter in the bottom rerouting as can be seen in Figure F.23.

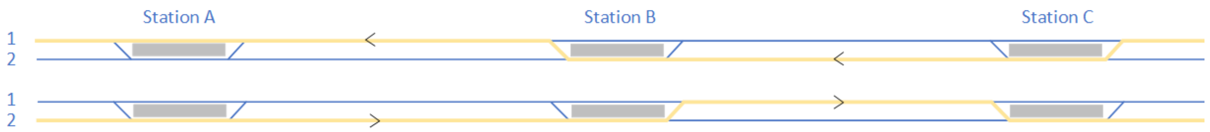


Figure F.23: Rerouting to bypass broken train between stations B and C.

As shown in Table 6.6 the score for this disruption is -8.88. In both stations B and C only one track can be used which causes eleven trains delayed and therefore a punctuality of 53 percent for all trains which is slightly higher than the threshold value of 50 percent. Again zero trains are being cancelled which however increases the time to recover till 60 minutes since there is no regular timetable pattern: all trains still run and need to wait for each other. In the conducted interviews, experts mentioned that trains should not be cancelled as fast as it happens currently in the Netherlands, but run with limited delay to keep capacity high. This happens in this layout where punctuality remains above the threshold and all trains are still running.

Table F.17: Timetable during broken train at track 1 between stations B and C (layout 5).

Layout 5 Start → End													
		IC 1	SPR 1	IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	IC 11	SPR 11
Start	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18
Station A	Arr.	|	06:04	|	06:19	|	06:34	|	06:52	|	07:04	|	07:19
Station B	Arr.	06:03	06:08	06:18	06:23	06:39	06:42	06:59	07:02	07:04	07:08	07:18	07:23
Station B	Dep.	06:04	06:09	06:19	06:24	06:40	06:43	07:00	07:02	07:05	07:09	07:19	07:24
Station C	Arr.	|	06:12	|	06:27	|	06:46	|	07:06	|	07:12	|	07:27
Station D	Arr.	|	06:16	|	06:31	|	06:50	|	07:10	|	07:16	|	07:31
End	Arr.	06:11	06:18	06:26	06:33	06:47	06:52	07:06	07:11	07:13	07:18	07:26	07:33
Layout 5 End → Start													
		IC 2	SPR 2	IC 4	SPR 4	IC 6	SPR 6	IC 8	SPR 8	IC 10	SPR 10	IC 12	SPR 12
End	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:47	06:50	07:06	07:09	07:15	07:18
Station D	Arr.	|	06:04	|	06:29	|	06:48	|	07:07	|	07:12	|	07:19
Station C	Arr.	|	06:08	|	06:33	|	06:52	|	07:11	|	07:17	|	07:23
Station B	Arr..	06:06	07:07	06:33	06:37	06:52	06:56	07:12	07:16	07:18	07:21	07:23	07:27
Station B	Dep.	06:07	07:07	06:34	06:37	06:53	06:57	07:13	07:16	07:19	07:22	07:24	07:28
Station A	Arr.	|	07:11	|	06:41	|	07:00	|	07:20	|	07:25	|	07:31
Start	Arr.	06:11	07:13	06:38	06:43	06:57	07:02	07:17	07:22	07:23	07:27	07:28	07:33

Disruption 3: Persons on the tracks between stations B and C

The third and final disruption that is simulated in layout 5 is the complete blockage of the line between stations B an C. The switch configuration in layout 5 enables short turning at stations B and C for all trains in case there are persons on the tracks between these two stations. Figure F.24 shows which tracks an Intercity and a Sprinter use to short turn at station B. Sprinters are using the upper track between stations A and B for both directions which is possible because of the shorter time it takes to short turn a Sprinter (5 minutes) compared to an Intercity (9 minutes) considering that these trains run every 15 minutes.

Figure F.24: Short turning at station B (layout 5).

Figure F.25 shows the time-distance diagram of all trains that are being short turned at stations B and C. The time to recover is 0 minutes since this rescheduling immediately starts. There is however a difference in delay by looking at the arriving IC trains into the model. From the start towards station B all trains can enter the model and arrive on time at station B. On the other side, IC trains coming from E (the end) towards station C need to slow down and arrive two minutes late at station C which can be seen in Figure F.25. These delays can be explained by looking at Figure F.25 where it becomes obvious that the upper track (1) is now used by the Sprinter on its way back to the end while the next Intercity already enters the model. This was not a problem in Figure F.24, because trains that were short turned all used the upper track back to the start of the model while new trains towards station B entered the model via the bottom track (2). Fortunately, delays are not stacking which causes a time to recover of 0 minutes.

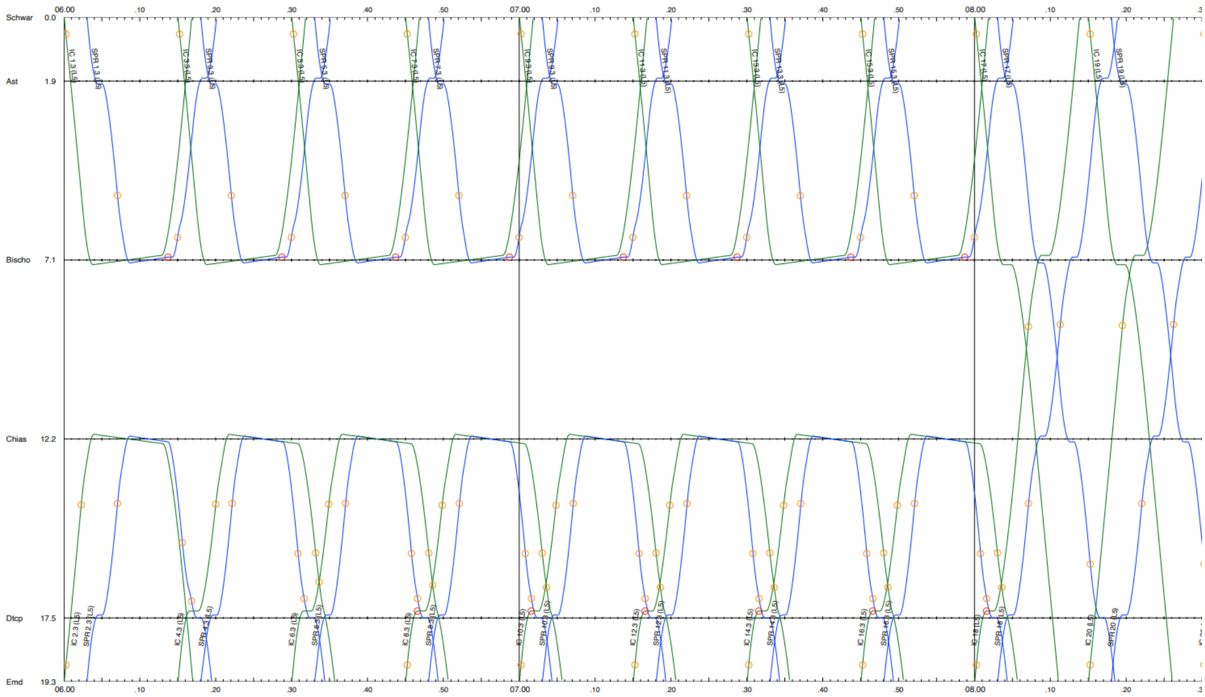


Figure F.25: Time-distance diagram persons on tracks between stations B and C (layout 5).

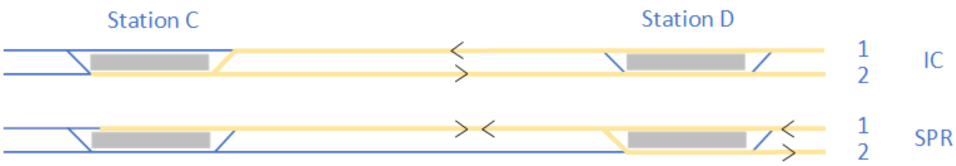


Figure F.26: Short turning at station C (layout 5).

The timetable during the two hour closure is periodic and the first hour is visualised in Table F.18Table 6.9 in which there are for the odd train numbers no departures at B and no arrivals at C and for the even train numbers no arrivals at station B. As example: IC 1 arrives on time at station B, becomes IC 2 as indicated and departs at station B at 6:12 which is 5 minutes later than IC 2 should depart, because it takes 9 minutes to short turn the train.

Table F.18: Timetable during persons on tracks between stations B and C (layout 5).

Layout 5 Start → End											
		IC 1	**SPR 1**	**IC 3**	**SPR 3**	**IC 5**	**SPR 5**	**IC 7**	**SPR 7**	**IC 9**	**SPR 9**
Start	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03
Station A	Arr.		06:04		06:19		06:34		06:49		07:04
Station B	Arr.	06:03	06:08	06:18	06:23	06:33	06:38	06:48	06:53	07:03	07:08
Station B	Dep.	to IC 2	to S 2	to IC 4	to S 4	to IC 6	to S 6	to IC 8	to S 8	to IC 10	to S 10
Station C	Arr.										
Station D	Arr.		06:17		06:32		06:47		07:02		07:17
End	Arr.	06:17	06:19	06:36	06:34	06:51	06:49	07:06	07:04	07:21	07:19
Layout 5 End → Start											
		IC 2	**SPR 2**	**IC 4**	**SPR 4**	**IC 6**	**SPR 6**	**IC 8**	**SPR 8**	**IC 10**	**SPR 10**
End	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03
Station D	Arr.		06:04		06:19		06:34		06:49		07:04
Station C	Arr.	06:06	06:08	06:21	06:23	06:36	06:38	06:51	06:53	07:06	07:08
Station B	Arr..	to IC 1	to S1	to IC 3	to S 3	to IC 5	to S 5	to IC 7	to S 7	to IC 9	to S 9
Station B	Dep.	06:12	06:14	06:27	06:29	06:42	06:44	06:57	06:59	07:12	07:14
Station A	Arr.		06:18		06:33		06:48		07:03		07:18
Start	Arr.	06:17	06:20	06:32	06:35	06:47	06:50	07:02	07:05	07:17	07:20

The punctuality for this disruption is 100 percent which is because cancelled trains are not included. However, as can be seen in Table F.18, all even IC numbers depart late at station B after being short turned and also leave the model (at the start) late. These delays are also not included as only arrival delays are counted and not departure delays. The rate of cancelled services is 30 percent, having 16 trains not having arrived at station B (weight 0.4), also 16 at station C (weight 0.2) and a total number of 32 services during the 2 hour disruption. The score for the alternative with the complete blockage is -3.00. A disadvantage for the situation in Figure F.24 is that Sprinter trains leave the model right before the Intercity which is not wished for. Otherwise, the Sprinter needs to wait a couple minutes longer and depart after the Intercity, but this will result in a delayed arrival of the next Intercity. Figure 6.9 in section 6.5.2 enables comparisons between all layouts by looking at the minimum and maximum values each layout scores for the simulated disruptions. The scores for the three simulated disruptions are calculated in the next four lines and the differences in scores can be seen.

$$S_{a,d} = R_{a,d} - C_a = P_{a,d} * w_P - RCS_{a,d} * w_{RCS} - T_{a,d} * w_T - NS_a * w_C \qquad (9)$$

$$S_{5,1} = 88 * 0.125 - 0 * 0.25 - 0 * 0.125 - 16 * 0.5 = 3.00$$

$$S_{5,2} = 53 * 0.125 - 0 * 0.25 - 60 * 0.125 - 16 * 0.5 = -8.88$$

$$S_{5,3} = 100 * 0.125 - 30 * 0.25 - 0 * 0.125 - 16 * 0.5 = -3.00$$

The weighted average of these three simulated disruptions is -1.13 which is the fifth highest score for the double track layouts. Layouts 6, 7, 7.1 and 8 all score higher as can be seen in Figure 6.10.

F7: Layout 6

The sixth layout is visualized in Figure F.27 and as can be seen there are four switches on each side of each station. However, the results show that all the switches at station D are not necessary. Also the switches on the west of station C and on the east of station A are not used. Therefore 16 switches in total are being used in this layout. The results are given in

Figure F.27: Layout 6.

For a broken train at station B track 1 the exact same results are gotten as in layout 3 and therefore Figure F.28 and Table F.19 show the same results as in Appendix F3.

Table F.19: Timetable layout 6 with broken train at station B track 1.

Start → End												
		IC 1	SPR 1	IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	...
Start	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station A	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station B	*Arr.*	06:03	06:08	06:18	06:23	06:33	06:38	06:48	06:53	07:03	07:08	
Station B	*Dep.*	06:04	06:09	06:19	06:24	06:34	06:39	06:49	06:54	07:04	07:09	
Station C	*Arr.*		06:12		06:27		06:42		06:57		07:12	
Station D	*Arr.*		06:16		06:31		06:46		07:01		07:16	
End	*Arr.*	06:11	06:18	06:26	06:33	06:41	06:48	06:56	07:03	07:11	07:18	
End → Start												
		IC 2	SPR 2	IC 4.1	SPR 4.1	IC 6.1	SPR 6.1	IC 8.1	SPR 8.1	IC 10.1	SPR 10	...
End	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station D	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station C	*Arr.*		06:08		06:23		06:38		06:53		07:08	
Station B	*Arr..*	06:06	06:12	06:26	06:29	06:41	06:44	06:56	06:59	07:11	07:12	
Station B	*Dep.*	06:07	07:10	06:27	06:30	06:42	06:45	06:57	07:00	07:12	07:13	
Station A	*Arr.*		07:13		06:33		06:48		07:03		07:17	
Start	*Arr.*	06:11	07:15	06:31	06:35	06:46	06:50	07:01	07:05	07:16	07:19	

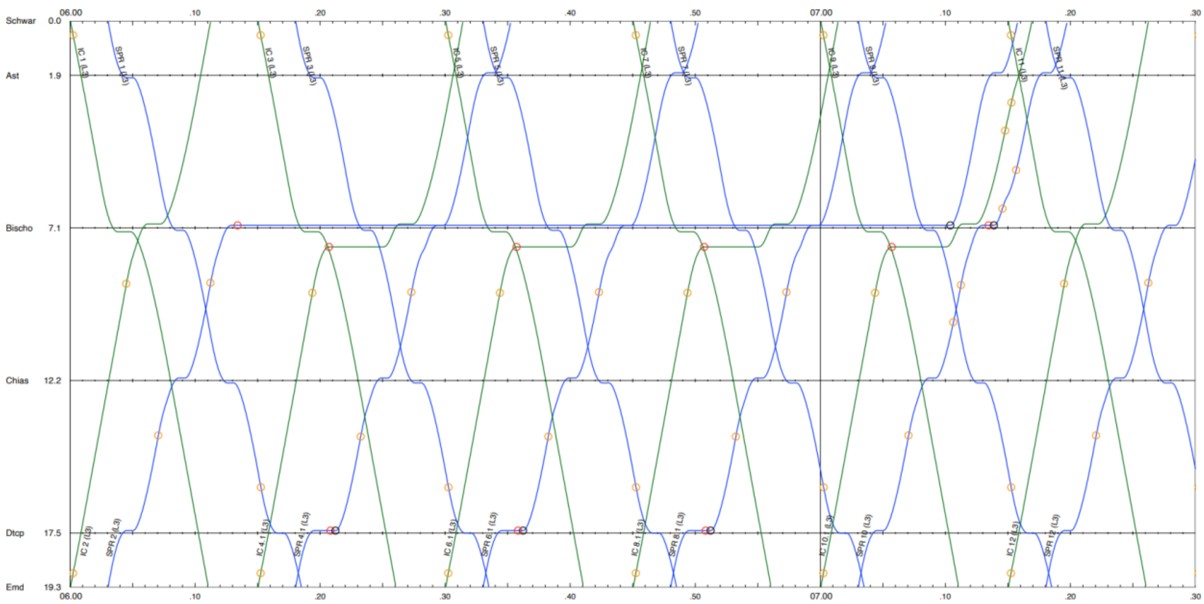


Figure F.28: Time-distance diagram layout 6 with broken train at station B track 1.

In case of a broken train between stations B and C at track 1 it is getting interesting as the distance of the single track part is now only approximately 5 km and compared to layout 5 all platform tracks at all stations still can be used. The timetable in case of this disruption can be seen in Table F.20 and Figure F.29. No trains are cancelled, there is some delay as can be seen in Figure F.29 as trains are bundled on the single track part and sometimes therefore need to wait at station A, B or D. From this simulation it follows that if switches are every 5 km no trains should be cancelled.

Table F.20: Timetable layout 6 with broken train between B1 and C1.

Start → End												
		IC 1	SPR 1	IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	…
Start	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station A	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station B	*Arr.*	06:03	06:08	06:18	06:23	06:33	06:40	06:48	06:56	07:03	07:08	
Station B	*Dep.*	06:04	06:09	06:20	06:24	06:39	06:41	06:54	06:56	07:06	07:09	
Station C	*Arr.*		06:12		06:27		06:44		07:00		07:12	
Station D	*Arr.*		06:16		06:31		06:48		07:04		07:16	
End	*Arr.*	06:11	06:18	06:27	06:33	06:45	06:50	07:00	07:06	07:12	07:18	
End → Start												
		IC 2	SPR 2	IC 4.2	SPR 4.2	IC 6.2	SPR 6.2	IC 8.2	SPR 8.2	IC 10.2	SPR 10.2	…
End	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station D	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station C	*Arr.*		06:08		06:32		06:47		07:02		07:13	
Station B	*Arr..*	06:06	07:08	06:21	06:36	06:38	06:51	06:53	07:06	07:14	07:17	
Station B	*Dep.*	06:07	07:09	06:22	06:36	06:39	06:51	06:54	07:07	07:15	07:18	
Station A	*Arr.*		07:12		06:40		06:55		07:10		07:21	
Start	*Arr.*	06:11	07:14	06:26	06:42	06:43	06:57	06:58	07:12	07:19	07:23	

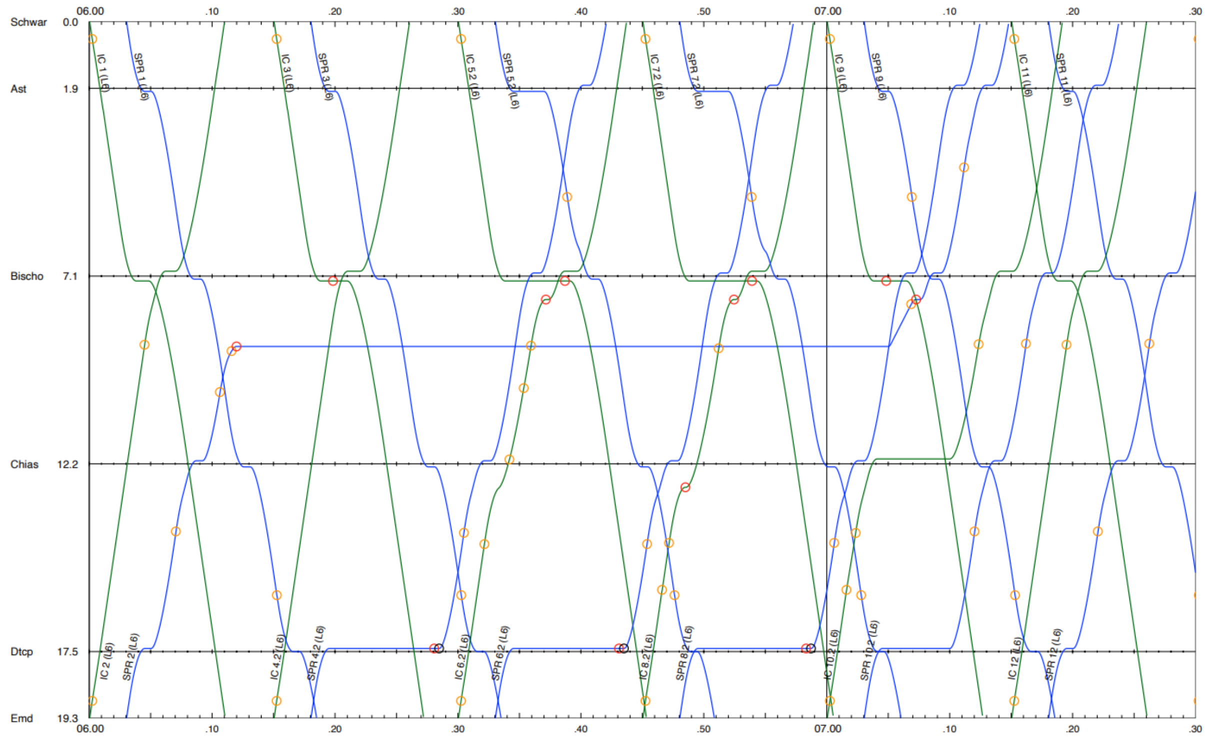


Figure F.29: Time-distance diagram layout 6 with broken train between B1 and C1.

Finally, also the persons on the tracks between the stations B and C have been simulated and these results are given in Figure F.30 and Table F.21 where it can easily be seen that all trains are short turned at stations B and C.

Table F.21: Timetable layout 6 with persons near or at the tracks between stations B and C.

Start → End												
		IC 3.3	SPR 3.3	IC 5.3	SPR 5.5	IC 7.3	SPR 7.3	IC 9.3	SPR 9.3	IC 11.3	SPR 11.3	...
Start	*Dep.*	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18	
Station A	*Arr.*		06:19		06:34		06:49		07:04		07:19	
Station B	*Arr.*	06:18	06:23	06:33	06:38	06:48	06:53	07:03	07:08	07:18	07:23	
Station B	*Dep.*											
Station C	*Arr.*											
Station D	*Arr.*		06:34		06:49		07:04		07:19		07:34	
End	*Arr.*	06:33	06:36	06:48	06:51	07:03	07:06	07:18	07:21	07:33	07:36	
End → Start												
		IC 4.3	SPR 4.3	IC 6.3	SPR 6.3	IC 8.3	SPR 8.3	IC 10.3	SPR 10.3	IC 12.3	SPR 12.3	...
End	*Dep.*	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18	
Station D	*Arr.*		06:19		06:34		06:49		07:04		07:19	
Station C	*Arr.*	06:18	06:23	06:33	06:38	06:48	06:53	07:03	07:08	07:18	07:23	
Station B	*Arr..*											
Station B	*Dep.*	06:27	06:29	06:42	06:44	06:57	06:59	07:12	07:14	07:27	07:29	
Station A	*Arr.*		06:33		06:48		07:03		07:18		07:33	
Start	*Arr.*	06:32	06:35	06:47	06:50	07:02	07:05	07:17	07:20	07:32	07:35	

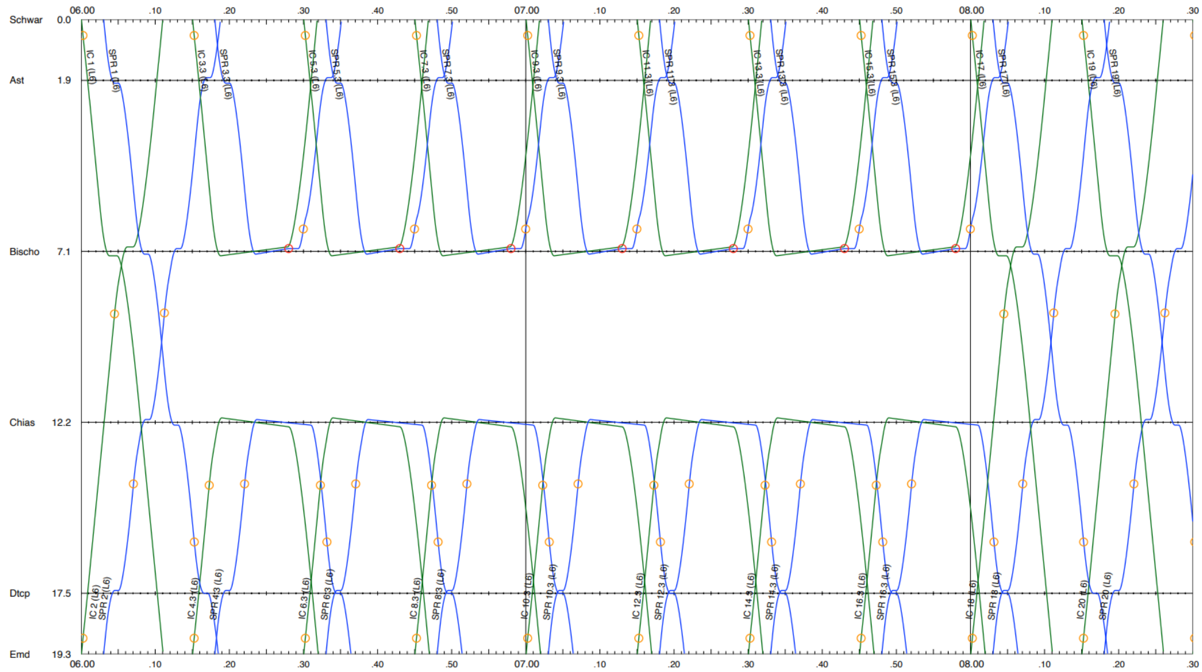


Figure F.30: Time-distance diagram layout 6 with persons near or at the tracks between stations B and C.

All results for layout 6 are summarized in Table F.22 and as can be seen the scores are relatively good compared to the other layouts.

Table F.22: Results layout 6 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L6	Broken train B1	16	0	88	0	11.00		3.00	
	Broken train B-C	16	0	78	15	7.86	3.62	-0.14	0.53
	Persons B-C	16	26	99	0	-0.78		-2.22	

F8: Layout 7

Figure F.31 shows layout 7 in which station B contains a third track which can be useful during disruptions as follows from the results which can be seen in Figure F.32 and Table F.23. All trains from the right are using track 3 instead of track 1 at station B. Some trains get small delays of maximum 2 minutes as trains are crossing each other on both sides of station B and therefore need to wait a bit longer than usual in station B.

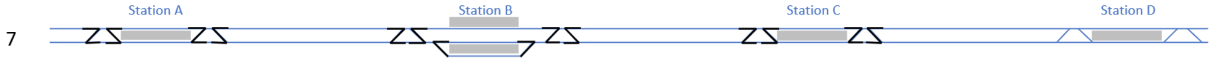


Figure F.31: Layout 7.

Table F.23: Timetable layout 7 with broken train at station B track 1.

Start → End												
		IC 1	SPR 1	IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	...
Start	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station A	Arr.		06:04		06:19		06:34		06:49		07:04	
Station B	Arr.	06:03	06:08	06:18	06:24	06:33	06:39	06:48	06:54	07:03	07:09	
Station B	Dep.	06:04	06:09	06:21	06:24	06:36	06:39	06:51	06:54	07:06	07:09	
Station C	Arr.		06:12		06:28		06:43		06:58		07:13	
Station D	Arr.		06:16		06:32		06:47		07:02		07:17	
End	Arr.	06:11	06:18	06:27	06:34	06:42	06:49	06:57	07:04	07:12	07:19	
End → Start												
		IC 2	SPR 2	IC 4.1	SPR 4.1	IC 6.1	SPR 6.1	IC 8.1	SPR 8.1	IC 10.1	SPR 10	...
End	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station D	Arr.		06:04		06:19		06:34		06:49		07:04	
Station C	Arr.		06:08		06:23		06:38		06:53		07:08	
Station B	Arr..	06:06	06:12	06:21	06:27	06:36	06:41	06:51	06:57	07:06	07:12	
Station B	Dep.	06:07	07:10	06:22	06:28	06:37	06:42	06:52	06:58	07:07	07:13	
Station A	Arr.		07:13		06:31		06:46		07:01		07:16	
Start	Arr.	06:11	07:15	06:26	06:33	06:41	06:48	06:56	07:03	07:11	07:18	

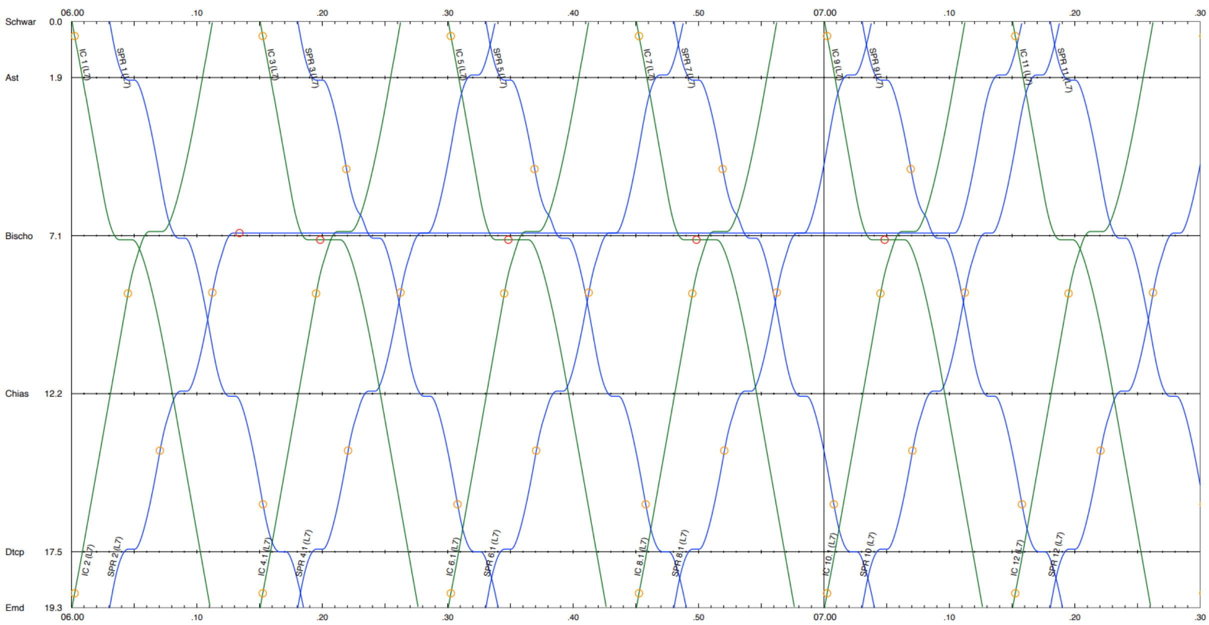


Figure F.32: Time-distance diagram layout 7 with broken train at station B track 1.

In case of a broken train between stations B and C this layout would give the same results as layout 6 because the same switches are used. However, in this situation also the switches on the west of station C are simulated and therefore the single track part is even more decreasing. Results are given in Table F.24 and Figure F.33.

Table F.24: Timetable layout 7 with broken train between B1 and C1.

Start → End												
		IC 3	SPR 3	IC 5	SPR 5	IC 7	SPR 7	IC 9	SPR 9	IC 11	SPR 11	...
Start	*Dep.*	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18	
Station A	*Arr.*		06:19		06:34		06:49		07:04		07:19	
Station B	*Arr.*	06:18	06:23	06:33	06:38	06:48	06:53	07:03	07:08	07:18	07:23	
Station B	*Dep.*	06:20	06:24	06:35	06:39	06:50	06:54	07:05	07:09	07:19	07:24	
Station C	*Arr.*				06:42		06:57		07:12		07:27	
Station D	*Arr.*		06:31		06:46		07:01		07:16		07:31	
End	*Arr.*	06:26	06:33	06:41	06:48	06:56	07:03	07:11	07:18	07:26	07:33	
End → Start												
		IC 4.2	SPR 4.2	IC 6.2	SPR 6.2	IC 8.2	SPR 8.2	IC 10	SPR 10	IC 12	SPR 12	...
End	*Dep.*	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	07:15	07:18	
Station D	*Arr.*		06:19		06:34		06:49		07:04		07:19	
Station C	*Arr.*		06:23		06:38		06:53		07:08		07:23	
Station B	*Arr..*	06:21	06:31	06:36	06:46	06:51	07:01	07:09	07:12	07:21	07:27	
Station B	*Dep.*	06:22	06:31	06:37	06:46	06:52	07:01	07:10	07:13	07:22	07:28	
Station A	*Arr.*		06:35		06:50		07:05		07:16		07:31	
Start	*Arr.*	06:26	06:36	06:41	06:51	06:56	07:06	07:14	07:18	07:26	07:33	

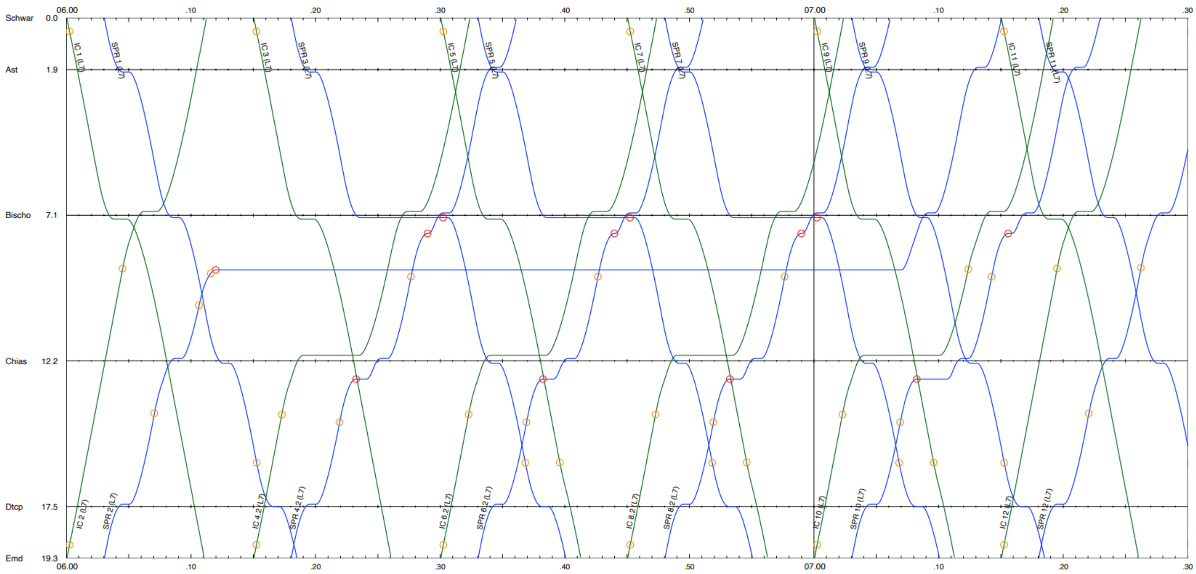


Figure F.33: Time-distance diagram layout 7 with broken train between B1 and C1.

In case of persons near or at the tracks between B and C the results are given exactly the same as for layout 6 and can therefore be found in Appendix F7. The overall results for layout 7 are given in Table F.25. As can be seen there is a difference between the middle score of layout 6 and 7. Layout 7 scores 5 points higher which can be derived from the fact that also the switches on the left side of station C are used in layout 7. Because of using those switches, the switches on the right side of station A are also included and therefore the difference of 8 switches between the different disruption scenarios in Table F.25.

Table F.25: Results layout 7 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L7	Broken train B1	22	0	99	11	10.96		1.96	
	Broken train B-C	22	0	89	0	11.17	3.83	2.17	0.02
	Persons B-C	22	26	99	0	-0.78		-3.22	

F9: Layout 7.1

Layout 7.1 is again a plus-version of layout 7 where the problem of waiting for crossing trains in the first simulated disruption is no longer a problem. The layout can be seen in Figure F.34 in which the different switch configuration layout can be seen where the middle track in station B is actually kind of the third track.

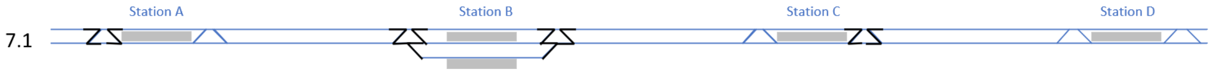


Figure F.34: Layout 7.1.

In regular service tracks 1 and 3 are used for all trains at station B. In case of a disruption at one of those tracks, all trains can be rerouted via the middle track. Therefore, there are 0 cancellations, 0 delays and 0 minutes of recovery time. In case of a broken train between B1 and C1 the results are given in Table F.26 and Figure F.35. All IC trains are running, 50% of the SPR trains are short turning at B and C, while the other half also continues as planned. Trains are also bundled again.

Table F.26: Timetable layout 7.1 with broken train between B1 and C1.

Start → End												
		IC 1	SPR 1	IC 3.2	SPR 3.2	IC 5.2	SPR 5.2	IC 7.2	SPR 7.2	IC 9.2	SPR 9.2	...
Start	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station A	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station B	*Arr.*	06:03	06:08	06:18	06:23	06:33	06:38	06:48	06:54	07:03	07:08	
Station B	*Dep.*	06:04	06:09	06:21		06:36	06:39	06:51		07:06	07:09	
Station C	*Arr.*		06:12				06:42				07:12	
Station D	*Arr.*		06:16		06:49		06:46		07:19		07:16	
End	*Arr.*	06:11	06:18	06:27	06:51	06:42	06:48	06:57	07:21	07:12	07:18	
End → Start												
		IC 2	SPR 2	IC 4.2	SPR 4.2	IC 6.2	SPR 6.2	IC 8.2	SPR 8.2	IC 10.2	SPR 10.2	...
End	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station D	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station C	*Arr.*		06:08		06:27		06:38		06:58		07:08	
Station B	*Arr..*	06:06		06:21	06:31	06:36		06:51	07:02	07:06	07:07	
Station B	*Dep.*	06:07	06:28	06:22	06:31	06:37	06:59	06:52	07:02	07:07	07:08	
Station A	*Arr.*		06:32		06:35		07:03		07:06		07:12	
Start	*Arr.*	06:11	06:34	06:26	06:37	06:41	07:05	06:56	07:08	07:11	07:14	

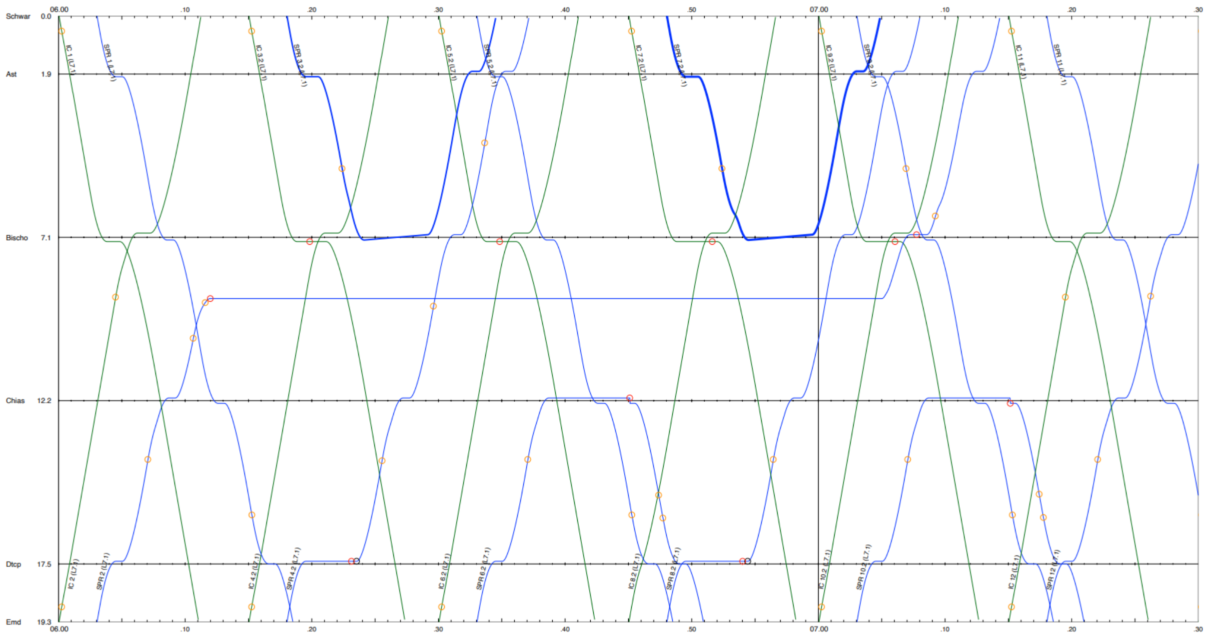


Figure F.35: Time-distance diagram layout 7.1 with broken train between B1 and C1.

For the disruption with the persons near or at the tracks between stations B and C the same results are obtained as in layout 6. The overall results for layout 7 and layout 7.1 are shown in Table F.27 where these two layouts can be compared easily. Layout 7.1 scores higher for the first disruption and the same for the third disruption. However, the second disruption is hard to compare since layout 7 uses 8 more switches otherwise the scores there would be exactly the same from which overall can be said that layout 7.1 scores slightly better than layout 7 based on the first simulated disruption.

Table F.27: Results layout 7.1 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L7	Broken train B1	22	0	99	11	10.96		1.96	
	Broken train B-C	22	0	89	0	11.17	3.83	2.17	0.02
	Persons B-C	22	26	99	0	-0.78		-3.22	
L7.1	Broken train B1	18	0	100	0	12.50		3.50	
	Broken train B-C	18	9	87	0	6.18	3.96	-0.47	0.32
	Persons B-C	18	26	99	0	-0.78		-3.22	

F10: Layout 8

Layout 8 has some similar characteristics as the previous layouts but there is a fourth track at station B. In case of a broken train at station B trains can easily be rerouted as there is enough space. In case of a broken train between B and C and in case of persons on the tracks between B and C the exact same procedures as for layout 6 are used. The overall results for layout 8 which can be seen in Figure F.36 are shown in Table F.28.

8


Figure F.36: Layout 8.

Table F.28: Results layout 8 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L8	Broken train B1	20	0	100	0	12.50		2.50	
	Broken train B-C	20	0	78	15	7.86	3.92	-2.14	-0.78
	Persons B-C	20	26	99	0	-0.78		-4.22	

F11: Layout 9

This layout is the last in the series of double track layouts and can be seen in Figure F.37.

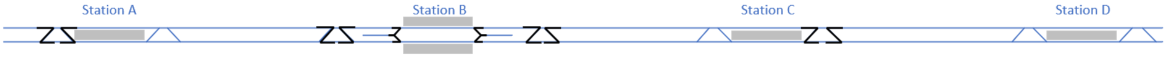
9 

Figure F.37: Layout 9.

The switches on both sides of station B are further away from platforms than in L3 because of the length of the tail tracks. Therefore the results for the first disruption with a broken train at B1 will be worse and a part of the trains will be cancelled. The results are shown in Table F.29 and Figure F.38. Sprinter trains are short turning in stations A and C. Nonetheless, Sprinter 3.1 uses the tail track at station B. During the disruption Intercity trains can make an additional stop at stations A (as visualized in Figure F.38 and also in C to let passengers travel between A and C.

Table F.29: Timetable layout 9 with broken train at station B track 1.

Start → End												
		IC 1	SPR 1	IC 3	SPR 3.1	IC 5.1	SPR 5.1	IC 7.1	SPR 7.1	IC 9.1	SPR 9.1	...
Start	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station A	*Arr.*		06:04		06:19	06:31	06:34	06:46	06:49	07:01	07:04	
Station B	*Arr.*	06:03	06:08	06:18	06:23	06:35	06:35	06:50	06:50	07:05	07:05	
Station B	*Dep.*	06:04	06:09	06:19		06:36	06:36	06:51	06:51	07:06	07:06	
Station C	*Arr.*		06:12			06:40	06:40	06:55	06:55	07:10	07:10	
Station D	*Arr.*		06:16		06:32		06:49		07:04		07:19	
End	*Arr.*	06:11	06:18	06:26	06:34	06:45	06:51	07:00	07:06	07:15	07:21	
End → Start												
		IC 2	SPR 2	IC 4.1	SPR 4.1	IC 6.1	SPR 6.1	IC 8.1	SPR 8.1	IC 10.1	SPR 10.1	...
End	*Dep.*	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station D	*Arr.*		06:04		06:19		06:34		06:49		07:04	
Station C	*Arr.*		06:08	06:18	06:23	06:33	06:41	06:48	06:56	07:03	07:11	
Station B	*Arr..*	06:06	06:12	06:26		06:41	06:41	06:56	06:56	07:11	07:11	
Station B	*Dep.*	06:07	07:10	06:27	06:31	06:42	06:42	06:57	06:57	07:12	07:12	
Station A	*Arr.*		07:13	06:30	06:35	06:46	06:46	07:01	07:01	07:16	07:16	
Start	*Arr.*	06:11	07:15	06:33	06:37	06:48	06:41	07:03	06:56	07:18	07:11	

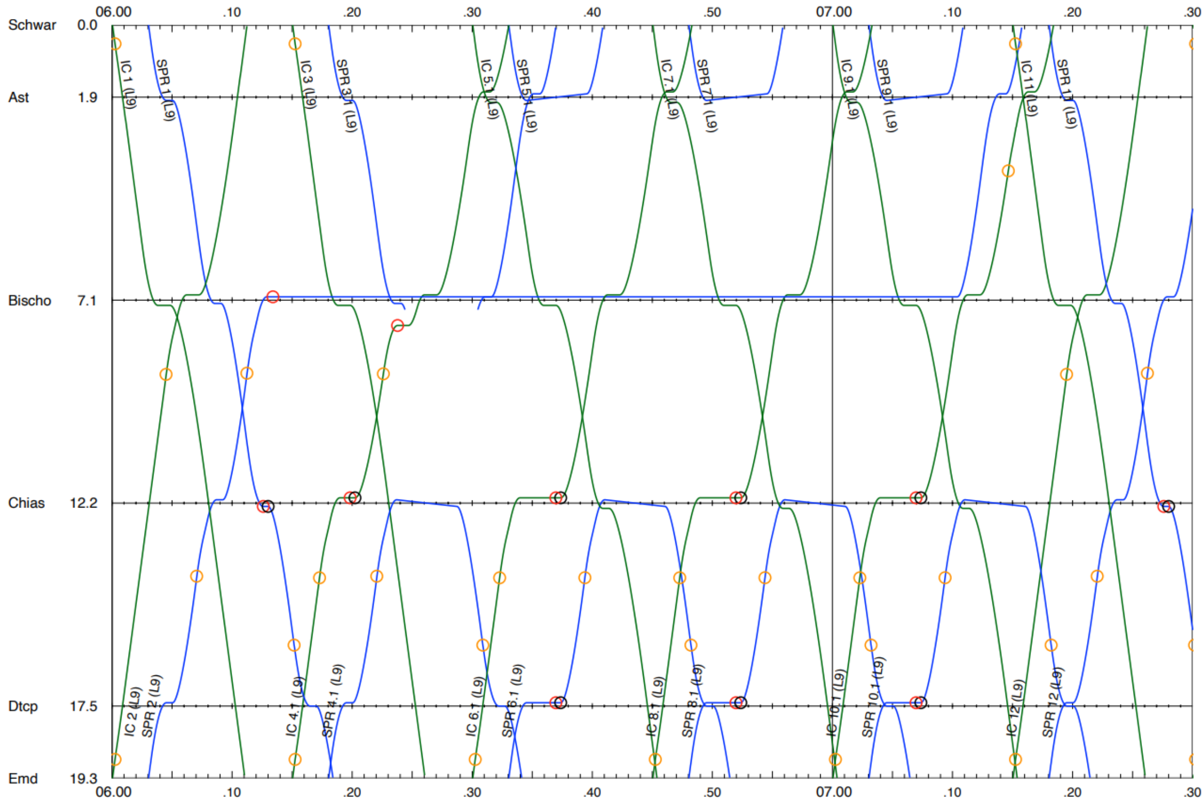


Figure F.38: Time-distance diagram layout 9 with broken train at station B track 1.

The tail track looks nice, but during disruption 2 it is also not used (there are no cancellations); switches around B are more important. The tail track can be used in case of the first stage (chaos) of the disruption in case of disruption 1. The tail track can also be useful for regular train services and in case of a disruption it creates an extra opportunity for trains to short turn in case there are no switches. For a broken train between B and C the results are shown in Table F.30 and Figure F.39 and are better because the switches between B and C are a bit closer to each other.

Table F.30: Timetable layout 9 with broken train between stations B and C.

Start → End												
		IC 1	SPR 1	IC 3.2	SPR 3.2	IC 5.2	SPR 5.2	IC 7.2	SPR 7.2	IC 9.2	SPR 9.2	...
Start	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station A	Arr.		06:04		06:19		06:34		06:49		07:04	
Station B	Arr.	06:03	06:08	06:18	06:23	06:33	06:38	06:48	06:53	07:03	07:08	
Station B	Dep.	06:04	06:09	06:19	06:27	06:34	06:42	06:49	06:57	07:04	07:12	
Station C	Arr.		06:12		06:31		06:46		07:01		07:16	
Station D	Arr.		06:16		06:35		06:50		07:05		07:20	
End	Arr.	06:11	06:18	06:26	06:37	06:41	06:52	06:56	07:07	07:11	07:22	
End → Start												
		IC 2	SPR 2	IC 4.2	SPR 4.2	IC 6.2	SPR 6.2	IC 8.2	SPR 8.2	IC 10.2	SPR 10.2	...
End	Dep.	06:00	06:03	06:15	06:18	06:30	06:33	06:45	06:48	07:00	07:03	
Station D	Arr.		06:04		06:19		06:34		06:49		07:04	
Station C	Arr.		06:08		06:25		06:40		06:55		07:10	
Station B	Arr..	06:06	07:09	06:21	06:29	06:36	06:44	06:51	06:59	07:06	07:14	
Station B	Dep.	06:07	07:10	06:22	06:29	06:37	06:44	06:52	06:59	07:07	07:14	
Station A	Arr.		07:13		06:33		06:48		07:03		07:18	
Start	Arr.	06:11	07:15	06:26	06:35	06:41	06:50	06:56	07:05	07:11	07:20	

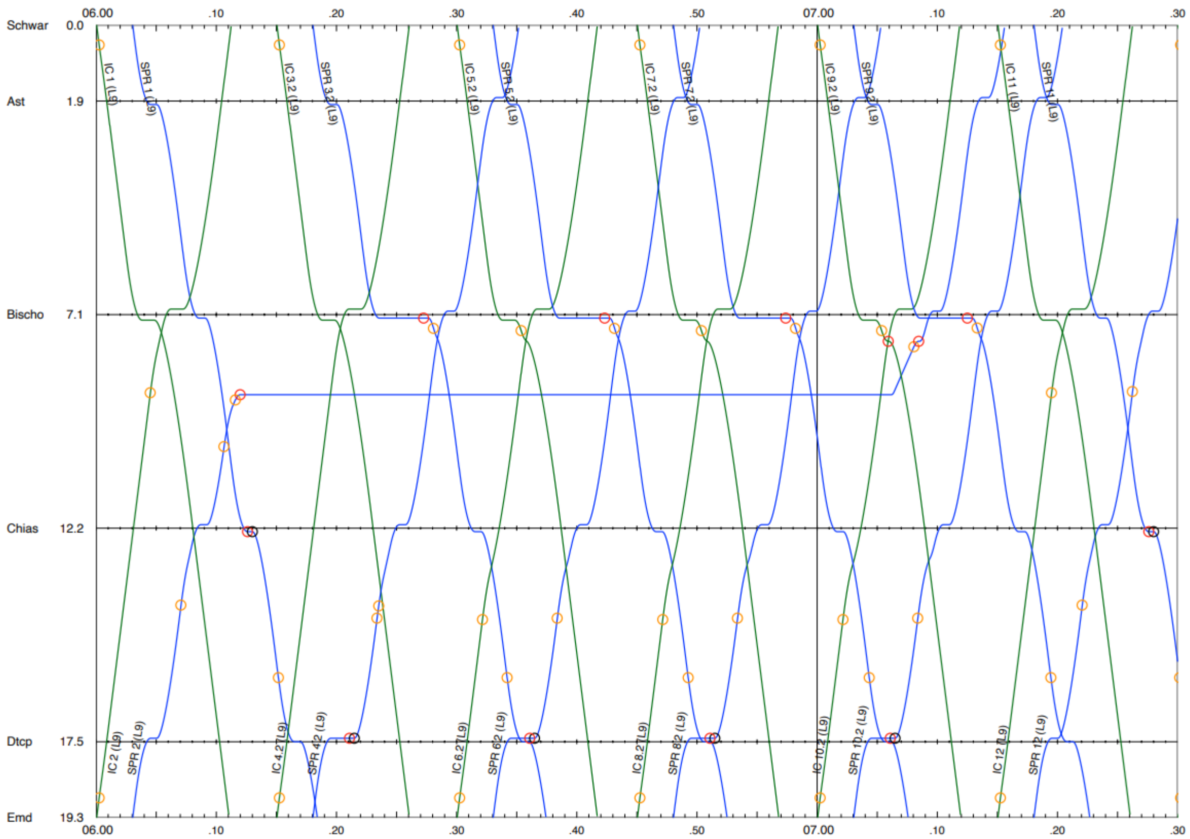


Figure F.39: Time-distance diagram layout 9 with broken train between B and C track 1.

For the persons near or at the tracks between B and C the same train rescheduling procedure is used as in layout 6. Therefore, the overall summarized results for layout 9 can be found in Table F.31

Table F.31: Results layout 9 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L9	Broken train B1	22	23	82	15	-3.26		-8.43	
	Broken train B-C	22	0	92	0	11.47	2.20	0.47	-5.83
	Persons B-C	22	0	99	0	-0.78		-5.22	

In case the tail tracks are there and the switches around station B not (a kind of combination between layout 4.1 and layout 9) this would result in: lower RCS as SPR can short turn at B from both directions (for disruption 1). For the second and third disruptions no changes are expected. Therefore the overall score for this layout will not be better than for layout 7 and 7.1 for example.

F12: Layout 10

Layout 10 contains four tracks and is shown in Figure F.40 which only contains switches at station B. A broken train at track 1 (upper track) lets Intercity trains use the Sprinter tracks in the middle at station B without delays or cancellations. The other way around if a broken train is located at track 2 (Sprinter track) trains cannot move from the inside track to the outside track before arriving at station B meaning that all trains on the inner tracks are cancelled for the whole hour. A broken train between B and C for all layouts with four tracks creates some challenges as there are no switches at the Sprinter stations A, C and D. Many trains will be cancelled at the previous larger station that is outside of the model. For the case of persons near or at the tracks between stations B and C the results can be found in Table F.32 and Figure F.41. As mentioned all trains from the right are cancelled outside of the model. From the left trains are using the tail track at station B and 20 minutes after the disruption many trains are also cancelled from outside of the model (and therefore being short turned at another large station left of the model). After that period the possible timetable is 4 IC trains per hour (instead of 8) and 2 SPR trains per hour (instead of 4). The tail track is then used at maximum capacity considering a 9 minute short turning time for the VIRM-10 Intercity and a 5 minute short turning time for the SLT-10 Sprinter. The results can be found in Table F.32 and Figure F.41 where in the time-distance diagram only trains are shown between the start of the model and the tail track of B since no trains are running on the right side of the model at all.

Figure F.40: Layout 10.

Table F.32: Timetable layout 10 with persons near or at the tracks between stations B and C.

Start → End															
		IC 1	SPR 1.3	IC 3.3	IC 5.3	SPR 3	IC 7	IC 9	SPR 5	IC 11	IC 13	SPR 7	IC 15	IC 17	*see below*
Start	*Dep.*	06:00	06:03	06:07	06:15	06:18	06:22							07:00	
Station A	*Arr.*		06:04			06:19									
Station B	*Arr.*	06:03	06:08	06:11	06:18	06:29	06:40							07:03	
Station B	*Dep.*	06:04													
Station C	*Arr.*														
Station D	*Arr.*														
End	*Arr.*	06:11	06:18												
Start → End															
		SPR 9	IC 19	IC 21	SPR 11	IC 23	IC 25	SPR 13	IC 27	IC 29	SPR 15	IC 31	IC 33	SPR 17	
Start	*Dep.*	07:03		07:15			07:30	07:33		07:45			08:00	08:03	
Station A	*Arr.*	07:04						07:34						08:04	
Station B	*Arr.*	07:08		07:18			07:33	07:38		07:48			08:03	08:08	
Station B	*Dep.*														
Station C	*Arr.*														
Station D	*Arr.*														
End	*Arr.*														
End → Start															
		IC 2	SPR 2	IC 4	IC 6	SPR 4	IC 8	IC 10	SPR 6	IC 12	IC 14	SPR 8	IC 16	IC 18	*see below*
End	*Dep.*	06:00	06:03	06:07	06:15	06:18	06:22	06:30	06:33	06:37	06:45	06:48	06:52	07:00	
Station D	*Arr.*		06:04			06:19			06:34			06:49			
Station C	*Arr.*		06:08			06:23			06:38			06:53			
Station B	*Arr..*	06:06	06:12	06:13	06:21	06:27	06:28	06:36	06:42	06:43	06:51	06:57	06:58	07:06	
Station B	*Dep.*	06:07	06:16	06:14	06:28	06:28	06:29	06:39	06:46	06:44	06:52	06:58	06:58		
Station A	*Arr.*		06:20			06:31			06:49			07:01			
Start	*Arr.*	06:11	06:22	06:18	06:29	06:33	06:33	06:44	06:51	06:48	06:56	07:03	07:03		
End → Start															
		SPR 10	IC 20	IC 22	SPR 12	IC 24	IC 26	SPR 14	IC 28	IC 30	SPR 16	IC 32	IC 34	SPR 18	
End	*Dep.*	07:03	07:07	07:15	07:18	07:22	07:30	07:33	07:37	07:45	07:48	07:52	08:00	08:03	
Station D	*Arr.*	07:04			07:19			07:34			07:49			08:04	
Station C	*Arr.*	07:08			07:23			07:38			07:53			08:08	
Station B	*Arr..*	07:12	07:13	07:21	07:27	07:28	07:36	07:42	07:43	07:51	07:57	07:58	08:06	08:12	
Station B	*Dep.*	07:23	07:17	07:22	07:28	07:35	07:37	07:53	07:47		07:58	08:05		08:23	
Station A	*Arr.*	07:27			07:31			07:57			08:01			08:27	
Start	*Arr.*	07:29	07:21	07:26	07:33	07:37	07:41	07:59	07:49	07:56	08:03	08:07	08:11	08:29	

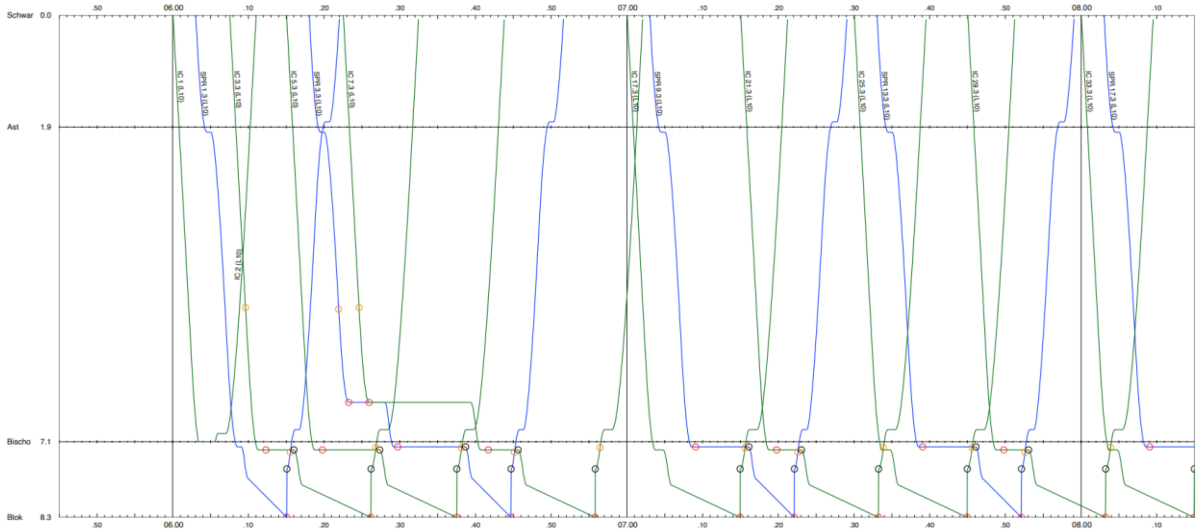


Figure F.41: Time-distance diagram layout 10 with persons near or at the tracks between B and C.

The summarized results for layout 10 are given in Table F.33 and as can be seen the range again is large which mainly because of the low capacity of the tail track at station B.

Table F.33: Results layout 10 for all simulated disruptions.

Line	Disruption	C [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L10	Broken train B1	14	0	100	0	12.50		5.50	
	Broken train B2	14	31	100	0	-2.88		-2.19	
	Broken train B-C (1)	14	29	100	0	-2.05	3.12	-1.77	-2.65
	Broken train B-C (2)	14	31	100	0	-2.88		-2.19	
	Persons B-C	14	47	97	50	-17.70		-12.90	

F13: Layout 11

A drawing of this layout is shown in Figure F.42 and the difference with layout 10 is that the tail track capacity is doubled (expected) since there is a second tail track. The results for the first four disruptions are therefore equal to the scores from layout 10. For persons near or at the tracks between B and C short turning capacity is higher. The results can be found in Table F.34 and Figure F.43.

11

Figure F.42: Layout 11.

Table F.34: Timetable layout 11 with persons near or at the tracks between stations B and C.

Start → End															
		IC 1	SPR 1.3	IC 3.3	IC 5.3	SPR 3	IC 7	IC 9	SPR 5	IC 11	IC 13	SPR 7	IC 15	IC 17	*see below*
Start	*Dep.*	06:00	06:03	06:07	06:15	06:18	06:22	06:30	06:33		06:45	06:48		07:00	
Station A	*Arr.*		06:04			06:19			06:34			06:49			
Station B	*Arr.*	06:03	06:08	06:11	06:18	06:23	06:26	06:33	06:38		06:48	06:53		07:03	
Station B	*Dep.*	06:04													
Station C	*Arr.*														
Station D	*Arr.*														
End	*Arr.*	06:11													

Start → End															
		SPR 9	IC 19	IC 21	SPR 11	IC 23	IC 25	SPR 13	IC 27	IC 29	SPR 15	IC 31	IC 33	SPR 17	
Start	*Dep.*	07:03		07:15	07:18		07:30	07:33		07:45	07:48		08:00	08:03	
Station A	*Arr.*	07:04			07:19			07:34			07:49			08:04	
Station B	*Arr.*	07:08		07:18	07:23		07:33	07:38		07:48	07:53		08:03	08:08	
Station B	*Dep.*														
Station C	*Arr.*														
Station D	*Arr.*														
End	*Arr.*														

End → Start															
		IC 2	SPR 2	IC 4	IC 6	SPR 4	IC 8	IC 10	SPR 6	IC 12	IC 14	SPR 8	IC 16	IC 18	*see below*
End	*Dep.*	06:00	06:03	06:07	06:15	06:18	06:22	06:30	06:33	06:37	06:45	06:48	06:52	07:00	
Station D	*Arr.*		06:04			06:19			06:34			06:49			
Station C	*Arr.*		06:08			06:23			06:38			06:53			
Station B	*Arr..*	06:06	06:12	06:13	06:21	06:27	06:28	06:36	06:42	06:43	06:51	06:57	06:58	07:06	
Station B	*Dep.*	06:07	06:16		06:24	06:34	06:32	06:43	06:49	06:47		07:04	07:02		
Station A	*Arr.*		06:20			06:38			06:53			07:08			
Start	*Arr.*	06:11	06:22		06:27	06:40	06:35	06:47	06:55	06:51		07:03	07:06		

End → Start															
		SPR 10	IC 20	IC 22	SPR 12	IC 24	IC 26	SPR 14	IC 28	IC 30	SPR 16	IC 32	IC 34	SPR 18	
End	*Dep.*	07:03	07:07	07:15	07:18	07:22	07:30	07:33	07:37	07:45	07:48	07:52	08:00	08:03	
Station D	*Arr.*	07:04			07:19			07:34			07:49			08:04	
Station C	*Arr.*	07:08			07:23			07:38			07:53			08:08	
Station B	*Arr..*	07:12	07:13	07:21	07:27	07:28	07:36	07:42	07:43	07:51	07:57	07:58	08:06	08:12	
Station B	*Dep.*	07:19	07:17		07:34	07:32		07:49	07:47		08:04	08:02	08:17	08:19	
Station A	*Arr.*	07:23			07:38			07:53			08:08			08:23	
Start	*Arr.*	07:25	07:21		07:40	07:36		07:55	07:50		08:10	08:05	08:21	08:25	

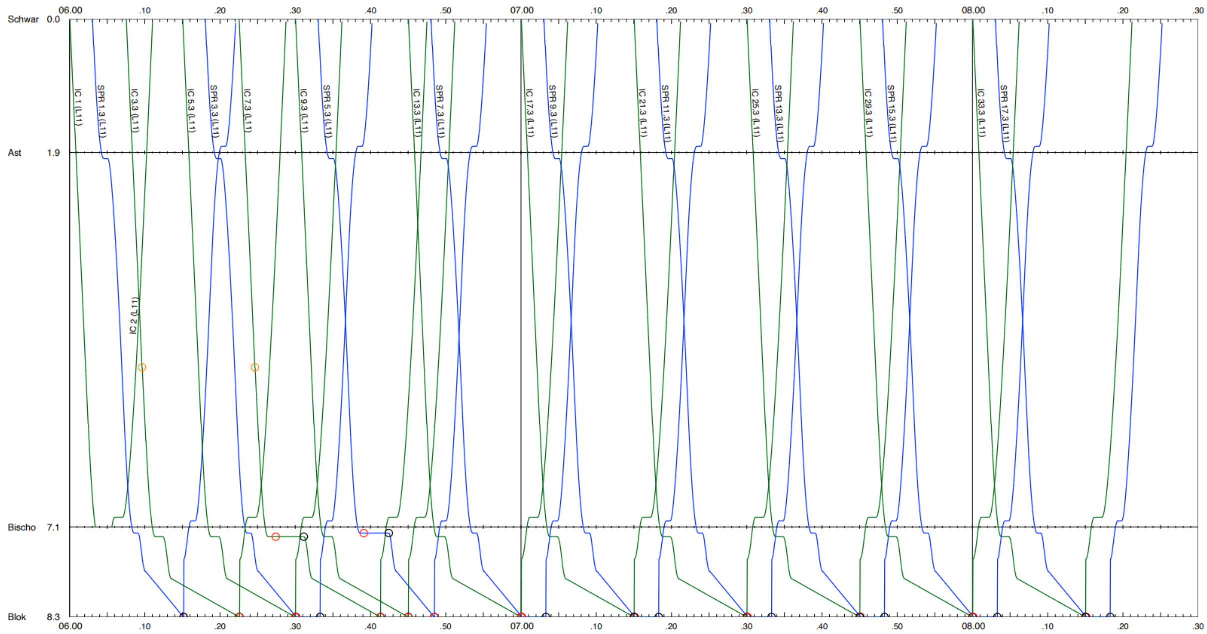


Figure F.43: Time-distance diagram layout 11 with persons near or at the tracks between stations B and C.

The summarized results for layout 11 can be found in Table F.35 in which still a negative score can be seen for the last disruption. This is mostly because all trains from the right are cancelled outside the model. 50% of all IC trains and 100% of all SPR trains coming from the left are now being short turned at B. There is room for more but than the high punctuality is decreased which is however not a problem since rate of cancelled services is more important than the punctuality as stated by the interviewees.

Table F.35: Results layout 11 for all simulated disruptions.

Line	Disruption	C [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L11	Broken train B1	18	0	100	0	12.50	3.90	3.50	-3.03
	Broken train B2	18	31	100	0	-2.88		-4.19	
	Broken train B-C (1)	18	29	100	0	-2.05		-3.77	
	Broken train B-C (2)	18	31	100	0	-2.88		-4.19	
	Persons B-C	18	39	97	27	-10.88		-10.08	

F14: Layout 12

Figure F.44 shows layout number 12 in which all black marked switches are used again. Still, trains cannot move from the outer track to the inner tracks before the stations but Sprinter trains using the inner tracks can even arrive on literally every track of station B. For a broken train on track 1 all IC trains are cancelled from both directions to get a balance at the start and at the end as mentioned which is required. In case a train breaks down at track 2, trains are easily rerouted to one of the other three tracks. In case of a broken train between B and C all trains of that category are cancelled in both directions. Of course, it is also possible to change tracks outside of the model and that IC and SPR trains use the tracks of the other train type. For a total blockage between B and C, again all trains coming from the right are cancelled outside of the model, while trains coming from the left can be short turned at B. IC trains have only one track to short turn (50% should be cancelled outside the model) and are not able to go back to the outer track on the other side and therefore need to use the Sprinter track to leave the model. Sprinter trains have two tracks to short turn although one would suffice. The results for a total blockage are given in Table F.36 and Figure F.45.

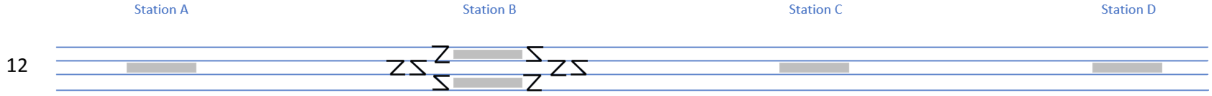


Figure F.44: Layout 12.

Table F.36: Timetable layout 12 with persons near or at the tracks between stations B and C.

Start → End															
		IC 1	SPR 1	IC 3	IC 5	SPR 3	IC 7	IC 9	SPR 5	IC 11	IC 13	SPR 7	IC 15	IC 17	*see below*
Start	*Dep.*	06:00	06:03	06:07	06:15	06:18	06:22	06:30	06:33	06:37	06:45	06:48	06:52	07:00	
Station A	*Arr.*		06:04			06:19			06:34			06:49			
Station B	*Arr.*	06:03	06:08	06:10	06:18	06:23	06:25	06:33	06:38	06:40	06:48	06:53	06:55	07:03	
Station B	*Dep.*	06:04	06:09	06:11	06:19	06:24	06:26	06:34	06:39	06:41	06:49	06:54	06:56	07:04	
Station C	*Arr.*		06:12			06:27			06:42			06:57			
Station D	*Arr.*		06:16			06:31			06:46			07:01			
End	*Arr.*	06:11	06:18	06:18	06:26	06:33	06:33	06:41	06:48	06:48	06:56	07:03	07:03	07:11	
Start → End															
		SPR 9	IC 19	IC 21	SPR 11	IC 23	IC 25	SPR 13	IC 25	IC 27	SPR 15	IC 29	IC 31	SPR 17	IC 33
Start	*Dep.*	07:03	07:07	07:15	07:18	07:22	07:30	07:33	07:37	07:45	07:48	07:52	08:00	08:03	08:07
Station A	*Arr.*	07:04			07:19			07:34			07:49			08:04	
Station B	*Arr.*	07:08	07:10	07:18	07:23	07:25	07:33	07:38	07:40	07:48	07:53	07:55	08:03	08:08	08:10
Station B	*Dep.*	07:09	07:11	07:19	07:24	07:26	07:34	07:39	07:41	07:49	07:54	07:56	08:04	08:09	08:11
Station C	*Arr.*	07:12			07:27			07:42			07:57			08:12	
Station D	*Arr.*	07:16			07:31			07:46			08:01			08:16	
End	*Arr.*	07:18	07:18	07:26	07:33	07:33	07:41	07:48	07:48	07:56	08:03	08:03	08:11	08:18	08:18
End → Start															
		IC 2	SPR 2	IC 4	IC 6	SPR 4	IC 8	IC 10	SPR 6	IC 12	IC 14	SPR 8	IC 16	IC 18	*see below*
End	*Dep.*	06:00	06:03	06:07	06:15	06:18	06:22	06:30	06:33	06:37	06:45	06:48	06:52	07:00	
Station D	*Arr.*		06:04			06:19			06:34			06:49			
Station C	*Arr.*		06:08			06:23			06:38			06:53			
Station B	*Arr..*	06:06	06:12	06:13	06:21	06:27	06:28	06:36	06:42	06:43	06:51	06:57	06:58	07:06	
Station B	*Dep.*	06:07	06:13	06:14	06:22	06:28	06:29	06:37	06:43	06:44	06:52	06:58	06:59	07:07	
Station A	*Arr.*		06:16			06:31			06:46			07:01			
Start	*Arr.*	06:11	06:18	06:18	06:26	06:33	06:33	06:41	06:48	06:48	06:56	07:03	07:03	07:11	
End → Start															
		SPR 10	IC 20	IC 22	SPR 12	IC 24	IC 26	SPR 14	IC 28	IC 30	SPR 16	IC 32	IC 34	SPR 18	IC 36
End	*Dep.*	07:03	07:07	07:15	07:18	07:22	07:30	07:33	07:37	07:45	07:48	07:52	08:00	08:03	08:07
Station D	*Arr.*	07:04			07:19			07:34			07:49			08:04	
Station C	*Arr.*	07:08			07:23			07:38			07:53			08:08	
Station B	*Arr..*	07:12	07:13	07:21	07:27	07:28	07:36	07:42	07:43	07:51	07:57	07:58	08:06	08:12	08:13
Station B	*Dep.*	07:13	07:14	07:22	07:28	07:29	07:37	07:43	07:44	07:52	07:58	07:59	08:07	08:13	08:14
Station A	*Arr.*	07:16			07:31			07:46			08:01			08:16	
Start	*Arr.*	07:18	07:18	07:26	07:33	07:33	07:41	07:48	07:48	07:56	08:03	08:03	08:11	08:18	08:18

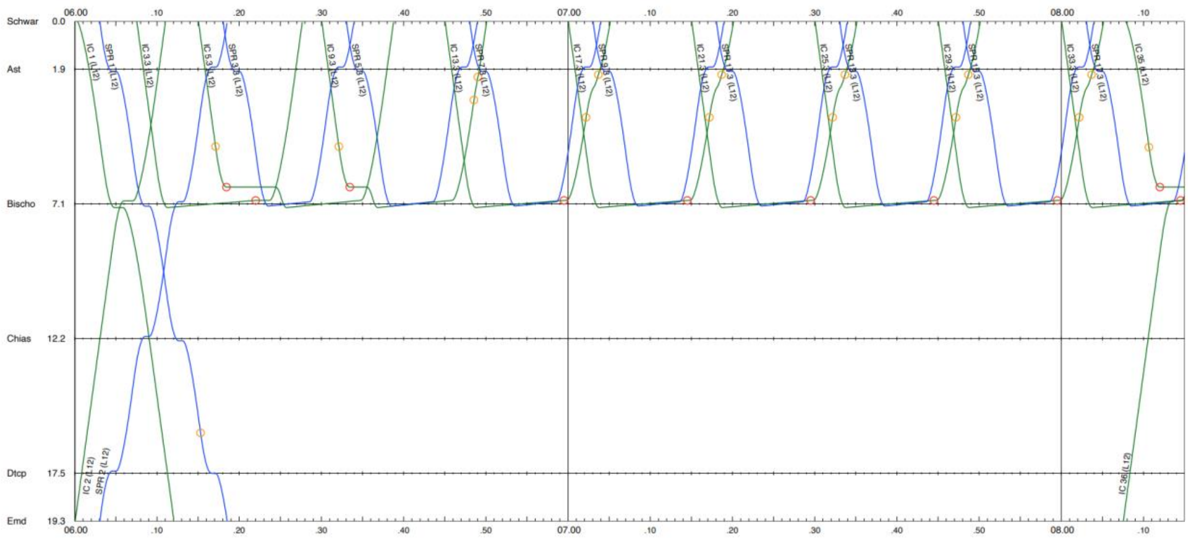


Figure F.45: Time-distance diagram layout 12 with persons near or at the tracks between stations B and C.

The results for layout 12 are shown in Table F.37 in which can be seen that the rate of cancelled services still is high, but at least under the 50% maximum that is allowed.

Table F.37: Results layout 12 for all simulated disruptions.

Line	Disruption	C [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L12	Broken train B1	16	25	100	0	0.19		-1.65	
	Broken train B2	16	0	99	0	12.40		4.40	
	Broken train B-C (1)	16	25	100	0	0.19	4.10	-1.65	-2.13
	Broken train B-C (2)	16	31	98	0	-3.17		-3.48	
	Persons B-C	16	39	100	37	-3.90		-9.93	

F15: Layout 13

This layout is given in Figure F.46 and as can be seen switches are in a different configuration as in the previous layouts. The switches in blue are not used in the simulations. In case of a broken train at tracks B1 or B2 this will not lead to any problem since trains are able to get rerouted easily within station B. A broken train between B and C will ensure short turning at B but better will be that trains outside of the model on the right side are being rerouted to the other tracks but this is out of scope for this research. For a complete blockage between B and C this layout offers more short turning possibilities in B for trains coming from the left since IC trains coming from track 4 can use tracks 1, 2 and 3 for short turning and leave the model via the outer IC track again. SPR trains can use tracks 1, 2 and 3 as well and can leave the model via track 2 which is a SPR track. Two tracks will be used for short turning IC trains and one for SPR trains meaning that all 8 IC and 4 SPR trains that are running per hour can be short turned in this switch configuration. The results are shown in Table F.38 and Figure F.47.

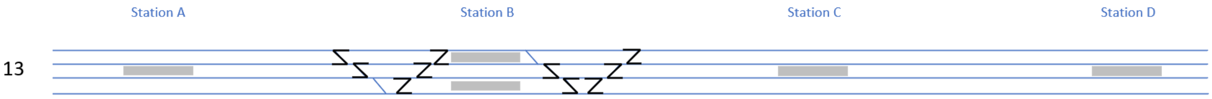


Figure F.46: Layout 13.

Table F.38: Timetable layout 13 with persons near or at the tracks between B and C.

Start → End															
		IC 1	SPR 1	IC 3	IC 5	SPR 3	IC 7	IC 9	SPR 5	IC 11	IC 13	SPR 7	IC 15	IC 17	*see below*
Start	Dep.	06:00	06:03	06:07	06:15	06:18	06:22	06:30	06:33	06:37	06:45	06:48	06:52	07:00	
Station A	Arr.		06:04			06:19			06:34			06:49			
Station B	Arr.	06:03	06:08	06:10	06:18	06:23	06:25	06:33	06:38	06:40	06:48	06:53	06:55	07:03	
Station B	Dep.	06:04	06:09	06:11	06:19	06:24	06:26	06:34	06:39	06:41	06:49	06:54	06:56	07:04	
Station C	Arr.		06:12			06:27			06:42			06:57			
Station D	Arr.		06:16			06:31			06:46			07:01			
End	Arr.	06:11	06:18	06:18	06:26	06:33	06:33	06:41	06:48	06:48	06:56	07:03	07:03	07:11	
Start → End															
		SPR 9	IC 19	IC 21	SPR 11	IC 23	IC 25	SPR 13	IC 25	IC 27	SPR 15	IC 29	IC 31	SPR 17	IC 33
Start	Dep.	07:03	07:07	07:15	07:18	07:22	07:30	07:33	07:37	07:45	07:48	07:52	08:00	08:03	08:07
Station A	Arr.	07:04			07:19			07:34			07:49			08:04	
Station B	Arr.	07:08	07:10	07:18	07:23	07:25	07:33	07:38	07:40	07:48	07:53	07:55	08:03	08:08	08:10
Station B	Dep.	07:09	07:11	07:19	07:24	07:26	07:34	07:39	07:41	07:49	07:54	07:56	08:04	08:09	08:11
Station C	Arr.	07:12			07:27			07:42			07:57			08:12	
Station D	Arr.	07:16			07:31			07:46			08:01			08:16	
End	Arr.	07:18	07:18	07:26	07:33	07:33	07:41	07:48	07:48	07:56	08:03	08:03	08:11	08:18	08:18
End → Start															
		IC 2	SPR 2	IC 4	IC 6	SPR 4	IC 8	IC 10	SPR 6	IC 12	IC 14	SPR 8	IC 16	IC 18	*see below*
End	Dep.	06:00	06:03	06:07	06:15	06:18	06:22	06:30	06:33	06:37	06:45	06:48	06:52	07:00	
Station D	Arr.		06:04			06:19			06:34			06:49			
Station C	Arr.		06:08			06:23			06:38			06:53			
Station B	Arr..	06:06	06:12	06:13	06:21	06:27	06:28	06:36	06:42	06:43	06:51	06:57	06:58	07:06	
Station B	Dep.	06:07	06:13	06:14	06:22	06:28	06:29	06:37	06:43	06:44	06:52	06:58	06:59	07:07	
Station A	Arr.		06:16			06:31			06:46			07:01			
Start	Arr.	06:11	06:18	06:18	06:26	06:33	06:33	06:41	06:48	06:48	06:56	07:03	07:03	07:11	
End → Start															
		SPR 10	IC 20	IC 22	SPR 12	IC 24	IC 26	SPR 14	IC 28	IC 30	SPR 16	IC 32	IC 34	SPR 18	IC 36
End	Dep.	07:03	07:07	07:15	07:18	07:22	07:30	07:33	07:37	07:45	07:48	07:52	08:00	08:03	08:07
Station D	Arr.	07:04			07:19			07:34			07:49			08:04	
Station C	Arr.	07:08			07:23			07:38			07:53			08:08	
Station B	Arr..	07:12	07:13	07:21	07:27	07:28	07:36	07:42	07:43	07:51	07:57	07:58	08:06	08:12	08:13
Station B	Dep.	07:13	07:14	07:22	07:28	07:29	07:37	07:43	07:44	07:52	07:58	07:59	08:07	08:13	08:14
Station A	Arr.	07:16			07:31			07:46			08:01			08:16	
Start	Arr.	07:18	07:18	07:26	07:33	07:33	07:41	07:48	07:48	07:56	08:03	08:03	08:11	08:18	08:18

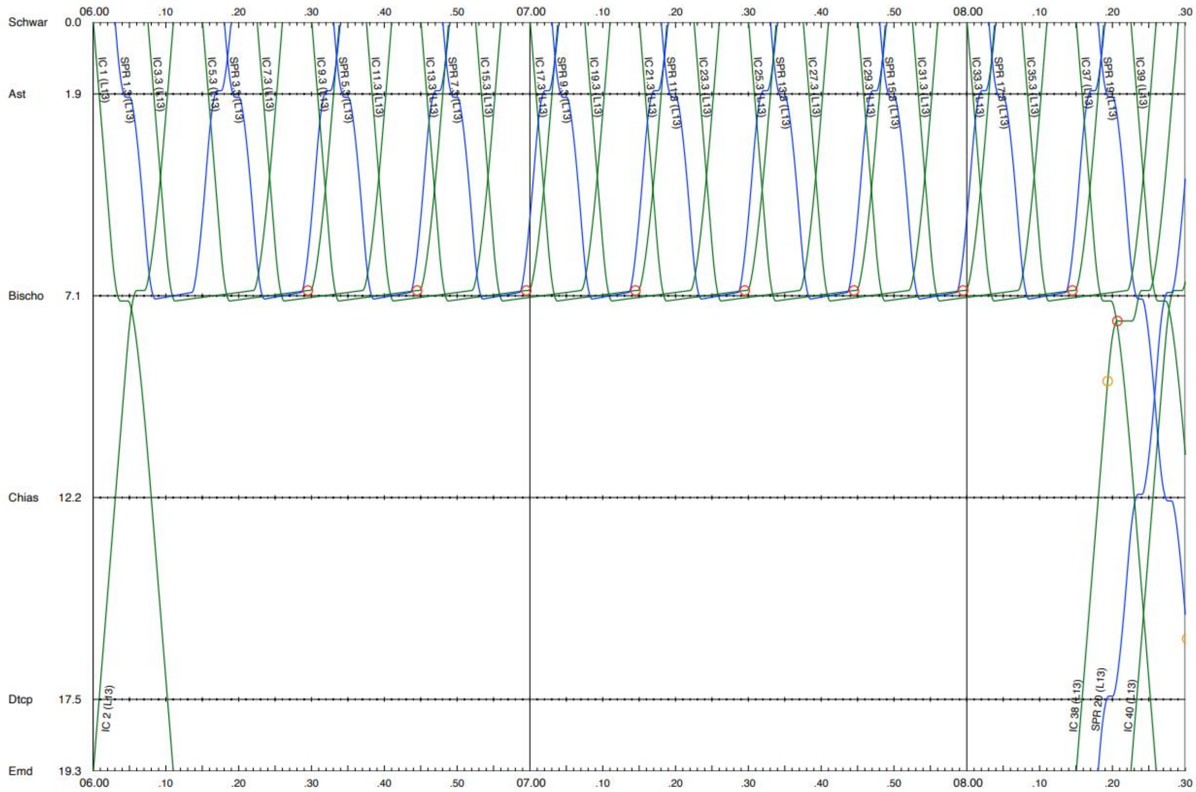


Figure F.47: Time-distance diagram layout 13 with persons near or at the tracks between B and C.

All results from layout 13 are summarized in Table F.38 and as can be seen scores are all positive and increased by multiple points compared to the scores of the previous layouts.

Table F.39: Results layout 13 for all simulated disruptions.

Line	Disruption	C [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L13	Broken train B1	20	0	100	0	12.50		2.50	
	Broken train B2	20	0	100	0	12.50		2.50	
	Broken train B-C (1)	20	25	100	0	0.19	6.34	-3.65	-0.96
	Broken train B-C (2)	20	31	98	0	-3.17		-5.48	
	Persons B-C	20	33	100	0	-3.90		-5.70	

F16: Layout 14

This last layout, shown in Figure F.48, is actually the only layout where the number of tracks changes after station B. There are thus also no other layouts to compare this layout with but it is interesting to look how trains are being rerouted, retimed, reordered and short turned in this layout. In the regular timetable two IC and two SPR trains are running from start to end and back, but frequency between start and B is doubled meaning that B is also a regular turning station and those trains that are turned have a relatively long turning time (around 25 minutes) which means after departure the next arrival is almost already there which makes train rescheduling during a disruption interesting. In case of a broken train at B1 which is the turning track for the SPR only the next SPR is hindered since the disruption takes one hour. This hindered SPR train is being rerouted to one of the through tracks and leaves station B within 5 minutes again as a slightly delayed train which was actually planned to be served by the broken train. The broken train however, will function as a replacement for the earlier departed train. Therefore the rate of cancelled services remains 0. The time-distance diagram can be found in Figure F.49.

Figure F.48: Layout 14.

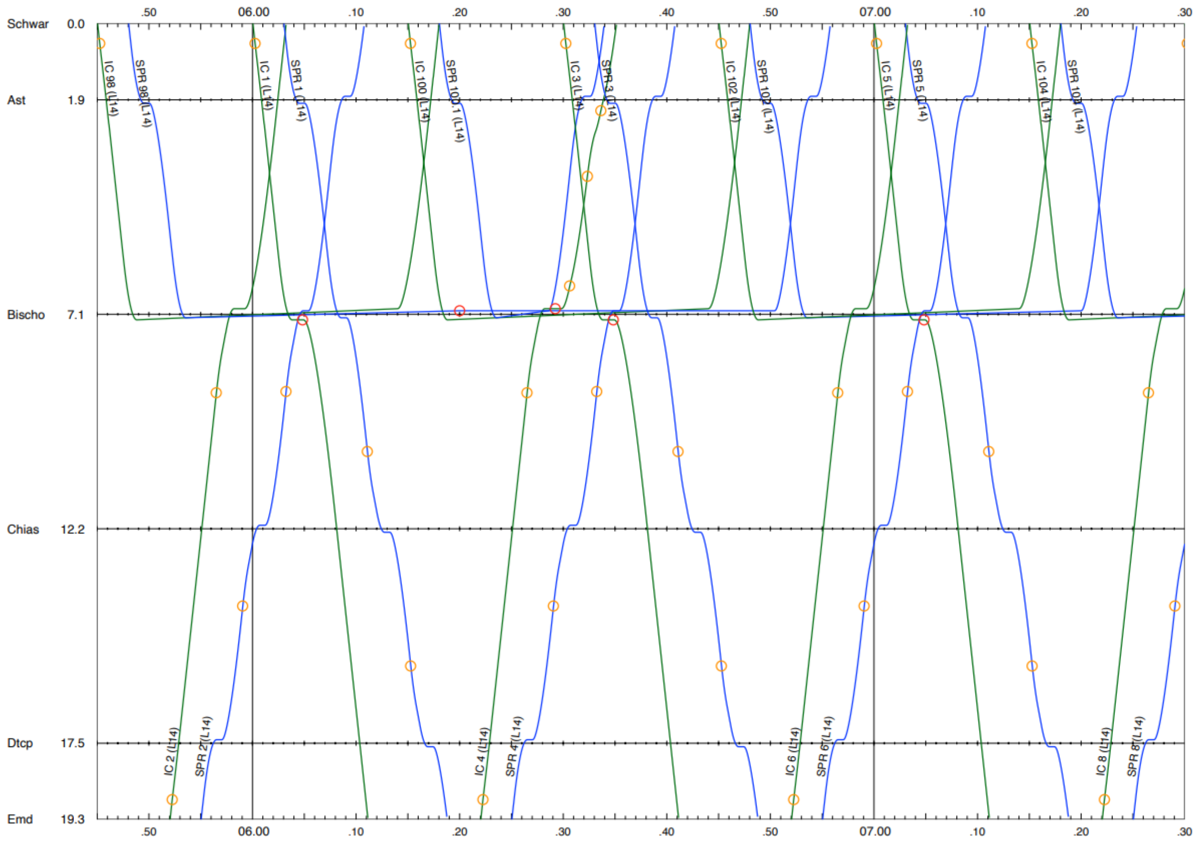


Figure F.49: Time-distance diagram layout 14 with broken train at B1.

For a broken train at the turning track of the IC trains a similar approach is possible, however the delay of the 'next' IC is a couple minutes longer which will not influence the punctuality as this is measured in a percentage of trains arriving at least 5 minutes late. A broken train on one of the through tracks however could lead to other problems and this is simulated for a broken SPR train on track 2. The results are shown in Figure F.50 but although tracks 1 and 4 are used for the turning tracks track 3 can be used for both directions in an alternating pattern: first two trains from the single track towards the double track and then two tracks towards the single track part.

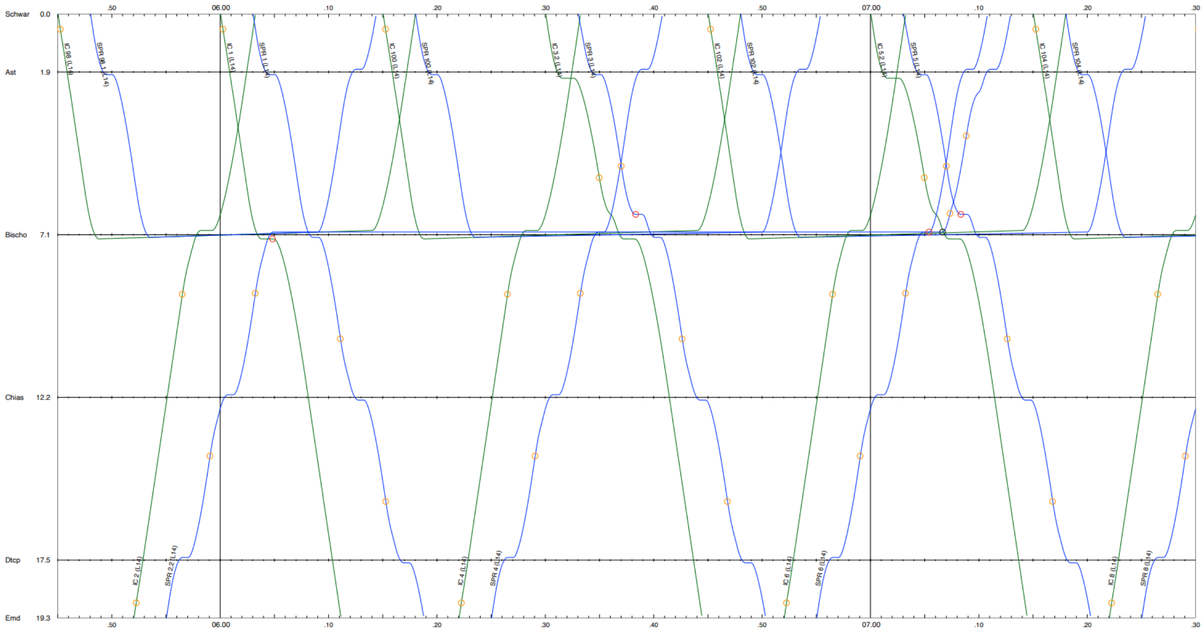


Figure F.50: Time-distance diagram layout 14 with broken train at B2.

In case of a full blockage of the line between B and C trains from the left can all be short turned at station B while trains from the right are short turned at C (all IC trains) and at D (all SPR trains). This on the right is chosen because an IC train enters the model first and afterwards a SPR train enters the model after 3 minutes. It is thus easier to let the IC train short turn at C and the SPR at D since there are no switches to overtake. The time-distance diagram is shown in Figure F.51.

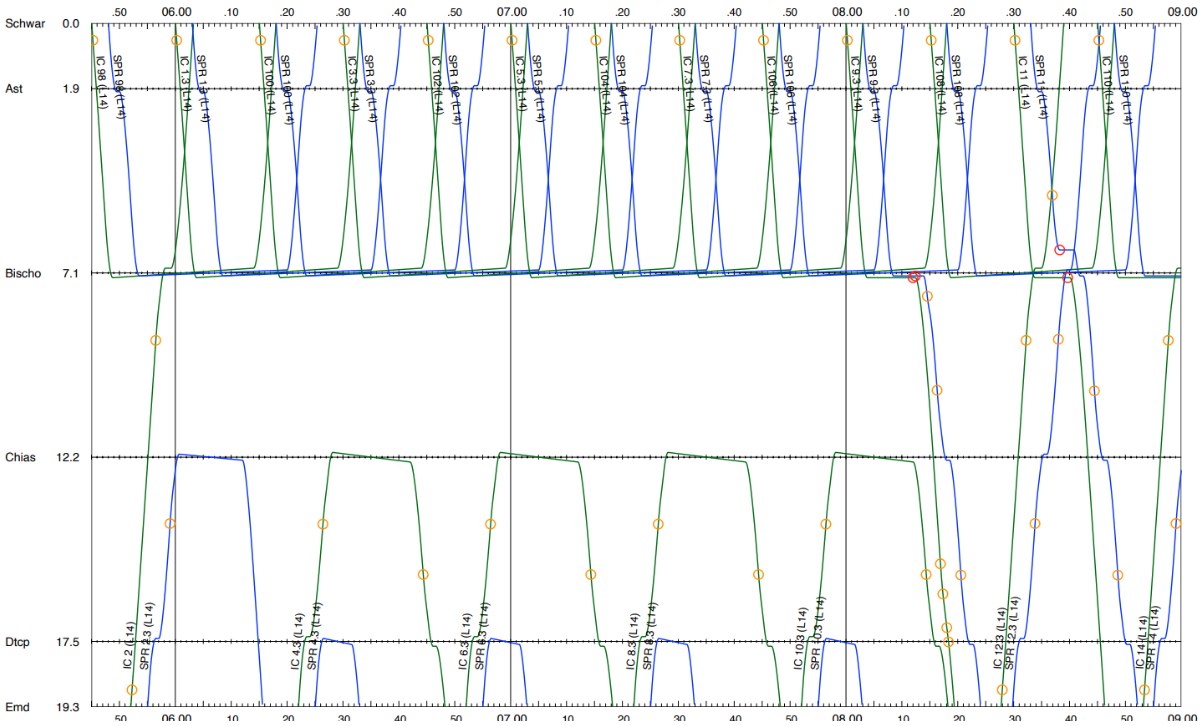


Figure F.51: Time-distance diagram layout 14 with persons near or at the tracks between stations B and C.

The results for this layout are summarized in Table F.40.

Table F.40: Results layout 14 for all simulated disruptions.

Line	Disruption	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
L14	Broken train B1	9	0	99	0	12.36	6.29	7.86	3.85
	Broken train B2	9	0	96	15	10.17		5.67	
	Broken train B-C	9	12	94	5	5.10		3.63	
	Persons B-C	9	12	94	5	5.10		3.63	

F17: Some switch configurations in the Netherlands

Figure F.52 to Figure F.54 show different kind of switch configurations in the Netherlands. There are many more variants, but these show some possibilities for short turning, overtaking and meet-pass operations and are also simplified and included in the given layouts in section 6.3. Figure F.52 shows a configuration that can be used for two of the three mentioned characteristics. Intercity and highspeed trains can pass the station at the outer tracks of Driebergen-Zeist, Sprinter trains and some Intercity trains can “meet” at the platform at one of the inner tracks while faster trains pass the slower trains at the same moment. Short turning is possible by using the reverse track on the east of the station and is only possible for trains coming from the west and heading back west. Between Bilthoven and Den Dolder in Figure F.53 there is a third track enabling the opportunity for fast trains to overtake slow trains. The single track depicted in Figure F.54 has a second track at the station of Soest. This facilitates meet and pass operations with trains coming from the other direction and thus enables crossing trains.

Figure F.52: Switch location configuration near Driebergen-Zeist (Sporenplan, 2023).

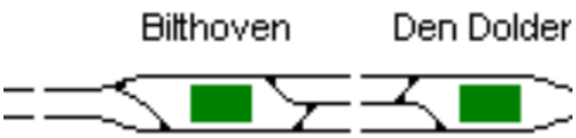


Figure F.53: Switch location configuration between Bilthoven and Den Dolder (Sporenplan, 2023).

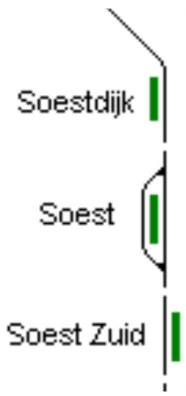


Figure F.54: Switch location configuration near Soest (Sporenplan, 2023).

One of the goals of this research is to find a good fitting switch location configuration to have an as high as possible capacity during disruptions. For this it is good to gain knowledge about headways of trains. A headway is the distance or duration between two consecutive trains riding on the same track. For different standard situations minimum headways are determined as a general norm that must prevent conflicts between trains (Bešinović, 2022). Especially for two trains that need to cross each other it is important to know how many minutes or seconds should be in between these two consecutive trains. If this is known, it is possible to manually calculate capacity on the tracks during disruption. There are some standardized headways introduced by ProRail, but headways depend on the signalling system and the layout of the block sections. In this model the trains enter the model with at least 3 minutes between each other. This also applies to a train that leaves the model until the next moment a train can enter the model again on the same track.

Appendix G. Case study

This Appendix gives all results from the case study which is the Dutch railway line Utrecht Centraal – Arnhem Centraal. This line was chosen because of the two IC stations along the route with different interesting switch layout configurations and different stopping patterns, overtaking and timetables. Nine different disruptions are simulated and for some cases new switch layouts were proposed. These are simulated as well and the results are compared to each other. In the main report in chapter 7.3 the results for a broken train at the station of Bunnik are shown. This Appendix will give all other results in detail and the switch layout for this line for all simulated disruptions is shown in Figure G.1. In some simulations switches are added but this will be explained clearly in the corresponding subsection. Again sub-weightings should be applied to all stations to be able to calculate scores for all alternatives. These sub-weightings should again sum up to 1 and the Intercity stations receive again a higher weighting than other stations because of the regional hub function. Different to the model, both endings, also should get weighting since trains also stop there. In the model there were no stations at both ends, but now these two stations (Utrecht Centraal and Arnhem Centraal) both get a weighting of 0.2 since trains are interfering with other trains there and continue their journey and delays can have an oil-slick effect. The two important Intercity station in between (Driebergen-Zeist and Ede-Wageningen) are also important and get a weighting of 0.1. All other six stations receive a weighting of 0.067.

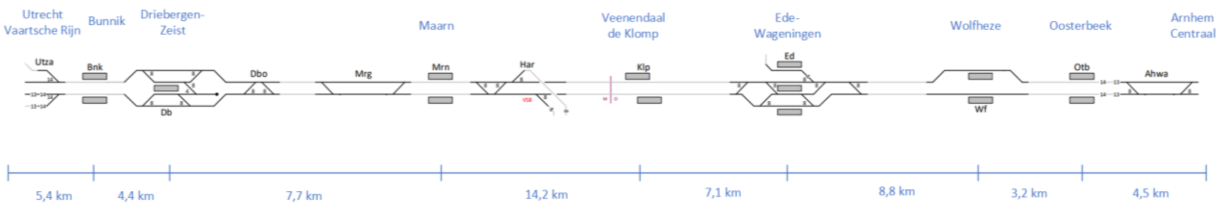


Figure G.1: Switch configuration Utrecht Centraal - Arnhem Centraal (Hofstra, 2022).

G1: Broken train Driebergen-Zeist track 1

The benefit of the station Driebergen-Zeist is the fact that there are four tracks which means that trains can overtake via the outer tracks. West (left on the map) and east (right on the map) are both double track parts which means that riding towards the station on the right track a train can reach the station on the platform track (inner track) or on the outer overtaking track. In the situation a train gets stuck on track 1 which is the upper inner track in Figure G.1 and is used by trains towards Utrecht, the station cannot be used in that direction until the broken train is moved away. However, all trains can use the outer track and cancel their stop at Driebergen-Zeist. This will lead to Sprinter passengers from Veenendaal and Rhenen that need to change at Bunnik on a train back to Driebergen-Zeist. Their travel time increases by 10 to 20 minutes depending on which train series they are taking since these Sprinter trains are not running every 15 minutes, but in a 10 - 20 minute pattern to fit in the pattern of the Intercity trains that run every 10 minutes. Intercity passengers from Arnhem will need to travel to Utrecht Centraal and then take a train back to Driebergen-Zeist which will increase travel time by 25 minutes. Unfortunately, it was not possible to add a temporary extra Intercity stop at Bunnik because of the length of the platform but this would only decrease the extra travel time for passengers coming from Ede-Wageningen, Arnhem and Nijmegen with destination Driebergen-Zeist which is estimated to be not a huge amount of passengers since most are through passengers towards Utrecht and Amsterdam. The time-distance diagram can be found in Figure G.2 in which can be seen that for a full hour trains towards Utrecht are skipping Driebergen-Zeist. As conclusion, this situation with a broken train can actually be solved pretty easy and without problems. Passengers from Arnhem with destination Driebergen-Zeist are hindered with some extra travel time, but for passengers starting their journey in Driebergen-Zeist it is inconvenient since no trains are running to Utrecht for a whole hour, but as Driebergen-Zeist is also a big regional hub for buses and buses to Utrecht are running almost every 5 minutes during rush hour the problems of skipping this station will be minimal.

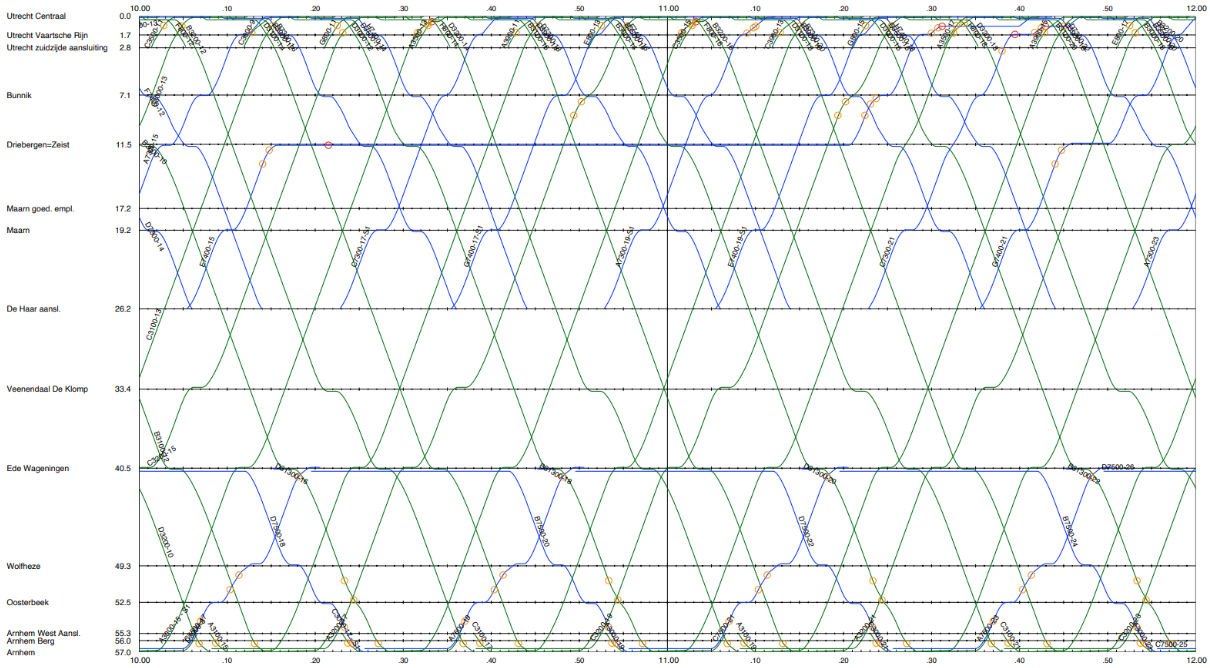


Figure G.2: Time-distance diagram broken train at Driebergen-Zeist track 1.

G2: Broken train Driebergen-Zeist track 2

A broken train at track 2 in Driebergen-Zeist will lead to trains coming from Utrecht skipping and thus overtaking Driebergen-Zeist. Intercity passengers need to travel via Ede-Wageningen (travel time increases by 60 minutes) and Sprinter passengers need to travel via Maarn and take a train back to Driebergen-Zeist which will lead to an increase in travel time of 40 minutes. Also in this case, it would be better for passengers with destination Driebergen-Zeist to take a bus from Utrecht Centraal since a lot of passengers are changing at Driebergen-Zeist from train to bus which can take already take place at Utrecht and only leads to a smaller increase in travel time. The results are shown in Figure G.3.

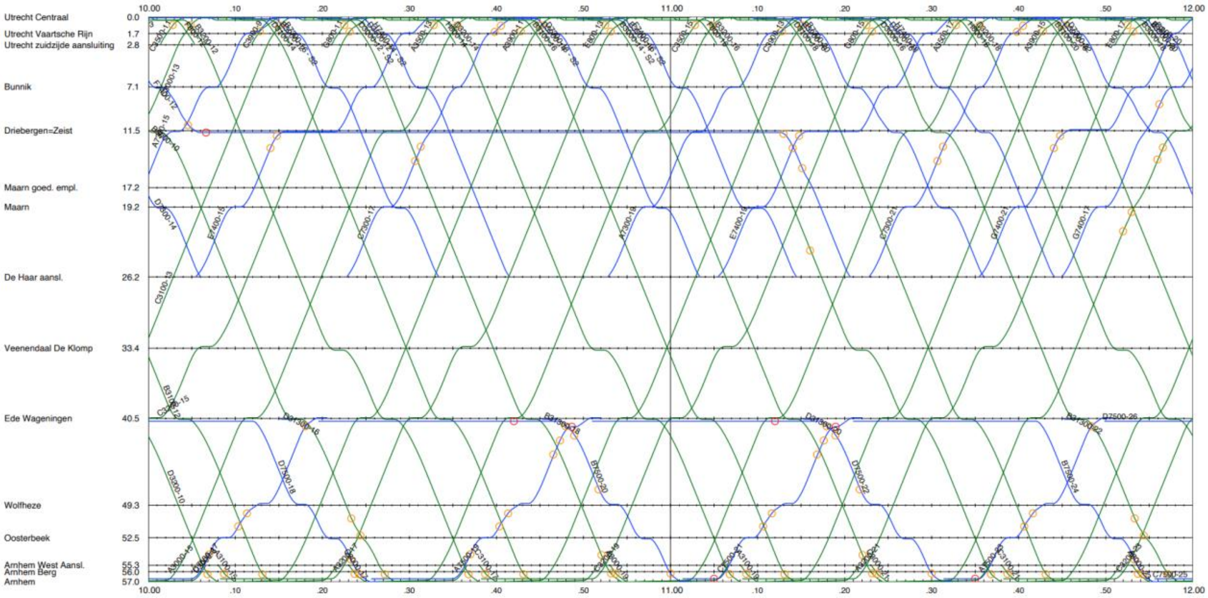


Figure G.3: Time-distance diagram broken train at Driebergen-Zeist track 2.

G3: Broken train Ede-Wageningen track 3

The station Ede-Wageningen has a completely different timetable than Driebergen-Zeist. Sprinter 7300 and 7400 are only at Driebergen-Zeist, but there is a Sprinter 7500 which has Ede-Wageningen as destination. That train thus turns at Ede-Wageningen which takes some time and uses a lot of track capacity. Furthermore, all six Intercity trains per hour per direction dwell at Ede-Wageningen while at Driebergen-Zeist this was only the case for two per hour per direction. Track 1 in Ede-Wageningen is used by another local train that serves passengers to Barneveld and Amersfoort but no disruptions are simulated on that track since those trains are not crossing or using the tracks used by NS trains. In case of a broken train at track 3 which is the track used by Intercity trains towards Utrecht, the next Intercity trains in that direction should use track 4 which is the track that is used to turn the Sprinter coming from Arnhem. Because of the high capacity on the line between Ede-Wageningen and Arnhem Centraal and the very small stations for the Sprinter in between (Oosterbeek and Wolfheze) the Sprinter service will be cancelled two times to clear this track 4 at Ede-Wageningen for the Intercity trains. The Sprinter could go back to Arnhem earlier than scheduled but it can also be rerouted to Maarn Goederen where it can be (short) turned. This is also done in the simulations and the results are shown in Figure G.4 in which two blue lines are shown towards Maarn Goederen.

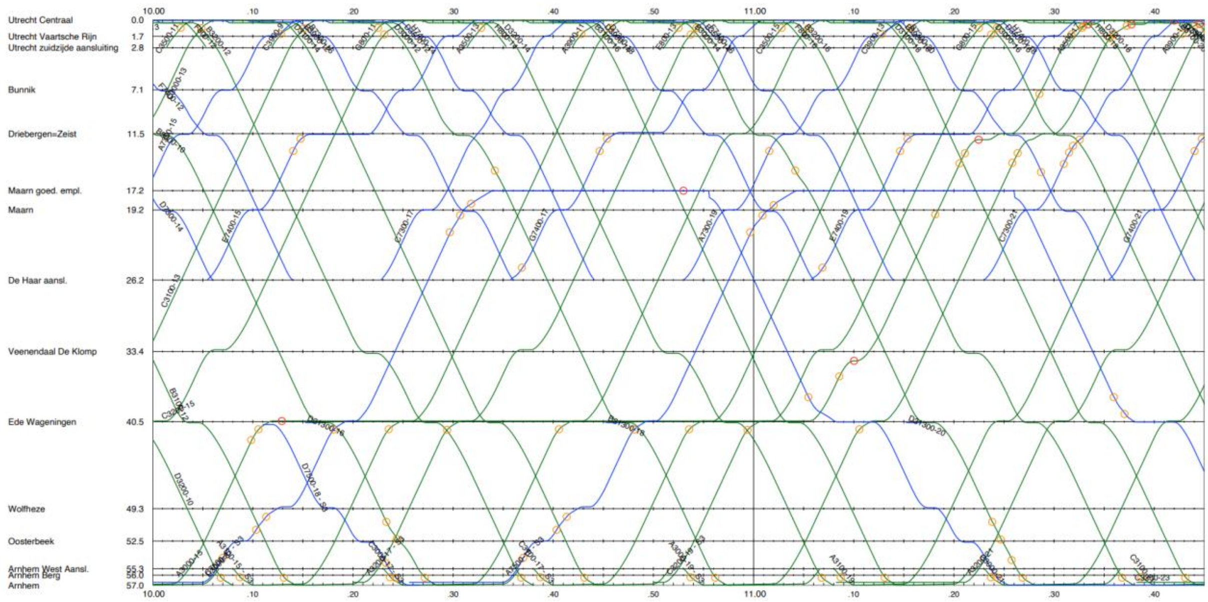


Figure G.4: Time-distance diagram broken train at Ede-Wageningen track 3.

G4: Broken train Ede-Wageningen track 4

A broken train at track 4 in Ede-Wageningen only influences the Sprinter train from Arnhem Centraal to Ede-Wageningen. One train to Arnhem Centraal and one train back to Ede-Wageningen are cancelled, but also one service is moved to Maarn Goederen again. The results are shown in Figure G.5

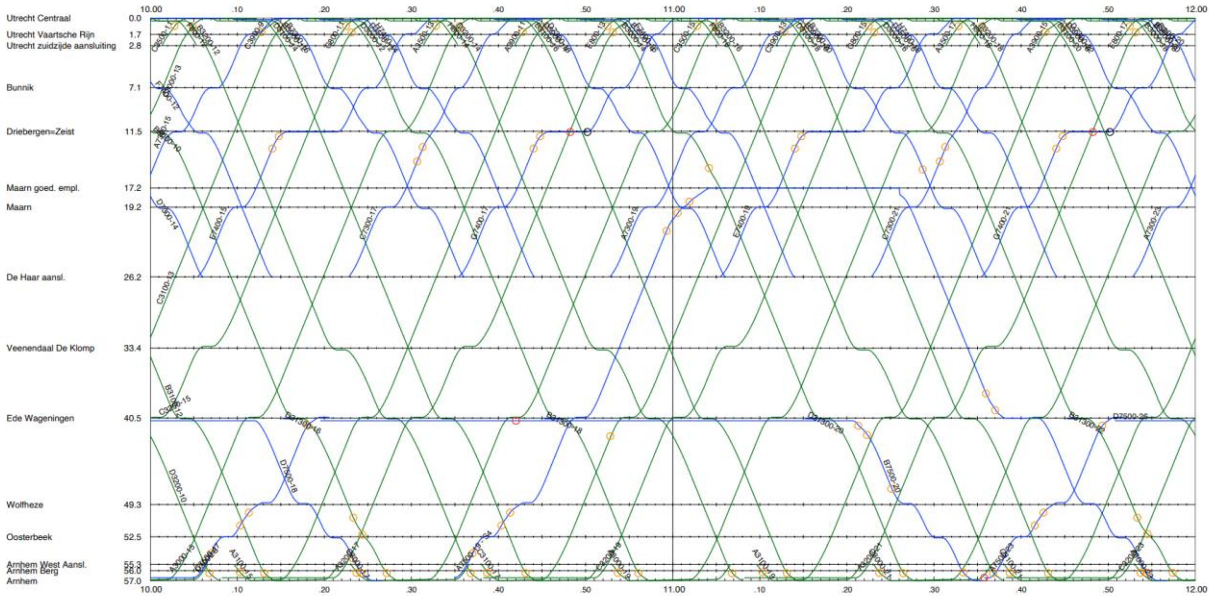


Figure G.5: Time-distance diagram broken train at Ede-Wageningen track 4.

G5: Broken train Ede-Wageningen track 5

A broken train at track 5 will lead to the same train rescheduling as a broken train at track 3 since track 5 is used by all Intercity trains towards Arnhem. The Intercity trains will use track 4 to Arnhem and two Sprinter services are turned at Maarn Goederen. The results are given in Figure G.6.

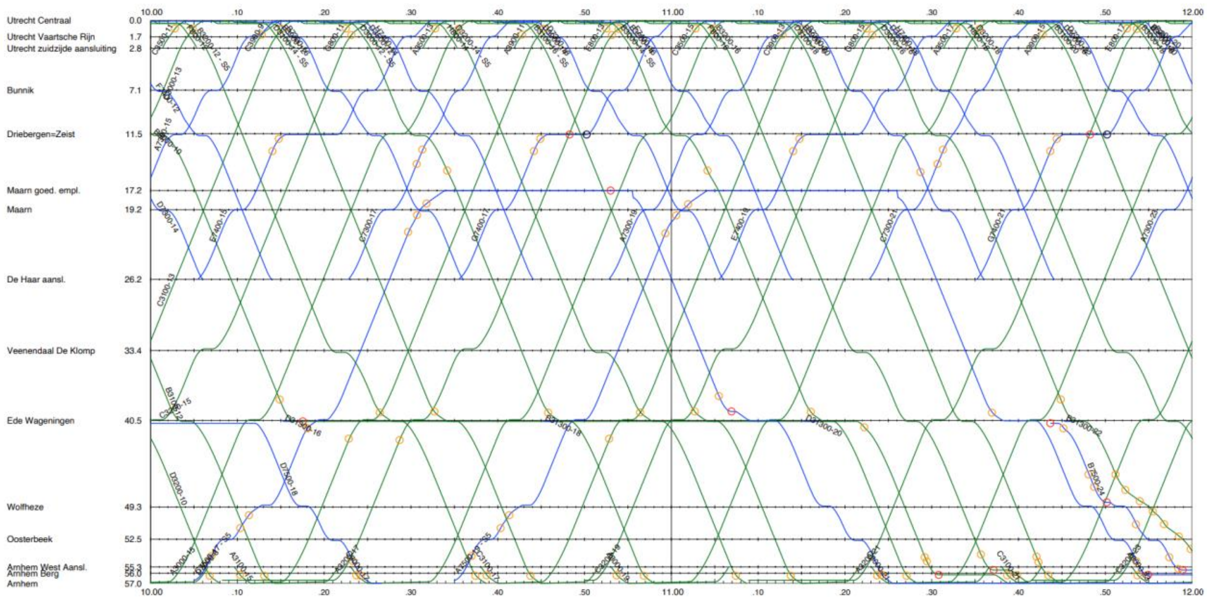


Figure G.6: Time-distance diagram broken train at Ede-Wageningen track 5.

G6: Broken train Bunnik track 1

The results for a broken train at track 1 in Bunnik are explained in detail in the main report in section 7.3. This is the first simulated broken train between two bigger stations (Utrecht Centraal and Driebergen-Zeist) and this led to problems in capacity between these two stations because of the switch layout at both stations. Therefore two alternatives have been designed and these are simulated as well and the results are compared to the current situation. As a conclusion: switches on the west side of Driebergen-Zeist can lead to lower rate of cancelled services and a higher score. Adding switches also on the east side of Utrecht decreases the score again slightly from which can be concluded that the switches are more necessary at Driebergen-Zeist as mentioned in section 7.3.

G7: Broken train Veenendaal de Klomp track 1

In case there is a broken train at de Klomp trains are able to take the switches west of Ede-Wageningen and at the junction 'de Haar' to move to the other track. Capacity is insufficient to accommodate all in total twelve trains per hour due to the signalling distance in the 'wrong' direction. This will lead to some cancellations and bundled train services between de Haar and Ede-Wageningen. The time-distance diagram can be found in Figure G.7.

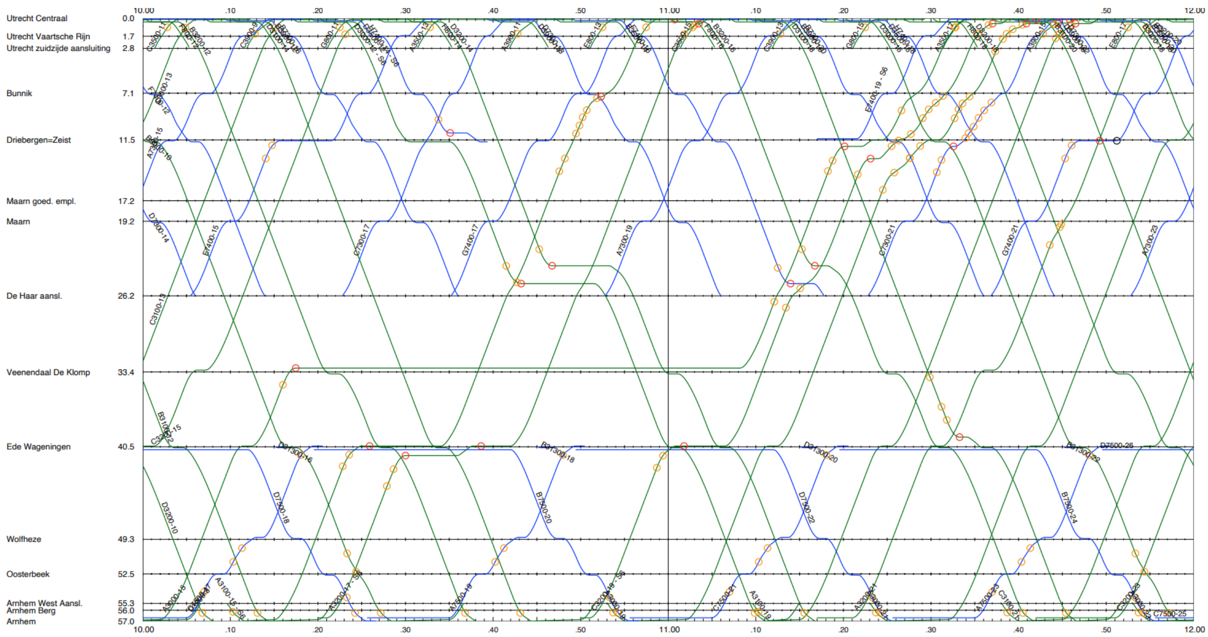


Figure G.7: Time-distance diagram broken train Veenendaal de Klomp track 1.

G8: Broken train Oosterbeek track 1

The same problem as in Bunnik and de Klomp arises in Oosterbeek when there is a broken train at track 1 there. The block distance is long and therefore capacity is low for trains running on the track that is actually for the opposite direction. All Sprinter trains are cancelled since it is a Sprinter that is simulated to be broken and even 2/3 of all Intercity trains are being short turned at Ede-Wageningen or Arnhem Centraal. To increase capacity between these two stations another, not simulated, tactic could be used in which trains are coupled to double the length. Between Utrecht Centraal and Ede-Wageningen and after Arnhem Centraal these trains can then be decoupled again and ride as separate trains. For this, the train length should be shorter than the longest platform in Ede-Wageningen or Arnhem Centraal. The model used VIRM-10, but the case study used VIRM-6 which can be doubled to VIRM-12. Doubling a VIRM-10 which already consist of two train parts is not possible as the train becomes too long for the longest existing platforms in the Netherlands. The results are shown in Figure G.8.

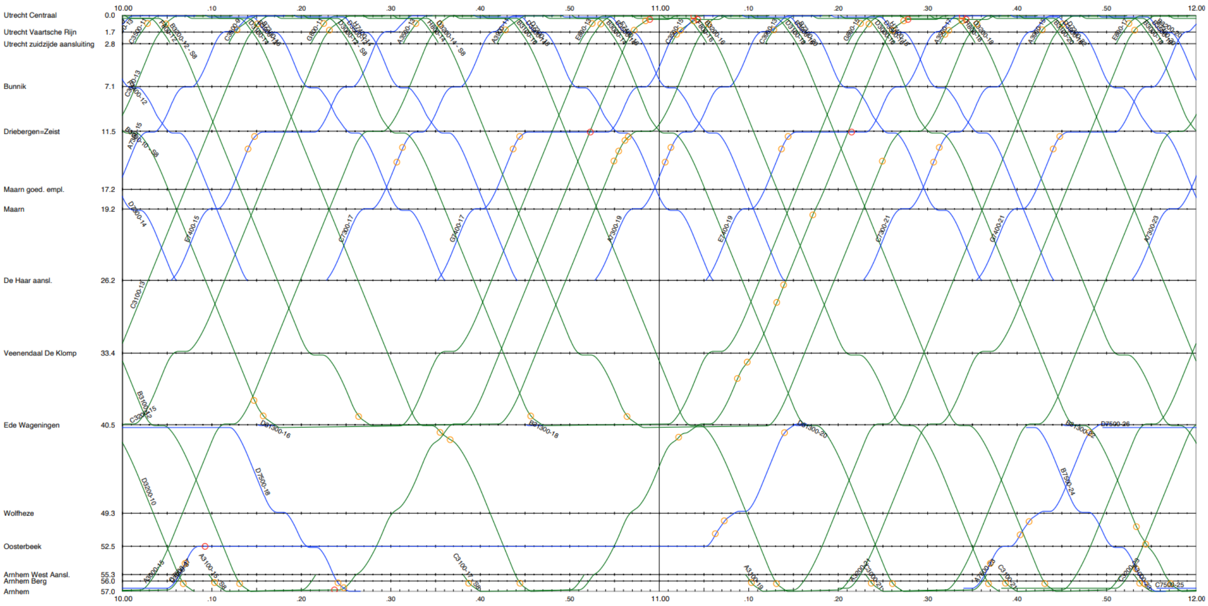


Figure G.8: Time-distance diagram broken train at Oosterbeek track 1.

G9: Persons near or at the track Bunnik

This is the only full track blockage that is simulated for the case study which causes short turning at Utrecht Centraal and Driebergen-Zeist. SPR 7300 and 7400 can short turn at both tracks at Utrecht Vaartsche Rijn. For this, the station should be accommodated with exit signals. Due to this short turning there, IC trains can use tracks 14/15 as well for their short turning movements because of the distance between corridors 18/19 and 5/7. If it is not possible to short turn six IC trains per hour at track 14/15 in Utrecht Centraal a part of these should be rerouted to Houten Castellum where they can turn and go back via the IC tracks to track 5. In case of a disruption after Houten the opposite should also be used as mentioned in chapter 7.3 where trains towards 's-Hertogenbosch can partly be short turned at Driebergen-Zeist. Trains from Rhenen are completely cancelled but at Driebergen-Zeist there is enough capacity to short turn six IC trains per hour since both tracks can be used and because of the four available switches on the east of the station. The results are given in Figure G.9.

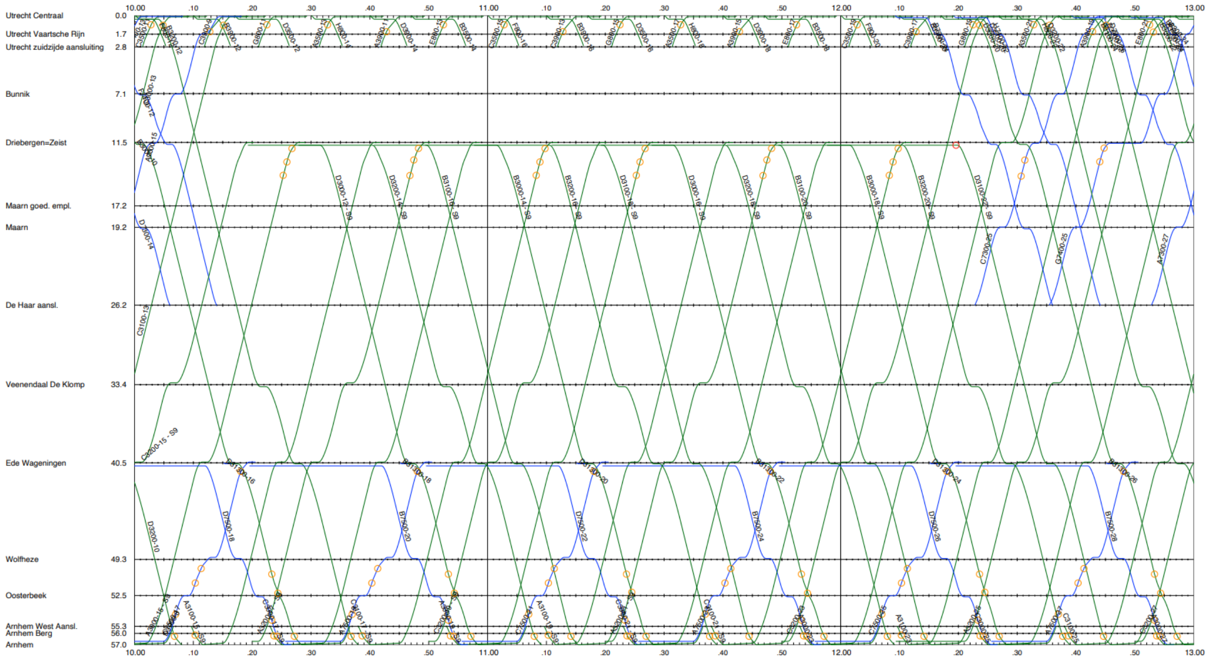


Figure G.9: Time-distance diagram persons near or at the tracks Bunnik.

All results and scores for all disruptions can be found in Table F.40.

Table G.1: Results case study.

Line	SW [# of switches]	RCS [%]	P [%]	T [min]	R	R̄	S	S̄
Broken train Driebergen-Zeist track 1	33	2.40	99.20	0	11.80		-4.70	
Broken train Driebergen-Zeist track 2	33	2.40	100	0	11.90		-4.60	
Broken train Ede-Wageningen track 3	33	3.46	98.80	0	11.49		-5.02	
Broken train Ede-Wageningen track 4	33	3.46	98.27	0	11.42		-5.08	
Broken train Ede-Wageningen track 5	33	3.46	98.67	0	11.47	10.8	-5.03	-6.12
Broken train Bunnik track 1	33	14.6	85.87	35	2.71		-13.78	
Broken train de Klomp track 1	33	7.47	93.73	25	6.72		-9.78	
Broken train Oosterbeek track 1	33	14.93	98.8	5	7.99		-8.51	
Persons on tracks Bunnik	33	13.8	99.8	5	8.40		-8.10	
Proposed solution Ut-Db (green)	37	11	84	7	6.88	10.58	-11.61	-6.02
Proposed solution Ut-Db (green/red)	41	8	91	7	8.50	10.66	-12.01	-6.31