Robustness by system untangling in large complex stations

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Robustness by system untangling in large complex stations

By

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Summary 'Explore part'

At large complex stations multiple railway lines come together which generates traffic and passenger flows in multiple directions. Mixing these flows, results in interdependencies which in case of an incident can lead to a complete disruption or even suspension of train services in all directions. A solution applied in Utrecht station is system untangling, which has been defined as the 'creation of multiple parts within the railway system that have less interaction with each other and therefore prevent irregularities from spreading and increase the system's robustness'. But through which infrastructure subsystems are all these flows connected in the 'spaghetti mix of lines' at complex stations and how should they be untangled in order to be effective?

This part of the research has the objective to gain insight in this untangling strategy and to provide an overview of untangling possibilities and their potential to decrease the spread of irregularities, and achieves this by answering the following research question: *which system untangling possibilities are (most) effective in limiting the impact of single incidents?*

By studying examples of untangling projects, the untangling strategy was explained and a few involved degrees of freedom were pre-identified. At the same time it also became clear that a comprehensive representation of the railway system and all of its subsystems was required to describe system untangling properly. Such a model was not found in literature, which led to the development of the Railway Service Model, a new rail system describing model (based on existing models), see Figure I.

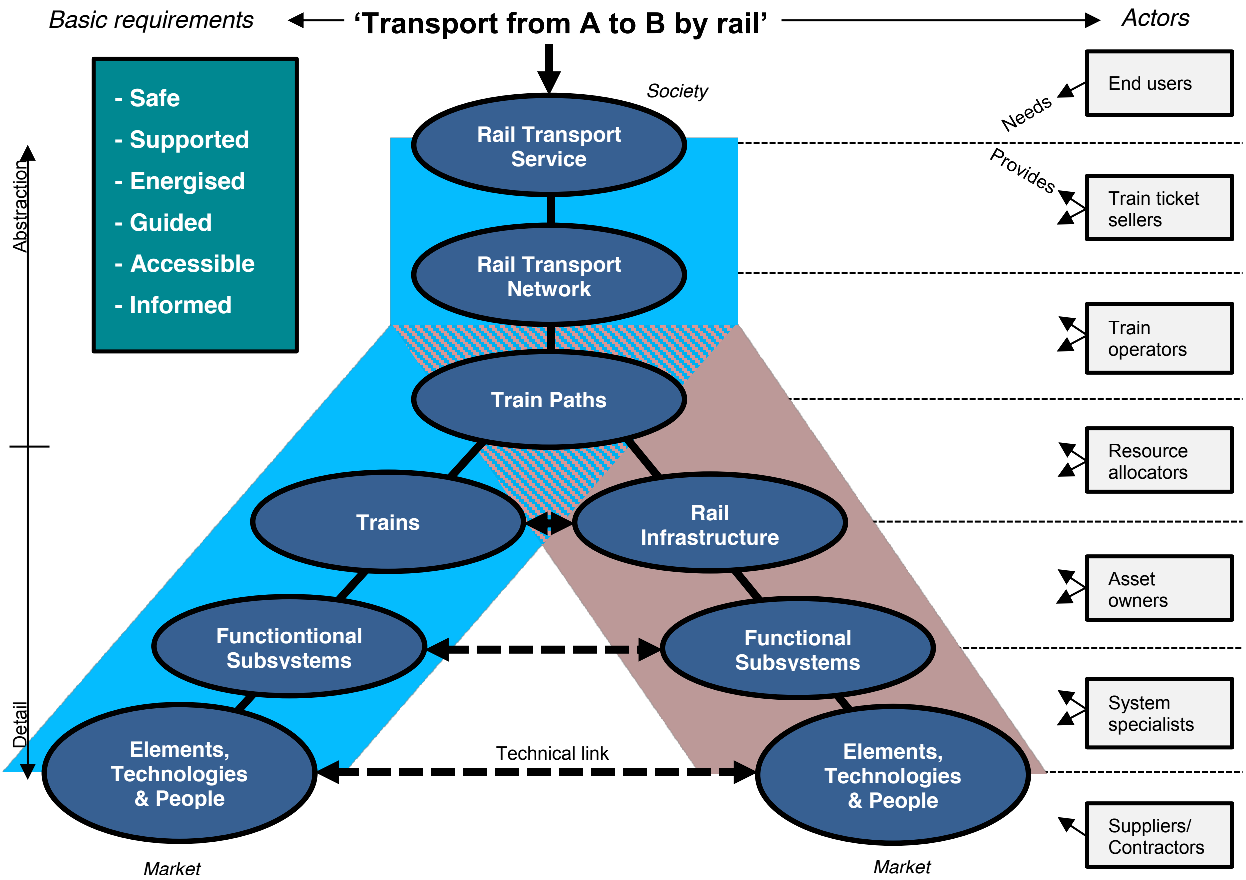


Figure I Railway Service Model

From that model, the following degrees of freedom of system untangling could be identified: '*type*' (untangling between subsystems or between corridors), '*level*' (splitting up transport systems or untangling within a single system), '*division strategy*' (untangling per direction or per TOC), '*geographical strategy*' (untangling in complex stations or on the line) and '*extent*' (untangling fully or just at some points). For every variable a suitable range was chosen; *untangling the subsystems of the railway system at complex stations per train corridor to all possible extents*.

In multiple workshops with experts of different fields, possible untangling options have been explored which resulted in a list of 25 options in 5 different subsystems that are all thought to be beneficial by the experts. The difficulty faced was that the effect of system untangling heavily depends on the local situation the option is installed in. To estimate the options' potential in a general way, an extensive incident data analysis was carried out.

Frequencies of occurrence and average incident duration values have been deducted from all reported incidents at the five largest Dutch stations in the period 2010-2015, and the amount of unavailability (product of average duration and frequency of occurrence) that could have been isolated by an untangling option has been used as indicator for potential benefit. Seven untangling options have been identified as a high potential in isolating the impact of incidents within the corridor of occurrence. Table I shows these untangling options and their potential benefits, expressed in minutes of infrastructure unavailability that could potentially be isolated from neighbouring tracks if the option was installed.

Untangling option	Potential benefit [min]	Rank (*#*)
Remove switches between corridors	4938	*1*
Deactivate flank protection if switch is unavailable	4334	*2*
Untangle relay houses per corridor	1890	*3*
Split tunnels & bridges per corridor	1549	*4*
Install separate 1500V power stations for each corridor	1054	*5*
Create a subsidiary circuit per corridor	775	*6*
Create safe working areas between corridors	0	*19*

Table I Seven untangling options that scored a high potential benefit

The first two are related to *switches* and have both scored so high because switch failures have a large share in the total number of reported incidents. Especially the fact that neighbouring switches are often also taken out of service during a switch incident – for safety reasons or because of the required flank protection – contributed to the high score. It is important to mention that the removal of switches has a large logistical effect that has not been taken into account here, but which could result in a lower robustness. In that light, the second option seems preferable since no switches need to be removed while the potential benefit is almost equal. Untangling the *relay houses* is also effective because the loss of a relay house leads to a prolonged unavailability of the area, which usually comprises a large part of the station area. The frequency of occurrence though is low, but the combination of both led to this high score. *Tunnels and bridges*, mostly tunnels, have a high unavailability. The large number of fire alarms found in the data resulted in the conclusion that having a form of physical separation in the tunnel will lead to a large reduction of impact spread. The options *untangling power stations* and *untangling subsidiary circuits* are strongly correlated and therefore both scored high. However, the difference in potential benefit is small while the difference in cost and effort to install both options is large. In terms of efficiency the subsidiary circuit untangling option is therefore much more interesting.

Lastly, the *safe working area* between tracks that allows for repair works to one track without causing hindrance to the neighbouring track is probably the most important untangling option, even though the score is zero. The strong correlation with almost all other untangling options is too large to estimate the individual potential benefit of this option: even when all switch pairs between corridors have been removed, if a failure in one track requires the neighbouring track to be taken out of service, the impact of this incident will not be contained in the corridor of occurrence.

Summary ‘Develop part’

At large complex stations multiple railway lines come together which generates traffic and passenger flows in multiple directions. Mixing these flows, results in interdependencies which in case of an incident can lead to a complete disruption or even suspension of train services in all directions. A solution applied in Utrecht station is system untangling, which has been defined as the ‘creation of multiple parts within the railway system that have less interaction with each other and therefore prevent irregularities from spreading and increase the system’s robustness’. But how should the ‘spaghetti mix of lines’ at complex stations be untangled in order to be effective in increasing robustness?

This part of the research has the objective to develop a model to assess the robustness of complex stations and to use it to determine the effectiveness of several untangling options in a case study. This objective is achieved by answering the following research question: w*hich system untangling options are (most) effective in increasing the robustness at large complex stations?*

Utrecht station (DSSU), which had been the trigger of this research was used as case study due to system untangling philosophy that had already been used in the design. Identified potential untangling options and alternative robustness increasing measures from the explore part were used to generate the scenarios in which the current situation of DSSU took a centre stage. To assess the robustness of these scenarios an existing ProRail risk analysis tool was modified and extended. The tool follows the modelling mechanism as depicted in Figure II in which the system design in the scenario determines which incidents are likely to take place and to what infrastructure unavailability they lead. The cancellation of trains for each unavailability is based on ProRail’s own contingency plans (VSMs).

Figure II Mechanism of the redeveloped risk analysis model

Unfortunately the results produced can only be used for comparison purposes, since it became clear during the validation that the absolute robustness values generated by the developed tool could not be used. The results from the 7 untangling options that were modelled have been summarised in Table II.

Untangling option	Highest robustness increase	Untangling extent in reference to DSSU	Decreasing failure rate more effective?
Create safe working areas between corridors	32%	More	-
Remove/add switches between corridors	23%	Less	No
Deactivate flank protection if switch is unavailable	16%	More	-
Untangle relay houses per corridor	10%	More	Yes
Create a subsidiary circuit per corridor	6%	More	-
Split EBP system per corridor	-1%	More	Yes
Split interlocking per corridor	-7%	More	Yes

Table II Summary of the results, percentage scores all in reference to the base scenario

Creating safe working areas around tracks and switches has the greatest impact on robustness. It has to be stated though that the difference between system designs in this scenario was more extreme than the difference in system designs of other scenarios which could explain the larger increase (32%). *Removing switches or adding extra switches* has the second greatest effect on the robustness: 23%. The model showed that in the DSSU case adding extra switches between corridors, or in other words tangling the corridors, would lead to a more robust system. Untangling the corridors further by removing switches had a negative effect on the robustness.

For deactivating the flank protection in disturbed conditions holds that further untangling DSSU leads to a robustness increase of 16%, which is substantial regarding the fact that the functionality of the switch pair is maintained. Untangling the relay houses also proved to be increasing the robustness, even though the effectiveness is low. An important benefit that is related to robustness from a passenger perspective, but which not has been captured in the definition used here, is that untangling the relay houses will ensure that trains in every direction continue to operate during a relay house incident, as each line will be handled by two different relay houses (one for the local train corridor and one for the intercity train service).

The subsidiary circuits even showed a smaller robustness increase, partly because the system design difference between the current DSSU situation and the fully untangled design is small. Untangling the interlocking installation or the EBP led in both cases to a robustness decrease. For these two options it was concluded that the failure rates should be recalibrated, but even then the effectiveness of these untangling options will remain low due to the low related infrastructure unavailability. A few conclusions have been drawn from these results:

- ***Only striving for a more untangled system does not always lead to a more robust system***
  Especially the option to untangle the system by removing all switches between corridors did not lead to a more robust system than a system in which some connections were kept. Having these switches proved to be beneficial for incidents such as faulty trains or section failures, which have a limited area of infrastructure unavailability, as trains were able to temporarily leave their dedicated tracks and be rerouted around the incident.
- ***Having safe working areas is very important***
  The results showed what the difference could be between not having these safe working areas and having them around each switch and track. On average the difference in robustness is 32%, which is far greater than the most effective untangling option that has been modelled.
- ***Decreasing failure rate of elements appears to be effective***
  As an alternative robustness increasing measure decreasing the failure rate of switches, relay houses, ES-welds and others have been modelled, and in some case this led to higher system robustness than the related untangled scenario. Especially for infrastructure elements with relatively high unavailability, such as the relay houses, this measure is more effective than untangling.
- ***Using the remaining infrastructure more intensively during incidents is cheap and effective***
  The model showed a robustness increase through simply increasing the usage of available infrastructure during incidents by adjusting the timetable in disturbed situations. This measure seems to be a real low-hanging fruit, as it can be implemented without any system design changes. On average a robustness increase of 7% could be realised.
- ***Important characteristics of untangled corridors were found***
  Two important infrastructure characteristics of untangled corridors were found that have a positive influence on the robustness of this corridor: the presence of a spare platform and the presence of infrastructure to turn trains around easily. In corridors where one of these characteristic was present, the robustness was 2% higher than on average.

Preface

Before you lie two (combined) research theses that form the partial fulfilment of the requirements for the degrees Master of Science in both Civil engineering and Transport, Infrastructure & Logistics at Delft University of Technology. The research has been carried out between March 2016 and March 2017 at the request of ProRail, who also offered me a workplace, data and daily supervision.

Both system untangling and robustness have become popular terms in the field of railway management but the progressive link between them did not feel inextricable to me. Investigating this phenomenon has not only been very beneficial for my personal development, it also seems to have produced valuable results for ProRail and the railway sector, which is a great honour.

I am grateful to ProRail and all colleagues for the opportunities and facilities they have offered me to carry out this research; I really felt included and involved in the company. My special thanks go out to Frank Bokhorst, who believed in me from the first time we met to discuss the research topic and supervised me all the way, and to Lisette van Duin, who provided mental support throughout the year. Without them the result lying here today would not have been possible.

To my committee members from TU Delft, who had to read lots of text in shorts amount of time, but always provided me with helpful and constructive council, I would like to say thank you. Also to my family and friends, especially to Melvin Kaats, who supported me unconditionally to achieve my goal, I would like to express my great gratitude.

I hope you will enjoy the reading.

Me and ProRail colleague Lisette van Duin during a field trip to a ProRail power station in Rotterdam

Justification

This document comprises a combined research that consists of two separate parts. The first part forms a Master of Science thesis for Transport, Infrastructure & Logistics while the second part forms a separate thesis for the Master studies Civil Engineering – Transport & Planning. Although both parts address the same problem, they each focus on a different part of it. The introduction chapter belongs to both parts, just as chapter 10 which describes the conclusions that can be drawn and the recommendations following from them. However, in both chapters clear distinctions are made between both parts.

The first part which holds the thesis for the Master study Transport, Infrastructure & Logistics (TIL) has been named the 'Explore part' of this research. In this part the system untangling mechanism and its degrees of freedom are under investigation and the various ways of system untangling are *explored.* The scope is initially broad and will be narrowed down further during the research process. Various subsystems are under investigation and input for plausible untangling options is provided by different experts in different fields. Eventually, an integral and uniform estimation of the potential benefits has to be made in order to distinguish between the effectiveness of each option. The broad character of this approach and the necessity to compare and evaluate solutions from different angles, perfectly reflect the values and required skills of the TIL master. Furthermore, the three components of the master, being transport, infrastructure and logistics, all take a dominant position in this research.

The second part comprises the thesis for the Master study Civil Engineering, specialisation Transport & Planning, and has been named the 'Develop part'. Although the focus does not lie solely on developing – a part also involves literature review and system analysis – the objective of this part is to *develop* a methodology and model to assess the robustness of (untangled) large complex stations. Translating real situations and system designs into a model that can be used to get insight in the performance mechanisms of a system, is a core skill of the Civil Engineering Master studies and is fully in line with the work in this part of the research.

Glossary

In this section a selection of the terminology and abbreviations used throughout the report is listed and has been complemented by a short description. Terms or phenomena that play a more dominant role in the report and require more explanation are elucidated in section 1.4 and have been italicised in this section.

Term/Abbreviation	***Explanation***
Access subsystem	Subsystem of the railway system with as main function to provide egress and access for passengers/freight
Ah	Arnhem station
Amf	Amersfoort station
ARI	Automatische Rijweg Instelling – Automatic Route Setting, computer module that based on the timetable sets routes in the PRL system automatically
Asd	Amsterdam Central station
ATB-EG	Automatische TreinBeïnvloeding Eerste Generatie – First generation of the Dutch ATP system
ATB-NG	Automatische TreinBeïnvloeding Nieuwe Generatie – Second generation of Dutch the ATP system
ATB-vv	Automatische TreinBeïnvloeding verbeterde versie – Improved version of the first generation of the Dutch ATP system. This version also responds if a train passes a red signal with a speed lower than 40 km/hr
ATP	Automatic Train Protection – System that supervises all trains their speed and interferes if the maximum speed is exceeded
Automatic area	Area that is equipped with automatic signals from which the aspect cannot be influenced by a signaller
BBT	Be-en Bijsturing van de Toekomst – Traffic management philosophy of ProRail and NS as a part of the 'Better and More' performance improvement programme
BD	Basis Dagen – Standard (week) day timetable
BU	Basis Uren – Standard (peak) hour timetable
Catenary system	System of electrified wires installed above the tracks to provide power to the trains. The system gets its strength through tension in the wires
Conductor rail	Steel bar on the ground parallel to the tracks that provides the trains with power (alternative to a catenary system)
Contact lines	Lowest wire of the catenary system that comes in contact with the trains' pantograph
Contact shoe	Steel structure at the bottom of the train that comes in contact with the conductor rail and transfers power from the conductor rail to the electrical engines

Crossover	Two pairs of switches between two tracks that form a 'cross' and enable trains in from both directions to change tracks
DAS	Driver Advisory System – System that advises train operators on speed
Db	Driebergen-Zeist station
Diamond crossing	Railway intersection
Dive-under	Tunnel passing one railway line below another
DONNA	Standard timetable development and planning software used in Netherlands by all operators
Double switch	Two switches in the middle of a diamond cross that enable trains to change between two continuous tracks
DSSU	DoorStroomStation Utrecht – FlowThrough Station Utrecht, remodelling project of Utrecht station that used the system untangling philosophy in the design
EBP	Elektronische BedienPost - Electronic Operating Box, electronical system that translates signals for requested routes from PRL into concrete signals for the various interlockings and sends back status updates
ECS	Empty Coaching Stock – Moving of empty trains
EMU	Electric Multiple Unit – Fixed set of coaches that can propel through installed electrical engines
Energy subsystem	Subsystem of the railway system with as main function to provide energy to move passengers/freight
ES weld	Electrical Separation Weld – Weld between two rails that form the borders of track detection section as they isolate electrical signals
ETCS	European Train Control System – Standard European signalling system
Flank protection	Safety regime to prevent that trains collide sideways on switches
Fly-over	Bridge carrying one railway line or road over another
FOC	Freight Operating Company – Company that transports freight by rail
Gd	Gouda station
Gdm	Geldermalsen station
Guidance subsystem	Subsystem of the railway system with as main function to guide passengers/freight in the intended direction
Ht	's-Hertogenbosch station
InfoPlus	Passenger Information module attached to the PRL system
Interlocking	Arrangement of signal apparatus that prevents conflicting movements through an arrangement of tracks
LCE	Locale Controle Eenheid – Local Control Unit used to exchange information between the interlocking and EBP, normally installed in a relay house
Nm	Nijmegen station
Normal switch	Common switch that connects a diverting track to a continuous track
NS	Nederlandse Spoorwegen – Dutch national railway company

OCCR	Operational Control Centre Rail – Dutch national traffic centre where the overal performance of the system is managed. There are no signallers present.
Pantograph	Steel structure installed on the roof a train that comes in contact with the overhead wires and transfers power from the overhead wire to the electrical engines
Pax	Abbreviation for 'passengers'
PPR	ProcesPlanRijwegen – Application that translates the timetable into concrete train paths and train routes that are fed to the PRL system
PRL	PRocesLeiding – Computer system used to set routes, which are then sent to the EBPs
PT	Abbreviaton for 'public transport'
Relay house	Building next to the line that holds the relays that form a part of the relay interlocking installation
Requiring switches	Also called switch pairs with demanded positions. Pair of switches that in order to be used always require a specific position of switch blades of both switches, even if one of the switches is not part of the route the train.
Route clearance	Entry signal shows a non-danger aspect and the train route is actually made available for train
Route clearing	A route in a station is freed up from other trains
Route conflict	Routes that share infrastructure elements and therefore cannot be requested by two trains simultaneously
Route release	The locked infrastructure elements part of a cleared train route are released and can be moved again
Safe working area installation	Installation that mimics the detection of train in an area to guarantee through the signalling system that the area is safe to work in
Safety envelope	Space around a train that is required to be free of objects to prevent collisions with them
Safety subsystem	Functional subsystem of the railway system with as main function to prevent derailments and collisions
Shl	Schiphol Airport station
Signal box	Part of the control centre where the signallers set routes
Sleeper	Concrete or wooden beam under the steel rail to transfer the (gravitational) forces from the train the ballast bed
Station area	Yards, junctions, platforms and platforms tracks in the area around a station
Stretching device	Part of the catenary system that provides tension to the lines through the gravitational force of concrete blocks hanging on cables connected to the catenary system
Support subsystem	Subsystem of the railway system with as main function to support the passengers/freight
Switch blades	Moveable part of a switch
Switch machine	Motor located next to a switch that changes the position of the switch through a set of steel pipes
System untangling	Creation of multiple parts within the railway system that have less interaction with each other and therefore prevent irregularities from spreading and increase the system’s robustness
TAO	Treindienst Aantastende Onregelmatigheid – Train Service Affecting Unavailability, indicator for incident quantity
TBP	TreinBeeldscherm Perron – Screens on the platform indicating the destinations and departure time of the train

Telegyr	System installed in power stations to manage energy distribution
TOC	Train Operating Company – Company that transports passengers by rail
TPR	Train planning rules – Rules set by the rail infrastructure manager that timetable planners need to take in account when building a timetable
Traffic control centre	Centre from where the train traffic is operated, monitored and controlled.
Train corridor	Fixed high frequency connections between cities, comparable with a metro line
Train path	A route through the station or over a line reserved at a specific point in time
Train route	Sequence of infrastructure elements a train follows
Train series	Train line with fixed origin, stopping pattern and destination
TRDL	TReinDienstLeider – Signaller, responsible for route setting
TROTS	TRain Observation and Tracking System – System that monitor the location of trains directly through physical train detection data from the EBP system
TVTA	Te Verklaren TreinAfwijking – Explainable Timetable Deviations, indicator for the number of trains that are affected by TAOs
Ut	Utrecht station
Uto	Utrecht Overvecht station
VSM	VerSperringsMaatregel – Predefined timetable measures that are taken if a certain track is unavailable
Wd	Woerden station

Content

1 Introduction

On 11 September 2015, a freight train with a faulty pantograph damaged the overhead wires over platforms 10 and 11 at Utrecht station, see Figure 1.1. Although there was little structural damage, the incident caused one of the largest disruptions of train services in Utrecht that year (ProRail, 2015b). The incident happened at 10:54 in the morning, while it took until 10:00 pm to get all trains running according to schedule again. More than 117,000 travellers, 29% of the daily travellers through Utrecht encountered severe delays and cancellations of train services (OCCR, 2015).

Figure 1.1 Freight train that came to a full stop at Utrecht station on 11 September causing the largest disruption of services of 2015

Unfortunately, this was not the only recent incident in Utrecht that led to a major disruption of train services for a large part of the day. As a consequence ProRail, the Dutch national rail infrastructure manager began to question the capability of its main stations to handle incidents and limit the hindrance experienced by passengers. Utrecht station is of particular interest as this station has just been rebuilt: The track layout, station buildings, platforms and all track related systems have completely been remodelled in the 270 million euro costing programme DoorStroomStation Utrecht (DSSU) or Flow Through Station Utrecht. The main idea in the design of the station was to 'limit the impact of a single incident' by isolation the different traffic flows. Even though the incident took place before the station was completely finished, it still raised the question whether the future Utrecht station would have been able to limit the hindrance in this case (ProRail, 2014b). In 2018 the redesign programme for Amsterdam Central Station will commence, in which the same design principles as in the DSSU programme will be used (ProRail, 2014a). ProRail therefore asks to investigate the robustness of its large complex stations.

1.1 Problem statement

‘Limiting the impact of single incidents’ seems straight forward and not too complex, but this is not the case: incidents come in many shapes and forms (e.g. broken overhead wire, faulty train, IT failures) and for every incident type the impact is different. Taking all possible incidents and all possible impacts into account in the design of the station is nearly impossible and very costly. In order to limit the impact of an incident as much as possible, the DSSU design team used a design philosophy in their approach: untangle systems as much as possible and always untangle them the same way (ProRail, 2014b).

The untangling of rail infrastructure systems is not a new development in the rail industry. Many rail projects in the past have already untangled or separated several parts of the rail system. Examples of untangling are the construction of fly-overs and dive-unders to physically separate individual routes at large junctions, and the implementation of new overhead wire design guidelines in the Netherlands, in which is stated designers should avoid that overhead wires cross multiple corridors (ProRail, 2015a), (ProRail, 2013a). Some of the system untangling has been done to achieve a capacity increase (fly-over) while others had the purpose of increasing robustness (e.g. overhead wire design guideline).

The use of the system untangling philosophy in DSSU resulted in a design where all train services through Utrecht use fixed routes and do not change direction (switch between so called train corridors). Besides that, each corridor mostly has its own platforms and tracks, so that a faulty train for instance will only affect other services in the same corridor.

But removing switches and dedicating platforms to specific train services are just two untangling options. The railway system consists of many subsystems, such as the physical tracks, trains, power supply system, communication systems and IT systems for traffic control and traffic management. All these subsystems together need to interact correctly to operate the railway system as a whole. The impact, benefits, and relevance of untangling the full system across this chain of subsystems are unknown. A chain is no stronger than its weakest link although a chain of subsystems might not be the best way to represent the railway system (the reciprocal dependencies are probably more complicated). The question remains what benefits (in terms of robustness, not capacity) can be gained by untangling a subsystem while not untangling an overlaying or cooperating subsystem. So, to which extent is it beneficial to unbundle your systems? Would it for instance be wise to also create multiple signalling and dispatching centres? An overview of how subsystems are tangled and which untangling options are most beneficial is currently not available.

An alternative approach to decrease the hindrance is increasing the availability of various subsystems, for instance by installing two independent power supply systems to reduce the risk of a power loss. A difference between the two options seems to be that applying the untangling design principle is focussing on the prevention of impact spread and thus reducing or limiting the total impact, while installing measures to increase the availability of a system is focussing on incident prevention. So, which strategy to use in what cases? Are there other strategies that could be used as well that are more effective?

These questions (should) take a centre stage in the design of a large complex station, but the size and fixed scopes of these projects often tend to muddle the integral view on robustness. Design dilemmas are resolved by analyses that do not always have the right system scope to oversee the full impact of the proposed options. An example is the reduction of switches simply for the reason that fewer switches will lead to fewer switch failure incidents, which is not untrue but neither telling the full story. Other incidents might be handled less well due to the absence of these switches. The problem statement therefore is:

> *Although ProRail already applies system untangling as measure to increase the robustness of its large stations, there is no integral consciousness on which untangling options there are, how they interfere and what their effect on the system’s robustness is.*

1.2 Approach

This document comprises a combined research that consists of two separate parts. The first has an exploratory character part forms a part of the input for the second part, in which model development takes a centre stage. Both parts address the problem as stated in the previous paragraph but each focus on a different part of it. This first chapter belongs to both parts, just as chapter 10 that describes the conclusions that can be drawn. Nevertheless, in both chapters clear distinctions are made between both parts.

1.2.1 Objective and research questions

This research should focus on the impact, benefits and relevance of total system untangling in order to increase the robustness of large stations such as Utrecht and Amsterdam Central. Also, the absence of an overview of how the various subsystems are tangled has been mentioned in the problem statement and should therefore be incorporated in the research objective.

The first step would be to investigate what the untangling strategy is and which forms and options there are. To prevent that an indefinitely long, useless list of options is produced, it is also key to find out what the potential of each option is, in terms of 'limiting the impact of single incidents'. Once the strategy of system untangling is better understood and the potential untangling options been identified, their effect on the robustness can be determined. For the latter a modelling tool or methodology that is able to assess the benefits and disadvantages of various combinations of untangling options will need to be developed. This has led to the following two objectives, split consistently according to the split of this research in an exploration part and a development part.

> *Gain insight in the untangling strategy and provide an overview of untangling possibilities and their potential. (Explore part)*
>
> *Develop a model or methodology to assess the robustness of large complex stations and determine the effectiveness of untangling options in increasing this robustness (Develop part)*

The problem statement contained four elements which all have been translated into the two research objectives. In Figure 1.2 these elements have been depicted in four different blocks. Based on the research objectives, the research questions and sub questions can be formulated.

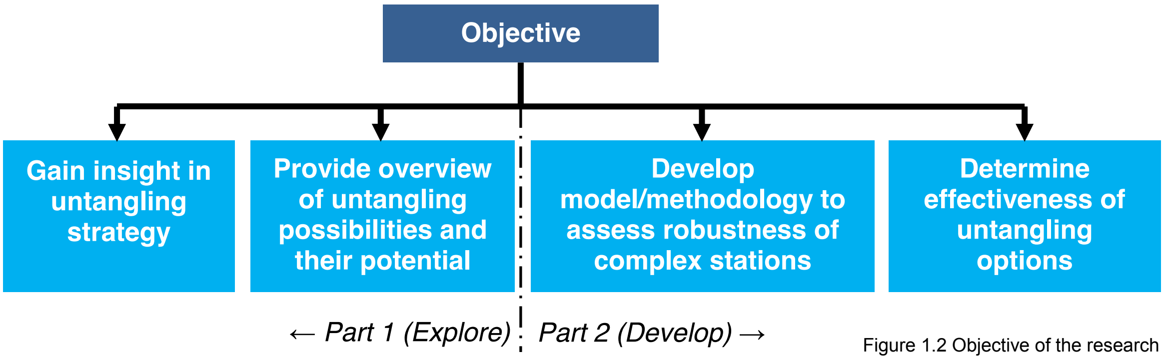


Figure 1.2 Objective of the research

In line with the dual objective the research question has also been built up of two parts, the first part being about gaining more insight in which untangling options there are across the rail system and to what extent they can limit the impact of single incidents, the second about assessing their influence in conjunction with each other on the robustness at large complex stations.

> *Which total rail system untangling options are (most) effective in limiting the impact of single incidents and in increasing the robustness at large complex stations?*

It would be helpful to also deduct two separate partial research questions from the general research question to be able to formulate sub questions more purposefully. In line with the partition used in Figure 1.2, the research question has been split up.

> *Which system untangling possibilities are (most) effective in limiting the impact of single incidents? (Explore part)*
>
> *Which system untangling options are (most) effective in increasing the robustness at large complex stations? (Develop part)*

To answer the first research question it is essential to first acquire insight in the untangling strategy and generate an overview of the untangling possibilities, which is in line with the objective. This also holds for the second question, for which developing a model or methodology to assess the robustness in relation to untangling options is necessary.

Obviously, there is also a strong cohesion between the two research parts. The first part will mainly be used to describe and gain better understanding of the system untangling strategy, make an inventory of which untangling options can be identified, and estimate what their potential is. This overview will be used in the second part, where the actual effectiveness of the untangling options will be determined. An important aspect of the second part is that the effectiveness of untangling options will not only be considered in relation to other untangling options, but also in relation to other robustness increasing measures. To keep this second part manageable with such a large amount of degrees of freedom, that part of the research will be case study based.

The exact steps to be taken to answer these questions will become clear by defining sub questions. In the next two sections the sub questions and report structure will be formulated for the explore part and develop part respectively.

1.2.2 Sub questions & report structure of the explore part

Sub questions will provide guidance throughout the research and will show the logical thinking path that eventually will lead to a comprehensive answer to the research questions. The set of sub question specified below forms the basis for research methodology and report structure of the explore part.

- ***What is system untangling and which variables are of interest? (1A)***
  As stated before, the philosophy of untangling a system in order to increase the robustness is not a new development, and has been used regularly in the design of rail infrastructure. Other industries might also have experience with this design principle. The variables or degrees of freedom that can be identified are relevant in the sequel of this research.
- ***How can this system be defined or modelled and which subsystems can be identified in order to describe system untangling?* (1B)**
  To be able to investigate the effectiveness of total system untangling it is important to first define the full railway system and to identify subsystems. In that way untangling options can be generated per subsystem.
- ***Which forms of system untangling are interesting to take into account? (1C)***
  With the a representation of the railway system and knowledge on system untangling gained, a selection can be made on which forms, types or extents of untangling should be taken into account. In the next section a preliminary scope will be set, but depending on the findings on the

previous two sub questions this scope has to be narrowed down further. This will be described in a separate section with the help of the developed rail system description model.

- ***Which (relevant) untangling options can be identified? (1D)***
  Within the range of the scope for the untangling strategy that has been defined under the previous sub question, multiple untangling options can be identified. The amount of possible untangling options is large, which means that besides only identifying them a preselection based on their potential should already take place.
- ***What is the (potential) effectiveness of these options? (1E)***
  The overview of relevant untangling options that is the result of the previous sub question almost fulfils one of the research objectives, but an estimation of the options' potential effectiveness in containing the impact of incident is still missing.

The sub questions form a path towards answering one of the research questions and can be translated into clear steps and a research and report structure. As a result of the merge of two theses into one single document, the chapters are large and sometimes answer more than one sub question.

Figure 1.3 shows the various steps that are to be taken in the approach of the first part of this problem. The format used for visualising these steps is to indicate what input is needed for each step, what the actions are, and what the result or output of that step will be. Obviously, the output from previous steps will be used as input in the next step, but this has not been shown in the figure as only external input such as data or expert views is mentioned. The fourth column shows where in the report each step is described and therefore forms the report structure. At the point where a sub question is answered, the number of the sub question is shown between brackets.

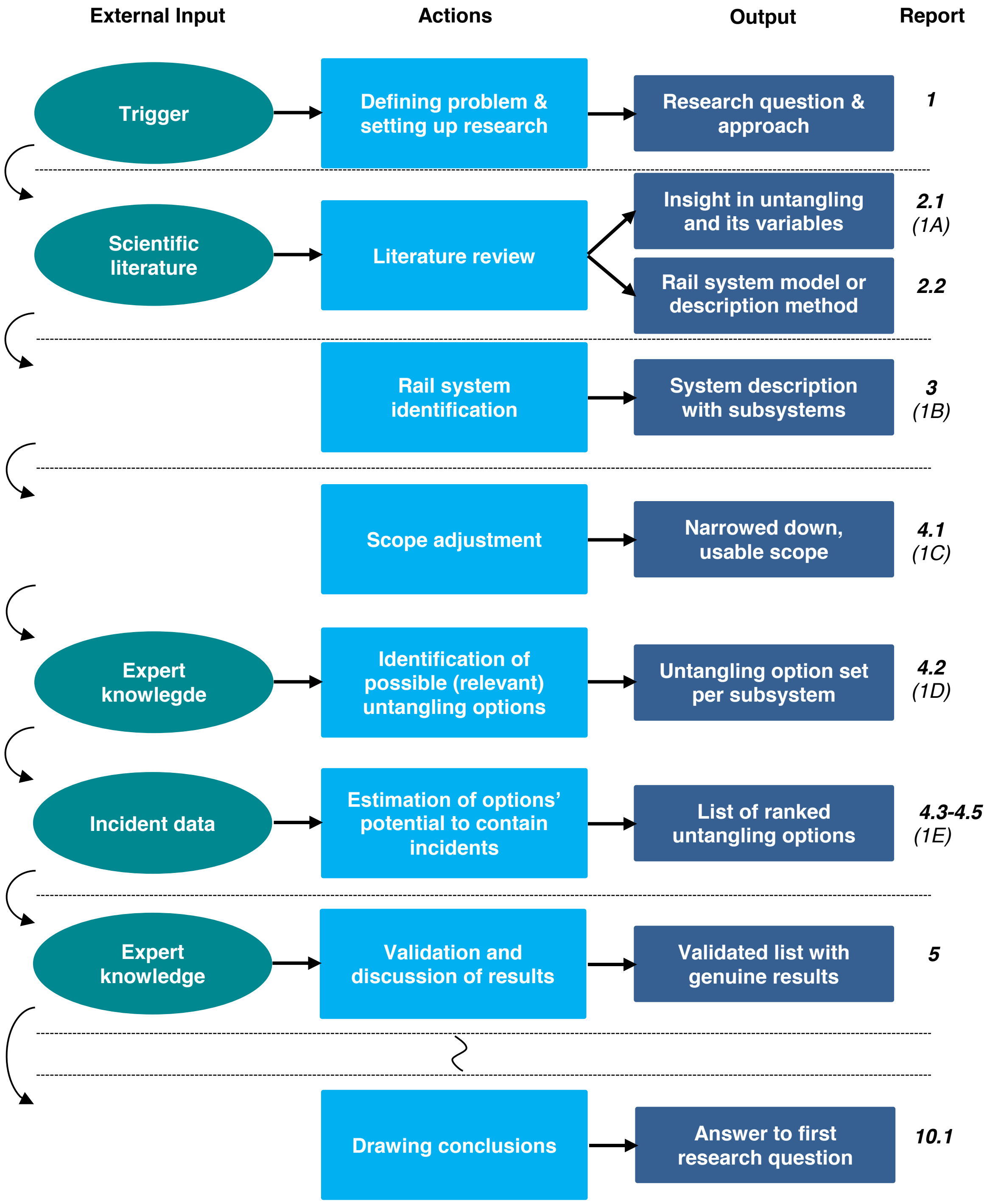


Figure 1.3 Approach and report structure of the explore part

1.2.3 Sub questions & report structure of the develop part

Also in the develop part sub questions will help to find a comprehensive answer to the research question, as they provide guidance and structure. The set of sub questions below forms the basis for the (report) structure of the second part.

- ***What is a proper definition of robustness for this research? (2A)***
  There are many definitions of robustness used in literature, each having a slightly different meaning or definitions that are open to various interpretations. Besides that, although terms as resilience, reliability, availability and redundancy have different meanings than robustness, they seem to be strongly related. Having a clear distinction in definitions would therefore be relevant.
- ***Which complex station is suitable to select as case study? (2B)***
  As has been stated briefly before, the amount of degrees of freedom under investigation is large and therefore requires a case study based approach. Taking all the possible design variations into account is impossible, so an existing complex station has to be selected for which the (to be developed) model can assess the effectiveness of selected untangling options.
- ***Which untangling options identified in the first part should be taken into account? (2C)***
  An objective of the explore part is to search for possible untangling options and quantify their potential benefits. Not all of these untangling options can be modelled in the develop part so a selection should be made preferably based on their potential score in the first part.
- ***What system variations are relevant to include for assessing the effectiveness of untangling? (2D)***
  The word ‘effectiveness’ in the research question has a double meaning. On the one hand it refers to the difference in robustness increase/decrease between untangling options while on the other hand it refers to the robustness increase/decrease an untangling option realises compared to other robustness increasing measures. In the explore part these alternatives to untangling will be identified but from these alternative measures a selection will need to be made.
- ***What should the model look like to assess the total system robustness for all generated scenarios? (2E)***
  Obviously this sub question is not targeting the physical appearance of a model but the requirements the model should meet. There a two leading objectives the model should be able to fulfil: assessing the robustness of the selected scenarios and keeping the options open to assess the robustness of other complex stations.
- ***What can be concluded from the robustness values calculated by model? (2F)***
  Since the type of research performed is a case study, the values for the robustness of a system that the model will generate do not automatically reflect the effectiveness of untangling options. A closer look at the results will be necessary in order to answer the research question.

This research started with information about an incident in Utrecht station and will eventually end with conclusions and recommendations regarding the research question. The path between the starting and end point follows from the sub questions and can be translated into clear steps and a research and report structure.

Figure 1.4 shows the various steps that are to be taken in the approach of the second part of this problem. The format used for visualising these steps is equal to the format of the explore part explained in section 1.2.2. The fourth column shows where in the report each step is described and therefore forms the report structure. At the point where a sub question is answered, the number of the sub question is shown between brackets.

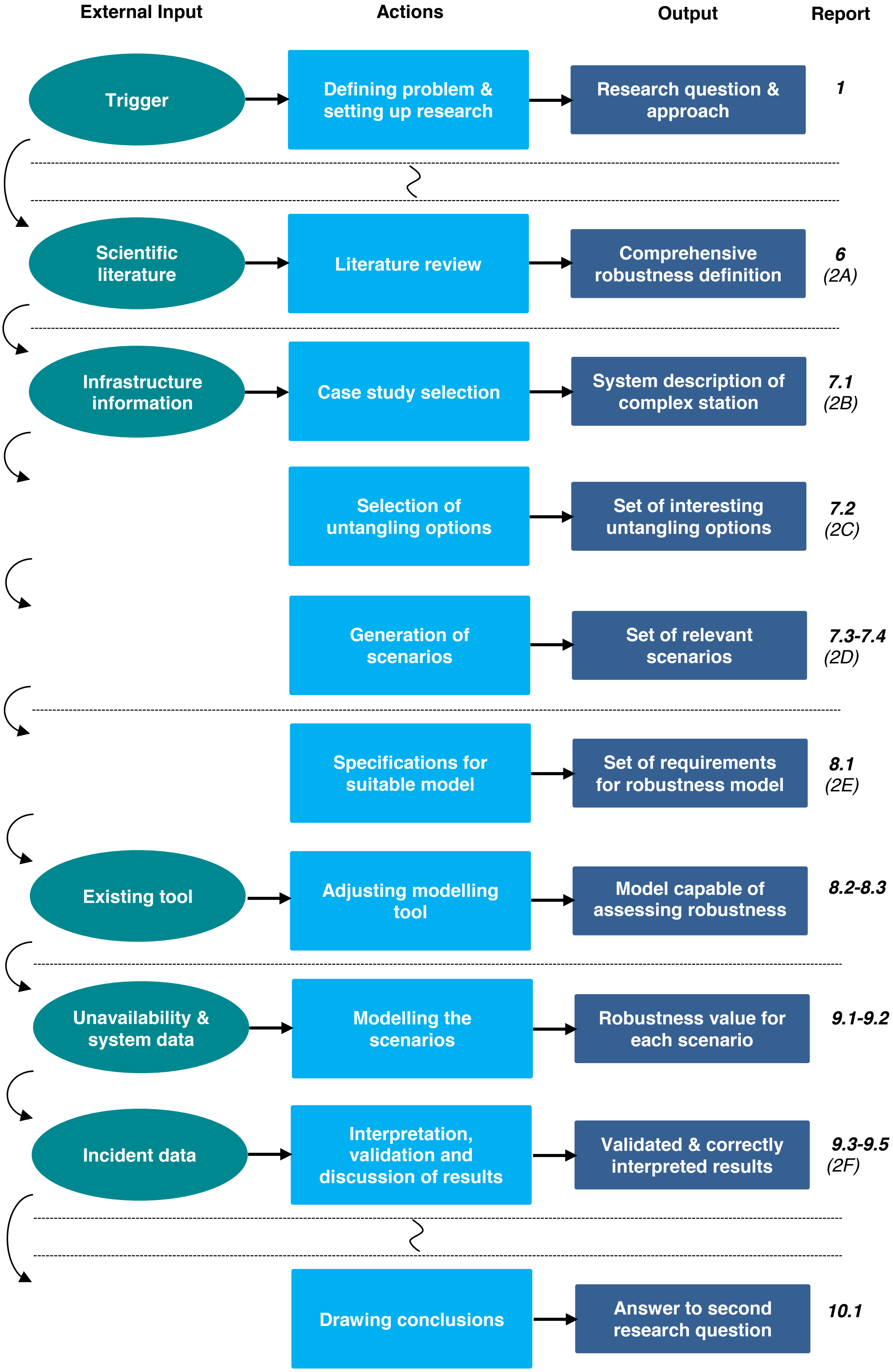


Figure 1.4 Approach and report structure of the develop part

1.3 Scope

The problem statement, research questions and research approach have been discussed in the previous sections, but a research scope has not yet been set. Unfortunately, the need for a scope automatically means that not all aspects of the problem will be investigated as thoroughly as others, as choices between them have to be made. This section will point out the focus and limitations of the research as a whole and will clarify differences in scope for the individual parts. The distinction between limitations and focus has been made to indicate what is deliberately not within the scope (*limitations*) and on what is focussed, but can be slightly altered in the research if necessary (*focus*).

1.3.1 Pre-identified limitations

The title of this section has been called pre-identified limitations as most of the limitations can only be set after the untangling strategy and the related degrees of freedom have been better understood. Since it is easier to explain these limitations with the help of the system description model that will be developed in chapter 3, this untangling scope is set and discussed in detail in section 4.1.

The most obvious limitation has already been mentioned in the research title, namely the fact that only the situation around large complex stations will be taken into account. Since the railway system is of a network of which these stations only form a small part, the solution or effective untangling options that will be found are only suboptimal and are not tested on the rest of the network.

Although the research focuses on large complex stations in the Netherlands in general, a single station will function as a case study in the second part. Completely redesigning a large and complex station is a complicated process with a huge number of design possibilities and dilemmas that takes many years and involves many stake holders. It is not realistic to assume this design process can be executed within the scope of this research. As an alternative, the system design of an existing station will be used as a basis for which design optimisations and differentiations will be made. As a result of that, the answers that will be found are specifically valid for the selected case study, but not necessarily for large complex stations in general. In the discussion section of the second part, this matter will be elaborated on.

One limitation only holds for the first part of the research has already been incorporated in the first research question: by focussing on containing the impact of single incidents, the logistical effects are automatically ignored. For example the fact whether a train can be rerouted around an incident is not of any importance in the first part, since the impact of the incident on this train is regarded as direct impact on a train that runs over the location of occurrence and not as impact spread to *other* trains. As a result of that, the potential effectiveness that will be estimated in the first part does not include the possible negative effects of the option. In section 5.2.5 this will be explained in further detail.

The railways have been around for a long time and the technical equipment and systems that are in use across the network can therefore vary per location. This research will only take the systems into account as they are installed today in the Netherlands, even though many of the systems that will be described are most likely to have similar equivalents abroad as well. New systems such as ETCS, which have not been installed yet at any large Dutch station, will not be taken into account.

As a conclusive note for this section it is important to state that the limitations that will be discussed in section 4.1 are also valid for the second part of this research. Although this link has not been drawn in Figure 1.4 a part of the scope for the develop part is thus specified in a chapter of the explore part.

1.3.2 Focus

The research is carried out in collaboration with ProRail B.V., the Dutch railway infrastructure manager. As a result of that, the focus will be on the technical infrastructure side of the railway system, and less on the logistic, rolling stock and staff sides since those responsibilities lie with the operator.

In large and complex stations the performance is not only influenced by the design and ability of the various systems present, but also by the way that the systems are operated. When investigating the robustness of a system, incident management can play a large role in the impact that certain disturbances have on the performance of a system: the impact on passengers could be completely different when the same incident is handled differently. As the research question suggests, the focus will be on the technical design and configuration of systems such as the catenary system, and not on traffic management, incident management, or internal ProRail procedures. In other words, how certain incidents are handled currently and how they could be handled in the future will not be focussed on. When needed, the incident management will be represented in a pragmatic way.

1.4 Frequently used terminology

For readability reasons it is beneficial to have clear definitions for the frequently used terminology. On page X a list of used terminology and abbreviations is briefly explained, but some terms require a more elaborate explanation or have not been mentioned there as they are not necessarily railway jargon.

- ***Robustness***
  There exist many definitions for robustness in literature and in chapter 6 a comprehensive definition will be deducted properly. The result of that quest is given as definition here. The robustness of a station is expressed as the number of yearly cancelled trains and the share of these cancellations in the total number of yearly departures at that specific station.
- ***System untangling***
  Similar to the definition of robustness, the search for a definition for system untangling will be described in chapter 2 and the results will be used here. System untangling is the creation of multiple parts within the railway system that have less interaction with each other and therefore prevent irregularities from spreading and increase the system's robustness. The definition is specific on the purpose of system untangling even though there are other reasons for system untangling, for example to increase capacity. These reasons and benefits are not taken into account in this research and have therefore deliberately been excluded from the definition.
- ***Train corridor***
  To facilitate the increasing demand for passenger transport train corridors have been introduced in the Netherlands. Instead of offering multiple direct destinations on a certain line, fixed high frequency routes with fixed stopper patterns are operated which makes the line comparable to a metro line. Passengers travelling to destinations that are not on the line are required to change lines. As a result, higher frequencies with strict intervals can be operated, since the timetables of various lines do interact less. Examples of train corridors in the Netherlands are the A2 (fast service Alkmaar-Eindhoven) and the VleuGel corridor (local service Vleuten-Geldermalsen) (Ministry of Infrastructure & Environment, 2014c).
- ***Train series***
  Each train service is given a unique number per day to be able to track the train, measure its performance, communicate with the train driver and for many other reasons. In the Netherlands it is common to operate half-hourly services with a fixed origin, stopping pattern and destination. These train series are given a number in hundreds and its individual train services all numbers between the same hundred and next hundred. For example, series 500 runs from Groningen to Rotterdam and vice versa and train 583 denotes the 22:05 service departing from Rotterdam (NS, 2012).

Part 1: Explore

MSc Thesis for Transport, Infrastructure & Logistics

Introduction 'Explore'

This report consists of a combination of two separate theses that, although they are closely linked to each other, both have their own objectives, research question and approach. Answering the research questions of both parts will lead to a solution to the single problem statement that was formulated for both parts as a whole. In chapter 1 this process and all details have been described and discussed, in chapter 10 the conclusions from both parts will be presented. Here, a short recapitulation of the research question will be given for the first part (explore part) of the research that is covered in chapters 2 to 5. The report structure and approach are shown in Figure 1.3, the research objectives in Figure 1.2. The research question for this part is repeated below.

> *Which system untangling possibilities are (most) effective in limiting the impact of single incidents?*

System untangling is applied to decrease the dependencies between parts of railway system in order to increase the robustness of the system. Through which ways the railway system is currently tangled is not clear and therefore an overview of which system untangling possibilities there are and what their effectiveness is, is not available. This thesis has the objective to investigate the system untangling strategy, explore the various untangling options and estimate their effectiveness in limiting the impact of single incidents. With the phrase 'effective in limiting the impact of single incidents', the ability is meant to contain the impact of an incident within the corridor or track of occurrence, or in other words the ability to prevent impact spread.

2 Literature review

To gain more insight how the system untangling strategy works and which variables are of interest, a literature review has been conducted. Examples of system untangling, available theory on the untangling strategy and alternative measures to increase the system's robustness will all be discussed in the first part of this chapter. In this review not only scientific literature will be taken into account, but also internal ProRail documents appeared to be of great importance.

When the system untangling strategy is better understood, the next step is to identify the rail system. Obviously, system untangling can only be scoped and investigated when the involved system, subsystems and their connections are well defined. Describing a large system such as the railway system is not an easy task as there are many ways of representation thinkable. In the second part of this chapter available representations of the railway system or suitable system modelling methodologies in literature will be identified and discussed, after which the most suitable will be selected. Unfortunately, an existing model suitable to describe system untangling properly was not identified. Therefore two system describing methodologies will be selected that can be modified and be transformed in to a suitable model in the next chapter. Figure 2.1 shows the step from the research approach that will be discussed in this chapter.

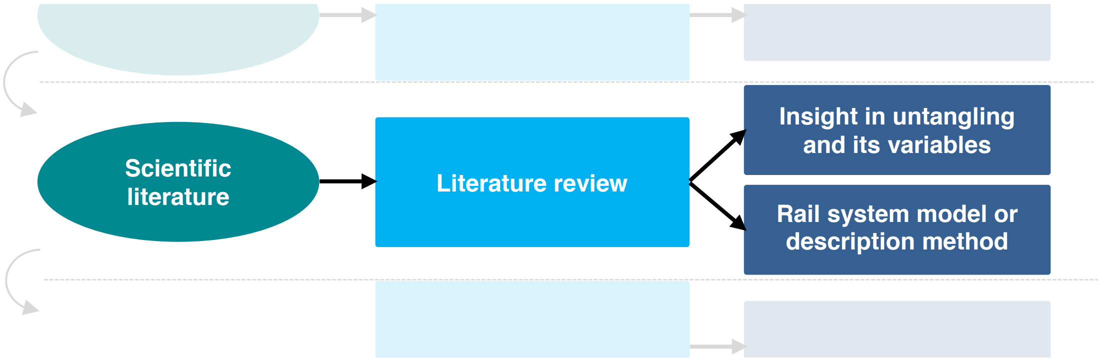


Figure 2.1 Step from the research approach described in this chapter

2.1 System untangling

According to Oxford Dictionaries 'tangled' means both 'difficult to unravel' and 'highly complex', and in the context of this research it also refers to the metaphorical spaghetti of tracks often present in the areas around large stations (Oxford Dictionaries, 2016e). Figure 2.2 shows this spaghetti of tracks at London Bridge station, where the many switches seem to indicate that trains criss-cross through the area to get to their destination. This section will try to answer what the system untangling mechanism used to increase the robustness implies, by assessing system untangling examples and identifying the parameters involved. Besides that, several alternatives to systems untangling will be mentioned.

Figure 2.2 ‘Tangled’ tracks at London Bridge station

2.1.1 System untangling theory

System untangling has been announced as a method to increase the robustness of the rail system, which has been defined as the number or percentage of cancellations caused by disruptions or incidents. By assessing several examples of untangled systems, the various degrees of freedom involved in system untangling should become visible.

2.1.1.1 Rail system untangling examples

Network Rail, Britain’s rail infrastructure manager provides an explanation how system untangling could contribute to an increased robustness. The tangled tracks of London Bridge station shown in Figure 2.2 were also an unpreferred situation for Network Rail, who announced a 6.5 billion pound costing redevelopment programme to improve the robustness of the station (Network Rail, 2014). They explain what led them to start the project:

> *The works taking place are part of the Thameslink project and will remove one of the nastiest rail traffic bottlenecks in the London Bridge area.*
>
> *At the moment, Thameslink trains have to cross two sets of east-west tracks to get onto the correct set of north-south tracks, and that causes delays as trains have to leave gaps in the schedule to allow for such movements, and delays in trains arriving at the correct place on time can be magnified by the tight schedule they run to, causing a cascade of delays down the line.*
>
> Reasons for untangling the tracks at London Bridge station (Network Rail, 2014)

Network Rail states that the Thameslink trains crossing other lines has two negative effects, one being the necessary gaps in the schedules to give way to crossing trains which reduces capacity of the station and the other being the dependencies between the various train services that cause delayed trains of one operator to delay other trains of other operators. The first reason could be classified as system untangling to increase capacity – relieving the necessity of having gaps in the schedules of other trains – but the latter definitely affects the robustness of the system: in the current situation a faulty train in the middle of the junction will probably result in many cancellations of services all over the station. By building a crossing facility for Thameslink trains that does not interact with other train services, the robustness will increase. Network Rail strives to build dedicated infrastructure for each train operator at London Bridge station, of which there are currently four. Each operator runs various services from this infrastructure, such as local and fast services and services with different destinations (Network Rail, 2014).

ProRail in the Netherlands seems to use a different strategy for one of its bottlenecks: Utrecht station. As briefly discussed in section 1.1, the large station is currently being completely remodelled and rebuilt in the 300 million costing project DSSU or Flow Through Station Utrecht (ProRail, 2014b). Other than in

London Bridge, there is only one TOC operating this station (and a few FOCs), so untangling the infrastructure by train operator is irrelevant. Instead it was decided to untangle the tracks per train service per direction, meaning that every local train to a certain direction and every fast train to the same direction each use dedicated infrastructure. Depending of the frequency of a certain service some tracks will only be used by 4 trains per hour while other tracks serve 13 trains per hour (Ministry of Transport, Public Works & Water Managment, 2010). Strangely enough, the FOCs' routes do not have their own infrastructure but instead use parts of the TOC's route related infrastructure and switch tracks at some point in Utrecht station. The full design of DSSU is discussed in detail in section 7.1.

A key feature of the DSSU project is that it does not only focus on untangling the tracks themselves, but also untangles other parts of the infrastructure such as the catenary system and train detection system. But although these parts are untangled, some other parts of the infrastructure are left untouched such as the IT infrastructure and traffic control centre (Movares, 2015). The question then rises how far the untangling process could be carried forward.

An example that at first sight does not seem to be related to system untangling is the transformation of the Hoekse Lijn railway to a metro line. The current railway line from Rotterdam Central to the harbour of Hook of Holland used to be a main connection for international passengers from England to continental Europe. Ferries between Hook of Holland and England's shore fed the national and international trains in Hook of Holland, and with the decrease of Ferry passengers due to the uprising of air transport and the opening of the Channel tunnel, the national and international importance of Hook of Holland's station disappeared (Rijksoverheid, 2015). Nowadays, the line's demand comes mostly from commuters living in the villages alongside the line and working elsewhere in the Rotterdam area. Only local services operate on the line up to a frequency of 8 trains per hour per direction, which shows more similarities with a service found on a metro line than on heave rail lines. It was therefore decided to disconnect the Hoekse Lijn from the railway network and attach the line to the metro system (Metropoolregio Rotterdam-Den Haag, 2016). Currently, the Hoekse Lijn uses dedicated tracks and platforms at all of its stations and it therefore does not seem improbable that also with the current railway system a more suitable service could have been delivered. Yet it was decided to completely separate the line from the railway network with the remark that because of this the service will become more reliable, although the grounds for this claim have not been found (Metropoolregio Rotterdam-Den Haag, 2016). The question is whether or not this could be regarded as a form of extreme system untangling.

2.1.1.2 System untangling examples outside of the rail sector

It is also interesting to find examples related to system untangling outside of the rail sector to see if there are similarities or other insights. Del Vecchio & Murray in their book on biomolecular feedback systems compare the feedback control loops used in engineering to the ones used in the human body (Del Vecchio & Murray, 2015). According to them, the engineering feedback control loop consists of three different elements: sensors that sense the current state of a system, actuators that are able to influence the current state and a computor that calculates the right settings for the actuator based on a pre-specified preferred condition for the system. They state that a common approach in engineering control systems is to clearly separate this sensing, computation and actuation in three different components to fully optimise the design of each of them to their purpose (Del Vecchio & Murray, 2015). The system untangling here results in a more robust system because the components are less likely to fail due to their improved design (Del Vecchio & Murray define robustness differently). In the human body on the contrary, the dynamics of the molecules that sense the environmental condition and make changes to the operation of internal components are integrated together, which opposes the strategy of artificial feedback loop control (Del Vecchio & Murray, 2015). This type of untangling seems to be different from the examples that have been discussed before: previously the systems were untangled to contain disruptions and keep impact limited while here the functions are untangled on component basis to improve the design.

Another example of system untangling found in biology has been described by Lesne in her paper on lessons learnt from physics and biology concerning robustness (Lesne, 2007). Lesne addresses the question whether the notion of robustness and resilience developed in physics are relevant to biology or whether specific extensions and novel frameworks are required to account for the robustness properties of living systems (Lesne, 2007). She attempted to identify the various mechanisms that underlie robust behaviour of either all natural systems or specific biological systems. One of these mechanisms is system untangling, although Lesne uses the term compartmentation instead.

> *A special […] (mechanism) is space compartmentation, either by membranes or dynamic segregation generating self-organised compartments. It has a direct impact upon robustness of the various phenomena that take place in the system, in preventing mixing of different inputs, signals or reactive elements and perturbations resulting in a complete production stop in all compartments. As such, it has been often selected in biological systems and it is observed for instance in living cells.*
>
> Compartmentation as robustness measure (Lesne, 2007)

She found that living cells often form membranes or other separating elements to physically split the various phenomena that take place in the cells in order to prevent that the disruption of one phenomenon leads to a complete disruption of all other phenomena as well, which for instance could happen if a reactive element enters the cell. According to Lesne, this compartmentation mechanism to increase a cell's robustness is a common practice in biological systems, but she also describes another dominant robustness mechanism: redundancy. By having redundant options installed the loss of a single production unit could be compensated by an increased production in the redundant option. An example of this mechanism in the human body is the presence of two kidneys, which each could handle the body's complete need for the kidney function. Yet both kidneys usually do not work at full capacity, leaving spare capacity to accommodate extra production in the case of a loss of one of the kidneys.

2.1.1.3 System untangling mechanism and definition

From what has been described in the examples in the previous section, a more comprehensive definition for system untangling can be deducted. Untangling a system means to compartmentalise the system in such a way that all other parts remain operable if one part of the system is unavailable. Applied to the railway system, the following definition of system untangling has been formulated:

> *Creating multiple parts within the railway system that have less interaction with each other and therefore prevent irregularities from spreading and increase the system's robustness*

Lesne gave an example of how in the redundancy concept is present in biological systems as alternative to system untangling (Lesne, 2007). The relation of system untangling to redundancy and installing spare capacity is interesting, but how can this redundancy concept be applied to the railway system? Nyström, in his journal article on the topic of system availability searches for various availability concepts outside of the rail industry and evaluates whether this concept could be beneficial for the availability of the railway system (Nyström, 2007). Where system untangling strives for isolation and limitation of the interaction between parts of the system, Nyström explains another philosophy that seems to do the opposite. He seems to favour the concept of redundancy which leads to the creation multiple incident absorbing layers in the railway network. According to the concept's theory, (technical) incidents do not always lead to a disruption of train services noticeable to the passengers because they can sometimes be covered by redundant systems or spare capacity. Spare capacity though, can also be regarded as a form of redundancy. In Figure 2.3 this availability concept has been attempted to be visualised in a schematic way. The incident, shown as a point in the centre, has to move through various layers of redundancy before it can become a disruption. Which layers this are exactly depends on the incident type, location and system design.

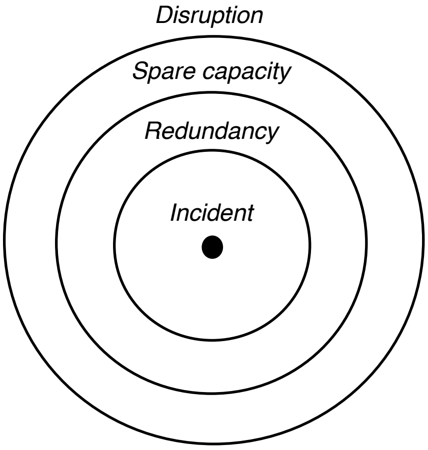


Figure 2.3 Schematic representation of redundancy availability concept

Theoretically, the availability concept of redundancy and system untangling are combinable as each of the untangled system parts can have spare capacity or be made redundant. However, since space is often limited in large complex stations and the land around it expensive, it is difficult to realise these redundancies and spare capacities. After all, in a tangled situation the redundancy (in terms of extra platforms, alternative tracks) is already realised by the possibility for trains to use the infrastructure meant for another train corridor (DSSU) or TOC (London Bridge). Since system untangling diminishes shared use of infrastructure, a high infrastructure availability level seems needed for untangled systems to compensate for this loss in redundancy. Due to this tension, the redundancy concept is regarded as counterpart or opposite of system untangling.

Based on the examples in the previous section and the mechanism described here, there are a few degrees of freedom that can be identified. A clearly noticeable difference between the examples in London and Utrecht is the used *division strategy*. Where London Bridge station is untangled per TOC, Utrecht is untangled per train corridor. Another difference seems to be the *extent* of untangling, as in London only the physical tracks are untangled while in Utrecht multiple systems are being untangled (Network Rail, 2014) (Movares, 2015). Looking at the example of the Hoekse Lijn, this seems to be system untangling on a totally different system *level* compared to examples of London and Utrecht, since here a complete part of railway system is separated from the rest. In biology another *type* of system untangling has been discovered that focused on optimising the design of components instead of limiting the impact of incidents to increase robustness.

Once a clear representation of the railway system has been presented, it is possible to describe these degrees of freedom in greater detail and define the range that fits within the scope of this research. Besides that it is possible that more degrees of freedom can then be identified. This scoping process is described in section 4.1.

2.1.2 Alternative approaches to increase system robustness

In the previous sections the system untangling mechanism has been discussed and several degrees of freedom related to system untangling have been found in various fields of engineering or science. As one of counterparts of system untangling redundancy has been mentioned by Nyström in (Nyström, 2007), but which other alternatives to system untangling are there? In order to determine the effectiveness of system untangling it is important to shed some light on the alternatives as well. This section will describe some other measures to increase the robustness of the railway system found in literature and ProRail documents.

2.1.2.1 Decrease failure frequency

An obvious alternative approach to increase the robustness of a station would be to prevent incidents and failures. Network Rail, Britain's rail infrastructure manager, recently launched a programme in which they aim for reducing the quantity of signal and switch failures (Network Rail, 2016). By all kind of measures, such as monitoring, intensifying maintenance and installing better performing switches, Network Rail hopes to increase the availability of the assets and to prevent disruptions of train services. A similar programme exists in the Netherlands and is called 'Better and More', in the philosophy that the performance of (amongst others) the infrastructure needs to be increased (better) before more trains can be added to it (more) (ProRail & NSR, 2013). The programme comprises a large set of measures varying from constructing extra fly-overs to replacing old switches, which should all lead to a TAO (Train Service Affecting unavailability) reduction of 20%.

Also in the Dutch programme, monitoring the infrastructure in order to prevent failures plays a large role. Permanently monitoring the infrastructure's state and is predicting a failure before it actually becomes a failure is a relatively new form of preventive maintenance. Wiberg & Karoumi describe how they achieved to document and predict the dynamic behaviour of a long-span railway bridge with the help of sensors and data analysis (Wiberg & Karoumi, 2009). By linking patterns in the measured data to the observed behaviour of the infrastructure, behaviour can become predictable. Ideally, in this way a switch for example can be 'repaired' at night before it fails during the day and affects the timetable.

2.1.2.2 Adding extra slack time to the timetable

If a train has more slack time in its timetable, small disturbances will not always lead to delay or cancellations. For example, if a faulty train blocks the platform another train is supposed to use and there are no other platforms available, the other train (theoretically) will have to wait until the faulty train has been removed. If the time it will take for the faulty train to leave is below the amount of slack time in the train's timetable, it will still (theoretically) arrive on time at its destination. The more slack time, the higher the chance the train arrives on time.

In (Goverde, 2007), Goverde uses slack time as indicator for timetable robustness for the same reason as described above. Although it can be argued whether this measure is desirable from a passenger's point of view, since it could also be stated that the train now is always late while without all the extra slack time it would arrive a few minutes earlier most of the times. There is another disadvantage of this theory in relation to the scope of this research that can be thought of. If every train in a large station is given a few extra minutes slack time, the time a train occupies a platform increases and with that the number of platforms required to facilitate the timetable. Platform capacity in a large complex station such as Amsterdam Central station is already heavily constrained (ProRail, 2016n).

2.1.2.3 Californian switch

A completely different measure that is currently only used for urban rail transport is the use of so called 'Californian switches' (Bloss, 1986). A Californian switch pair is a set of switches that can be installed on top of the rails in temporary situations to allow trams to run around obstacles such as engineering works. The set can be assembled in a relatively short amount of time and does not require work on the roadbed or ballast bed. Figure 2.4 shows two pictures of these switches, one of how to assemble the switches and one where they have already been installed.

A huge advantage of these switches is the flexibility that can be gained by them: trains can easily surpass – although with a very low speed – faulty trains or avoid unavailable pieces of infrastructure. Unfortunately, the list of disadvantages is a lot longer. The absence of an overhead wire, automatic operation possibilities, and above all a train protection system makes it not realistic that this solution can be used at a large complex station.

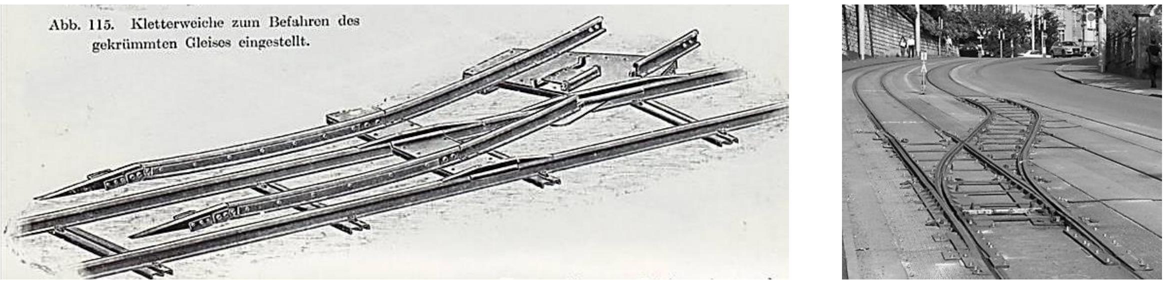


Figure 2.4 Sketch of how to assemble a Californian switch (left) and a Californian switch in use (right)

2.1.2.4 Traffic management

When an incident occurs at a large complex station, the signallers' and other traffic managers' response towards the incident is crucial for the effect it has on the performance of the system. Focussing on always having an appropriate reaction to an incident and using the available infrastructure around the incident to its maximum in order to keep as many services running as possible, can therefore be regarded as a robustness improving measure.

The Dutch Railways (NS) and ProRail have initiated a programme called 'Be- en Bijsturing van de Toekomst' (BBT – Rail traffic management of the future) that develops policies, guidelines and plans on how to operate the railway system in disturbed situations and how to cope with incidents (Ministry of Infrastructure & Environment, 2014b). Key terms found in the document on the topic of incident handling are *predictable*, *reliable*, *action perspective* and *controllable*, but unfortunately the applied philosophy does not seem to strive for system performance, limited impact or robustness (ProRail, 2014c). Nevertheless, if a slightly different approach in the BBT programme would have been chosen, it could have functioned as alternative approach to system untangling in increasing the robustness.

Panou et al. claim that another system could contribute to improved traffic management during incidents and therefore to an increased robustness: a driver advisory system (DAS) (Panou, et al., 2013). Driver advisory systems are installed in cabins to provide the train driver with up to date information on the traffic ahead of him and to advise him on the optimal speed. In the case of an incident, the system could not only be used to inform the train drivers on the taken traffic measures, but the system could also slow trains down to prevent traffic jams in the station area and keep the traffic flowing (Panou, et al., 2013). The fact that the traffic flow becomes more manageable with DAS installed could prevent the signaller from losing overview and thus could allow for more train services to remain operable during incidents (fewer cancellations).

2.1.2.5 Physical incident handling

The previous section focussed on the handling incidents from a traffic management point of view. But besides the traffic management, ProRail is also responsible for making the infrastructure available again as soon as possible after an incident has occurred. Figure 2.5 shows one of ProRail's incident management trucks that have been designed to assist emergency services and solve incidents as quickly as possible (ProRail, 2014e).

Extensive safety regulations and company procedures attached to incident handling often impede the repair process and lead to long periods of unavailability. The incident at Utrecht station described in the trigger of this research forms an excellent example of that. It took several hours to pull the faulty freight train out of the station which blocked several important switches it was standing on (ProRail, 2015b). To make things worse, the second locomotive of this train was a diesel locomotive which could have moved the train away without any additional power. So why did it take so long to make the tracks available again?

Figure 2.5 ProRail and emergency services managing a level crossing incident

Although no literature has been found on physical railway incident handling and although finding out what caused the treacly incident handling at Utrecht on 11 September 2015 is not within the scope of this research, it triggered a possibility to increase the system's performance. If for instance the duration of incidents could be reduced by 10%, this could incur a 10% infrastructure unavailability decrease and thus be a potential alternative to system untangling.

Section summary

System untangling has been defined as 'creating multiple parts within the railway system that have less interaction with each other and therefore prevent irregularities from spreading and increase the system's robustness'. Within the system untangling theory, several degrees of freedom have been identified: division strategy, extent, level and type. Besides that, the redundancy availability concept has been labelled as main counterpart to the system untangling strategy.

In the search for alternative measures to increase robustness various concepts have been assessed so that the effectiveness of untangling options can also be compared to other measures. The most promising found alternatives are decreasing the failure frequencies, improving traffic management in disturbed situation and improving the physical incident handling or in other words reducing unavailability duration.

2.2 Rail system identification

In several preceding sections references to the railway system have been made without defining this specific system. In order to investigate the robustness of the system it is vital that the system is first well defined, but complex systems such as the railway system can be described and visualised in various ways. Choosing a model to describe a system starts with deciding on all kind of different aspects: should the model describe a process, state or causal relation? What is the purpose of the model and what level of detail is required?

First commonly used methods and models for describing systems and examples of railway system descriptions will be explored and explained. Secondly, the criteria for a suitable model or method will be determined after which a suitable model will be selected as basis for describing the railway system for this research. The difference in definitions for model and method used here is that a model is a finished product that can be applied to the Dutch railway system directly, while a method is only the approach taken to develop the model. In case the model is not fit for purpose, it does not mean the used method to create the model is not suitable as well.

2.2.1 Available models and methods

Ways of describing the system will not only have been developed within the railway sector, but also in other fields. According to Medvedeva & Umpleby there are four methods for describing systems: as a set of *variables*, *actors*, *ideas* or *events* (Medvedeva & Umpleby, 2004). Which of these methods is feasible and most suitable obviously depends on the system to be described and the purpose of the description. This section describes and sums up the various models found in literature in predatory to the selection of the most suitable one in the next section.

2.2.1.1 Functional model

ProRail has multiple models to describe the railway system, although they are often limited to the infrastructure part of the railway system, for which ProRail is responsible. The functional model consists of an object tree with several levels of detail, describing all assets on and near the tracks categorised by their function. It would be classified by Medvedeva & Umpleby as a description model based on a set of *variables* (ProRail, 2016b), (Medvedeva & Umpleby, 2004).

The functions the infrastructure should facilitate take a centre stage in this model and are defined by ProRail as follows: support, cross, guide, energise, control, protect, transfer and communicate. Together they represent the key tasks of the infrastructure manager and create a location for each asset ProRail controls. Figure 2.6 visualises the two highest levels of this model including some examples per function. A drawback of the model is that the functions are actually specified as either tasks or responsibilities of ProRail instead of real functions of the railway system. Furthermore it does not show the interaction between the assets, any relation to the processes within ProRail or the involvement of different parties such as the train operating company.

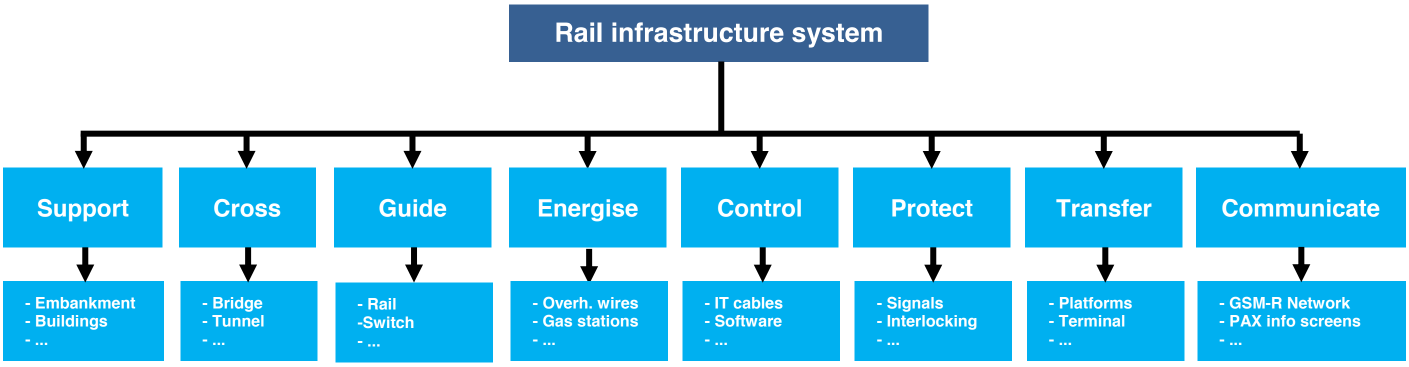


Figure 2.6 High level overview of ProRail's object tree containing all assets they are responsible for. (ProRail, 2016b)

2.2.1.2 Physical demarcation

A very simplistic yet approachable method is to define the physical boundaries of the system and to state that everything within these boundaries is part of the railway system. Though, the difficulty of this method emerges when the system is too spread out or does not form a continuous area. This method does not seem to fit in the categorisation made by Medvedeva & Umpleby, as the description does not comprise any ideas, variables, actors or events (Medvedeva & Umpleby, 2004).

If this method would be projected on to the railway system, the physical boundaries would follow from the areas that are under control of the infrastructure manager. ProRail controls a fixed area next to the physical tracks which should typically be around 8 metres, but varies slightly per location due to lack of space or historical developments. Nonetheless, the inner side in curves needs a wider area in order to guarantee the visibility of signals and signs (ProRail, 2016c). The space often contains columns for the catenary system, signals, fences, noise screens, small buildings for electrical equipment and ditches for drainage. In station areas the situation differs per location, although ProRail is always the owner of the stations. A possible physical boundary would for instance be to only include the locations of the infrastructure manager's assets instead of using a fixed amount of space. The boundary could then be defined as:

> *The physical area of the railway system contains the railway tracks including the space next to it where railway related assets are present such as the columns for the catenary system, signals, station buildings and ditches for drainage.*

2.2.1.3 Task-related description

Large systems such as the railway system often comprise many actors that all have tasks or responsibilities to fulfil. As a result of that, these systems lend themselves to be described on the basis of these tasks and actors including the interaction and the hierarchy between them. ProRail has used this method to describe their Operational Control Centre Rail, which has as main goal to manage a smooth operation of the timetable through cooperation of all involved actors (OCCR, 2016). According to Medvedeva & Umpleby this is an idea-based system description and not – as the word suggests – an actor-based description. They state that idea-based models describe the system by the ideas, values, tasks and responsibilities of different actors, which is in line with ProRail's model for their OCCR as it focuses on the responsibilities and tasks of the actors and how they interact (Medvedeva & Umpleby, 2004).

Figure 2.7 shows a small (translated) part of this model, in which each puppet represents a job description that comprises one or multiple tasks (ProRail, 2016d). Although there is no clear visualisation of interaction present in the figure, the order in which the large blue boxes and puppets are placed is such that the most important partners are always near. A disadvantage of the method is that it is difficult to guarantee the completeness and relevance of all tasks: some may not be in sight directly or are executed by an actor as a second extra task instead of main task. On top of that, it is hard to identify a logical structure in organisation, as many categorisations may have grown historically.

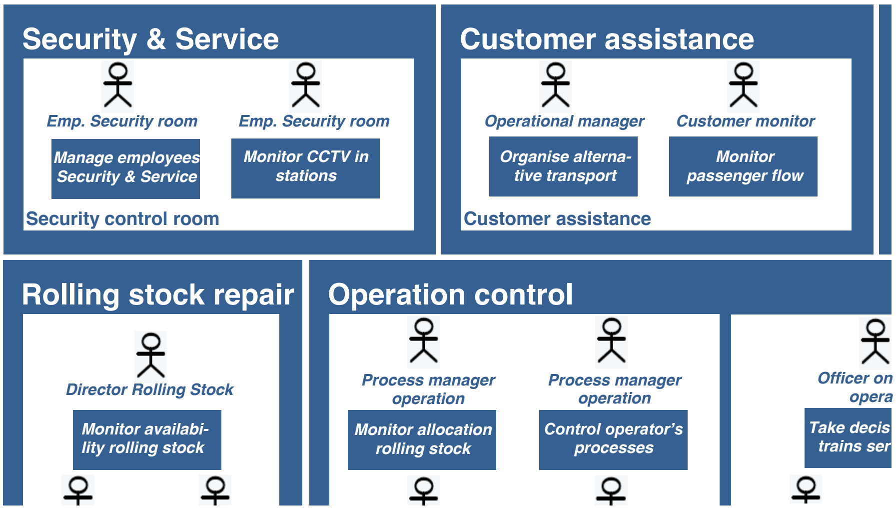


Figure 2.7 Translated part of ProRail's chart to describe the tasks at OCCR (ProRail, 2016d)

2.2.1.4 Rich picture

A rich picture is a tool that originates from Peter Checklands' research in 1972, in which he searched for a method that was able to describe complicated and large 'soft systems'. He reasoned from the well-known phrase that 'a picture paints a thousand words' and believed that a drawing of the system would assist the systems' problem owners to get an overview and to better understand the dynamics of a system (Bell & Morse, 2012). The approach to draw a rich picture is straight forward: draw a picture of the system and add as many details – make it as 'rich' – as possible. Although there have been several attempts to create uniformity in the use the various types of lines or signs, a successful and widely accepted manual has not yet emerged. As a result of that rich pictures still exist in many different shapes forms and the definition when to call a diagram a rich picture is vague (Bell & Morse, 2012).

Figure 2.8 is an example of a rich picture found on the wall in the head office of ProRail in Utrecht, where the vision of ProRail is projected on the railway system with the purpose to identify the future changes from a local resident's point of view. A drawback of this method is that it is difficult to capture the full system or to show multiple levels of detail in one picture. Medvedeva & Umpleby would classify this model as idea-based (Medvedeva & Umpleby, 2004).

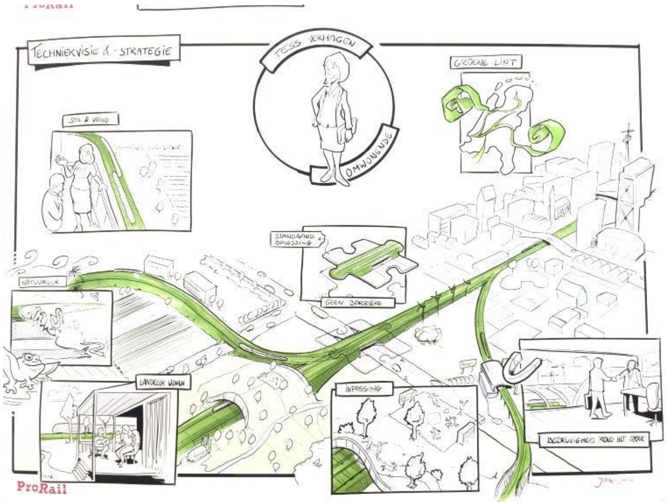


Figure 2.8 Example of a rich picture describing the railway system from a local resident's point of view

2.2.1.5 Railway actor model

Instead of displaying the various tasks present in the system, another approach is to depict the actors or groups that are involved. It seems inevitable that depending on the type of actions taken in relation to the system, such as modifying or operating the system, the composition of the group involved actors differs. ProRail is attempting to capture these actors or parties in one model consisting of various layers with equal purposes to be able to match actors that are fulfilling the same function in different stages prior to the departure of a train. As an example, during the development of the railway system, product developers are responsible for the creation of the transport experience for the customer, while the service employees have this task during the operation. If for instance the transport experience is wished to be strengthened, it is easy to see which actors should closely work together.

Figure 2.9 shows an interpretation of this model, which is at this point in time only available in draft version. The left column is defined by ProRail as the 'railway chain' between customers and assets (ProRail, 2016e). A disadvantage of this model is that there is neither an identification of subsystems given, nor a clear indication to which company or group each actor belongs. Medvedeva & Umpleby would classify this method as actor based (Medvedeva & Umpleby, 2004).

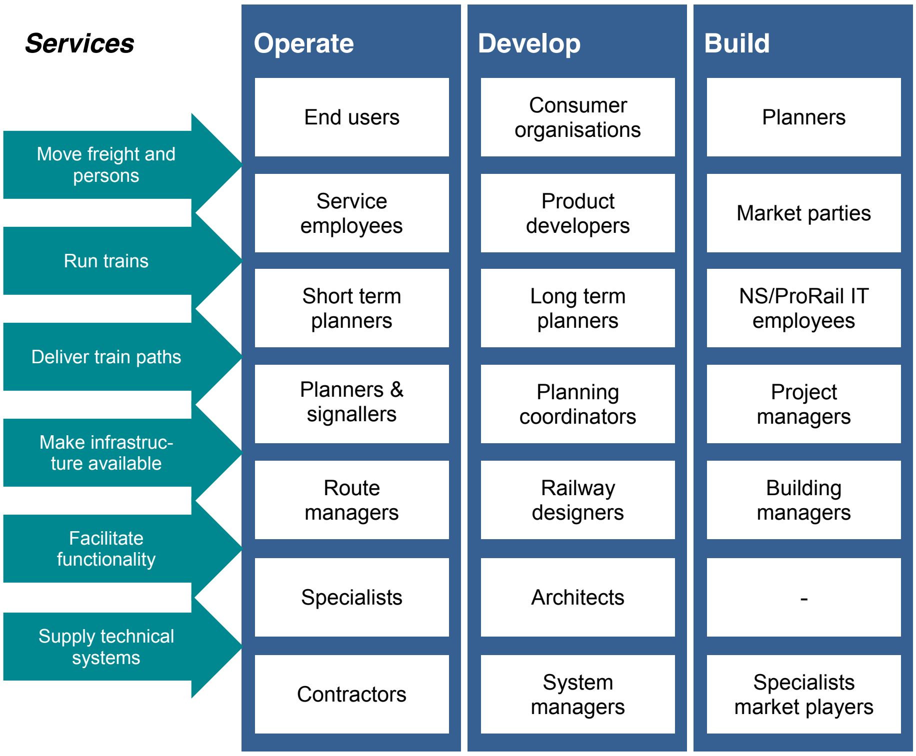


Figure 2.9 Interpretation of ProRail's draft model describing the actors with equal functions per stage (ProRail, 2016e)

2.2.1.6 TRAIL Layer Model

A very high level model is the TRAIL Layer Model, depicted in Figure 2.10. The model tries to capture the dynamics of the transportation system and forms the basis for many other models; some of the layers for example could also be identified in Figure 2.9. The starting point for this model is the assumption that activities lead to a need for transportation, because not all activities in a person's life can take place in one location. As a result of that there will be a demand for transport services that will be answered by the transport companies. They will then need to enter the traffic market searching for vehicles to carry out the promised transportation, which will be supplied by traffic services. The traffic service and transport service could easily be the same company; they just have been depicted separately to indicate the different roles they fulfil (Schaafsma, 2001). Medvedeva & Umpleby would classify this model as an actor based model, since the focus is on the interaction between different groups or roles (Medvedeva & Umpleby, 2004). The main disadvantage is the high level of the model that leaves no room for a more detailed description.

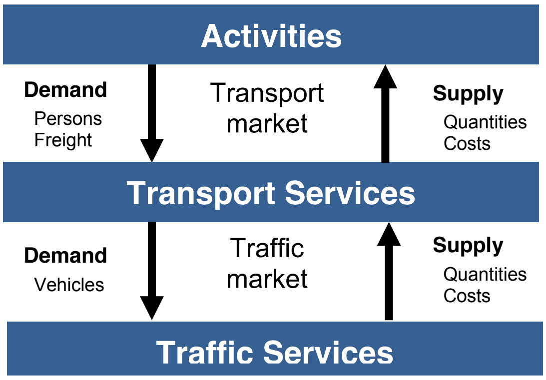


Figure 2.10 TRAIL layer model (Schaafsma, 2001)

2.2.1.7 Event modelling

A completely different approach is one that takes an end user perspective and describes the system as it is used, which is done in discrete event modelling. Lemeire explains in his tutorial on how to use discrete event modelling that this method is specifically suitable for gaining insight in the interrelations between various components of a system (Lemeire, 2006). First, the system – in Lemeire's case a supermarket – is divided into logical processes from an end user's perspective, which are connected by channels or interchange arrows. This static part of the model is then used to describe the system's dynamics by events, which 'travel' through the channels between the logical processes (Lemeire, 2006). As an example, Lemeire defines the following logical processes: living in town, parking, entering, shopping, queuing, desk-selecting, paying, exiting. Obviously more could be identified depending on how detailed the model should be to fulfil its purpose. These processes can be classified as *sources* (event initiators), *queues* (event stackers), *sinks* (event terminators), *delays* (event delayers) *multiplexers* (channel mergers) or *de-multiplexers* (channel splitters), each with their own symbol, see Figure 2.11.

Running the model means processing the events through the logical processes and monitoring the travelling of the events along the channels. In every time-step, there will be many events spread out in the model, each with a certain timestamp, indicating at what time it arrives in the next logical process (Lemeire, 2006). According to Lemeire the purpose of this event-driven simulation is that the systems dynamics are triggered and become visible by events. This model is classified as an event-based system description by Medvedeva & Umpleby (Medvedeva & Umpleby, 2004).

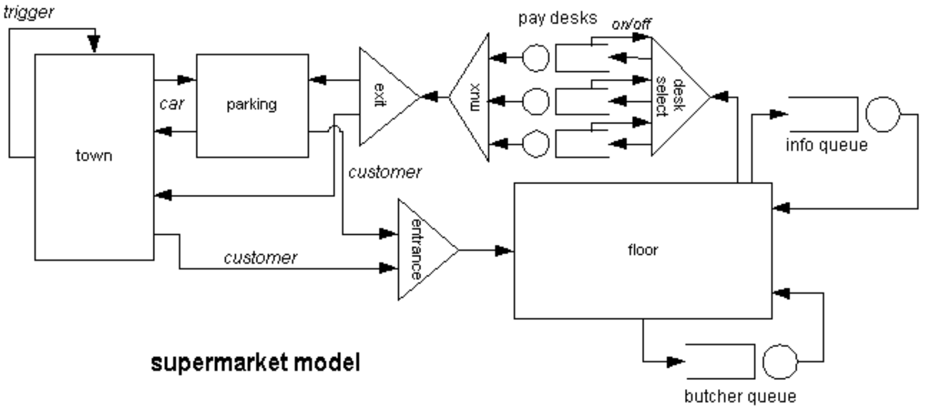


Figure 2.11 Static part of the event-driven simulation model of a supermarket (Lemeire, 2006)

2.2.2 Selection of a suitable model or modelling methodology

In the previous section seven models and methods for describing systems have been discussed, each being very different. The purpose of the section was to find both commonly used methods and models for describing systems and examples of railway system descriptions. To do so the research of Medvedeva & Umpleby, in which they state there are four different ways to describe a system, has been used as guidance (Medvedeva & Umpleby, 2004). And although for some of the seven models and methods it has been found difficult to assign them to one of the four categories, an example for three of the four categories has been found. Besides looking for examples that fitted Medvedeva & Umpleby's research, the focus in this part of the literature review has also been on identifying practical models and methods within the ProRail organisation instead of in scientific literature alone, because they are already tailored to the Dutch railway system. Based on the scope and research question, several selection criteria can be set up to identify the most suitable method or model. These criteria a described below.

- ***Stratification***
  In the problem description it was stated that the untangling possibilities on all different levels of the railway system are of interest in this thesis. The model to describe this system should therefore have a form of stratification, for instance in level of detail, abstraction or time.

- ***Logical subsystems***
  Not only are the untangling possibilities on all different levels of interest, it is also mentioned that the research scope comprises untangling options *across* the railway system or in other words untangling options in different subsystems. Examples of untangling found tend to untangle just a specific subsystem such as the overhead wires. To be able to explore these untangling options of the system as a whole it is necessary that the model contains subsystems. Not only should these subsystems be comprehensive, they should also be formed logically and consistently because when the untangling options per subsystem will be identified, it must be possible to define clear borders between the different subsystems.
- ***Scope***
  As the term total system untangling in section 1.2 suggests, the model to describe the system should describe the whole railway system. Taking into account that ProRail does not represent the whole railway system, it is important to find a model that also takes into account the parts of the TOCs and FOCs, contractors, end users and other involved parties.
- ***Actors/roles***
  In addition to the previous criterion, it would be interesting to see if a system untangling option would affect multiple actors or roles within a company. Being able to identify which actors and roles are present at which location in the railway system is therefore required.
- ***Interactions***
  Adjunct to the actors and roles are the interactions between them. The same way of reasoning used for the required ability of the model to position the actors and roles also holds for these interactions: if a part of the system is untangled it is key to not only be able to see who is affected by it, but also how they are affected. The model should therefore provide the possibility to describe relations and interactions between roles or actors.

Table 2.1 shows for all models and methods which of the above criteria they meet and which they do not. Again, the difference between a model and method is that model is defined as the exact system description as shown in the examples in the previous section and method is defined as the approach that was taken to develop the specified model. So, if for instance the scope in the example would not have been large enough resulting in the model not being suitable, the method on the other hand could still be suitable if it can be used to create another version of the model with a more satisfying scope. In that case, the scope of the model would be labelled ‘No’ in Table 2.1 while the scope of the method would be labelled ‘Yes’.

According Table 2.1 none of the described models meets all five requirements and therefore none can be used directly to describe the railway system. Nevertheless, there is one suitable method: the method used for the railway actor model is capable of creating logical subsystems, while this was not the case with the railway actor model described here. Thus, based on the five criteria, an adjusted version of the railway actor model in which the subsystems are created logically, would be the most suitable model for describing the railway system.

	Stratification	Logical subsystems	Scope	Actors/ roles	Inter-actions
Functional model					
Model	Yes, level of detail	Yes	Only infrastructure	No	No
Method	Yes, level of detail	Yes	Yes	Yes	No
Physical demarcation					
Model	No	No	Only physical	No	No
Method	No	No	Only physical	No	No
Task-related description					
Model	No	Subsystems present, not logical	Only man-handled part	Yes	Yes
Method	Yes	Yes	Only man-handled part	Yes	Yes
Rich picture					
Model	No	Yes	Yes	No	Yes
Method	No	Yes	Yes	Yes	Yes
Railway actor model					
Model	Yes, levels of abstraction, detail and time	Subsystems present, not logical	Yes	Yes	No
Method	Yes	Yes	Yes	Yes	Yes
TRAIL layer model					
Model	Yes, three levels of abstraction	No	Yes	Yes	Yes
Method	Yes	No	Yes	Yes	Yes
Event modelling					
Model	-	-	-	-	-
Method	No	Yes	Yes	Yes	Yes

Table 2.1 Scoring table of all seven models and methods

A logical subdivision of subsystems is seen in the functional model, the rich picture and in the event modelling methodology. In the functional model it was based on the functions the infrastructure had to fulfil, although some of the mentioned functions tended to be responsibilities instead of functions. The rich picture divided the system in categories based on users' requirements and the event modelling methodology based the subdivisions on the specific moment in the customer journey the users use a certain part. So far, the functional model seems the most suitable to be combined with the railway actor model because of the similar shape and non-user point of view, in contrast to the rich picture and event modelling. Nevertheless, some modifications to identified functions by ProRail are necessary, since some of them were responsibilities instead of functions. Therefore it can be concluded that adjusting and combining the railway actor model and the functional model forms the basis for a suitable model to describe the railway system.

Section summary

An adjusted version of ProRail's railway actor model including the (adjusted) logical subsystem built up based on ProRail's functional model would be the most suitable model to use for describing the railway system, as they meet most of the requirements.

3 System identification

ProRail's railway actor model and functional model met most of the requirements and were therefore selected to serve as basis for the model to be developed in this chapter. Figure 3.1 shows this step from the research approach.

The developed model has been named the Railway Service Model as the service offered to the end user forms the starting point for the model. In the first part of this chapter the theory behind the model and the development process are described, while in the second part the model is applied to the Dutch rail system. Specific information on the technologies used in the Netherlands will also be given there in preparation to the untangling option identification process in chapter 4.

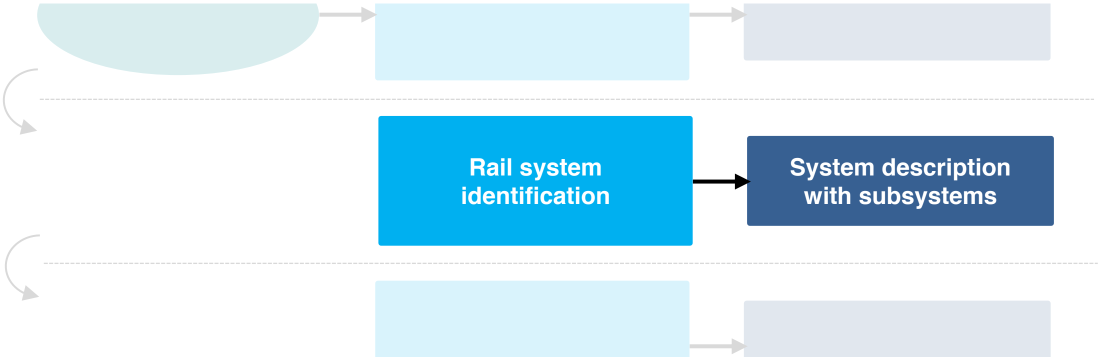


Figure 3.1 Actions and output covered in this chapter

3.1 Railway Service Model explained

The developed model describes the railway system from a service point of view with as central question what it actually is that the system provides. Obviously, the main goal of the railway system is providing a transportation mean to travel or transport freight from A to B, but the way this takes place is subject to several requirements such as on safety and guidance. A bidirectional approach has been taken to include both the requirements and purpose of the system, starting with the latter. By repeatedly asking the same questions 'What is needed to accomplish this?' and 'Who is providing it?', several layers or levels of abstraction can be identified, the first one being the purpose of the system and the last one the individual physical elements present on the tracks. Per layer the involved or responsible party can be named and it can be made clearly visible what they provide and what they need or request from each other.

The second step is identifying the main requirements that clients have when using the railway system, which will be based on a ProRail business intelligence document (ProRail, 2016b) – introduced as the functional model in the literature review – and reverse reasoning: with the absence of which requirement would the railway system become unused or far less effective? The systems that fulfil these requirements will be identified as the functional subsystems of the railway system.

3.1.1 Theory

This section will go through the development process of the previously introduced model that has been visualised in Figure 3.2, and will explain the model in detail. The basic requirements shown in the top left corner though, will be explained in the next section.

The starting point is the main function of the system: facilitate rail transport of persons or goods from A to B. To do this, a *rail transport service* is necessary, which comprises an agreement between a customer (*End user*) and a third party (*Train ticket seller*) that arranges the rail transport the customer asks for. This third party could be the TOC or FOC as well as an intermediary party, which is frequently the case with freight transportation.

The ticket seller will then be in need of a *rail transport network* to be able to provide the transport agreed with the customer. This network is offered by TOCs and FOCs (*Train operators)* and consists of a network of locations with links between them that indicate the access and delivery points of their network and the available connections. Figure 3.3 shows an example of a traffic network, in this case a part of the network NS offers in 2016. In this example the route a train will roughly take between two cities can be seen by the lines drawn through the stations, but there also exist network graphs including train series that show the stopping pattern, frequency and origin-destination combinations of the trains.

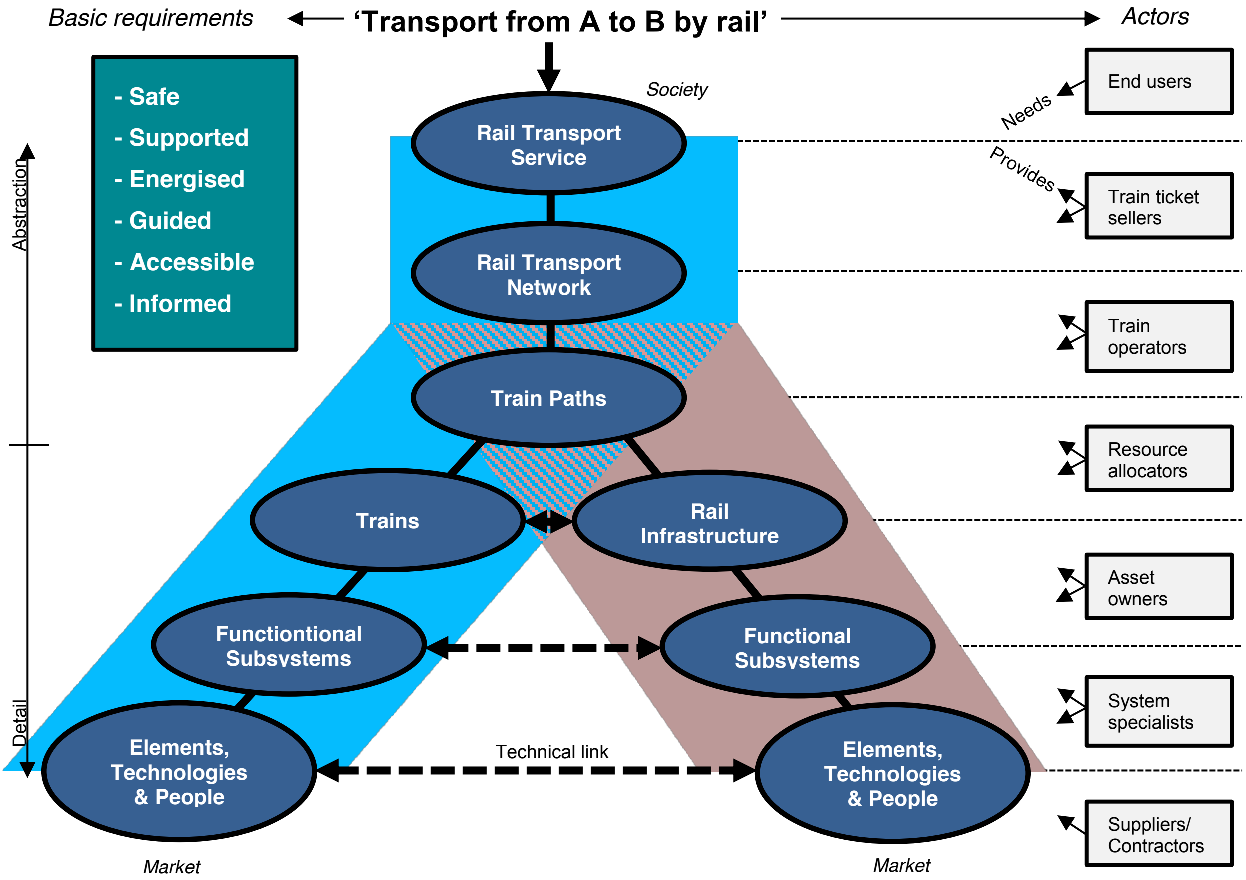


Figure 3.2 Railway Service Model

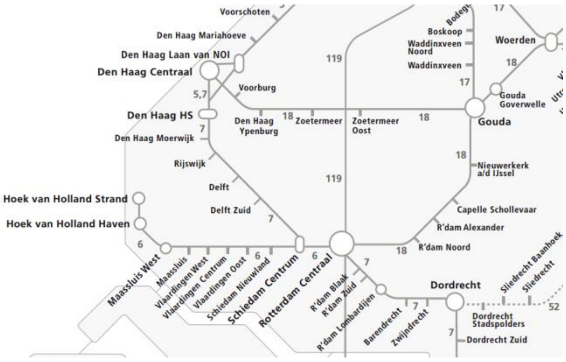


Figure 3.3 Part of the traffic network offered by the Dutch Railways

The train operating companies will look for available train slots or *train paths*, which can be defined as a specific time a train is allowed to take a specific route. The requested train path is provided by the *resource allocators* who can be planners that allocate the capacity of the infrastructure or rolling stock a year in advance, or signallers who actually provide the specific path during the operation.

To use these train paths the allocators are in need of available assets. At this point the physical part of the model has been reached and there is no lower level of abstraction possible. Nevertheless, by persistently asking the question ‘what is needed for that’, another form of stratification is triggered: level of detail. Thus, the levels from this point onwards will all be at the same level of abstraction but will differ in level of detail.

The assets needed by the allocators can be split in available *trains* (moving assets) and available *rail infrastructure* (fixed assets). The reason of this subdivision is that from this point in the chain downwards, the correlation of interests and co-operation between the involved actors decreases. What remains strong is the technical link between the infrastructure and trains in order to guarantee compatibility in operation. Beware that *trains* do not only consist of rolling stock, but the personnel to operate the train is also included while the *rail infrastructure* also comprises all related assets such as signals and the catenary system., see Figure 3.4. The responsible actors that provide this could be called infrastructure managers and train owners – who are frequently also the train operator – or *asset owners*.

Figure 3.4 ‘Trains’ are including operating staff and ‘rail infrastructure’ is more than just tracks

The asset-owners need to deliver available infrastructure and trains that are able to fulfil all critical functions during operation, and therefore they are relying on the well-functioning of all the asset’s *functional subsystems*. *System specialists* take care of this well-functioning by designing, building and maintaining the subsystems. In a company a ‘tractive effort specialist’ for example is fulfilling this role by making sure that there is always energy available to run trains.

In order to do so, the system specialists need *technologies, elements and people* which form lowest level of detail in the model. Obviously the signals, detection loops and train engines that amongst others belong to this level could again be subdivided further into smaller groups, but this is not relevant for the scope of this research. The technologies, elements and people are provided by *contractors and suppliers.*

3.1.2 Identifying the subsystems

As said before, the second step to be taken in defining the railway service model is identifying the subsystems. So far, the railway service model has mainly been based on the railway actor model, which explains the absence of specified subsystems, although the location of these subsystems in the model has already been identified. The functional model should provide input for this logical subdivision that enables the railway service model to show where multiple functions are present in certain technologies or elements.

The functional model identifies eight different functions: support, cross, guide, energise, control, protect, transfer and communicate, which could be used as subdivision strategy for the railway system without any adjustments. But, when taking a closer look at these functions it becomes clear that not every mentioned function is actually a function of the railway system. Communicating and (acceptably) crossing infrastructure of other modalities are not functions of the railway system, but facilities that ProRail (the developer of the functional model) should make available. Therefore the subdivision in the railway service model has been made in an alternative way which is purely based on the critical requirements that are given by the end user. In other words, which requirements that end users have for rail transport do the functions in the functional model actually represent? For example the function 'transfer' represents the requirement that the end users want to access and egress from the system, and the 'energise' function the requirement that end users do not want to be moved from A to B at the expense of their own energy. Table 3.1 shows an overview of the functions mentioned in the functional model and the end user requirement they relate to. If there is an end user requirement, the function will be identified as a subsystem in the railway service model.

Functional model	End user requirement	Railway Service Model subsystem
Support	Being carried over water and land	Support
Cross	-	-
Guide	Arriving without having to drive	Guidance
Energise	Arriving without using own energy	Energy
Control	-	*Resource allocation level*
Protect	Arrive safely	Safety
Transfer	Being able to get in and off the trains	Access
Communicate	Knowing where to go when	Information

Table 3.1 Relations between functions mentioned in the functional model, the name in the railway service model and the requirement of the end user

Six out of the eight functions have been selected as logical subsystems, though sometimes the name or focus had to be changed. The cross function has not been selected since acceptably crossing the landscape is a requirement from people living near the railway system, not from the end users. It is for that reasons not regarded as functional subsystem of the railway system that can be untangled.

The same holds for the control function, which is not a function on itself but a mechanism to enable the system to fulfil its function. Systems that have a control function, such as the IT systems that monitor the traffic state and enable signallers to interfere in the train traffic, cannot be called functional systems that the infrastructure or trains should fulfil. Therefore the control mechanisms are not regarded as an asset-related subsystem but a tool to improve the resource allocation (in real time). The resource allocation has been given a separate layer in the Railway Service Model, which is one abstraction level higher and has a train path as product (see Figure 3.2).

The other functions of the functional model have all been selected as subsystems and will be discussed in detail below. Besides that a more precise definition of each subsystem will be given. In Figure 3.2 the subsystems are depicted in the left upper corner.

3.1.2.1 Support subsystem

The first requirement is support, meaning that the passengers or freight are carried through the land scape via tunnels, bridges, viaducts and beddings. A well-known non-supporting transport system is a ski-tow that drags skiers to the top of the mountain. This type of transport system is obviously not suitable for the railway system due to the weight, comfort and large distances. Besides supporting perpendicularly to the surface, the vehicles also need fixation in the directions parallel to the surface. The function of the supporting subsystem could therefore be described as the impediment of movement in unintended directions (Up, downwards and sideward movements). Support is a difficult function to assign to specific elements and technologies as almost all materials between the passengers or freight and the load-bearing layer in the ground have a part in carrying the weight. A satisfying definition of the support subsystem would therefore be the collection of elements and technologies that have as main function to carry the trains through the landscape.

3.1.2.2 Guidance subsystem

Guided vehicles are one of the most characteristic differences between road transport systems and rail transport systems and therefore a key requirement of the railway system is that the transport is guided: no passenger will ever have to steer or guide the vehicle. The guidance follows from the specifically designed contact between an iron rail and wheel, where the flange or rim on the wheel with the help of the train's weight pushing down on it, makes sure the train follows the rail (see Figure 3.5).

A disadvantage of this rail-flange guidance technique is the complex systems that are needed to guide trains in different directions, since the technique requires a continuous unidirectional rail. These systems, known as switches or points consist of moving elements that are operated by small engines or muscular force, and therefore add a new aspect to guidance: guidance also includes the setting of switches in the right position. Summarily, the overarching function of the guidance subsystem could be defined as making sure that the train is following the intended route.

Figure 3.5 Interaction between rail and wheel that provides guidance

3.1.2.3 Energy subsystem

Transporting freight or passengers requires energy and a very important requirement therefore is that energy is delivered to the system. The alternative would be that the passengers generate tractive effort themselves, but this would most likely lead to a large decrease in users of the system. Besides energy subsystem the subsystem could also have been called the propel subsystem, as its main function is to propel the train from A to B, but since ProRail always refers to energy it was decided to adopt this term (ProRail, 2016b) .

Although many elements and technologies in and around the tracks require energy, such as signals and points, the energy subsystem only provides energy for the transport itself. Energy supply for signals for instance would be an element in the safety subsystem, since a disruption in the supply would lead to unsafe transport instead of the loss of tractive effort. The function of the energy subsystem is therefore unambiguous and could be defined as the subsystem that comprises all systems that provide energy meant for movement of trains.

3.1.2.4 Safety subsystem

Naturally, end users and especially passengers give the highest priority to arriving safely and in one piece. Safety is a very broad term that takes many things into account which do not all lie within the scope of this research. First it needs to be clear what is meant with safety, starting by making a distinction between preventive safety that prevents accidents from happening and reductive safety that reduces the impact of an incident. Examples of reductive safety are doors in noise screens that provide a safe evacuation route, a crumble zone in a train that absorbs the kinetic energy during a collision and specially designed tray tables in trains that reduce injuries caused in a collision. Nevertheless, the focus is on the preventive safety system and especially the part that is needed due to the movement of trains.

In relation to movement of trains ProRail (ProRail, 2015c) identifies three risk groups: derailment risks, collision risks and train destruction risks (fire, explosion, and electrocution). The risk groups that are present due to the movement of trains are the groups that lie within the scope, because of the strong relation that then exists between infrastructure and train. According to ProRail this relation is strong in the first two groups, and less in the latter (ProRail, 2015c).

So although there are many other forms of safety, the safety subsystem in the Railway Service Model only addresses two groups of risk. The same ProRail source that identified these two groups of risks also identified four measures that – when enforced – mitigate the risks in the two groups. These four (general) measures are explained below.

- ***Keep trains separated***
  Trains can move around the network and therefore could also collide with each other. The involved high speeds contribute to the severity of the collision risk because on the one hand trains have long breaking distances and on the other hand the impact of the collision is larger at these high speeds. Keeping trains separated from each other is therefore a key sub function of the safety subsystem.
- ***Guarantee trains' safety envelopes***
  Besides colliding with each other, trains can also easily collide with other objects as they have no possibility to avoid obstacles due to their fixed side-wise position on the tracks. For example a warning system installed at a level crossing is a measure that opts to empty the train's safety envelope from cars in case a train approaches.
- ***Check the state of operation of elements and technologies***
  A broken rail or faulty break in the train can result in a serious incident and should therefore be noticed before a trains runs over it or departs. How this measure is currently enforced is not always clear. An example of the measure is a function (amongst others) of the interlocking system that actively reports if switches are in a locked in the correct position.
- ***Enforce speed limits***
  If a train drives faster than the infrastructure was built for, a derailment can be the consequence. Enforcing the speed limit is therefore an important sub function of the safety subsystem, which is generally handled by an ATP system.

The technologies in the safety subsystem that fulfil most of these sub functions are the signalling systems and interlocking systems, which will be explained in further detail when the Railway Service model will be plotted onto the Dutch railway system in section 3.2.

Concluding, the safety subsystem of the Railway Service Model can be defined as the system that prevents derailments and collisions. The sub functions of this subsystem are keeping trains separated, guarantee the safety envelope, checking the failure of elements and technologies and enforcing the speed limit.

3.1.2.5 Access subsystem

Vehicles that run from A to B are useless for passengers if they cannot get from their origin to the vehicle or from the vehicle to their destination. The same holds for freight if there are no transfer possibilities to other modalities. The egress and access trips that are made with other modalities, such as by bus or by foot, need to reach the railway in centralised locations due to the railway's mass transportation character: Railway transport is most efficient for larger numbers of passenger or freight and over fairly long distances (Menger, et al., 2014). These centralised locations are currently the stations and terminals, providing the access to the railway from other modalities and vice versa. In the future though, it could be possible that for instance smaller bimodal vehicles operate in a more door-to-door transport concept. As a result of that access points would be more similar to level crossings, where the trains could leave the tracks and continue the last part of the journey as a road vehicle. For now, the access subsystem is defined as the system that provides access to and egress from the vehicles.

3.1.2.6 Information subsystem

Although it is possible to use the railway system to its fullest capacity with only the previous five subsystems present, this extra subsystem is added with as main function to inform end users. Without real-time information on departure times, platforms of the departing trains or disruptions of train services, the railway system will no longer be able to fulfil its main function. An example has been shown by the chaos in train stations caused by the failure of all traffic information screens in The Netherlands on 20 January 2016 (Algemeen Dagblad, 2016a). In that case, only one of the channels that are used to provide information was unavailable, since real-time information on mobile devices and through announcements on the stations was still available. Especially in relation to system untangling, it is interesting to investigate what the influence of a loss of information would be. The information subsystem is defined as all technology and elements that have as main function to inform end users on traffic information.

3.1.3 Train or infrastructure related subsystems

Because the subsystems are defined as functional subsystems, the fact whether the function of the subsystem is fulfilled by technology and elements in the rail infrastructure, in the train, or in both, is still variable. Nevertheless, one subsystem seems to have a unique place in the model, namely guidance which is provided by rail-wheel contact. This contact lies on the intersection between infrastructure based and vehicle based and does not seem to have an alternative: without this rail-wheel contact it would be incorrect to talk about a rail transport system. Table 3.2 gives both a vehicle based and infrastructure based example of technologies and elements that fulfil the main function of each subsystem to show the independent locations of functional subsystems. However, not all technologies and elements mentioned in the table seem realistic or probable to be successfully installed.

Subsystem	Vehicle based	Infrastructure based
Support	Hovercraft technology on trains to cross the river	Bridge to carry train across the river
Guidance	Rail-flange interaction	Rail-flange interaction
Energy	Solar energy panels installed on trains	Electrical overhead wires
Safety	On-board system that communicates with surrounding trains to keep trains separated	Signals along the line that guarantee separation
Access	Extendible ramps on trains to alight at random locations	Platform in station
Information	Screens in trains based on train GPS	Screens on platforms based on detection loops

Table 3.2 Examples of vehicle based and infrastructure based technologies and elements in each subsystem

3.1.4 Other passenger requirements

In the search for logically created subsystems the validity of the functions in ProRail's functional model has been tested from an end user's perspective. By investigating what the underlying customer requirements were, it was checked whether all eight functions were actually fulfilling a function for the end users. Out of this check six subsystems have been selected, which fulfil the following requirements: rail transport from A to B should be supported, guided, energised, safe, accessible and informed. Obviously, these are not the only requirements end users set for rail transport, passengers for instance also value certain on-board facilities and require that they are protected from the outside environment during the journey.

Customer requirements are present in many shapes and at many levels, and together they form the attractiveness of the railway system. The Railway Service Model was never intended to incorporate all these requirements, but only used customer requirements to verify the functions of ProRail's functional model. The found requirements behind the functions do seem to be amongst the most basic customer requirements though. The goal of the model is to facilitate the explanation and description of system untangling, which is not directly linked to customer requirements.

3.1.5 Multiple branches

Up and until now, the Railway Service Model has been visualised as a model with just two branches in the physical part: one for the infrastructure and one for the trains. If the train branch represents a train with specific subsystems and elements and technologies, it is imaginable that at a large node more than one train type will be used for operations. Even more train types and differences in technologies and elements will be present if also multiple operators use a station. To cope with this multiplying factor a part of the Rail Service Model should be extended.

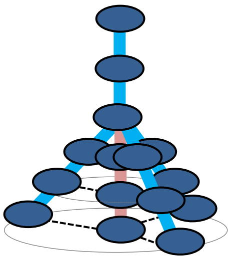


Figure 3.6 Railway service model with 3 train branches

Figure 3.6 shows an abstracted version of the railway service model in 3D, where three train branches have been depicted, all connected on the resource allocation level. Each branch could represent a train type or even an individual train, that all have to be allocated to the same infrastructure. The dashed black lines between the trains and infrastructure depict the technical link that always has to be present to guarantee interoperability.

Comparable to the multiple branches for the various train types, the infrastructure branch could also be split: not all locations in the whole railway system are equipped with the same infrastructure. The safety subsystem for instance could make use of different technologies per location such as ATB or ETCS, which requires different specialist and different technical links with trains. In one location though, the infrastructure should be represented by a single branch.

In general, all branches always need to be joined on the research allocation level. After all, no matter how many train types, operators or safety subsystem technologies there are, train paths can only be allocated once and can never be conflicting.

3.2 Applying the Railway Service Model

In the previous section the Railway Service Model designed to describe the railway system has been explained and visualised. To get a deeper understanding and to align with the scope of the research, the Dutch situation will be projected onto the model. Three different aspects will be plotted in three different sections: the involved actors, the relevant time aspect, and the technologies and elements used in each subsystem. Since not all of these aspects are equal across the country, the situation of large complex station Utrecht – as main node of the railway system in the Netherlands – is chosen to be used as example.

3.2.1 Involved actors

The key players of the railway system around Utrecht are ProRail, which is the national rail infrastructure manager, and NS (Dutch Railways) which is by law assigned as the only company allowed to operate passenger trains in the area until 2025 (Ministry of Infrastructure & Environment, 2014c), (ProRail, 2015d). They each have their own responsibilities and tasks within the system and in Figure 3.2 these have been marked by a red colour if they belong to ProRail and by blue for NS.

To start with the upper part, where the end users are located, society could be plotted. The end users, as a part of society are asking for a rail transport service to fulfil their need for travelling simultaneously specifying the requirements this service should fulfil. The government, which could be seen as the representative of society, facilitates this transport service by investing and regulating the railway system. Although ProRail and NSR have been privatised in the past, the companies are still strongly linked to the government (NS, 2016), (ProRail, 2016f).

NS provides this transport service by operating its transport network, and mostly sells train tickets directly to the end users. To operate their transport network that consists of multiple fast train and local train connections (Spoorkaart.nl, 2015) they are highly dependent on the available capacity of ProRail's infrastructure. ProRail is therefore already involved in the design phase of the network structure, but carries no responsibility for it. If NS could provide reasonable proof that end users are rightfully asking for higher frequencies, extra lines or other matters for which there are no suitable train paths available, ProRail would be obliged to facilitate this (Overheid.nl, 2016). So, although the responsibility and initiative of transport network lie with NS, there are certainly already many interactions and common interests between NS and ProRail at this level.

Besides NS, several FOCs also apply for infrastructure capacity as they too want to operate a transport network. ProRail has been assigned to provide train paths and allocate the available capacity independently, meaning with no commercial interest who actually operates the provided train path. ProRail, in consultation with NS and the FOCs, then has a complex puzzle to solve where the rolling stock planning, crew planning and infrastructure use planning need to be feasibly aligned. The provided train path should meet the five main requirements mentioned in the model: safe, supported, energised, guided and accessible. To illustrate these five requirements, let us imagine NS would like to operate a 10-car EMU (Electric Multiple Unit) to Utrecht. The train path ProRail provides for it should not conflict with another train path (safe), be able to carry the weight of the train given the desired speed (support), have overhead wiring to provide energy to the train (energy), have tracks and switches that form a continuous track (guidance) and a platform that is long enough to fit the train (access).

ProRail, as the main resource allocator demands the presence and well-functioning of the five main functional subsystems that handle these requirements, where both ProRail as the owner of the infrastructure and NS as the owner of the trains and employer of the personnel are responsible for. The fulfilment of the various roles by ProRail is arranged by having multiple departments in the organisation with each their own responsibilities (Ministry of Infrastructure & Environment, 2014c). The train owner and operator do not necessarily have to be the same company; the operator could for instance rent the train and personnel from a lease company. Depending on the contract details, the lease company could then be responsible for the well-functioning of the subsystems instead of the operator.

The functional subsystems that fulfil these requirements consist of technologies, elements and actors located in the train, in the infrastructure or in both, and often rely on the interaction between the train and infrastructure. The technical link between train and infrastructure systems therefore always has to be guaranteed even though there are different responsible parties for infrastructure and rolling stock. ProRail, as the main and independent resource allocator and above all as linking party between operators has specified which elements and technologies are present in the infrastructure at each location and demands interoperability with the rolling stock an operator would like to use (ProRail, 2015d). The system specialists of all companies are responsible that the assets comply with each other and result in the well-functioning of the subsystems. NedTrain, part of the NS Group, is the system specialist for NS and is constantly servicing, renewing and improving the trains (Nedtrain, 2016). Within ProRail there are various departments involved such as the departments of 'Train Safety' and 'Tractive Effort Supply' (ProRail, 2016f).

Finally, the system specialists reach out to the market, where suppliers, contractors and secondment agencies are present to deliver the elements, technologies and people.

3.2.2 Time aspect

Preparations to run a train start a long time before a train actually runs. Many things need to be arranged such as forecasting the demand, building the infrastructure, buying trains, producing a timetable and so on. The Railway Service Model can be used in both the planning stage and the operational stage because it is not directly related to time. For this research only the 'now' stage is of interest, since the effect of untangling in the operation phase of the the station will be assessed. However, in order to better explain the Railway Service Model this section will illustrate the use of is in three different stages: long term (design phase), short term (planning phase and now (operation phase).

In Figure 3.7 the Railway Service Model has been depicted in these three different stages of the path towards the realisation of rail transport. The tasks and deliverables in each layer correspond to the activities prior to the arrival of a train, which can be up to several years. The three different phases are not the only phases imaginable, but solely serve as examples to illustrate the time aspect of the model. Since the model is abstract at the top and physical at the bottom, the nearer the future is the lower is the leading layer that triggers changes.

3.2.2.1 Design phase

The design phase or long term stage occurs typically more than 5 years before the departure of a train and mainly focuses on development (Hansen & Pachl, 2008). In each layer and for all requirements the central question is 'What will the future probably look like and how should the system be adjusted to facilitate it?' The transportation service layer will seek to forecast the future demand and the long term network planning will try to facilitate this future demand. The resource allocators need to investigate what the timetable might look like in the future, based on the operators' requested networks, and specify what resources they will need to have available then. The asset managers will have to decide whether to act or not on these future needs and if so, to start making them available. One layer below the system specialists must guarantee that their subsystems are still sufficient in the future and meet the requirements. For this they depend on the technologies, elements and actors that are affected by wear and tear, new developments and new standards. Implementation or renewal of technologies and elements can be a lengthy and costly process (Ross, et al., 1996).

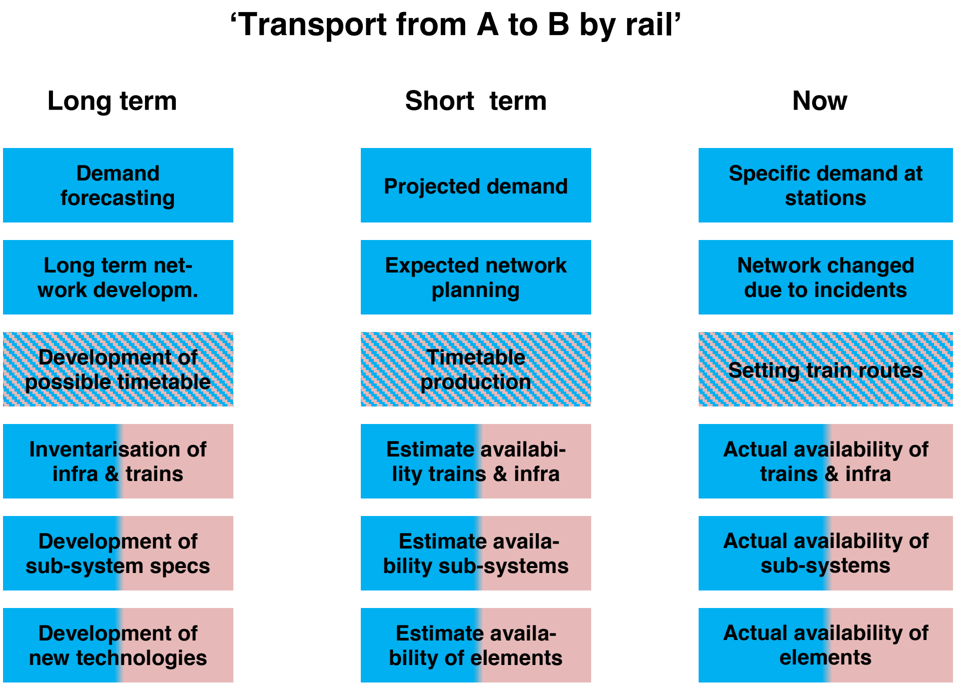


Figure 3.7 Tasks or deliverables per layer in three time stages in a simplified version of the Railway Service Model

3.2.2.2 Planning phase

The time span between approximately 5 years and a day prior to departure is defined as the planning phase or short term phase and it is assumed here that the flexibility to adjust the infrastructure and fleet is limited (Hansen & Pachl, 2008). Unsurprisingly, the focus in this phase is on planning of the current infrastructure and trains, with as basis the possible improvements of today’s operation. The demand of the transport service is easier to predict, because the discussed future is nearer and the small demand changes will probably result in just a slightly adjusted network plan. In this phase, the train paths must be planned in detail and the operators need to be able to rely this planning. As discussed before, ProRail is assigned to divide the infrastructure capacity by combining all requested train paths into one timetable. For this detailed timetable they depend on the availability of infrastructure, trains, subsystems and technologies which might be affected by planned engineering works or implementation schemes.

3.2.2.3 Operation phase

Finally, the last possible phase is the operation phase, which typically occurs from 1 day before the departure of the train until the arrival of the train. Everything has been planned in detail and all involved people in the operation will strive to follow the plan as much as possible. The triggering layer in this phase is at the bottom of the model: elements and technologies. In previous phases, their availabilities have been estimated which does not guarantee that the actual availabilities are the same. Deviation in availability will inevitably lead to a disruption in the layers above and will eventually affect the transport service that the end user is experiencing at the top. To which extent the failure of an element leads to a disruption of passenger service has been defined as the robustness of the system. The signaller, located between the third and fourth box on the right in Figure 3.7, is the final allocator of the capacity by actually setting the available routes for the available trains. Based on these set routes, the actual operated network becomes visible and with that the transport service provided to customers.

3.2.3 Technologies and elements used in the Netherlands

The functional subsystems in the Railway Service Model consist of various technologies, elements and people, which all together fulfil the function of the subsystem. How these techniques and elements look like, differs per country, region, location, TOC and so on. To better understand the untangling options that will be generated in the next chapter, this section describes the currently used elements and techniques in the Netherlands and more specifically Utrecht, since the data collection process has been carried out with design experts from DSSU.

3.2.3.1 Support subsystem

The support subsystem ensures that the passengers are ‘carried through the landscape’, by providing tunnels, bridges, foundations, fly-overs and more. There are no specific techniques or elements in this subsystem that require further explanation to understand the generated untangling options in the next chapter. A small remark though is that even though all the material between the passenger and ground fulfils a support function, the rail and sleepers are regarded as part of the guidance subsystem.

3.2.3.2 Guidance subsystem

Infrastructure that guides the train automatically is a key feature of the railway system, but the characteristic rail-wheel flange contact that is responsible for the physical guidance results in a need for rail infrastructure that is expensive to construct and maintain. It is therefore economically unattractive to have separate rails and sleepers for every train series: for instance rails and sleepers for the train service from Rotterdam to Deventer and separate rails and sleepers for the train service from Rotterdam to Zwolle while they use the same route over a large part of the journey. Instead it is much cheaper to have the services run over the same track until Amersfoort, and then split the tracks into a track to Zwolle and a track to Deventer. Being able to guide trains on the same track in multiple directions creates a large cost reduction. The element that provides this functionality is the switch: a device with movable rail points that can be set in multiple positions depending on the direction the train is supposed to take. Besides being able to send trains in multiple directions at junctions, switches serve more purposes such as enabling trains to get to the opposite track if they reverse in stations, adding extra platforms or sidings to a line, enabling locomotives to attach at the opposite end of the train, enabling trains to overtake and many more. In short, switches provide flexibility.

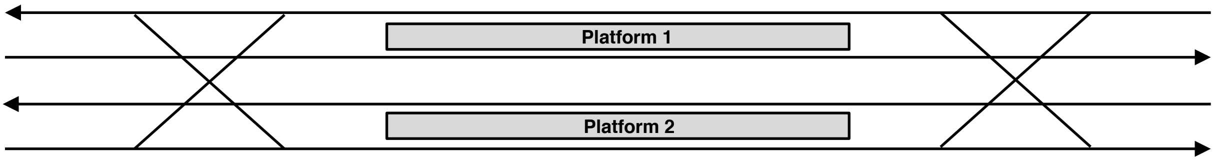


Figure 3.8 Fictional station with four tracks, four platform tracks and sixteen switches. The arrows indicate the intended directions of the tracks.

With switches present, the guidance subsystem becomes a lot more complex: there are now moveable objects in the infrastructure that always need to be set and held in the right position to guide the trains in the intended direction. In Figure 3.8 there are sixteen switches shown of which there are 8 normal and 8 double switches. These switches enable trains to go from every track on one side to every platform and from there to every track on the other side, meaning that there are 4^3 = 64 different potential routes through the station. Operation of the switch blades is done by electric switch motors that convert the rotational motion of the motor into the linear motion required to switch the switch blades. Besides moving them, the motor also locks the blades and monitors their position to guarantee a correct guidance of the train running over the switch. The switch motors are controlled by signallers in the traffic control centres who set the switches in station in the right position (through interlocking devices though).

If for example a train service in Figure 3.8 would like to run from the bottom left track to the top right track (second top corner track), it would at least require 5 switches to be set and held in the right position. To do so a signaller would ‘call’ for a route, meaning that he sets and holds a series of switches in a preferred position so that they form a correct route through the station. This makes that the guidance subsystem, especially in complex stations with many switches, is strongly linked to the safety subsystem.

Holding routes for train paths, guaranteeing the proper and safe positions of the switches and preventing other conflicting routes from being set at the same time are essential safety measures that constantly need to be covered during operations. In most Dutch stations and junctions, the actual setting of the switches is done by the EBP system, EBP standing for Electronic Operating Box, which is an electronical system that enables signallers to set routes through their resource allocation software (ProRail, 2005). The EBP system is regarded as part of the route allocation level and will therefore not be discussed in this section. The various signals send from the EBP to the infrastructure pass through the interlocking, a safety device that ensures that safe routes can be set through the station area. The point where the electronic pulse to operate the switch motor leaves the interlocking installation to travel through a wire towards the switch, is start of the guidance subsystem and the end of the safety subsystem. This point is usually located in the neighbourhood of the switch in a so called relay house, referring to the relay technique often used in the interlocking system. The full route calling and train path allocation process is discussed in section 3.2.3.7 as part of the resource allocation level, and a full overview of the Dutch resource allocation and element steering process is available in appendix A.

3.2.3.3 Energy subsystem

The energy subsystem’s main function is enabling the train to move forward from one point to another, but besides that it also provides energy for train equipment such as lights, WiFi, computers, automatic doors and so on. The propulsion is realised by engines that turn the wheels around which leads to movement due to the friction between the train wheel and the rail. As energy source for the engines electricity or diesel is used, although most ‘diesel’ trains are actually diesel-electric trains, also using electricity for their traction motors by converting the diesel into electricity first in their own generating station. Providing this necessary energy can be done in a few ways: fuelling stations for diesel or diesel-electric trains, a catenary system with electrical wires over the tracks in combination with a pantograph on the train, and conductor rails alongside the tracks with so called contact shoes on the trains (Ogunsola & Mariscotti, 2013). Each technique has its own advantages and disadvantages, but all large stations in the Netherlands are equipped with a catenary system that provides electricity of 1500V, direct current.

3.2.3.4 Safety subsystem

The safety subsystem is probably the broadest subsystem since its function is the least specific. Based on the ProRail risk index (ProRail, 2015c) the safety subsystem can be subdivided in four parts with each their own sub function: enforce speed limits, check the state of operation of elements and technologies, guarantee trains’ safety envelopes, keep trains separated (see section 3.1.2.4).

To start with the first part; keeping the trains separated. Trains have a relatively long braking distance, travel at high speeds and together with the fact that train drivers have no control over the train’s route, this results in the need for a signalling system that permanently ensures a safe distance between trains. In the most basic format, signalling systems detect the positions of trains and with the help of signals communicate to train drivers whether it is safe to proceed or not. (Besides that the signalling system is able to communicate more details on for example the speed and which aspects to expect at the next signals.) There are multiple techniques available to detect the presence of trains such as axle counters or track circuits; the latter is used at all large stations in the Netherlands (ProRail, 2009). The track circuit technique applies power to each rail and has a relay coil wired across them. When there is no train present, the current flowing from the power source through the rails is energising the relay. When there is a train is present, the train’s axles shunt the rails together resulting in a drop of the current to the track relay coil; it is de-energised. Other circuits also run through the relay contacts and therefore are able to report whether or not the track is occupied (Lawrence, 2011).

In junctions or stations it is more complex to decide if it is safe to proceed, because whether the train can safely proceed heavily depends on the route the train will take. Not only does the intended route have to be clear when the train path is allocated, it also has to be prevented that conflicting train paths are allocated at the same time. Conflicting routes are routes that do not start or end at the same point but do use the same parts of the infrastructure or such that the safety envelopes of the trains touch (Railway Technical, 2016). This latter type of safety is called flank protection referring to the side of the trains where the collision would take place if it was unprotected.

Flank protection is achieved in multiple ways, by preventing the setting of conflicting train routes in the interlocking, adding safety distances between signals and switches and requiring positions of switches that are not on the route.

The interlocking fulfils an important part of the second safety sub function: ensure the right state and position of elements. If a certain route is set and the signal aspect at the beginning train route has cleared up, it is essential that the position of the elements is maintained until the train has safely travelled out of the block and cleared its route. The interlocking, as the name suggests, handles the locking and holding of routes to prevent that elements are moved or other conflicting routes are set while the involved elements are blocked for another route. Even if a signaller needs to cancel an already cleared train route, a timer will keep the elements locked in their position to prevent that a train which was already on its way would derail or collide with another train (Bosschaart, et al., 2014). Beware of the somewhat confusing terminology and the differences between releasing a route, clearing a route and train route clearance (see glossary).

Modern interlocking techniques rely on computer coding but an older technique, which is still commonly used and built in the Netherlands, is based on electrical circuits with relays that change position if certain circuits are electrified. A drawback of this technique is the amount of space needed for all the relays and the large number of cables between the relays to create the power circuits. The relays therefore are installed in relay houses, which are buildings next to the tracks that house the large relay installations and protect them from weather influences. From the relay houses, LCEs (Local Control Units) send encrypted signals back and forward to the computers of the traffic control room where the train path allocation is handled.

The third sub function of the safety system is speed enforcement which prevents train from derailing. ATB is the Dutch train protection system installed at all large stations that compares the allowed speed and actual speed of a train and interferes if the speed limit is exceeded. With the setting and holding of a route the interlocking also sets a matching speed in the ATB-EG system, which is translated in an AC frequency that is applied to the rail tracks. Because of this technique the ATB-EG also contributes in the fulfilment of the sub function to keep trains separated: if a train passes the a red signal (the speed after the signal is set to zero) the ATB-EG act as well by stopping the train and preventing it from colliding with other trains. Unfortunately this is only true if the speed of the train is higher than 40 km/hr. For speeds under 40 km/hr Dutch systems ATB-EG vv or ATB-NG are required. Luckily the ATB-EG system will already interfere if the train passes the preceding yellow signal without breaking, to prevent it from passing the red signal in the first place. In the future, the European train protection system ETCS is due to replace ATB (ProRail, 2016i). The ATB-EG signal encoded in the tracks is picked up by receivers in the train that are able to interfere in the train's movement.

The last part of the safety subsystem focuses on the safety envelope of the train, or in other words prevents that objects other than trains come within the train's path. An example is a level crossing installation, which strives to clear the level crossing when a train approaches. These installations are coupled to the interlocking or signalling system and the closing process initiates with the detection of a train or setting of a train route. Also fences next to the tracks, meant to keep people clear from the passing trains, are part of the safety subsystem.

3.2.3.5 Access subsystem

The access subsystem provides access from the trains to other modalities and vice versa. The main asset for the access subsystem is the station with platforms that enable passengers to board and leave the train easily. Besides this main function, the stations are often full of shops, restaurants, waiting lounges, ticket halls and even grocery stores that all add to the passenger's experience and needs (NS Stations, 2016). There are no specific techniques or elements in this subsystem that require further explanation to understand the generated untangling options in the next chapter.

3.2.3.6 Information subsystem

The last subsystem of the physical level is the information subsystem, which fulfils the function of announcing and communicating the planned and actual departures of trains to the users. There are channels through which this information is communicated, for instance by screens on the platforms (TBP), screens in the stations, smart phone apps, internet websites and spoken announcements. InfoPlus is the system in the Netherlands that gathers the actual train information and shares it with all the individual channels; see appendix A for how InfoPlus collects the information from the resource allocation IT-systems.

3.2.3.7 Resource allocation

ProRail sets thousands of train routes every day and hundreds of trains of various TOCs and FOCs use the paths allocated to them. The planning and development of the timetables is therefore a lengthy and complex process, with as result a very detailed timetable that states exactly what train path is available when and for whom. In the operation phase this plan is carried out, and the allocation of a train path is handled by the signallers that use the signalling system (which is part of the safety subsystem) to inform the train driver it is safe to proceed: the train path has been allocated to the user. In areas that do not contain any switches, the train paths are normally not allocated by signallers: a section in that area is always available unless it has already been taken by another train. These areas are called automatic signalling areas.

The signallers in the Netherlands use the PRL (Process Management) system in controlled areas to set routes and give clearance to the train drivers to use the routes. The system visualises the infrastructure on screens and projects the actual train locations and set train routes onto it. TROTS – TRain Observation and Tracking System – is the application that identifies and follows the trains and provides PRL with a correct train ID. To help the signaller, the timetable has been translated into pre-specified infrastructure settings (Procesplan Rijwegen) enabling a computer to take over the task of setting the routes and give train path clearances. A module within PRL called ARI (Automatic Route Setting) is capable of doing this and relieves the signaller of this primary task.

Ideally, the infrastructure capacity and trains are allocated as planned in the timetable, but unforeseen deviations of the plan are inevitable, for example caused by unplanned infrastructure unavailability, delayed trains or failures in the operating systems. The presence of a signaller therefore remains essential, although he will sometimes be monitoring system instead of operating it himself.

The requested routes in PRL are sent to various systems that will handle the request, by checking the availability of the route, setting and holding the elements in the right position and making the train path available for the train with the help of the signalling system. In most large stations the EBP (Electronic Operation Unit) is the computer software that handles the train path requests of PRL. The EBP is constantly updated by the interlocking on the current state of the infrastructure and will always first check if the requested route is available before it will send out commands. When the route is available, it will determine which elements will need to change state (aspects of signals, positions of switches and so on) to set the route.

The commands are transmitted from the EBP to the right LCEs (Local Control Unit) in the form of encrypted electrical signals, which then decrypt the signal and send specific commands to the interlocking (ProRail, 2005). The interlocking, part of the safety subsystem, will do the final check whether it is safe to move the elements, because the moveable elements and possible conflicting routes could be a cause of collisions or derailments. The LCEs are linked to the interlocking parts and therefore form the connection between the infrastructure level and resource allocation level. The full overview of the Dutch resource allocation and element steering process is available in appendix A.

Chapter summary

In this chapter the Railway Service Model has been introduced and applied to the Dutch railway system. The model consists of various levels of detail and levels of abstraction and has six logically deducted functional subsystems: the support, guidance, energy, safety, access and information subsystem. Also the involved actors all have a place in the model and a red colour indicates the area ProRail is responsible for. The model and its subsystems will be used in the next chapter to describe the untangling scope and identify possible untangling options.

Besides that, a lot of system knowledge on the used technologies and resource allocation process has been gathered and presented. This knowledge is required since some of the untangling options will apply to these specific technologies and elements.

4 System design

Previously, a representation of the railway system has been developed for describing system untangling, and insight has been gained in this system untangling strategy. This chapter comprises a combination of three steps in which the (untangled) system design will be scoped (4.1), designed (4.2) and evaluated (4.3-4.5). The (re)scoping process is executed to limit the ranges of the degrees of freedom identified for system untangling, which could not have been done before as the Railway Service Model is necessary to explain the chosen scope. With these clear new demarcations the various untangling possibilities can be explored and listed, and most important, their interrelations and dependencies can be mapped. For this process workshops will be held with experts. The most complicated matter then is to estimate which untangling options are most effective in limiting the impact of single incidents to the corridor of occurrence; this estimation will be made with the help of incident data analysis. In the introduction paragraph of each of the three steps, the approach that will be followed is shortly discussed.

4.1 Untangling scope

In section 2.1 the untangling philosophy has been discussed and illustrated with untangling examples in various systems. Not only did these examples occur in different systems, also the level, type and other degrees of freedom of system untangling varied. Although identifying the promising levels of untangling is key to answer the research question, narrowing down the search to a few untangling levels and one type is necessary to stay within the focus of the research.

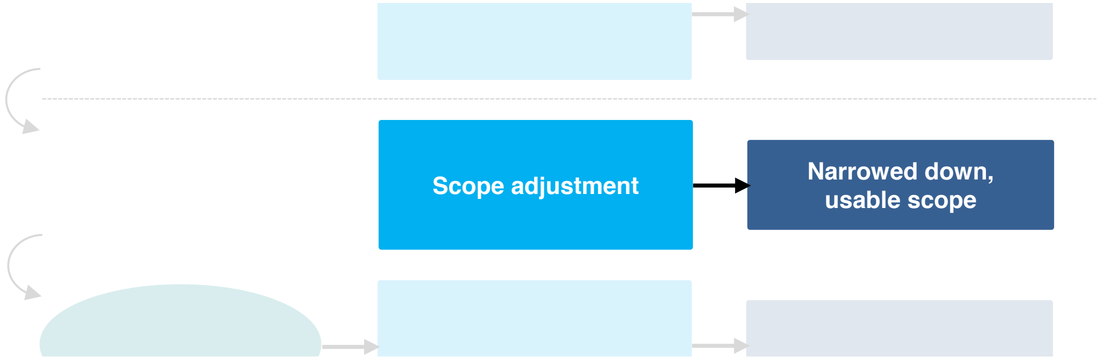


Figure 4.1 Step of the research approach described in this section

First, the two identified types and multiple levels of untangling discussed and scoped with the help of the Rail Service Model. The last part of this section will provide an overview of all other variables or degrees of freedom that come with system untangling besides *type* and *level*, being *system division strategy*, *geographical strategy* and *extent*. From these variables both the possible ranges and ranges that fit within the scope of the research will be indicated. This step of the research approach is depicted in Figure 4.1.

The fully explained and elaborated version of the Railway Service Model can be found in Figure 3.2 but here abstracted and partial drawings of this model will be used to illustrate the various types and levels of untangling. The relation of each drawing to the full model is always stated in the text, nevertheless it is advised to keep the colours, shape, layers and actors of the full model in mind to be able to interpret the drawings more easily.

4.1.1 Type of untangling

For most examples studied in the literature review the type of untangling could be described as separating parts of the system in order to prevent the incident impacts from spreading to all train series (vertical untangling). From one example in biology though, it was found out that another type of untangling exists: untangling the functions a technology fulfils in order to improve the robustness of the technology or element (horizontal untangling) (Lesne, 2007). Both types will first be discussed and explained before the scope will be set in the last part of this section.

4.1.1.1 Horizontal untangling

The first type is horizontal untangling, which is defined as having the objective to avoid the use of technologies, elements and actors for more than one function. This type of untangling takes place at the bottom layer of the service model and separates the subsystems ‘horizontally’, meaning that each subsystem uses its own technologies, elements and actors without interference. Figure 4.2 schematically shows this horizontal untangling, indicated by the blue dashed lines between the subsystems in the bottom layers. Each white box represents a subsystem: **e**nergy, **g**uidance, **sa**fety, **su**pport, **a**ccess and **i**nformation. In the figure the infrastructure side of the model has been used, but naturally also the technologies on the train side or even on both sides could be untangled horizontally.

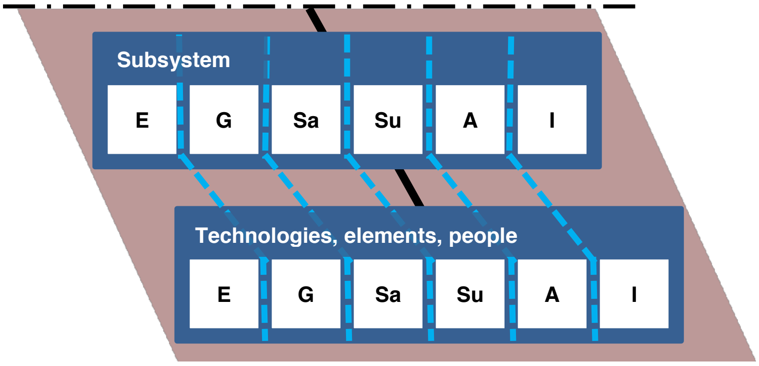


Figure 4.2 Horizontal untangling takes place between the subsystems in the bottom layers

A striking example for an element that fulfils multiple functions is the rail, which is used in the energy, guidance, safety and support subsystem. In the energy system the rail functions as a return path for the electrical current from the overhead wires, while simultaneously electrical currents in the rail from the safety system detect whether a train is present on the rail or not and transmit the allowed maximum speed. The surface of the rail that contacts with the wheel rim provides the adhesion that is necessary in the energy subsystem. The strength and structure of the material supports the train while the shape of the rail interacts with the wheel flange to provide guidance (ProRail, 2016g).

The fact that all these functions are combined in one element does not necessarily cause a decrease in robustness, after all the failure or absence of one subsystem is already enough to make rail transport impossible (see the definition of subsystems in section 3.1.2). To clarify, if for instance the rail breaks, rail transport on that piece of infrastructure becomes impossible any way, independent of the rail has one function or four. A robustness issue that is affected by the combined use of elements is that the design of the element may not be optimal for all functions. The material used for the rail – steel – is a strong material very suitable for supporting the heavy trains and withstanding the strong forces from the wheel flanges in curves. It is also a good conductor for electrical currents, although the conductivity between rail and wheel is heavily affected by rust that forms on the rail. The wheel rims of passing trains remove the rust on the rail in their motion, and keep the conductivity at an acceptable level, which therefore requires that all rails are ridden frequently (Railsystem.net, 2015). Hence a different material that does not suffer from corrosion would probably – for conductivity reasons – be more suitable in the safety subsystem.

The same way of reasoning holds for the adhesion quality of the rail: the steel-to-steel-contact is low in friction since both the surface of the wheel and rail are smooth. As a result the adhesion is low and the acceleration and deceleration rates of the trains limited. At some of the Parisian metro lines separate bars and wheels with rubber tyres have therefore been installed in addition to the regular rail and steel wheels (Railsystem.net, 2015). The elements have now been split per subsystem, since these rubber tyres provide grip for a faster acceleration (energy subsystem) while the rails and steel wheels still provide guidance, conductivity, and support (guidance, safety and support subsystems). Figure 4.3 shows the system installed at these lines which horizontally untangles the energy subsystem and the guidance, safety and support subsystems to some extent.

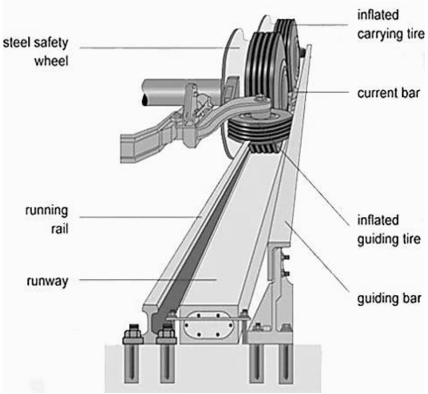


Figure 4.3 Bar and rubber tyres installed in Parisian metro to increase acceleration rate

4.1.1.2 Vertical untangling

The other type to be discussed is vertical untangling, which can be described alongside the vertical axis of the Railway Service Model. This type of untangling splits the system including subsystems in parts, for example per direction, train corridor, area or other categorisation, in order to prevent the incident impacts from spreading to all train series. An example for this type of untangling is the DSSU project, in which some subsystems have been separated per train service to prevent the impact of infrastructure failures from spreading to other train services than the ones that are directly affected (ProRail, 2014b).

Figure 4.4 shows an abstracted version of the Railway Service Model that has been fully vertically untangled in – only as example – three different groups. Where there used to be a single rail trainsport system, each group now represents a separate railway system that has no interactions with the other systems. Each group is split up from the other groups over all layers of Railway Service Model. Naturally, there are a lot of system configurations thinkable that lie between this fully untangled and not untangled, such as only untangling the infrastructure or by just having groups of train series operated by different operators. The levels at which these untangling options take place are different: untangling of infrastructure is located in the infrastructure-train layer, while splitting the transport services lies in the transport network layer.

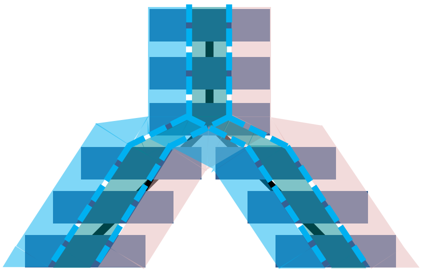


Figure 4.4 Schematic representation of fully vertically untangling the railway system. The original railway system is split over all layers of the Railway Service Model in three new independent railway systems

4.1.1.3 Untangling type scope

Although not horizontally untangling the subsystems may lead to suboptimal technologies and elements and therefore a lower robustness of the total system, this is not type of untangling described in the first chapter that formed the trigger for this research. Investigating if the untangling of systems will reduce the cancellations of trains, for instance by removing switches between train corridors or splitting the power stations per track, is a form of vertical untangling.

4.1.2 Level of untangling

As explained in section 3.1.1, the Railway Service Model describes multiple levels of abstraction and detail. These layers in the model are useful to describe the various levels of untangling that can be identified. However, not all of them lie within the scope of this research. In this section the levels of untangling will be explained and illustrated by realistic examples in order to determine the levels of untangling that fit within the scope. In the last part the

For the sake of illustrating the concept, an abstracted version of the Railway Service Model is shown for each discussed level of untangling. These abstracted versions are always located on the left sides of the figures that show the untangling examples, and are always fully untangled including all levels below. In reality the levels do not necessarily have to be untangled to the full extent, for example only untangling one subsystem instead of all subsystems in the subsystem layer is a plausible option. Besides that, the abstracted Railway Service Model always shows a system that is split in two parts, even though the systems in the examples might be split in more parts.

Figure 4.5 shows an example of how untangling on the various levels will be illustrated, by showing a fully tangled representation, which forms the starting point for untangling. In a tangled system there is only one rail transport service present, with just one transport network that uses the same infrastructure, subsystems, elements and technologies. Hence the single Railway Service Model shown in the figure on the left side. Large stations function as a node in the network and the subsystems are clustered and operated centrally. Traffic control for the whole area is bundled in one building and executed by one computer system. Figure 4.5 shows this by a picture of the old situation at Utrecht station including a single signaller that allocates all train paths to the trains. The tangling of overhead wires, tracks and operation is clearly visible.

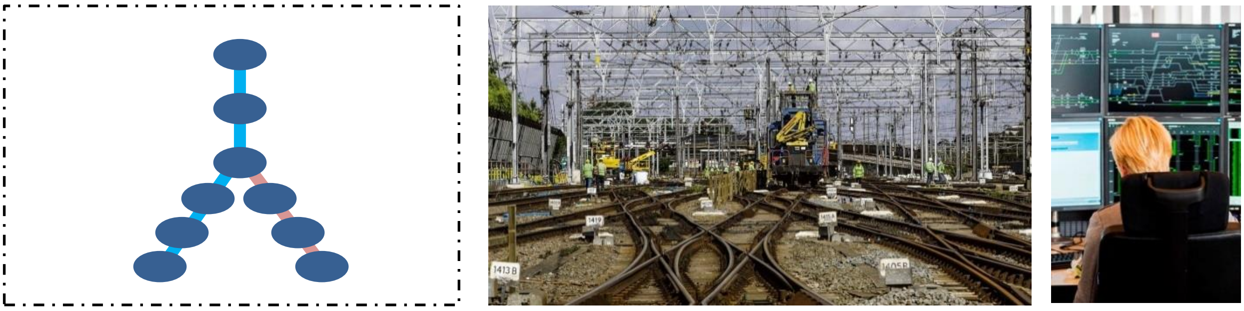


Figure 4.5 Fully tangled railway system that forms the starting point for describing the various levels of untangling

4.1.2.1 First level of untangling

The first possible untangling level lies within the physical part of the Railway Service Model – in other words the infrastructure and trains – and is called level 1 untangling. It means that the infrastructure and trains are split into uncorrelated groups of infrastructure and trains, for instance per line, direction or operator, avoiding the spread of disturbances. The allocation of resources is still organised centrally, although this might not be necessary; the resources are split in groups after all. Untangling at this physical level 1 can still be done to different extents which can be different for each subsystem and per location: for instance fully untangling the energy subsystem but not the safety subsystem in one location and the other way around in another location, or fully untangling the guidance subsystem but only untangling the access subsystem to a limited extent. Figure 4.6 depicts untangling at the first level with an example of the DSSU project , in which the infrastructure is split per direction and service resulting in six different groups. Nevertheless, the allocation of all train paths is still done in a central traffic control centre.

Figure 4.6 Level 1 untangling: splitting the assets in groups with less correlation. Example: DSSU in which the infrastructure is split per train corridor

4.1.2.2 Second level of untangling

Untangling one level higher in the Railway Service Model results in a system that has also untangled the resource allocation. This means that there is still a single transport network, but separated control and planning centres. Again the system could be untangled to different extents in different ways, such as, geographically, line wise, direction wise or service wise. Currently, the ProRail control centres are untangled geographically on a national basis, and also geographically in larger station areas where each signaller has its own part of the station (ProRail, 2014d) .

A fully level 1 and 2 untangled system would mean for end users that they travel through one transport network with various lines that form one network but where disruptions of single lines do not interfere with operations of other lines. An example of this system is the Barcelona metro, where most of the eleven lines are operated independently from each other (Qushair, 2006). There are multiple operators present – just two, not eleven – which each have a group of lines of which the operation, assets and subsystems are completely independent of each other. Lines 6, 7 and 8 are operated by the FGC, who also operates heavy rail train services on the same infrastructure, while the rest of the eleven lines are operated by TMB as dedicated metro lines with no interaction with heavy rail (Metropolitan Transport Authority, 2015).

For the end users on the contrary, there is no difference visible, they use the various lines with the same tickets, in the same way. Figure 4.7 shows this level 2 of untangling schematically, including a map of the Barcelona metro network with an overview of lines per operator.

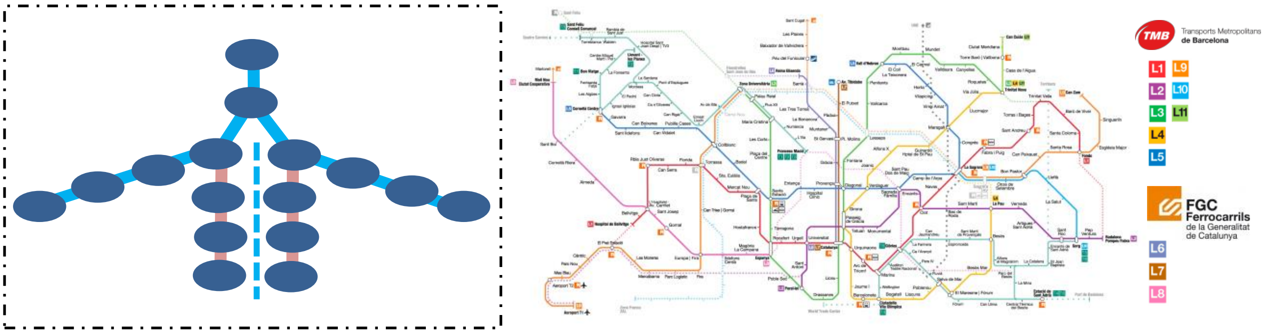
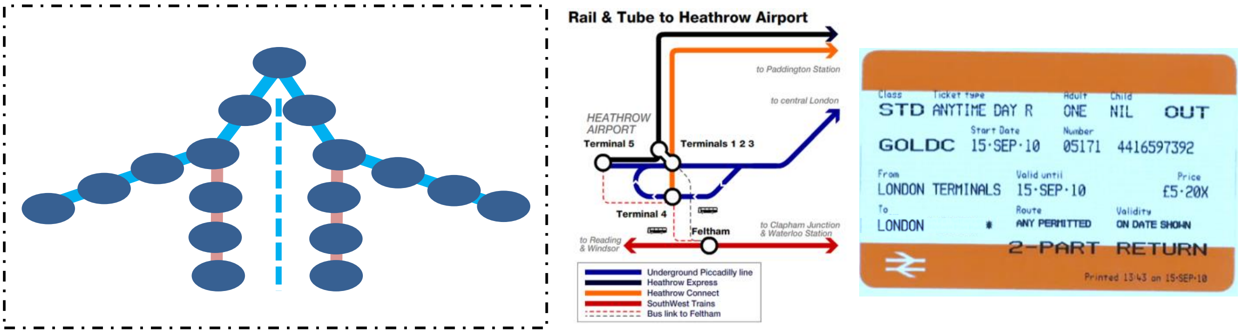


Figure 4.7 Level 2 untangling: One transport network with independently operated lines. Example: Metro of Barcelona with even different operators per line

4.1.2.3 Third level of untangling

A fully untangled system up and until another level higher in the Railway Service Model would implicate that the transport service is still sold to end users as a single service, but that there are multiple parties with each their own networks, resource allocation, infrastructure and trains.

Untangling at this level is identified as level 3 untangling and means that the end user buys a ticket to get from A to B, but that he or she has multiple transport networks to choose from each having their own traffic control and planning centres, subsystems and elements. An example of where this situation is present is the rail connection between London Heathrow and Central London, which is shown in Figure 4.8. Three heavy rail services and one tube service run between the city and airport, all part of different networks and operated by different operators. There are tickets available that are valid on all four services (although these are far more expensive than tickets for specific services) (Heathrow Airport, 2016). So, from the passenger point of view there is just one system, but from all the other actors' perspective there are multiple systems with no interrelations. Disturbances such as signal failures or companywide IT-failures in one part of the system will most likely not spread to other parts.



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To LONDON · Route ANY PERMITTED · Validity ON DATE SHOWN
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Figure 4.8 Level 3 untangling: Single transport service consisting of multiple transport networks. Example: Rail transport between Heathrow and central London

4.1.2.4 Fourth level of untangling

The absolute highest level of untangling within a system is reached by splitting the system into two separate systems with no interrelations. This level of untangling is called level 4 and is the highest thinkable level of system untangling, because at this level or even higher levels there is no longer being dealt with *one* system.

An example of two rail systems that are often split completely is the urban metro system and national rail system, as they each function on a different geographical scale and therefore have different secondary requirements regarding comfort, speed, dimensions, noise and so on. In Rotterdam the urban metro system and national railway system function in such completely segregated way, each having its own transport service, network, traffic control centres, subsystems and elements. Even the co-shared station Schiedam Centrum is split in a metro part and train part with independent building constructions, platforms, roofs, and access gates. The ticketing system and tariffs also differ per system and are not interchangeable: both systems offer for instance a direct service from Schiedam Centrum station to Rotterdam Blaak station, but both have different fares and do not accept each other's tickets (RET, 2016). So, from a passenger point of view these are two completely different transport services.

Figure 4.9 depicts the Railway Service Model with level 4 untangling and the Schiedam Centrum train and metro stations, where a funny detail is that even the roof structures of the access subsystems do not touch each other (although this was for aesthetic reasons).

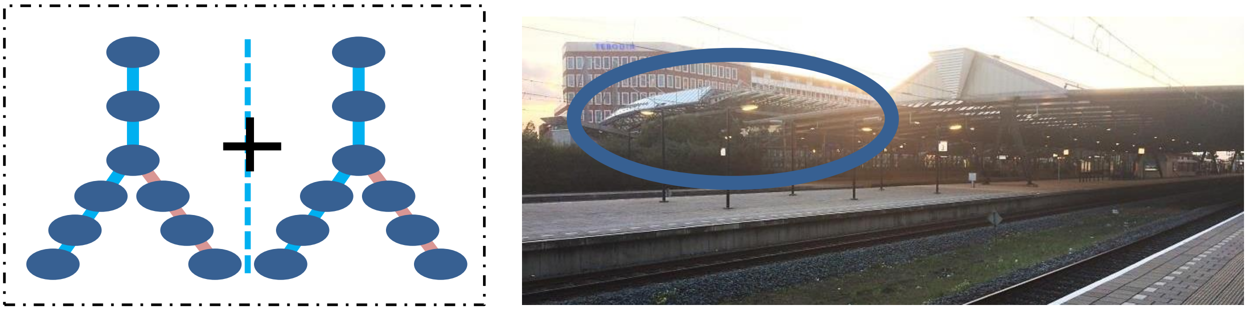


Figure 4.9 Level 4 untangling: two systems function completely independently. Example Rotterdam metro and national rail systems meet in Schiedam Centrum station

Obviously, a completely untangled system requires complete untangling at all four levels. Although the model was always depicted with all layers below the discussed layer being fully untangled, this is not always the case. If for instance the transport network and transport service are split in multiple services and networks, they could still be using the same infrastructure. But generally, it can be stated that untangling starts in level 1 and works its way up to the top. However, even if a system is fully untangled at all identified levels, it does not mean that there are no common factors left that still could affect both parts of the system – or actually both systems, since the system is completely split up at this level – simultaneously. For example the weather, a national power supply disruption and internet connectivity failures will always affect multiple systems in an area, including multiple railway systems.

4.1.2.5 Untangling level scope

In the previous section it has been explained and shown that vertical untangling of systems could be done at four different levels within the Railway Service Model: level 1 (physically), level 2 (resource allocation level), level 3 (network level) and level 4 (service level).

An important aspect of the scope set in chapter 1.3 is that the focus lies on large complex stations which function as a node in a network. Therefore levels 3 and 4 of vertical untangling seem not suitable to investigate as untangling at these levels focuses more on splitting the system itself than untangling specific locations in the system. Level 2 untangling on the contrary could be plotted on a large complex station area of a single rail network. The resource allocation in the traffic control and planning centres would be handled separately per corridor or direction, although the processes might still interfere because of the possible interaction of lines outside the station area. The same way of reasoning holds for level 1 untangling, in which some or all of the subsystems and assets within the complex station could be split per line or service.

Level 1 and 2 are strongly related as level 2 steers, plans and controls the assets in level 1. The way and to which extent level 1 is untangled therefore inevitably affects the way and to which extent level 2 could or should be untangled. If for instance the infrastructure is not untangled at all, in other words all assets are connected to single elements and technologies and all trains zigzag through the station, it is very difficult to not allocate the train paths centrally. Exploring the untangling options for both level 1 and level 2 would therefore be in line with the scope.

4.1.3 Other untangling variables

As seen in section 2.1, system untangling can take place in many different ways and the amount of possible variations to untangle systems is large. Besides the degrees of freedom *type* and *level*, that already have been described and scoped, there have been identified three other degrees of freedom in the system untangling strategy that contribute to the large amount of variations: *system division strategy*, *geographical strategy* and *extent*. These variables are less complex to explain and will all three be described and scoped in this section.

4.1.3.1 System division strategy

The system division strategy determines in which way a system is untangled. A system could be split in parts in various way, for example by direction, meaning that southbound trains do not interfere with northbound trains, or by service, meaning that each train service such as an intercity service from Rotterdam to Groningen uses its own system. Other possibilities are per geographical area, per line or per train service type. ProRail uses a division strategy per train corridor and in Utrecht station even per train service (Movares, 2015).

It is definitely interesting to investigate which division strategy is more effective, but to prevent the research from becoming too complex and on request of ProRail only a division strategy per service will be used in this research.

4.1.3.2 Geographical strategy

The geographical strategy handles the physical locations of untangling in the system, for instance whether the whole system – location-wise – should be untangled or just at specific locations. Obviously, in an ideal situation the whole system is untangled, since only this will completely remove dependencies between corridors, directions or lines (depending on the applied system division strategy). Unfortunately, it will probably be far too expensive if for example each train series would need its own dedicated infrastructure across the country.

Some system untangling options, especially at higher levels, are only possible if the untangling scope comprises all locations of the system, such as untangling the transport network. Nevertheless, the scope of this research is on large complex stations, which therefore automatically sets the geographical strategy that will be used: system untangling in complex stations and tangled systems outside of this area, assuming tangled systems are the current standard (ProRail, 2014b).

4.1.3.3 Extent

Lastly, the extent to which the system is untangled is probably the most important variable in this research. Whether to fully untangle one subsystem or to untangle all subsystems partly has a great effect on how the impact of incidents spreads. The extent of untangling can vary widely, from removing a few switches or splitting tasks between signallers to completely remodelling stations and building separated traffic control centres per corridor. This degree of freedom therefore lies at the heart of the research question and should be limited as little as possible: the extent of untangling, which exists at both the first (physical) and second (resource allocation) levels, can be nil, fully or everything in between.

4.1.4 Overview of variables and their ranges

Table 4.1 provides an overview of both the discussed theoretical untangling variables' ranges and the parts of the ranges that lie within the scope of the research.

Each untangling variable that has been discussed here, directly followed from the scope that was chosen for the previously discussed untangling variable. For example the level of untangling is only relevant if the vertical type of untangling is selected, since (the same) levels do not exist for the horizontal

untangling type. The table can therefore not be used as a complete framework that describes untangling in general, but has to be regarded as a part of a funnel shaped scoping process.
The main conclusion that can be drawn from this table is that the two variables of interest for this research are **level** and **extent**. It has to be kept in mind that the latter variable in level 1 has an extra dimension, because level 1 consist of multiple subsystems which all could be untangled to a different extent.

Untangling variable	Theoretical range	Scope
Type	Horizontal and vertical	Vertical
→ **Level**	Level 1, level 2, level 3 & level 4	Level 1 & level 2
→ **Division strategy**	Line-wise, service-wise, direction-wise, etc.	Service-wise
→ **Geographical strategy**	All locations or specific locations	Specific: large complex stations
→ **Extent**	Nil, fully and everything in between	Nil, fully and everything in between

Table 4.1 Overview of the range and scope of all untangling variables

Based on Table 4.1 the possible untangling options mentioned in the research question have been limited. Figure 4.10 visualises the scoped research question: given a certain transport network where each line represents a train service, to which extent should the infrastructure's subsystems and the resource allocation facilities be untangled per service to be most effective in limiting the spread of incident impact?

Beware that Figure 4.10 contains picture of the NS transport network around Utrecht station, the full network also includes the FOCs. As discussed before, besides investigating the physical level with the functional subsystems, the resource allocation level is also part of the scope. So even though it is not a subsystem, various untangling options within the resource allocation level will also be generated in the next section.

Figure 4.10 How should the infrastructure (level 1) and resource allocation (level 2) be untangled given a certain transport network?

Section summary

In this section the range of all five identified degrees of freedom related to system untangling – *type*, *level*, *division strategy*, *geographical strategy* and *extent* – have been discussed and scoped. It was concluded that service-wise vertical untangling at the first two levels of the Railway Service Model to all possible extents at large complex stations is the scope most suitable scope of this research to answer the research question.

4.2 Subsystem untangling options

The previous section has narrowed down the investigation and therefore this section now can address the sub question how the subsystems could be untangled. ProRail's experts have been consulted to provide input for the generation of these untangling options through various workshops. The workshops resulted in a list of 25 untangling options in different subsystems and levels. First, the data collection process will be described and after that the findings will be described per level and per subsystem. This step in the approach to find an answer to the research question has been visualised in Figure 4.11.

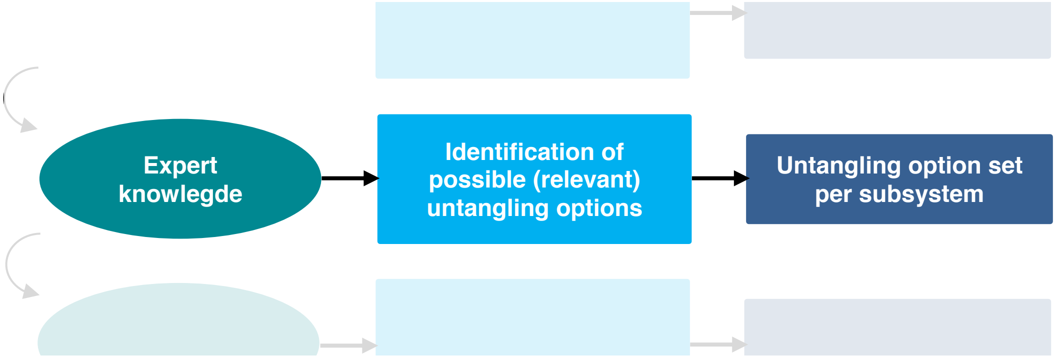


Figure 4.11 Step of the approach (input-action-output) discussed in this section

4.2.1 Data collection

To generate the untangling options six workshops have been organised with various experts mostly from ProRail, but also from contractors involved with the DSSU project. Because the ProRail uses another subsystem division, the workshop topics sometimes do not align with the functional subsystems used in this research. DSSU has also been selected as case study in the develop part of this research. More detailed information on DSSU including drawings can therefore be found in section 7.1.

4.2.1.1 Workshop topics

The workshop topics were energy supply, civil engineering & switches, PT terminal, signalling system, operations & construction phasing and IT & connectivity. Each untangling option that has been mentioned in the workshops has been assigned to the involved functional subsystem as defined in this research. The relations between the workshops and the various functional subsystems and levels are described in Table 4.2. A *strong* relation indicates that many untangling options found in the workshop belong to the subsystem, a *limited* relation indicates only a few options, and a '-' that none of untangling options found in the workshop belong to that subsystem or level.

Level	Subsystem	Energy supply	Civil eng. & switches	PT terminal	Signalling system	Operations & construction phasing	IT & connectivity
1	**Energy**	Strong	-	-	-	-	-
	Access	-	-	Strong	-	-	-
	Safety	-	Limited	-	Strong	-	Strong
	Support	-	Strong	-	-	-	-
	Guidance	Limited	Strong	-	Limited	-	Strong
	Information	-	-	Strong	-	-	Strong
2		-	-	Limited	-	Strong	Strong

Table 4.2 Relations between the organised workshops and defined subsystems & levels (1 = physical level, 2 = resource allocation level)

Because the focus is on existing techniques, an untangling option sometimes untangles two or more subsystems at the same time (due to horizontal tangling, see section 4.1.1). In that case, the option will be discussed in one subsystem and just be mentioned in the other.

4.2.1.2 Workshop set up

Every workshop took two hours, included three fixed members and progressed according to a predefined framework. The full workshop reports, framework and attendees can be found in appendix B.

Besides the author this thesis, whose role was to guide the workshops and ask the questions, the attendees always included a senior system architect and the rail system engineer responsible for the DSSU project. The senior system architect F. Bokhorst MSc is experienced in assessing the holism and consistency of large system designs while rail system engineer Van Deelen MSc knows the DSSU project thoroughly, enabling him to link and denominate issues and options that transcend the workshops' topics. Besides them, on average three experts were present, whose specialisms were thought to be contributory to the topic of the workshop.

The framework used in the workshops consists of two different parts: one part with questions about untangling options and one part discussing the reasons for using or not using the various untangling options. Both parts were focused on the design of DSSU, the first large station project of ProRail with a focus on system untangling (Movares, 2015). The questions asked in the first part were:

- ***Without restrictions in time, money, space or current techniques, how would you adjust the design of Utrecht station?***
  Obviously, the focus of this question was on the design of the part of the system that was discussed in that specific workshop, although occasionally comments of a more general level or suggestions for other parts of the system were made.
- ***In a perfect world, how would you untangle this part of the system?***
  In contrast to the previous question that tried to find improvements of the DSSU design, this similar question attempted to trigger a more conceptual mind set and searched for a general design principles.
- ***If you were asked to change one thing in the design of DSSU in order to increase the robustness, what would you change?***
  The purpose of this question was twofold, on the one hand identifying the weaknesses in the design and on the hand quantifying the answers given in the previous two questions. The latter was achieved by asking why the previously given answers would not be the one thing to change.
- ***What would you consider as the key system untangling improvement that was realised within the DSSU project?***
  By asking this, the options that are thought to be efficient by ProRail will emerge, since these are the options that actually have been built.

In the second part of the workshops, the reasons for using or not using certain untangling options have been investigated. To do so, five matters in the design have been pointed out to the experts where the system untangling was either inconsistent, incomplete or absent. These matters were used as examples in more broadly phrased questions, often starting with the words '*How to cope with…*', '*When to use…*' or '*How could…*'. By doing so, not only the reasons for some design choices and the present considerations to use various untangling options became clear, but also possible improvements of the design emerged.

Table 4.3 shows per workshop two examples of questions that were asked to the experts. The questions were formed with the help of DSSU's previously mentioned rail system engineer Niek van Deelen. The answers, comments and solutions are all shown in appendix B and have been categorised in three different groups, but this division is irrelevant for this research. The split was made by a taskforce within ProRail that is trying to evaluate and improve the DSSU design, with whom the workshops were in cooperation.

Workshop	Example question 1	Example question 2
Energy supply	Why do the subsidiary circuits not always follow the train corridors?	Should the catenary systems of all corridors be on one gantry or on multiple?
Civil engineering & switches	How could the track layout be fully untangled?	How to cope with scarcity of space?
Public transport terminal	How to cope with different users of the electricity network?	How could the terminal be split per corridor during disruptions such as a fire alarm?
Signalling system	How could the signalling system be untangled if there are switches present between corridors?	When to build two separate buildings and when to untangle systems within a building?
Operations & construction phasing	How to build an untangled system from a tangled system?	How could a smooth train service be maintained when some elements fail?
IT & connectivity	Is it beneficial to split the element control systems of a station?	How could a split of the whole traffic control chain contribute to a higher robustness?

Table 4.3 Two questions asked in the workshops, the full version can be found in appendix B

4.2.1.3 Data input from the design of DSSU

Besides the data gathered in the workshops, the rail system design of DSSU (Movares, 2015) has been a main source of information on itself as well. The document describes the design of various subsystems including the motivation for this specific design.

Many untangling options have been incorporated in the design of DSSU which makes this project of particular interest. As stated before, the DSSU project has also been used as a basis for the workshops, in which both the attendees and questions asked were strongly linked to DSSU, and has been selected as case study in the develop part.

4.2.2 Untangling option generation

The results of the workshops and the information found in the rail system design of DSSU have been translated into concrete system untangling options and will be presented per level and per subsystem. Beware that the list of options mentioned per subsystem does not necessarily comprise all possible untangling options, as it was gathered in the workshops based on expert judgement.

4.2.2.1 Energy subsystem

Multiple options to untangling the energy subsystem have been identified; an overview is shown in Table 4.4. The first is option is untangling the *contact lines* which are the part of the catenary system that comes into contact with the train's pantograph. By splitting the contact lines per corridor a faulty pantograph that damages the overhead wires or pulls the wires down will only have effect in the own corridor. Obviously there is a strong relation with the support subsystem, because if there is a flat junction in a station area with planned crossings of train series, it is impossible to untangle the contact lines. But, when there is just a single pair or a few pairs of switches present between two corridors, it could be opted for to not equip the relatively short connection distance with a contact line in order to keep the energy subsystems untangled. By ProRail's regulations though, this is not allowed due to the risk that the pantograph does not lower automatically but rises instead and damages the overhead wire it runs in to (ProRail, 2015a).

Energy subsystem untangling options
Contact lines
Subsidiary circuits
Power stations
Tensioning system
Gantries

Table 4.4 Untangling options for the energy subsystem

Creating *subsidiary circuits* is another untangling option, which prevents a power shutdown of the full system when a short circuit has been detected. Subsidiary circuits mandatorily exist in the railway because the whole system cannot possibly be fed by one circuit for capacity reasons. But, by arranging these necessary subsidiary circuits per corridor, it can also function as untangling option. The wiring diagrams of stations always contain electric switches between subsidiary circuits that allow the current to be rerouted when one section of a circuit is short circuited (Movares, 2015). Nevertheless, the identification of the location of the short circuited section and the operation of the electrical switches take a certain amount of time, which for instance in Utrecht can reach up to one hour. By having subsidiary circuits per corridor this initial shutdown, the power off before the current can be rerouted, will only occur in one corridor instead of in multiple, preventing a disruption of services in the other corridor.

In the same line of reasoning could be stated that if the subsidiary circuits are untangled per corridor, the *power stations* (also called traction substations) that feed these circuits could also be untangled. Currently, the various circuits in one area all run to a central building where transformers convert the high voltage AC from the national grid into the necessary 1500 Volt DC. A fire in that particular building for example, will inevitably lead to a complete power loss. By having multiple power stations, one for each corridor, the unavailability of one power station will not lead to a disruption of train service in another corridor. Obviously, power station untangling requires that the subsidiary circuits have been untangling as well.

The overhead lines require a certain tension to abduct the mechanical oscillations caused by the train's pantograph. By having a variable mechanical tension in the wires, it is avoided that the wires start to vibrate heavily, which may eventually lead to breakage of the line. The variable mechanical tension is produced by a *tensioning system* that consists of a tensioning pulley mounted on an arm hinged to the mast of the catenary system or a separate mast. At the end of the line, which runs over the pulley, a weight is connected, resulting in a gravitational force within the wire. Particularly when this tensioning system is mounted on a separate mast the possibility exists that this mast is also used by tensioning systems of other corridors. A derailment of a train in a certain corridor, or breakage of the line that unbalances the shared mast, will then again lead to a disruption of services in both corridors. Untangling the tensioning systems therefore means that all tensions system are mounted to masts that are not placed near the tracks of other corridors.

The last option is somewhat related to the previous option where masts with tensioning systems mounted to them should be placed within the own corridor. The *gantries* on which the overhead lines are mounted also have masts that often are not placed within the own corridor or even span the full width of the railway in the station (all tracks). Splitting these large gantries into separate gantries that only span the tracks of one corridors means that a failure of one gantry will not lead to a disruption of service in the other corridors. Not all experts agree on the fact that this untangling option contributes to the robustness of the system: they state that the dominant failure mechanism of a gantry is a collision between a mast and a derailed train. By splitting the gantry, the number of masts at leasts doubles and so does the risk of a collision. So although the impact of a gantry failure is larger when only one gantry is used to span all corridors, the risk of the failure is much lower. Nevertheless, the option will be taken into account because the collision risk in an untangled situation could also be decreased by for instance allowing more space between the masts of the gantries and the tracks or by installing crash barriers around the masts.

4.2.2.2 Guidance subsystem

Table 4.5 shows an overview of the untangling options within the guidance subsystem as discovered in the expert workshops and design of DSSU. Perhaps one of the most striking untangling options is the removal of *switches* between the corridors. Switches consist of moveable elements that are sensitive for malfunctioning and failure and could therefore lead to a disruption of train services (ProRail, 2016h). From that point of view, a pair of switches within a corridor for instance to get reversing trains to the right track, would have the same impact as a pair of switches between two corridors. The difference is that switches between corridors that are used by trains in service imply the shared use of the guidance subsystem for both corridors, or in other words the absence of a dedicated guidance subsystem for a certain train service. However, even if train corridors has have their own infrastructure and if the installed switches between corridors are only used for shunting purposes, the risk of a single faulty train blocking multiple corridors remains. Unfortunately, only removing the switches between two corridors does not always reduce this risk of one train blocking multiple corridors as it could still result in a track layout schematically depicted in Figure 4.12. The intersecting lines represent diamond crossings instead of double switches. Although there are no switches present anymore, the guidance subsystem of both corridors still interacts through the diamond crossings: they cannot be used simultaneously, for that the support subsystem needs to be untangled as well (installing fly-overs or dive-unders).

Guidance subsystem untangling options
Removing switches
Switch control cables
Power supply switches
Switch heating

Table 4.5 Untangling options for the guidance subsystem

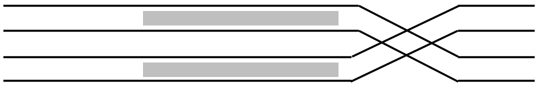


Figure 4.12 Schematic example of track layout where the switches between two corridors have been removed, but the guidance subsystem still interacts through diamond crossings.

The commands for the position of the switches reach the switches through *control cables* that run between the switch motors and relay houses. Not putting all the switches' cables in the same (underground) cable tube (also called cable route) ensures that excavators accidently hitting the tubes during construction works at a certain corridor do not disable the operation of switches in other corridors.

Besides receiving commands from the interlocking, the switch motor also requires *power* to operate the switch. The power is provided to the motor by cables that are connected to a power station. Similar to the subsidiary circuits in the energy subsystem, by untangling the power station it can be prevented that a short circuit in the power station leads to a complete loss of switch functionality across the station. The same power stations are used to supply energy to the signals and interlocking equipment, which are part of the safety subsystem, which is a form of horizontal tangling.

In winter times temperatures could drop below freezing point and frozen water or snow between the rail and switching blades could easily obstruct the switch's movements. A *switch heating* system is therefore often installed on important switches to guarantee operability in winter conditions. There are various heating systems currently in use, some are based on gas heated fluids that run in tubes alongside parts of the switches other systems use heat producing resistors to keep the moveable parts free of ice and snow. For sustainability reasons ProRail prefers electrical systems and therefore new switches are only equipped with electrical switch heating (Movares, 2015). The heating systems require much power and although they are not used frequently, in case they are used they are all in use at the same time. This could result in unexpected short circuiting or power losses, which may eventually lead to the switches becoming unusable (Ministry of Infrastructure & Environment, et al., 2012). By splitting the power supply per corridor, the power disruption caused in a single switch will remain within the corridor the switch is located in. One of the main differences with the other untangling options is that a failure in one of the other options always leads to a disruption of train services, while here this is only the case in certain weather conditions. The impact of this option is therefore different.

4.2.2.3 Support subsystem

An overview of the untangling options within the support subsystem can be found in Table 4.6. A single support system is often shared by all tracks because it is easier, cheaper and more space efficient to bundle the infrastructure on bridges, viaducts, beddings and in tunnels. Nevertheless, an unavailability of the support subsystem will then always lead to a disruption of all train services. Examples of this unavailability could be the discovery or hairline cracks in a bridge's construction, or a false fire alarm in a tunnel. The first untangling option therefore is to split *tunnels and bridges* per corridor to prevent that the unavailability of a bridge or tunnel leads to a disruption of all train services.

Support subsystem untangling options
Tunnels & bridges
Elevated junctions

Table 4.6 Untangling options for the support subsystem

The second option is related the switch untangling option in the guidance subsystem, where it was stated that the disconnection of the guidance subsystem (removing switches) means that a faulty train will not have impact on train services in more than one corridor. The diamond crossings that remained – see Figure 4.12 – actually nullify that option because the rails and safety envelopes of the trains of two different corridors keep interacting at that point. The only way to clear this interaction is by separating the support subsystems that enable tracks to pass each other without crossings: *elevated junctions*. Creating elevated junctions by installing fly-overs and dive-unders means that the guidance subsystem is completely untangled and that faulty trains in a corridor do not affect trains in other corridors. This correlation between untangling options is described in appendix C.

4.2.2.4 Access subsystem

Untangling a station is beneficial from a robustness perspective, but not necessarily from a passenger point of view: theoretically a fully untangled access subsystem – outside the scope of this research – would mean two separate buildings in two separate locations. Transferring would take passengers a lot longer compared to transferring within the same station and would therefore increase their journey time and decrease the attractiveness of the railway system. But also within the scope of the research this contradiction exists: it is very attractive to offer cross-platform transfers to customers, but in that case a fire in one train will also lead to a disruption of service of the neighbouring train. Below two untangling options are described that were identified by the experts, see Table 4.7.

Access subsystem untangling options
Station hall evacuation
Terminal power grid

Table 4.7 Untangling options for the access subsystem

Fire alarms or emergency services dealing with an incident often lead to the *evacuation* of the passengers and suspension of train services. If this evacuation could be split per corridor, disruptions of train services would not spread to other corridors. The key challenge for this to be possible is how to arrange this partial evacuation. Smoke shields, flexible barriers, local announcements and information on screens could assist in keeping the unaffected parts of the station running while safely evacuating the other parts.

The *power grid* in the station building is probably heavily used by not only the many retailers and restaurants, but also by equipment that is more essential for a smooth train operation. When there are no working lights, ticket barriers, ticket machines, escalators and lifts in a certain station building, the train services will definitely get disrupted. By creating a power grid per corridor, in a similar way as was done with the subsidiary circuits in the energy subsystem, it can be prevented that a short circuit at one of the platforms leads to disruption in the other corridors.

4.2.2.5 Safety subsystem

Table 4.8 provides an overview of all untangling options that have been identified in the workshops. The first untangling option is the split of *element control cables* per corridor. The cables that transmit the electronic pulses from the interlocking to the signals and switches often lie in a single cable tube which means that an accident with a misplaced sheet pile immediately interrupts the operation of services in multiple corridors. This is the same reasoning as applied for the control cables untangling option in the guidance subsystem.

Safety subsystem untangling options
Element control cables
Signal gantries
Power supply
Relay houses
Interlocking
Flank protection: requiring switches
Safe working area

Table 4.8 Untangling options for the safety subsystem

Another option that has similarities with an option discussed before is the use of *signal gantries*, which has the same effects as the gantries used in the energy subsystem. Placing the signals for all tracks at a certain location on one gantry instead of on gantries or columns per corridor means that the collapse of the gantry affects all corridors. A drawback untangling the signal gantries is that more poles need to be installed next to the tracks, which are potential hazards if a train derails.

The *power supply* to the signals relay houses, communication devices, ATB and other safety subsystem elements and techniques could be untangled to prevent a power loss in multiple corridors if a short circuit or other failure emerges. This option is similar to the power supply option in the guidance subsystem.

Track circuits are used to detect the presence of trains in a certain section. The relays connected to the circuits become de-energised if the axles of a train short circuit the loop. Although the mechanism always consists of dedicated relays, coils and wires, they are often installed in the same building or *relay house*. In these relays houses groups of relays from the interlocking mechanism are present that fulfil different functions such as train detection and operating the positions of switches and aspects of signals. Installing all the relays of different corridors in one building means that destruction or unavailability of the relay house – for instance as a result of fire – immediately leads to disruptions in all train corridors.

But even if there are relay houses per corridor, the *interlocking* could still be not untangled. Especially a modern interlocking based on computer technology can be a single point of failure, because if the interlocking computer crashes or fails to restart after it has been updated incorrectly, no routes can be set anymore in all corridors. Untangling a conventional relay interlocking system could be done by installing parts of interlocking in multiple locations and connecting them through cables, meaning that destruction of a relay house would never lead to a complete loss of the safety subsystem in a station.

Flank protection has been introduced as a requirement for interlocking and implied the prevention of a side-to-side collision in an area with possible conflicting routes. One of prevention measures used by ProRail, is to demand a diverting position of switches that are directly connected to switches on the intended route (but are not part of it). By doing so, a train that accidently passes a red signal is less likely to enter the safety envelope of the train for which the train route has already been cleared. The problem emerges if a pair of switches has been installed between two corridors and if one of these switches is out of control: the interlocking then demands a position of switch in another corridor that is temporarily not controllable (RIGD-LOXIA, 2013). This causes the prohibition of the train route clearance in the own corridor, even though none of the elements in the own corridor are unavailable. The untangling option comprises the temporary relief of the required positions in case one of the switches is unavailable (and will therefore not be used anyway). In the guidance subsystem the removal of switches between corridors has been mentioned as an alternative untangling option.

The last untangling option is related to assurance of the safety envelope of the train, namely creating a *safe working area*. If engineering works have to take place or repairs have to be made to certain switches, the construction workers should be given the space to safely carry out the works. If the space between the tracks of two corridors is insufficient, the train services of both corridors will need to be suspended. The 'safe' amount of space is subject to policies that are currently in place and will probably change over time. By installing the tracks with a greater spacing or by installing fences between the corridors, the corridors can be taken out of service independently.

4.2.2.6 Information subsystem

Because InfoPlus does not take any information directly from the infrastructure or trains, untangling the information subsystem is strongly related to the untangling of the systems within the resource allocation level. In the workshop results and design of DSSU no untangling options for the information subsystem have been found, even though certain failures or incorrect updates in the InfoPlus systems currently sometimes lead to a complete loss of information supply (Algemeen Dagblad, 2016a). Perhaps the right experts for this specific topic were not invited to the workshop, also bearing in mind that providing correct information to customers is mainly the responsibility of the TOC.

4.2.2.7 Level 2: resource allocation

Table 4.9 shows an overview of the untangling options found at the resource allocation level. The first one is the previously explained *LCE*, which translates the encrypted route setting messages from the EBP into commands for individual switches. LCEs could be a cause of failure, and if switches located in multiple corridors are connected to the same LCE this failure will lead to a disruption of train services in multiple corridors. Just as in the infrastructure subsystems, the *power supply* of the LCEs could be untangled to prevent a total infrastructure communication loss if the power is cut off unintendedly.

Untangling options resource allocation level
LCE
Power supply
EBP
PRL
Signaller

Table 4.9 Untangling options on resource allocation level

The *EBP* is the system addressed by the PRL system to actually operate the infrastructure. A single EBP often covers a large area with multiple interlockings and many LCEs and therefore the impact of an EBP failure is large. Untangling the EBP is technically challenging, because there has not yet been installed a functionality in the EBP to set a train route that contains infrastructure elements controlled by multiple EBPs. As a result EBPs always have to be surrounded by automatic signalling areas where, from an EBP system perspective, trains can 'appear' from and 'disappear' to. A solution for this is currently under investigation by ProRail (ProRail, 2017a).

The EBP is operated through the *PRL* system, which consists of multiple applications. Unavailability of the PRL system would implicate a regional disruption of train services that surpasses the scale of impact of the other untangling options. A separate PRL system per corridor would therefore be a possible untangling option.

The last untangling option concerns the *signaller* who constantly monitors the train traffic and makes adjustments to the plan when needed. Especially during incidents his workload steeply increases because more adjustments and manual route settings are required. This means that if the signalman is occupied with a disruption, other routes that for other reasons need to be adjusted are also affected. A signaller per corridor could therefore be an option to keep a disruption of service within the corridor.

Section summary

In this section 25 untangling options in various subsystems and levels of the railway system have been identified though expert workshops. An overview of all options including the involved subsystems and system level is depicted in Table 4.10.

Identified untangling option	Railway system level	Subsystem	Identified untangling option	Railway system level	Subsystem
Contact lines	1	Energy	**Signal control cables**	1	Safety
Subsidiary circuits	1	Energy	**Signal gantries**	1	Safety
Power stations	1	Energy	**Power supply infrastructure**	1	Safety
Tensioning system	1	Energy	**Relay houses**	1	Safety
Gantries	1	Energy	**Interlocking**	1	Safety
Removing switches	1	Guidance	**Flank protection**	1	Safety
Switch control cables	1	Guidance	**Safe working area**	1	Safety
Power supply switches	1	Guidance	**LCE**	2	-
Switch heating	1	Guidance	**Power supply signal box**	2	-
Tunnels & Bridges	1	Support	**EBP**	2	-
Elevated junctions	1	Support	**PRL**	2	-
Station hall evacuation	1	Access	**Signaller**	2	-
Terminal power grid	1	Access			

Table 4.10 Overview of all identified untangling options including involved system levels and subsystems

4.3 Incident types related to the untangling options

A long list of untangling options has been generated in the previous section. Creating this overview was one of the research objectives, but the effect of each untangling option has not been quantified yet. Which untangling option is most effective in containing the caused hindrance within the corridor of occurrence? In the next three sections (4.3 to 4.5) this question will be answered for the identified untangling options.

As has been explained in the system untangling theory in section 2.1.1.3, incidents are inextricably linked to the untangling philosophy. Each untangling option affects both the impact and chance of occurrence of certain incidents. The untangling options' relations to incidents have already been mentioned many times in the previous sections, where it was discussed how each untangling option could prevent the spread of certain incidents' impact.

To quantify the relevance of each untangling option it is therefore necessary to first identify the incidents types linked to each untangling option or in other words the impacts of which incident types are mitigated or affected by installing a certain option. This methodology will be explained with the help of Figure 4.14. Once these related incident types are known for each untangling option, the incident types' average frequency of occurrence and impact can be abstracted from incident data. By estimating which share of the occurrence frequency and impact could be kept within a corridor by installing a specific untangling option, the potential benefit of this untangling option can be quantified.

In section 4.4 the quantification process will be explained in further detail, this section will first identify the related incident types for each untangling option. Finally, in section 4.5 the results will be presented and interpreted. The input, action and output of this step carried out in these three sections is visualised in Figure 4.13.

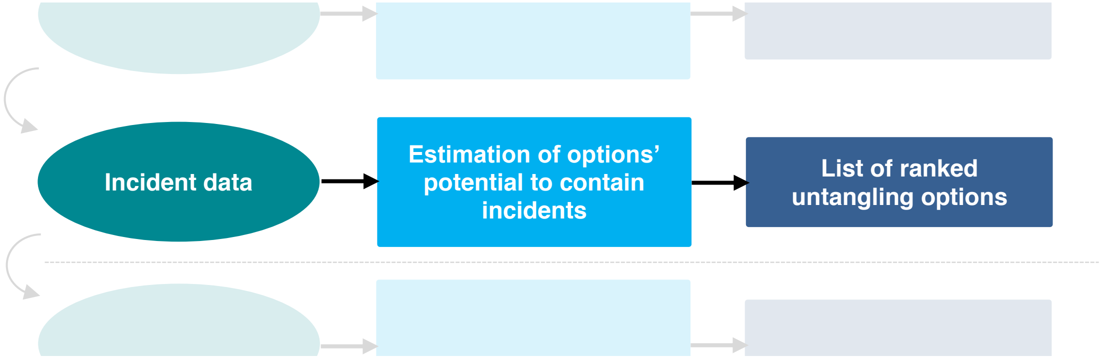


Figure 4.13 Input, actions and output of sections 4.3 to 4.5

4.3.1 Methodology

Explaining which incident types are related to certain system untangling options and quantifying this relation can be difficult, because of the many ways an untangling option can be installed (the *extent* of untangling). If for instance the untangling option 'splitting the signal gantries' would be installed in a large station, it is still undetermined whether the gantry is split for every corridor or just for some and whether it is split over the full area. Besides that, each large complex station is different, which creates a great dependency for the benefits of the untangling option on the local situation. So although the degrees of freedom have already been narrowed down strongly in the previous sections, there are still many variations within the untangling options left.

For explaining how incident types are related to untangling option a less complex fictional station area will be used as basis. Figure 4.14 depicts a representation of this (realistic) fictional non-complex station, where there are just two train corridors present; corridor A and corridor B, both calling at station X. As can be seen, all subsystems are quite tangled; a single power station, no elevated junctions, cables of both corridors bundled in the same cable tube, single information system, switches between the corridors and so on. The only subsystem not explicitly shown is the support subsystem, which in this case would only consist of an embankment or foundation the tracks lie on.

The blue boxes 'Switch control' and 'Train detection & signals' have been visualised as separate boxes to illustrate the difference between the guidance subsystem and safety subsystem. In reality both functionalities will be connected to the interlocking, often located in a single relay house. The same holds for blue boxes 'Dispatching' (resource allocation level) and 'Info' (information subsystem), from which the IT systems are often located in a data centre and the people operating them in a traffic control centre. The blue lines connecting them should therefore not be regarded as physical cables, but as required connections between the systems.

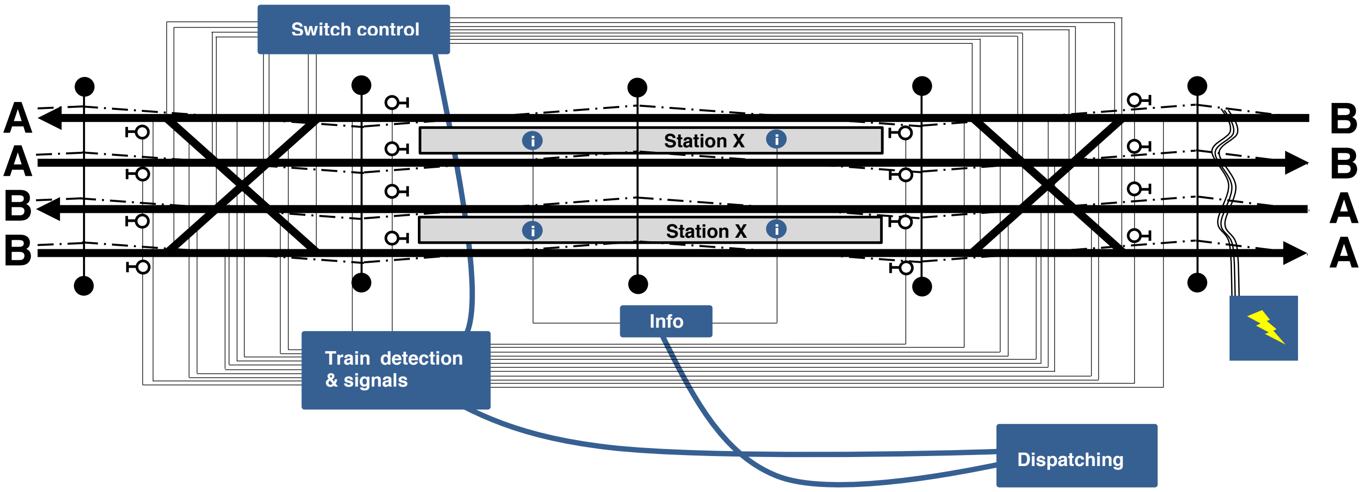


Figure 4.14 Representation of a fictional Dutch station with subsystems that will be untangled into two corridors: A and B

So, if an untangling option would be installed in Figure 4.14 – in the most optimistic way in order to quantify *potential* effectiveness – which incident types occurring in corridor A will then no longer have an impact on corridor B or at least will have less impact on corridor B? Those incident types will be listed as related in order to be quantified in the next section.

An example of an incident type that does reduce the impact of the incident is 'Multiple cables damaged due to engineering works'. Since the cables in the tube do not belong to elements in a single corridor, the service on both corridors would be hindered. Although the untangling option 'Untangle switch control cables' of the guidance subsystem would not have changed the impact of this incident within the corridor occurrence, for example corridor A, it would have prevented that the incident impact also affected corridor B. The incident type would then be added to that specific untangling option so that it can be quantified in the next section. The option 'untangle signal control cables' in the safety subsystem would have the same effect as the 'untangle switch control cables' in the guidance subsystem, so the incident type would therefore also be assigned to that untangling option.

4.3.2 Data collection and preparation

For the identification of the involved incident types two sources of data have been used, one to actually identify the incident type and the other to check if the list of incident types per option is complete.

Computer software from SAP is used within ProRail to log all reported incidents and has the possibility to register 75 aspects of each incident. One of the main advantages of this system is that the rail emergency response room's employees, contractors, mechanics, performance analysts and asset managers all use the same system which makes that the quantity of data available per incident is usually very high.

Incident data of the total network from 1-1-2011 until 31-12-2015 has been collected. An important first filtering is the removal of many columns that are not relevant for the identification of risks. The columns that are kept are *moment of occurrence, location, system description level 1 and 2, cause, effect, functional repair time* and *component repair time*. The moment of occurrence is the time the incident or failure was reported to ProRail's emergency response room and always consists of a date and a specific time. The location though is not the location wherefrom the incident has been reported but contains information on the location of the failure. So if for instance a broken level crossing installation is reported, it is first investigated whether it is really the level crossing that is faulty or if it is something else in the safety subsystem. The location of the object that is actually broken or faulty is then registered in the form of an area code. The failing system is described on two different levels; the first one describes the responsible subsystem, which strangely enough could also be 'weather' or a 'third party', and therefore tend to classify the causes instead of proving system descriptions. Third party incidents also include incidents caused by the TOCs' trains. The eleven possible categories are *third party, weather, infrastructure power supply, traction power 1500V, support subsystem, crossing subsystem, signalling system, IT, transfer subsystem, guidance* and *information subsystem*. On the second level the part of the system that is failing is classified in 35 different categories of which most are only present in one first level category whilst others occur in multiple first level categories.

In the cause column the general cause of the failure or the general failure mechanism is mentioned, varying from 'lightning damage' to 'general switch failure' and 'flooded tunnel'. In total 674 unique causes have been identified, of which most are part of only one or two description categories.

The effect column contains a very short description of the effect a certain failure has, which is sometimes general and sometimes very specific. Unfortunately, almost 50% of this column either shows blanks or one of the many 'unknown' categories such as 'unknown level crossing failure' or 'unknown interlocking restriction'.

The functional repair time is the time between the report of an incident and the effect clearance notice given to the rail emergency response room. Generally this means that the failure has been solved completely. Nevertheless, sometimes the effects are cleared because a redundant system has been booted up or an emergency power unit has been installed. In that case a difference shows between the functional repair time and component repair time.

A distinction is made by ProRail between incidents that cause hindrance (TAOs) and incidents that do not cause hindrance to the train services. Both have been taken into account here to by-pass the influence of any redundancy that might have been installed on forehand. If not done so, a failing power station which function has directly been taken over by a neighbouring power station would not be identified as a related incident type while without the redundant power station the train services would definitely have been affected.

The second data source is a FMECA analysis that has been created by Assetrail, a contractor responsible for the maintenance of a part of the network. FMECA stands for Failure Mode, Effects and Criticality Analysis (Assetrail, 2016) and is used by the contractor to identify and describe failure mechanisms of various infrastructure elements. The analysis helps them to optimise the maintenance process and to monitor the frequency of incidents and similarities with other incidents. This database contains 312 different failure mechanisms and has been used to check whether the list with identified incidents from SAP data is complete, or that certain failure mechanisms have been overlooked due to the unexpected way some incidents are logged in SAP. Because Assetrail is only responsible for a specific part of the network, failure mechanisms of elements that are not present in the area are not included in the data.

4.3.3 Related incident types

The process of identifying all incident categories of which a certain untangling option could either affect the frequency of occurrence or the impact has been a lengthy one. For every incident category-cause combination it has been assessed by interpreting the effects whether an untangling option selected in the previous section would be able to prevent or reduce the impact to spread from the corridor of occurrence to another corridor. Or in other words, if the untangling option had been installed, would the impact of an incident then be less present or even absent in the corridor the incident did not take place? Table 4.11 shows an overview of the selected incidents groups per untangling option.

#	System description L1	System description L2	Cause	R/FR
1	*Removing contact lines between corridors (Energy subsystem)*			
a	Traction power 1500V	Catenary system	Contact line - disconnection	R
b	Third party	Catenary system	Contact line - disconnection	R
2	*Installing subsidiary circuits for every corridor (Energy subsystem)*			
a	Third party	Catenary system	Contact line - damage	FR
b	Weather	Catenary system	Lightning damage	R
c	Third party	Catenary system	Short circuit	FR
d	Traction power 1500V	Power station	Power switch failure	FR
3	*Each corridor has its own power supply (Energy subsystem)*			
a	Traction power 1500V	Power station	Power station fault	FR
b	Traction power 1500V	Power station	Telegyr communication error	FR
c	Third party	Catenary system	Contact line - damage	FR
d	Weather	Catenary system	Lightning damage	R
e	Third party	Catenary system	Short circuit	FR
f	Traction power 1500V	Power station	Power switch failure	FR
4	*Not installing tensioning systems on poles next to tracks of other corridors (Energy subsystem)*			
a	Third party	Catenary system	Steel structure – train collision	R
b	Traction power 1500V	Catenary system	Steel structure – train collision	R
5	*Not using large gantries that span more than one corridor (Energy subsystem)*			
a	Third party	Catenary system	Steel structure – train collision	R
b	Traction power 1500V	Catenary system	Steel structure – train collision	R
6	*Removing all cross overs between two corridors including switches (Guidance subsystem)*			
a	Third party	Train	Faulty train	R
b	Guidance	Switch	Switch out of control	R
c	Guidance	Switch	Switch motor fire	R
d	Weather	Switch	Snow/Ice in switch	R
e	Train protection	Track section	ES weld failure	R
7	*Not putting switch control cables of different corridors near each other (Guidance subsystem)*			
a	Third party	Cable	Broken cables due to construction works	R
b	Train protection	Cable	Broken cables due to construction works	R
c	Weather	Cable	Water in cable tube	R
d	Train protection	Cable	Melted cables	R
e	Train protection	Cable	Fire in cable tube	R
8	*Installing dedicated power supply for the infrastructure of each corridor (Guidance subsystem)*			
a	Infra power supply	3kV installation	Local power supply disruption	R
b	Infra power supply	3kV installation	Depot power interrupted	R
c	Infra power supply	Power station	Faulty 3kV transformer	R
d	Infra power supply	3kV installation	Central power divider failure	R
9	*Building separate switch heating installations for each corridor (Guidance subsystem)*			
a	Guidance	Switch heating	Failure in installation	R
b	Guidance	Switch heating	Power supply failure	R
10	*Never putting more than one corridor through a single tunnel or over a bridge (Support subsystem)*			
a	Support	Tunnel	Safety system failure	R
b	Support	Tunnel	Fire alarm	R
c	Crossing	Bridge	Structural damage	R
d	Weather	Tunnel	Flooding (danger)	R

11	*Building elevated junctions to prevent shared use of infrastructure elements (Support subsystem)*			
a	Third party	Train	Faulty train	R
b	Train protection	Track section	Faulty track clear section	R
12	*Creating separate power grids per corridor for the train related infrastructure (Access subsystem)*			
a	Third party	Station hall	Local power supply disruption	R
13	*Designing the station hall in a way it can be evacuated per corridor (Access subsystem)*			
a	Transfer	Station hall	Fire alarm	R
b	Transfer	Station hall	Emergency with passenger evacuation	R
14	*Not putting element control cables of different corridors near each other (Safety subsystem)*			
a	Third party	Cable	Broken cables due to construction works	R
b	Train protection	Cable	Broken cables due to construction works	R
c	Weather	Cable	Water in cable tube	R
d	Train protection	Cable	Melted cables	R
e	Train protection	Cable	Fire in cable tube	R
15	*Not using large gantries that span more than one corridor (Safety subsystem)*			
a	Third party	Signal	Steel structure – train collision	R
16	*Installing dedicated power supply for the infrastructure of each corridor (Safety subsystem)*			
a	Infra power supply	3kV installation	Local power supply disruption	R
b	Infra power supply	3kV installation	Depot power interrupted	R
c	Infra power supply	Power station	Faulty 3kV transformer	R
d	Infra power supply	3kV installation	Central power divider failure	R
e	Train protection	Relays house	Power supply failure	R
17	*Building separate relay houses for each corridor (Safety subsystem)*			
a	Train protection	Relays house	Fire damage	R
b	IT	Housing	Relay house – Damage	R
c	Weather	Housing	Relay house – Damage	R
18	*Developing and using interlockings that operate independently per corridor (Safety subsystem)*			
a	Train protection	Relay interlocking	B-relay failure	R
b	Train protection	Relay interlocking	Faulty fuse	R
c	Train protection	Relay interlocking	General ATP failure	R
19	*Installing procedures or systems that enable the safe use of a switch that requires a position of another switch that is out of control (Safety subsystem)*			
a	Guidance	Switch	Switch out of control	R
b	Guidance	Switch	Switch motor fire	R
c	Weather	Switch	Snow/Ice in switch	R
20	*Creating a safe working area around each corridor (Safety subsystem)*			
	-	-	-	R
21	*Using separate LCEs for the control each corridor’s infrastructure (Resource allocation level)*			
a	IT	Sub control unit	Connectivity error	R
22	*Installing dedicated power supply for the control of each corridor (Resource allocation level)*			
a	IT	Housing	Local power supply disruption	R
b	IT	Housing	Control room – Power loss	R
23	*Using a separate EBP system per corridor (Resource allocation level)*			
a	IT	Traffic control	POST21 – EBP failure	R
24	*Using a separate PRL system per corridor (Resource allocation level)*			
a	IT	Traffic control	POST21 – PRL network error	R
25	*Assigning a dedicated signaller per corridor in a separate building (Resource allocation level)*			
a	IT	Housing	Control room – Evacuation	FR

Table 4.11 Overview of all untangling options and the identified related incident categories

The sizes of the incidents groups vary largely because of the different levels of detail that have been used in defining the groups. For instance the cause ‘POST21-EBP failure’ is rather general and contains more sub types of incidents than the cause ‘Snow/Ice in switch’, which is a more specific description of the failure mechanism behind the incident.

Some untangling options have the same related incident types as others, which suggests a certain similarity or correlation between the options. Only in the next phase these relations can be described, because even though if the incident types are the same, there might still be differences in the quantification of each incident type in each option.

Another striking aspect is the absence of incident types for untangling option 20 ‘Creating a safe working area around each corridor’. Ironically this is not because the untangling option does not affect the impact of any incident type, but because it affects the impact of almost every incident type.

During the identification process of the related incident types the question repeatedly asked was whether (a part of) the impact of the incident type could have been isolated in the corridor of occurrence if the untangling option would have been installed. The focus here was on the impact caused by the incident itself, not on the impact resulting from the repairing works that had to be carried out to repair the infrastructure or train. This resulted in a high correlation between option 20 and the other options, since the impact of all incidents for which mechanics had to go out onto the tracks to carry out engineering works would be affected by this untangling option. It has therefore been decided to indicate which other untangling options would require option 20 to be installed (see appendix C) to maximise the potential benefits of the options instead of investigating the benefits of option 20 itself. However, in the develop part of this research option 20 will be taken into account.

The last column in Table 4.11 indicates whether the option would influence the repair time ‘R’ or functional repair time ‘FR” of an incident type. In most cases it affects the repair time of in an incident, but not for instance in 2a. In a tangled situation, without subsidiary circuits installed, a damaged overhead wire in one corridor will lead to a power loss in all corridors. After the location of the damage has been discovered, the other corridors will shortly have the power restored because switches in the power station will isolate the broken wire from the rest of the catenary system (functional repair time). Then the damaged wire itself will be fixed by mechanics after which the incident can be called off (repair time). Installing subsidiary circuits would therefore only influence the functional repair time, as the technique of the catenary system is already able to isolate the damage itself.

For all 312 failure mechanisms from Assetrail’s FMECA analysis it has been checked whether failure mechanisms that could lead to incidents with corridor isolatable impacts have been represented by an incident type. The FMECA analysis is limited to technical failures and infrastructure components that lie within Assetrail’s contract area and has therefore not provided a complete check. Most failure mechanisms were either not relevant, did not cause incident types with corridor isolatable impacts or had already been represented in an incident type. One failure mechanisms though had not yet been incorporated: switch damage caused by fire (6c and 19b in Table 4.11). It was assumed that fire damage could only occur outside the cities as a result of grass fires that occur during hot periods in the dry grasses that grow on the side of tracks. The FMECA analysis revealed that the switch fires occur in switch motors and that it is mainly caused by short circuiting.

4.4 Quantifying the potential benefits of each untangling option

With the incident types related the untangling options identified, it is now possible to estimate the benefits of each untangling option. An appropriate approach would be to quantify these benefits and then compare them to see which untangling option is most effective. The most difficult aspect of this approach is that the benefits are highly dependent on the local situation in which the untangling options have been applied. For instance how the untangling option is used, in what locations in the station area the option is used, how many train corridors there are, how many trains run every hour through the station et cetera. In the previous section this has been solved by using the fictional station of Figure 4.14 to reason whether the impact of an incident type could be isolated by an untangling option. However, for the quantification process where the benefits are estimated, a broader reference is necessary than the non-complex fictional station area shown there.

The purpose of knowing these benefits is to be able to select untangling options to be modelled in the develop part of this research in order to determine the most effective untangling option to increase robustness. This stage here can therefore be regarded as a pre-selection stage where each individual untangling option is inspected and its benefits estimated. To overcome the dependency of the untangling options' benefits on the local situation and to which extent the option has been installed, a methodology has been used to roughly quantify each untangling option's *potential benefit*, where the actual benefit then still depends on the local situation and to which extent the untangling option has been installed.

The potential benefits are expressed as potential reduction of unavailability of the infrastructure instead as a reduction of the severity of the incident's logistical effect, which (too) heavily depends on the local situation. The relations between the untangling options are also of great interest, because when there are mutual dependencies or other correlations between the options, it is essential that these become visible before a selection of untangling options is made.

This section will first describe the general analysis method used to estimate untangling options' potential benefits and will present the results found from the data in a large table. Per untangling option the estimation will be explained in further detail.

4.4.1 Analysis method

The main data source that will be used is the SAP incident data from 2011-2015 that has already been used for the incident type identification process and which collection and preparation process has been described in section 4.3.2. The overall approach that will be taken here is to assess the frequency of occurrence of the various incidents types, and then estimate the part of the infrastructure unavailability that is spread over multiple corridors in a tangled situation but can be isolated in one corridor in an untangled situation.

A challenge that comes with this approach is the estimation or prediction of the incident occurrence frequency, because simply comparing the number of reported incidents is not possible. For instance incident type 1a, a broken overhead wire, can occur anywhere in the network and depends on the amount of overhead wires and the amount of trains that run under them, while option 23a, a failure of the EBP system can only occur in an area with switches. A large station where typically many switches are present would therefore have a larger part in the total EBP incidents than in broken overhead wires.

To overcome this disparity the method only uses data of incident occurrences at five selected complex stations. The five complex stations have been selected based on the number of trains that call at the station in an average hour of the day in the 2013 timetable, which was valid between 9 December 2012 and 8 December 2013 and forms the middle year of the 2011-2015 data set. (NS, 2012). Table 4.12 shows the selected complex stations, including some feature characteristics of the infrastructure in the station area as it was present in 2013. The characteristics have been collected by both manually counting the infrastructure elements from station drawings and retrieving data from Railmaps, which is one of ProRail's asset management systems. In order to make the smaller airport Schiphol Airport and The Hague more comparable to the larger three, the areas regarded as part of the station have been extended for these two. Hoofddorp and Hoofddorp yard (centrally controlled area) have been added to Schiphol Airport station while the stations The Hague Central and The Hague Hollands Spoor have been merged.

Infrastructure elements (x)	Utrecht	Amsterdam	Rotterdam	Schiphol Airport	The Hague	Average
Area codes	Ut	Asd	Rtd	Hfdo-Hfd-Shl-Asra	Gvc-Gv	-
Train services	55	44	42	38	55	**46,8**
Switches	158	203	140	102	123	**145,2**
Overhead wire length	24900	28100	20600	24000	23400	**24200**
Track detection sections	178	252	163	116	144	**170,6**
Relay houses	3	3	2	3	3	**2,8**
Interlocking installations	1	1	1	3	2	**1,6**
Signals	76	116	87	61	69	**81,8**
Power stations	3	2	2	3	2	**2,4**
Platforms	16	11	13	10	15	**13**
Control units	8	7	9	7	6	**7,4**
Tunnels	0	0	0	1	0	**0,2**
Bridges (fly-overs)	2	0	3	2	0	**1,4**
Traffic control centres	1	1	1	0	1	**0,8**

Table 4.12 Characteristics of the five busiest stations in the Netherlands (NS, 2012) (RIGD-LOXIA, 2013) (Railmaps, 2016)

The next step is to quantify the yearly average frequency of occurrence of each incident type on a typical complex station in the Netherlands. To do so, mathematical formula (4.1) will be applied to the data, where Q_y is the average yearly frequency of occurrence of incident type *y* on an average complex station, q_{ya} represents the 5-year amount of data occurrences of incident type *y* at location *a* and n_{xa} the number of infrastructure elements *x* installed at location *a*. The accumulated weighted frequencies are divided by 5 and the total number of components to get an average yearly frequency on an average Dutch complex station.

$$\bar{Q}_y = \frac{\left((q_{yUt}\cdot n_{xUt}) + (q_{yAsd}\cdot n_{xAsd}) + (q_{yRtd}\cdot n_{xRtd}) + (q_{yShl}\cdot n_{xShl}) + (q_{yGvc}\cdot n_{xGvc})\right)}{5\cdot(n_{xUt} + n_{xAsd} + n_{xRtd} + n_{xShl} + n_{xGvc})} \tag{4.1}$$

The range of variable x is shown in Table 4.12 and which value is used solely depends on the type of incident. The purpose of the n_{xa} variables in formula 4.1 is to level out differences of incident occurrences between two stations caused by the differences in size, use, or quantities of infrastructure elements. The variable x selection for each type is done by logical reasoning and interpretation, and is therefore a potential source of error or misinterpretation. Nevertheless, given that the analysis is meant as a rough estimation together with the fact that the results will be validated by experts before they will be used, the error margin is regarded as acceptable.

Another formula will be used for determining the average repair time or functional repair time which is not considered to be dependable on the same n_{xa} as the frequency of occurrence. Mathematical formula (4.2) describes how the average functional repair time at an average complex station of incident type *y* will be calculated (FR_y). The functional repair times of the first reported incident (*k=1)* of incident type *y* at location *a* to the last reported incident ($k=q_{ya}$) of type *y* at location *a* are summed up and divided by the number of occurrences of incident type *y* at location *a* (q_{ya}). The sum of all locations' average functional repair times divided by 5 eventually gives the average functional repair time of a certain incident type at an average complex station. Functional repair time and repair time (R_y) are interchangeable in formula (4.2).

$$\overline{FR}_y = \sum_{a\in A}\left(\frac{\sum_{k=1}^{q_{ya}}(FR_{kya})}{q_{ya}\cdot 5}\right) \rightarrow A = \{Ut, Asd, Rtd, Shl, Gvc\} \tag{4.2}$$

The average repair time and average frequency of occurrence of the selected incident types do not automatically represent the potential benefits of untangling options: sometimes installing an untangling option will in the most optimistic case only affect a part of the occurrence frequency or repair time. The maximum or potential benefit of an option for a certain incident type is calculated by formula (4.3).

$$B_{yz} = \left(p_{yz} \cdot \bar{Q}_y\right) \cdot \left(r_{yz} \cdot \overline{FR}_y\right) \tag{4.3}$$

The potential benefit *B* of untangling option *z* for incident type *y* is obtained by multiplying both the average frequency of occurrence Q_y and average functional repair time FR_y with a factor p_{yz} or respectively r_{yz} that represents the share of the incident type *y* affected by option *z.* For most incident types holds that the untangling option affects the full occurrence frequency and average repair time, in which case the *p* and *r* constant are equal to 1. For the other incident types a tailor made approach or estimation is necessary, completely depending on the untangling option and incident type combination. All these exceptions will be discussed and explained individually, including the assumptions made.

With the potential benefits now quantified for each untangling option and incident type combination, it is now possible to discuss the relations between the various untangling options. If two untangling options affect the same incident types with the same potential benefits, the options are regarded as being *equal.* If an untangling option affects more incident types than the same, but with the same potential benefits as another untangling option, the first option *cancels out* the second option because it makes the second one dispensable. The last identified relation is when a certain untangling option *requires* another untangling option to be installed. As discussed before, this was the case with option 20 ‘Creating a safe working area around each corridor’ that is required by all incident types where mechanics have to go on to the tracks to carry out the repair works. Other untangling options that are required are discussed in the results section and have been depicted in appendix C.

Finally, the total potential benefit *TB* of an untangling option *z* is determined by formula (4.4), where the benefits *B* for individual incident types *y* are summed up from the first type up and until the last type (c_z).

$$TB_z = \sum_{y=1}^{c_z} B_{yz} \tag{4.4}$$

4.4.2 Calculated and estimated values

Following the methodology description in the previous section this section will discuss the outcomes of the formulas and clarify the estimation of potential benefits for each untangling option. Table 4.13 contains all outcomes and used parameter values used in formulas (4.1), (4.2), (4.3) and (4.4).

The first column refers to the untangling option *(z)* and selected incident type *(y)*, see Table 4.11 for details. The second column shows the averaging component *(x)* that has been used to come to an ‘average’ Dutch complex station, see Table 4.12 for the individual station values and section 4.4.1 for the explanation of this averaging component. With the help of formula (4.1) the average occurrence frequency *(Q_y)* has been calculated, which is shown in the 3rd column, while the average (functional) repair times *(FR_y/R_y)* calculated with formula (4.2) are shown in the 4th column. The factor *(p_{yz})* that expresses the part of the incident type occurrence *(Q_y)* for which the impact could be contained in one corridor by a certain untangling option *(z),* varies between 0 and 1 and is calculated differently for every incident type. The same holds for the (functional) repair time factor *(r_{yz}).* In columns 5 and 6 of Table 4.13 shows both the chosen values for these factors and references to the involved formulas in the text. Because the potential benefit of each untangling option is simply estimated per incident type, column 7 indicates whether this estimation is optimistic, neutral or pessimistic, which could be relevant information in a case that two untangling options with similar potential benefits are compared. Finally, the last column 8 contains the results of formula (4.3), which expresses the potential benefit of a certain untangling option for each incident type *(B_{yz}).*

Option & Incident (z) (y)	Averaging component (x)	Occurrence frequency (Q_y)	Repair time [min] (FR_y/R_y)	Potential Q factor (p_{yz})	Potential (F)R factor (r_{yz})	Indication	Potential Benefit [min] (B_{yz})
1	*Removing contact lines between corridors (Energy subsystem)*						
a	Overhead w.	0.0	-	1	1	Neutral	0
b	Trains	0.2	1621	1	1	Optimistic	324
2	*Installing subsidiary circuits for every corridor (Energy subsystem)*						
a	Trains	4.1	93	1	1	Neutral	381
b	-	0.2	198	1	1	Optimistic	40
c	Trains	3.9	81	1	1	Neutral	316
d	Power stat.	2.1	18	1	1	Neutral	38
3	*Each corridor has its own power supply (Energy subsystem)*						
a	Power stat.	0.3	344	1	1	Optimistic	103
b	Power stat.	0.7	251	1	1	Optimistic	176
c	Trains	4.1	93	1	1	Neutral	381
d	-	0.2	198	1	1	Optimistic	40
e	Trains	3.9	81	1	1	Neutral	316
f	Power stat.	2.1	18	1	1	Neutral	38
4	*Not installing tensioning systems on poles next to tracks of other corridors (Energy subsystem)*						
a	Trains	0.1	2288	0	1	Pessimistic	0
b	Trains	0.0	-	0	1	Pessimistic	0
5	*Not using large gantries that span more than one corridor (Energy subsystem)*						
a	Trains	0.1	2288	0	1	Neutral	0
b	Trains	0.0	-	0	1	Neutral	0
6	*Removing all cross overs between two corridors including switches (Guidance subsystem)*						
a	Trains	54.8	33	0.11 (4.5)	3.64 (4.6)	Optimistic	268
b	Switches	86.5	65	0.67 (4.7)	1	Optimistic	3748
c	Switches	1.2	217	0.67 (4.7)	1	Optimistic	174
d	Switches	14.3	41	0.67 (4.7)	1	Optimistic	391
e	Sections	23.4	130	0.11 (4.8)	1	Neutral	335
7	*Not putting switch control cables of different corridors near each other (Guidance subsystem)*						
a	Overhead w.	1.0	176	1	1	Optimistic	176
b	Overhead w.	0.3	212	1	1	Optimistic	64
c	Overhead w.	0.1	297	1	1	Optimistic	30
d	Overhead w.	0.6	158	1	1	Optimistic	95
e	Overhead w.	0.1	613	1	1	Optimistic	61
8	*Installing dedicated power supply for the infrastructure of each corridor (Guidance subsystem)*						
a	Switches	0.2	118	1	1	Neutral	24
b	Switches	0.4	33	1	1	Neutral	13
c	Power stat.	0.5	48	1	1	Neutral	24
d	Power stat.	0.7	106	1	1	Neutral	74
9	*Building separate switch heating installations for each corridor (Guidance subsystem)*						
a	Switches	2.0	71	1	1	Neutral	142
b	Switches	0.7	65	1	1	Neutral	46
10	*Never putting more than one corridor through a single tunnel or over one bridge (Support subsystem)*						
a	Tunnels	1.0	189	5.0 (4.9)	1	Optimistic	945
b	Tunnels	3.9	22	5.0 (4.9)	1	Optimistic	429
c	Bridges	0.0	-	-	-	Neutral	0
d	Tunnels	0.2	175	5.0 (4.9)	1	Optimistic	175
11	*Building elevated junctions to prevent the shared use of infrastructure elements (Support subsystem)*						
a	Trains	54.8	33	0.02 (4.10)	3.64 (4.6)	Neutral	137
b	Sections	37.7	130	0.04 (4.11)	1	Neutral	184
12	*Creating separate power grids per corridor for the train related infrastructure (Access subsystem)*						
a	-	0.2	32	1	1	Neutral	6
13	*Designing the station hall in a way it can be evacuated per corridor (Access subsystem)*						
a	-	7.6	17	1	1	Neutral	129
b	-	4.0	52	1	1	Optimistic	208

14	*Not putting element control cables of different corridors near each other (Safety subsystem)*						
a	Overhead w.	1.0	176	1	1	Optimistic	176
b	Overhead w.	0.3	212	1	1	Optimistic	64
c	Overhead w.	0.1	297	1	1	Optimistic	30
d	Overhead w.	0.6	158	1	1	Optimistic	95
e	Overhead w.	0.1	613	1	1	Optimistic	61
15	*Not using large gantries that span more than one corridor (Safety subsystem)*						
a	Signals	0.2	1891	0	1	Neutral	0
16	*Installing dedicated power supply for the infrastructure of each corridor (Safety subsystem)*						
a	Switches	0.2	118	1	1	Neutral	24
b	Switches	0.4	33	1	1	Neutral	13
c	Power stat.	0.5	48	1	1	Neutral	24
d	Power stat.	0.7	106	1	1	Neutral	74
e	Relay house	0.4	64	1	1	Neutral	26
17	*Building separate relays houses for each corridor (Safety subsystem)*						
a	Relay house	0.1	17240	1	1	Pessimistic	1724
b	Relay house	0.1	471	1	1	Neutral	47
c	Relay house	0.3	396	1	1	Neutral	119
18	*Developing and using interlockings that operate independently per corridor (Safety subsystem)*						
a	Interlockings	0.3	281	1	1	Pessimistic	84
b	Interlockings	0.9	47	1	1	Pessimistic	42
c	Interlockings	0.2	74	1	1	Pessimistic	15
19	*Installing procedures or systems that enable the safe use of a switch that requires a position of another switch that is out of control (Safety subsystem)*						
a	Switches	86.5	65	0.67 (4.7)	1	Optimistic	3748
b	Switches	1.2	217	0.67 (4.7)	1	Optimistic	174
c	Switches	14.3	41	0.67 (4.7)	1	Optimistic	391
20	*Creating a safe working area around each corridor (Safety subsystem)*						
-	-	-	-	-	-	-	-
21	*Using separate LCEs for the control each corridor's infrastructure (Resource allocation level)*						
a	Control units	3.9	18	1	1	Neutral	70
22	*Installing dedicated power supply for the control of each corridor (Resource allocation level)*						
a	Control cent.	4.5	92	1	1	Neutral	414
b	Control cent.	0.0	-	-	-	Neutral	0
23	*Using a separate EBP system for the control each corridor's infrastructure (Resource allocation level)*						
a	-	0.1	508	0	1	Unknown	0
24	*Using a separate PRL system for the control each corridor's infrastructure (Resource allocation level)*						
a	-	1.6	189	0	1	Unknown	0
25	*Assigning a dedicated signaller per corridor in a separate building (Resource allocation level)*						
a	Control cent.	0.1	194	0	1	Unknown	0

Table 4.13 Outcomes and used parameter values in formulas (4.1), (4.2), (4.3) and (4.4)

4.4.2.1 (1) Removing contact lines between corridors

For the first untangling option two incident types have been identified, which are similar in effect but different in cause. No broken overhead wires have been reported that were caused by for instance a fallen tree, engineering works or incorrect maintenance: only incidents caused by third parties have been reported, which in this case always involved wire damage caused by a train.

Because there are no level crossings present near the selected stations, the possibility of damage caused by road vehicles can be ruled out, which justifies the choice of the number of trains that pass through the station as averaging component.

Both potential factors (p_{yz} and r_{yz}) have been estimated to be equal to 1 since overhead wire damage caused by a train could in almost all cases be isolated to one corridor if the lines are not connected. Nevertheless, the estimation might be slightly too optimistic because it assumes that even a completely broken wire will never come within safety envelope area of a neighbouring track.

Some untangling options are required to have been installed for this option, either to make the installation of the option possible or to fully gain the estimated benefits. Obviously the safe working area (20) should be present to allow for repair works that do not interrupt the service on other tracks. Also should all switches between corridors (6) and flat junctions (11) have been removed as they automatically lead to overhead lines that will come into contact at some point (see Figure 4.12 for an example).

4.4.2.2 (2) Installing subsidiary circuits for every corridor

By having subsidiary circuits per corridor, short circuiting caused by weather and (the damage of) third parties (trains) will not interfere with services in other corridors. The time it would have taken to set the power switches in the catenary system to redirect the current, could be saved by this untangling option. Also the impact of a faulty power switch in the circuit would have been isolated by this untangling option. The effects of these four incident types are regarded to be fully retainable within the corridor of occurrence; hence all the potential factors were given a value of 1.

For the isolation of lighting damage, this only holds if both option 1 (separate contact lines) and option 5 (not using large gantries) have been applied for 100%. Because the correlation between these untangling options is only present for this incident type and the quantity of the type’s impact relatively low, the correlation is not listed. To compensate, the estimation is regarded as too optimistic.

The applied averaging component for third party incident types is the number of trains, while for the failure of the power switch in a power station the number of power stations has been used. Ideally, the number of power switches would have been used there as averaging component, but unfortunately this information was not available. For the estimation of the chance of being struck by lightning no suitable averaging component has been found, so a value of 1 has been used in formula (4.1).

4.4.2.3 (3) Each corridor has its own power supply

This untangling option can be seen as an improvement or aggravation of the previous option: instead of having subsidiary circuits per corridor, each corridor is now equipped with an isolated power station. All the benefits estimated under 4.4.2.2 are also valid for this untangling option. Moreover, any other power station failure that used to influence the train service operation in the whole area fed by the power station could now also be isolated.

An assumption made for this estimation is that the number of power stations needed to feed the station area remains equal: if for instance the number of power stations increases, the incident type occurrence frequency is likely to increase with it. The only difference then compared to a tangled situation is that even though a power station failure occurs more frequently, when a power station failure actually occurs only one corridor is affected. Or in other words, the total yearly hindrance in a single corridor caused by a power station failure remains equal, but the hindrance will almost never occur simultaneously with hindrance caused by a power station in other corridors. For this reason, the number of power stations in a station area is used as averaging component.

4.4.2.4 (4) Not installing tensioning systems next to other corridors’ tracks

Tensioning systems possibly form another kind of physical tangling of systems between corridors when one tensioning system is attached to a pole in or close to another corridor. The risk exists that if a train derails it could collide with a pole that also holds the tensioning system of this other corridor.

Quantifying the potential benefit of this untangling option is difficult because estimating the chance a colliding train hits a specific pole is hard. Not only is the impact of a train collision very different per case, there are also hardly any data points for this incident type. So what would for instance be the benefit of locating the pole with tensioning system 1 meter further from the neighbouring corridor? How much less like is it for a colliding train to hit this pole at its new location? Besides that it also makes a difference whether a tensioning system is adjoined to another corridor's gantry or to a separate pole which is located closely to the other corridor.

Because the uncertainty is too high and the quantity of data points too little, it is impossible to come to a suitable estimation, even for level the roughness of the analysis. To be on the safe side the potential benefit is stated as 0, although the theoretical maximum benefit would be 229 minutes per year (0.1 x 2288). Hence the value of 0 is regarded as pessimistic.

4.4.2.5 (5) Not using large gantries that span more than one corridor

The same difficulty that has been faced with the estimation of the benefits in 4.4.2.4 applies here: the identified incident types are both structural damage caused by trains that collide with a column of a gantry.

With only a few derailments present in the data, which each a very different impact, it is hard to predict what the chance would be for a single column to get hit. It could even be argued that the fewer poles there are, the lower the chance of structural damage to the catenary system when a train derails. In that way, structurally bundling the corridors by gantries would be more robust than untangling them, due to the reduction of collidable objects. Moreover, even if each corridor would have its own gantries, what would be the chance that when a derailed train runs the gantry down it will keep clear of the safety envelope of a neighbouring corridor?

With the previous argumentation it could be stated that smaller gantries (untangled) would even have a negative benefit, but Figure 4.15 shows that is not always the case. A derailed train hit the columns of two large gantries, resulting in the unavailability of the catenary system in all corridors. If the gantries would have been untangled, the impact would have been limited to the corridor of occurrence. Because the uncertainty is too high and the quantity of data points (collisions) too little, it is impossible to come to a more specific estimation than 0.

Figure 4.15 Derailed train in Amsterdam in 2006

4.4.2.6 (6) Removing all crossovers between two corridors including switches

Within the station area, the direct effect of removing switches is that trains do not switch between corridors anymore and that for instance a faulty train can never block more than one corridor. The incident type faulty train amongst others has therefore been selected for this option, but obviously not all faulty trains used to block multiple corridors, especially keeping in mind that the switches that are removed in this option are not meant for regular operation: trains run in train service corridors and do not change to other corridors in the station (see scope, section 4.1.3). The remaining switches between corridors that are removed in this option are used for shunting moves or traffic management manoeuvres.

To estimate the benefits, a more detailed insight in faulty train incidents is required. The question is how many faulty trains per year stand on the (removed) switches and actually block multiple corridors? Formula (4.5) was used for the estimation and consists of three parts. The first factor was added because an extra reduction factor was needed for compensating an overrepresented location of faulty trains: 83% of all reported faulty trains broke down at a platform, where no switches are present ($P_{platformtrain}$). The second factor estimates the chance a faulty train actually comes to a hold on a switch, where it has been assumed that all tracks are used equally frequently. Obviously this is too optimistic, because there are fewer shunting train paths provided by ProRail than regular train paths (ProRail, 2016f). The chance a part of the faulty train blocks a switch is approximated by adding two times the average train length (l_{train}) to the average switch length (l_{switch}), multiplying it by the average number of switch pairs (n_{switch}) and finally dividing it by the average total length of non-platform tracks. This total length was calculated by deducting the average platform length ($l_{platform}$), multiplied by the average number of platforms ($n_{platforms}$), from the average overhead wire length ($l_{overhead}$), which is only true because all tracks at the five selected stations are equipped with a catenary system. Finally, a third factor was added to estimate the amount of removed switches and thus the share of benefits that will be gained with this option ($P_{reduction}$).

$$r_{6a} = \overline{(1 - P_{Platformtrain})} \cdot \left(\frac{(\bar{l}_{Switch} + 2 \cdot \bar{l}_{Train}) \cdot \bar{n}_{Switches}}{\bar{l}_{Overhead} - (\bar{l}_{Platform} \cdot \bar{n}_{Platforms})} \right) \cdot \bar{P}_{Reduction} \tag{4.5}$$

The average length of a train and the number of removed switch pairs were not directly available from the previously introduced data, but had to be assumed or interpreted from other data sources. In the design documents of DSSU it can be seen that the programme removed approximately 2/3 of the switches in Utrecht in their attempt to untangle the infrastructure (Movares, 2015). For the average train length the lengths of involved faulty trains in the incident data have been averaged, resulting in a length of 188 meters. For the average switch pair length 30 meters has been used and for the number of switch pairs 73. With these numbers, the chance for a faulty train to stand on a switch pair is 100% (second part of formula (4.5) >1), meaning that it is almost impossible for a faulty train to not stop on a switch. Since a value for r_{6a} greater than 1 is not realistic (it would imply more incidents are contained in the corridor that there actually occur) a value of 1 has been chosen.

Generally there would be no reason to deviate from the average repair time found in the data, but since 83% of the faulty trains incidents have been excluded it would only make sense to use the average repair time of the remaining 17%. Formula (4.6) shows how the potential factor for incident type 6a in Table 4.13 is calculated.

$$p_{6a} = \frac{\sum_{x \in A} \left(\frac{\sum_{k=1}^{q_{nonplatformftrain,x}} \left(FR_{faultytrain} \right)}{q_{nonplatformftrain,x} \cdot 5} \right)}{\overline{FR}_{faultytrain}} \quad \rightarrow A = \{Ut, Asd, Rtd, Shl, Gvc\} \tag{4.6}$$

The functional repair times of the first reported non-platform incident ($k = 1$) at location x to the last reported non-platform incident ($k = q_{nonplatformftrain,x}$) at location x are summed up and divided by the total number of non-platform faulty train occurrences at location x ($q_{nonplatformftrain,x}$). The sum of all locations' average functional repair times divided by 5 eventually gives the new average functional repair time of a non-platform faulty train at an average complex station. The potential factor for this functional repair time (p_{6a}) is obtained by dividing the average functional repair time of non-platform faulty train incidents by the average functional repair time of all faulty train incidents ($FR_{faultytrain}$). As expected, the value of the factor is greater than 1: faulty trains located outside the station take longer to be fixed, for instance because they are harder to reach for mechanics.

Another series of incident types of which the impact could be isolated by this option are malfunctioning switches. The largest part of the potential benefit is not a direct result of the removal of switches, but is obtained because of the logistical aspect that comes with untangling: trains run in fixed corridors and no longer depend on the well-functioning of switches. The question is how many malfunctioning switches influence multiple corridors? Due to the required flank protection, almost every problem with a switch influences the availability of neighbouring switches. This flank protection interdependency is explained in further detail in section 4.4.2.19. It is therefore assumed that all switch incidents currently lead to a disruption of multiple corridors, which implies a potential factor equal to the percentage of removed switches in this untangling option (see formula (4.7)).

$$r_{6b,c,d} = \bar{P}_{Reduction} \tag{4.7}$$

The last related incident type which impact is isolated by the untangling option is the failure of an ES weld (Electric Separation weld). ES welds form a separation between two track sections which are used for track free detection and transmitting electrical pulses for the ATB system. Because the welds do not conduct electricity, an electrical circuit between the two rails only exists if a train is present in the section. Unfortunately, ES weld failures often occur, leading to incorrect notifications of train presences in sections.

ProRail equips each switch with a separate section to be able to set multiple non-conflicting routes simultaneously in a single junction or station area. If the area would be a single section, only one train would be able to enter it at the time. The reduction of switches would therefore automatically leads to a reduction of sections and with that a reduction of ES welds. Each switch section has three borders (and thus 3 three welds), and the removal of a single pair of switches reduces the number of welds with 1. See Figure 4.16 for a schematic view. Obviously, the exact amount of removed ES welds heavily depends on the local situation, which switches are removed and how many sections are necessary for achieving optimal headways.

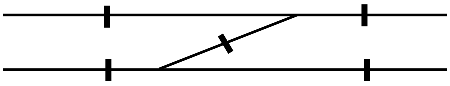


Figure 4.16 Schematic pair of switches with ES welds

Formula (4.8) has been used for calculating the potential factor that estimates the part of the incidents occurrences that would benefit from the untangling option. As explained before, it is assumed that per 2 removed switches (*1/2 x* $P_{reduction}$) one third (*1/3*) of the ES welds is removed.

$$r_{6e} = \frac{1}{2} \cdot \bar{P}_{Reduction} \cdot \frac{1}{3} \tag{4.8}$$

All in all it can be concluded that untangling option 6 is more difficult to quantify than the other untangling options so far, mostly because the extent and exact way the option is installed has great influence on the ability of the system to encyst the impact of an incident type within the corridor. Besides that, the logistical impact, in benefits and negative benefits, has been neglected so far while it would especially here make a great difference. This option is required by option 1, since the presence of switches between corridors, which are equipped with connecting contact lines, automatically makes it impossible to untangle these contact lines.

4.4.2.7 (7) Not putting switch control cables of different corridors near each other

Switch control cables and all other cables that run underground face the potential risk of being incidentally damaged during engineering works due to unawareness of their presence or exact location of the cables. Unfortunately, based on the current data source it is not possible to distinguish the benefits of untangling element control cables from the benefits of untangling any other underground cable type. Option 14, which describes the untangling of cables that are related to the safety subsystem, will therefore be given the same benefits as this option, while actually the estimated benefits form the sum of the benefits if both options are applied: the division of the benefits between the two individual options is simply undeterminable. Moreover, it is not only option 7 and 14 that should share the benefits, but the benefits account for all rail bound underground cables, also the ones that have not been mentioned in one of these two untangling options. The best solution would be to merge and rewrite the untangling options 7 and 14 as ‘not putting underground cables of different corridors near each other’. Nevertheless, because merging options would not be consistent with the used methodology anymore at this point, each option is given the full benefits. In the conclusions section the overrated benefits will be taken into account.

Underground infrastructure is not directly visible and construction workers often have to rely on drawings and maps which could be inaccurate, incomplete or outdated. Two incident types are therefore related to construction works, three other types are related to technical damage. Putting these cables in separate cable tubes would isolate the impact of the incidents. As averaging factor the length of overhead wires is used, because it represents the length of tracks and with that probably the length of the underground cables.

4.4.2.8 (8) Installing dedicated power supply for the infrastructure of each corridor

Besides the trains, the infrastructure itself as well needs power to function. If the power supply would be blocked the switches will not be usable anymore. The reasoning of having a dedicated power supply per corridor is similar to option 3 which comprises a separate 1500V power supply to the overhead wires per corridor.

For the determination of the potential benefits of option 7, it was impossible to make a distinction between the benefits of option 7 and of option 14, because of the simple reason that the two types of cables they untangle are often located in the same tube. For this option, the same difficulty exists as it cannot be determined from the data whether a certain power supply disruption concerned the switch, the safety system of the switch or another part of the interlocking system. This option and option 16, which untangles the power supply in the safety subsystem, are therefore treated equally as option 7 and 14. See section 4.4.2.7 for the details.

The impact of all types of power disruption incidents found in the data would be affected by this untangling option, assuming that the number of power stations remains equal. After all, with an increase in power stations, the occurrences of power station related incidents will increase as well. For the non-power station related incident types the amount of switches has been used as averaging component since it represents the amount of objects that have to be powered, while for the power station related incident types the number power stations has been used.

4.4.2.9 (9) Building separate switch heating installations for each corridor

If a malfunctioning switch heating installation leads to frozen switches in multiple corridors, the untangling of these installations will isolate the impacts of the failure of one of these installations. The local failure of a switch heater on a single switch is less interesting, unless the switch is part of a switch pair between two corridors. Because of that and the small amount of reported incidents that actually affected the train services – most were reported failures during nightly tests – the individual switch heating incident types are neglected. The incident types that comprise a larger installation malfunctioning are of interest when building a separate installation for each corridor.

The newest standards within ProRail prescribe an electrical switch heating system (ProRail, 2016j), which is why only incidents types that correspond with an electrical switch heating system have been selected. Because there was no data available on the sizes of the switch heating installations at all five selected stations, the number of switches has been used as averaging component.

4.4.2.10 (10) Never putting more than one corridor through a single tunnel or over one bridge

Multiple corridors that run through a single tunnel easily face disruption of train services, as every kind of unavailability of the tunnel immediately has an effect on all corridors.

The number of tunnels and bridges per station has been used as averaging component, but for the tunnel related incident types this results in an unfair comparison. Since only one of the selected stations has a tunnel (Schiphol Airport), the averaging component meant to mediate the data of the five locations and to flatten peaks in the data resulted from station size differences, suddenly has another effect: an average station has 0.2 tunnels and the effects of untangling the tunnel systems are thus only quantified for 20%. Since the results of this thesis are meant to be used locally (per complex station), it would in this case be a more fair comparison to quantify the benefits as if there is one tunnel present at the imaginable average station instead of 0.2.

Untangled tunnels are assumed to have separate tunnel installations and warning systems, and enough space or material between them to remain operational when a neighbouring tunnel is unavailable. Structural damage incident types have not been found in the data, so a single tunnel with a thick fire resisting wall between the two corridors could also be regarded as two untangled tunnels. The found incident types are errors in the tunnel system, fire alarm and tunnel flooding and the frequency of their occurrences all have been multiplied by 5 (see formula (4.9)).

$$r_{10a,b,d} = 5 \tag{4.9}$$

Flooding of the tunnel has also been taken into account although it can be argued that not all incidents in that category could be isolated by the untangling option. When the flooding has for instance been caused by heavy rainfall for which the pumping systems have not been designed, it would not have made any difference whether the tunnels were untangled or not. The same holds for the tunnel installation failures: with more tunnel installations installed, the occurrence frequency will most probably increase. The quantified potential benefit has therefore been labelled as optimistic.

4.4.2.11 (11) Building elevated junctions to prevent the shared use of infrastructure elements

The option of building elevated junctions shows a similarity with option 6, the removal of switches between two corridors: the options make it physically impossible for trains of two different corridors to interact with each other and with that guarantee that all trains in a corridor use dedicated rails. The relevance of logistical effects, on capacity and traffic management possibilities, that come with the installation of this option are therefore also high. In the second part of the research there is a greater emphasis on the effect of these logistical effects.

The potential benefits that can be gained from the reduction of incidents with a multiple-corridor effect have been identified in two categories of incidents. Within these incident types – faulty trains and track section failure – a faulty train that comes to a stop exactly at the diamond crossing and a failure in section that is shared by both corridors (in other words on the diamond crossing), form the incidents from which the effects could be isolated by this untangling option.

To start with the first incident type, for which the potential factor is estimated by formula (4.10). This formula is similar to formula (4.5), which estimates the chance that a train would come to a stop while standing on a switch, but here the formula approximates the chance a train comes to a stop while standing on a specific track clear detection section. The share of faulty trains that do not stand next to a platform ($P_{platformtrain}$) forms the first part of the formula. The second part's upper half calculates the area in reach of the section, which comprises two times the section length (1/2 l_{switch}, 15 metre) plus two times the average train length (l_{train}, 188 metre) multiplied by the number of diamond crossing sections in the station area that are to be removed ($n_{xsections}$, 4). The applied values have been based on the standard non-elevated junction depicted in Figure 4.12, where two tracks of one corridor cross two tracks of a neighbouring corridor. Each track therefore contains two diamond crossings on which a faulty train could block with its tail, head and everything in between, hence two times the section length plus two times the train length. The average diamond crossing section length has been assumed to be equal to half the average switch pair length or in other words the average length of a single switch. The bottom half of the factor divides the section area by the average total length of the tracks in the station area ($l_{overhead}$) excluding the tracks next to the platforms ($l_{platform}$ x $n_{platforms}$).

$$r_{11a} = \overline{\left(1 - P_{Platformtrain}\right)} \cdot \left(\frac{(2 \cdot \frac{1}{2} \cdot \bar{l}_{Switch} + 2 \cdot \bar{l}_{Train}) \cdot \bar{n}_{XSections}}{\bar{l}_{Overhead} - (\bar{l}_{Platform} \cdot \bar{n}_{Platforms})} \right) \tag{4.10}$$

According to the most simple track layout depicted in Figure 4.12 in section 4.2.2, the amount of diamond crossings ($n_{xsections}$) is 4. In reality, this amount could be higher, but the difference this makes is little: with values for $n_{xsections}$ of 2, 4, or 6 the value of r_{11a} becomes 0.01, 0.01 or 0.02 respectively.

For the repair time potential factor formula (4.5) has been used, since all faulty train incidents taken into account are trains that came to a stop outside the station and not next to a platform (see section 4.4.2.6).

The other related incident type is a section failure and the incidents within this type of which the impact could be isolated by the untangling option, are section failures of the shared sections on the diamond crossings. The proportion between the number of diamond crossing sections ($n_{xsections}$) and average total number of train detection sections in the station area ($n_{sections}$) represents the proportion of section failure incidents that could be affected by this untangling option (see formula (4.11)). Obviously this is only valid if assumed that each section fails equally often.

$$r_{11b} = \frac{\bar{n}_{XSections}}{\bar{n}_{Sections}} \tag{4.11}$$

Besides the benefits from the incident types mentioned above, the installation of elevated junctions forms a starting point for the untangling of the safety subsystem. Without elevated junctions and thus the shared use of certain (diamond crossing) sections, the interlocking and signalling systems of both corridors at least need to be able to interact. Nevertheless, this option is only required by option 1 (untangle contact lines) because the required interaction of two corridor's safety subsystems still means that an interdependency between the two systems (system tangling) can be ruled out.

4.4.2.12 (12) Creating separate power grids per corridor for the train related infrastructure

Power losses in the station hall, for example caused by a deep fat fryer – located in one of the commercial areas of the station – which created a short circuit, could lead to a disruption of services. If the ticket barriers, escalators, information screens, speakers for service announcements and platforms lights are all powered off at the same time, it becomes difficult for passengers to find their way through the station and to board their intended train service in time.

Only one incident type found in the data seems to have these characteristics: a power failure in the station hall that has not been caused by a large power supply disruption on the electricity company's side. If the power grids in the station would have been untangled, only a small part of the corridors had been affected by these incidents. For that reason a value of 1 has been chosen for both potential factors, as it is likely that this incident type can be fully accounted to the potential benefit of this option.

Although the indication ‘neutral’ has been given to this estimation, a small remark on the feasibility of this untangling option is in order. Important rail related infrastructure such as ticket barriers and ticket machines are usually located at a central place in the terminal building and can perhaps not be split per corridor easily.

4.4.2.13 (13) Designing the station hall in a way it can be evacuated per corridor

This option is meant to prevent that for example an unattended bag or small fire in an ashtray of the designated smoking area could lead to the disruption of all train services. By evacuating only the platforms and a part of the station hall where these incidents take place, the other corridors can continue to operate according to the timetable.

Two related incident types have been identified: passenger evacuation after a fire alarm and passenger evacuation after an emergency. Naturally, whether evacuating only a part of the terminal building is sufficient or not heavily depends on the details of the emergency and the magnitude of the fire. Amongst the fire alarm incident data, no reports of a large fire have been found – by far the most appeared to be false fire alarms – so it is assumed that this incident type can be counted 100% as potential benefit.

For the other broader incident type this is more difficult to assess, since the safety risk is harder to evaluate and many other factors could play a role in deciding whether evacuating only a part of the station hall could suffice. Nevertheless, due to a lack of data a potential factor of 1 has been used, but the indication has been set to ‘optimistic’. Also for this untangling option of the access subsystem a remark can be made about its feasibility. It is not easy to communicate to passengers what parts of the terminal building are being evacuated in case of an emergency.

4.4.2.14 (14) Not putting element control cables of different corridors near each other

As described in section 4.4.2.7, this option and option 7 are very similar and the share of the total benefits for each of these options is undeterminable. See section 4.4.2.7 for further details and discussion of the related incident types, chosen potential factors and given indications.

4.4.2.15 (15) Not using large gantries that span more than one corridor

The use of large gantries has also been discussed in section 4.4.2.5, where it was the topic of a similar untangling option, namely not using large gantries in the catenary system. A main difference with this option the quantity of gantries needed in an area, and therefore the amount of signals has been used as an averaging component instead of the overhead wire length.

Unfortunately, the same difficulties faced with the determination of benefits of option 5 are faced here. Even though a specific incident type was defined for train derailments that caused damage to the signalling system, the number of occurrences is very low. Because of that, determining whether separate signal posts would have kept the damage and thus disruption of service within the corridor or would actually have worsened the situation is impossible. Likewise option 5 the potential factor has therefore been set to 0.

4.4.2.16 (16) Installing dedicated power supply for the infrastructure of each corridor

Although this untangling option is not exclusively related to the safety subsystem, it is regarded to be in its right place there since most of the equipment near the tracks that needs power is part of the safety subsystem. The switch motors, which are part of the guidance subsystem, are an exception and their power supply has been described in untangling option 8. As stated there, it cannot be distinguished from the data which potential benefits would apply to this option and which to option 8. The potential benefit factors have all been set to 1 to see the potential benefit of power supply untangling while realising it represents the benefits of both options.

The fifth related incident type, which can actually be distinguished from option 8, is a failure of the power supply to the relay houses: this type of failure will not be contained if only the power supply to the switch motors has been untangled. Naturally, it makes sense to use the number of relay houses in the area as averaging factor for this incident type instead of the number of switches.

None of the five incident types are incidents that have an area wide impact character, such as a power failure caused by the electricity company. After all, the effect of these incidents would not be limited when the elements are powered separately per corridor, since it would still lead to a power disruption in all corridors. Only incidents with local impacts are relevant and have therefore been identified. There is no reason to assume that the effects of these incident types would not be fully contained in the corridor by this untangling option, so the potential factors and indications for all incidents types have been set to 1 and 'neutral'.

4.4.2.17 (17) Building separate relays houses for each corridor

Inside the relay houses much equipment has been installed that is part of the interlocking, ATP system, traffic centre communication system or another system or technology. By bundling a large amount of technical equipment in a single building, not only would damage to this building result in a large effect (because many systems become unavailable), it also influences the repair time negatively, as a large amount of equipment will need to be replaced at once. In the data this can be seen in the very large repair time that is necessary if a fire would destroy the relay house. Luckily, an all destroying relay house fire is a rare occasion but not unthinkable, as becomes clear from a large incident reported in Germany recently (WDR, 2016). A fire in an old signal box in Mülheim destroyed the relays located on the ground floor and heavily disrupted the train services for over half a year (see Figure 4.17).

Figure 4.17 Fire in the relay room inside a signal box in Mülheim (WDR, 2016)

Obviously, as averaging factor the number relay houses has been used. The identified incident types all relate to housing damage, either caused by the weather, third parties or ProRail itself. Since having a dedicated relay house per corridor would contain all these incident types fully, the potential factors have been set to 1 and the indications to neutral, with exception of the relay house fires. The indication for the estimated benefits from that incident type is pessimistic, as a destructive fire as seen in Germany has not occurred in the data.

4.4.2.18 (18) Developing and using interlockings that operate independently per corridor

The interlocking functions as a spider in the web as it is receives commands from the signal box or traffic control centre and translates them into safe, set and held routes through the station area with all switches and signals secured in their proper position. It is easy to imagine that a malfunction of this interlocking has great consequences.

Even if the interlocking devices are split per corridor, the need to communicate will always remain present when switches connect two corridors and facilitate a route between corridors. In an untangled situation, it is assumed that this communication is only needed if such route is attempted to be set, and not required constantly, as it is in a tangled situation.

The related incident types are all technical failures of an interlocking component or component attached to the interlocking (ATP-system). Having separate interlocking devices per corridor will contain the effects of these incidents within the corridor, for which the potential factors have been set to 1. Nevertheless, a pessimistic indication has been given for the estimated potential benefits, as both the failure rate and repair time could probably be reduced because of the decreased complexity that will be sufficient for the smaller interlocking devices. In that case the benefits would be higher.

4.4.2.19 (19) Installing procedures or systems that enable the safe use of a switch that demands a position of another switch that is out of control

This option addresses a form of system tangling that is related to switches in the guidance subsystem, but tangles two corridors through the safety subsystem. If a switch has a malfunction, it could cause hindrance for the trains running over it. When the switch leads directly to another switch in a neighbouring corridor, the train service in neighbouring corridor will be hindered as well, as the interlocking requires a correct and controlled position of both switches for flank protection reasons.

Figure 4.18 explains this interdependency: if switch 2973 is out of control, it is not possible to clear a train path in corridor AA that passes by signal 2976 and over switch 2975, even though the route does not use switch 2973 at all. The risk that is sought to be mitigated is that a train impermissibly passes red signal 2974 and collides with the train in corridor AA, which is possible since the position of switch 2973 cannot be guaranteed. The chance for that to occur in this situation is very limited, as the traffic in corridor BB will probably already have been suspended due to the malfunctioning of switch 2973 it needs to run over. This untangling option relieves this interdependency (either by procedures or system design changes) and would in the case of Figure 4.18 allow trains to run in corridor AA.

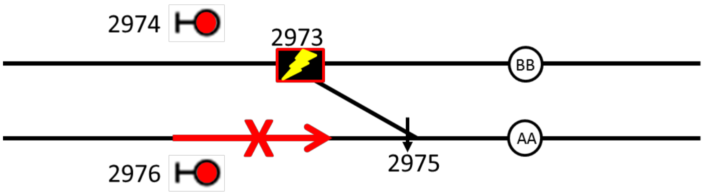


Figure 4.18 Flank protection by switch pairs with required positions visualised

The tangling in the safety subsystem for flank protection reasons is standard and has already been incorporated in the estimation of option 6's potential benefits, which cancels out this option. After all, if all the switch pairs between corridors are removed, there will be no need for flank protection anymore.

The potential benefits for all technical switch failure incident types are the same as for this option as for option 6, because whether the switch pair or the interdependency between them is removed, the effects of the incidents will be kept within the corridor. The same potential factor of 0.67 has therefore been used, according to formula (4.12) and (4.7). See section 4.4.2.6 for details on the estimation indication, averaging factors and reasoning behind this formula.

$$r_{19a,b,c} = \bar{P}_{Reduction} \tag{4.12}$$

4.4.2.20 (20) Creating a safe working area around each corridor

The used analysis methodology is not directly suitable for this untangling option, as explained before. During the identification process of the incident types the question was asked whether (a part of) the impact of the incident type could have been isolated in the corridor of occurrence, if the untangling option would have been installed. The focus here was on the impact caused by the incident itself, not on the impact resulting from the repairing works that had to be carried out to repair the infrastructure or train. As a result of that, untangling option 20 became a required option to be installed for all options that have incident types that require mechanics going out onto the tracks to carry out the repair works. In that way, option 20 contributes to many of the potential benefits estimated under the other untangling options. In the result section, where the interrelations of the untangling options are discussed, this will be shown and described in further detail.

4.4.2.21 (21) Using separate LCEs for the control each corridor's infrastructure

LCEs or Local Control Units are installed in the relay houses and receive commands from the traffic control centre or signal box which they feed into the interlocking system. Status updates from the interlocking are transmitted back to traffic control centre or signal box. LCE failures result in a communication problem between the controllers and infrastructure, which has a large impact on the train services. Having a LCE installed for each corridor would limit this impact to the train services in one corridor.

Naturally, the number of LCEs is used as averaging factor. Furthermore there is no reason to assume that the effects of the identified incident type would not be fully contained in the corridor by this untangling option, so the potential factor and indication has been set to 1 and 'neutral'.

4.4.2.22 (22) Installing dedicated power supply for the control of each corridor

Although this option seems similar to options 8 and 16, which untangle the power supply to the switches and rest of the infrastructure, this option focusses on the power supply to the traffic control centre and its systems. Taking into account the importance of these systems, there is a good chance that the power supply facilities have been made redundant with the help of emergency generators. The question then is whether power supply disruptions will still appear in the data. For the second identified incident type, a power loss in the control room, no data has been found indeed.

The effectiveness and feasibility of untangling only the power supply of the control centre when all other systems including the building itself are still tangled, is questionable. Nonetheless in combination with other options it is relevant to know how much this particular option could contribute to the potential benefit. The identified incident type's effects theoretically would have been contained within the corridor by this untangling option, for which the potential factors has been set to 1.

4.4.2.23 (23) (24) (25) Untangling options 23 to 25

Options 23 to 25 have in common that their benefits are difficult to quantify with the chosen methodology as they fundamentally differ from the other untangling options. Where other untangling options comprised a revision of the subsystem, different technical scheme, other layout or different way of bundling, the total amount of equipment needed never increased much. For example if the theoretically station layout in Figure 4.14 currently has two relay houses (one on the left side and one on the right side) and installs untangling option 17, the content of the two relay houses will simply be remodelled: all equipment related to corridor A in one relay house and all equipment related to corridor B in the other one. The number of relay houses and amount of equipment will (primarily) stay the same whether or not this untangling option is installed.

By definition, this is not the case for last three options, because all stations belong to only one EBP system, one PRL system and one signaller (although the latter is not necessarily true, but at least significantly fewer than the number of corridors). Splitting these systems per corridor would mean that the number of systems increases significantly.

And with that increase a difficult dilemma emerges: although the untangling option will contain the effects of an incident within the corridor, the frequency of these incidents will rise. When the incident takes place not all train services will be effected, but if the failure rate equally increases, all train services will still be affected as much as in the tangled situation (only not simultaneously). From an untangling point of view, this is an improvement as it allows passengers to take detours to reach their destinations. But from an infrastructure manager's point of view this might be different, as more equipment needs to be bought, installed and maintained while the number of incidents and robustness remains equal. Besides that, it is very difficult without extensive knowledge of the system to determine how much the failure rate will increase. Because the uncertainty is too high, potential factors of zero have been used with an indication of unknown.

4.5 Results

In the previous section a lengthy process has been described in which the untangling process has been described and scoped, untangling options have been identified and their potential benefits quantified. This section will present the results of the applied methodology, discuss their relevance and draw conclusions based on these results.

4.5.1 Relevance of the results

Table 4.14 shows the total potential benefit of each untangling option as estimated in the previous section and has ranked them from 1 to 25 based on these benefits. Many comments have already been made in section 4.4.2 on individual estimations, including on the suitability of the used methodology for that option, the uncertainty faced in the quantification process and the relation to other options. Appendix C elaborates on these interrelations and shows a matrix in which several interdependencies have been plotted. Appendix D comprises a more detailed overview of the benefits by showing the frequency of occurrence (probability) and average duration (impact) of the related incident types of all untangling options.

Untangling option (*z*)	Potential benefit [min] (TB_Z)	Rank [#]	Untangling option (*z*)	Potential benefit [min] (TB_Z)	Rank [#]
(6) Removing switches	4938	*1*	**(8) Power supply switches**	161	*14*
(19) Flank protection	4334	*2*	**(18) Interlocking**	141	*15*
(17) Relay houses	1890	*3*	**(16) Power supply infra**	135	*16*
(10) Tunnels & Bridges	1549	*4*	**(21) LCE**	70	*17*
(3) 1500V power stations	1054	*5*	**(12) Terminal power grid**	6	*18*
(2) Subsidiary circuits	775	*6*	**(4) Tensioning system**	0	*19*
(14) Signal control cables	426	*7*	**(5) Overhead wire gantries**	0	*19*
(7) Switch control cables	426	*7*	**(15) Signal gantries**	0	*19*
(22) Power supply signal box	414	*9*	**(23) EBP**	0	*19*
(13) Station hall evacuation	337	*10*	**(24) PRL**	0	*19*
(1) Contact lines	324	*11*	**(25) Signaller**	0	*19*
(11) Elevated junctions	321	*12*	**(20) Safe working area**	0	*19*
(9) Switch heating	188	*13*			

Table 4.14 Ranking of identified untangling options with highest potential benefits

The ranking in Table 4.14 shows *which of the 25 selected untangling options can potentially isolate the most minutes of unavailable infrastructure within the corridor of occurrence, where unavailability of infrastructure has been defined as the number of yearly occurrences multiplied by the average repair time.*

The word 'potentially' has been added across this chapter several time because the actual benefits heavily rely on the local situation and to which extent the options have been installed. The used methodology is not very precise and therefore has a large range of uncertainty, which is suitable for the purpose it was used for: roughly indicating which options are interesting for further investigation in the second part of this research. Small differences in the untangling option's potential benefits can therefore be neglected, as it is the magnitude of the values that was of interest: the difference between 0, 300 and 4000 unavailable minutes of infrastructure. Generally, a score of zero meant that the either the used methodology was not able to estimate the benefits or the untangling option was too dependent on other untangling options. More details for each untangling option have been described in the previous section.

An important aspect of research question has been left out in this analysis, namely the link between infrastructure unavailability and cancelled trains, which is referred to the robustness of the system as will be explained in chapter 6. To describe this link, a more detailed model is needed that also takes into account the logistical possibilities during incidents. The second part of this research will attend to that matter.

4.5.2 Interpretation of results

The two untangling options that were given the highest potential benefits are both related to switches, which can partially explain their high score: malfunctioning switches and faulty trains (standing on them) are both within the top 3 of most common technical failures. Besides that, a great logistical benefit can be accredited to these options as well, even though this has not yet been taken into account. It is striking to see that the potential benefit difference between removing a pair of switches and lifting the flank protection restriction for malfunctioning switches is so small, while the efforts needed to install each untangling option probably differ greatly.

Option 19 was ranked third, predominantly because of the extremely long average repair time of the equipment installed in these relay houses. Due to this unbalance of small chance versus large impact, the question that should be asked here is whether precautionary measures that prevent a fire from destroying the relay house or having a spare, generally equipped, relay house would not be more efficient than untangling all the relay houses. The equipment inside the relay houses, mostly part of the interlocking, is also part of an untangling option. If that option – interlocking option 18 – is already being installed, it might become more interesting in terms of efficiency to install option 19 as well.

Since Schiphol Airport is the only station area that has a tunnel, the averaging effect that has smoothened out the peaks of individual stations in other untangling options was absent here. The high score of tunnels and bridges could therefore be explained by the persevering false fire alarms Schiphol has dealt with over the past few years (ProRail, 2013b).

The next two options are from the energy subsystem and interestingly scored in the same range with their potential benefits, while the magnitude of the installation is very different. Subsidiary circuits are relatively easy to create and change, but the costs for installing a new power station will lie in another range. At first sight, the subsidiary circuit option therefore seems more efficient.

All other options have scored below the 500 yearly unavailability minutes, which can be caused by various reasons. The relatively low score for the untangling option of a rather crucial and extensive system, the switch heating untangling option, could be explained by the short period per year it is in operation. For the power supply related untangling options (8, 12, 16 and 22) on the other hand, it might have been caused by installed redundancy in the current systems that could camouflage disruptions and incidents.

Several options have a score of 0, but this does not always indicate that installing them is of no use. On the contrary, option 20 is probably one of the most important options to install, as it is required by so many other options (see appendix C). For two options though the fact whether there are benefits at all in untangling them is unsure: it could not be concluded from the data whether using separate signal posts or columns for the overhead wires per corridor is better than using large gantries. On the one hand because of the small amount of data (collisions luckily do not occur frequently), on the other hand because of the large differences in incident details amongst the individual incidents of the involved incident types: for some studied collisions an untangled system would have been beneficial, for others it worked counterproductive.

As stated before, a difficulty that has been faced with the used methodology it that it does not cope well with estimating the benefits of options that increase the amount of equipment. Or in other words, the balance between failure rate increase, as a consequence of all the extra assets, and the effect decrease they will generate is unknown and undeterminable without extensive knowledge of the involved systems. As a result of that, options 23, 24, and 25 have been scored 0, while actually further research with another approach is required instead.

4.5.3 Conclusions drawn from the results

Based on the findings in the previous section, conclusions that have been drawn from the results will now be described. The final conclusions, including the answer on the research question and all sub questions are described in chapter 10.

- ***Untangling options related to switches have scored high***
  Switch failures have a large share in the total number of reported incidents. Especially the fact that neighbouring switches are often also taken out of service during a switch incident – for safety reasons or because of the required flank protection – contributed to high score of these untangling options. It is important to mention that the removal of switches has a huge logistical effect that has not been taken into account here.
- ***Untangling the relay houses is effective despite the low failure rate***
  The loss of relay house leads to a prolonged unavailability of the area, which usually comprises a large part of the station area. The frequency of occurrence though is low, but the combination of both led to this high score.
- ***Although the tunnels and bridges option scored high, the effectiveness is not evidential***
  The large number of fire alarms found in the data for Schiphol Airport (the only large station with a tunnel taken into account) resulted in the conclusion that having a form of physical separation in the tunnel will lead a large reduction of impact spread. Nevertheless, considering the large amount of false fire alarms, it is probably more effective to adjust the fire alarm settings.
- ***Untangling the subsidiary circuits seems more efficient than untangling the power stations***
  The options strongly correlated and therefore both scored high. However, the difference in potential benefit is small while the difference in cost and effort to install both options is large. In terms of effectiveness the power stations are wiser to untangle, but in terms of efficiency the subsidiary circuit untangling option is much more interesting.
- ***Presence of safe working areas is required for many other untangling options***
  Safe working areas between tracks that allows for repair works to one track without causing hindrance to the neighbouring track is probably the most important untangling option, even though the score in Table 4.14 is 0. In appendix C the strong correlation with almost all other untangling options can be seen: even when all switch pairs between corridors have been removed, if a failure in one track requires the neighbouring track to be taken out of service, the impact of this incident will not be contained in the corridor of occurrence. For this reason, this untangling option has also been taken into account in the develop part.

Section summary

The potential benefits of 25 untangling options – expressed in yearly minutes of infrastructure unavailability an untangling option can potentially isolate in the corridor of occurrence – has been estimated with the help of incident data. A list of ranked untangling options formed the output of this phase together with conclusions on the effectiveness of these untangling options, which will be validated and discussed in the next chapter.

5 Validation & discussion

In the previous chapter a set of results was generated in the form of a list with untangling options ranked towards their potential benefits to isolate incidents in the corridor of occurrence. An expert team of ProRail has been asked to participate in a result validation session in which they were asked to rank the untangling options according to their expertise. This process and the differences found between their ranking of untangling options and the ranking found through the incident data analysis will be described in the first part of this chapter.

In the second part five aspects of this research will be part of a discussion in order to see whether the drawn conclusions throughout the research are genuine. These aspects are the Railway Service Model, scoping process, generation of untangling options, related incident type selection and the benefit estimation process. In chapter 10 the final conclusions can be found. See Figure 5.1 for a visual representation of the research approach step described in this chapter.

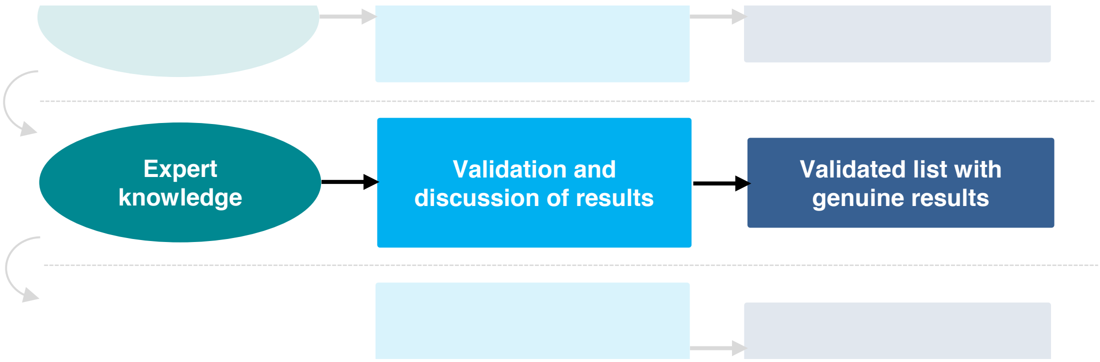


Figure 5.1 Step of the research approach described in this chapter

5.1 Validating the results

Before the discussion on the results can be started, it is important that some form of result validation has taken place. The results in the explore part of this research express the potential benefits that each of found untangling options could gain and with that try to express a measure of the untangling option’s effectiveness in limiting the impact of single incidents.

As stated before, the actual effectiveness of an untangling option heavily depends on the local situation, which makes it difficult to generate results of a general character that show the relevance and potential of each option. Nevertheless, with the applied approach in this research it is assumed that these general results have been generated and now can be used to select untangling options that are interesting to be further investigated (see chapter 7). The question is whether this assumption is correct, for which a validation has been carried out through expert judging.

5.1.1 Expert team

Two types of experts were asked to join a session in which the various identified untangling options have been explained. The first group consisted of system architects of the *IT* department, *Asset Management* department and the *Innovation & Development* department.

System architects often have worked in the railway sector for a long period of time and have gathered much experience in the various roles they have fulfilled there. With all their knowledge they now evaluate, assess and discuss projects and developments within the sector and try to safeguard the consistency, compatibility and future proofing also in relation to other ongoing developments. The word architect has been added to the title of their role because of the conceptual and structural way of thinking they have to use. Their different backgrounds and current fields of expertise contribute to the ability of transcending the specific problems and dilemmas of a project. With the high level of abstraction they are used to face and their conceptual way of thinking they have a suitable profile to validate the results.

The second type of experts is a group of rail system engineers who are heavily involved in the design of all rail related systems in several projects. Among these projects is the DSSU project, which has been mentioned before as it was the first ProRail project that focussed on system untangling as measure to increase the robustness. These experts have already gathered a lot of knowledge and experience on the topic of system untangling and have seen in practice which untangling options seem to work better than others. This obviously qualifies them to validate the results produced in this research. Figure 5.2 shows the expert team at work during the validation session held at 5 September 2016. The validation process itself will be discussed in the next section.

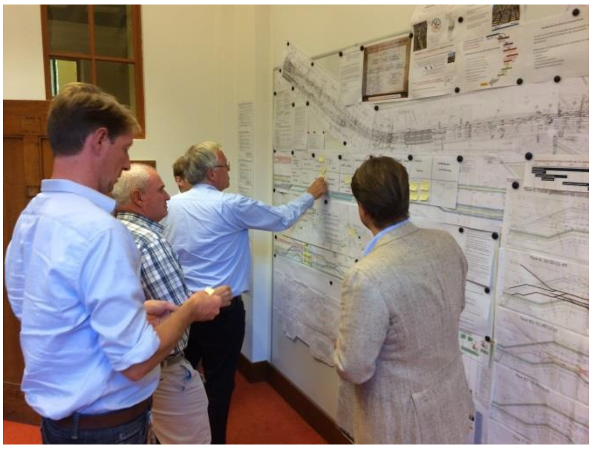


Figure 5.2 Experts Frank Bokhorst, Jan van Keulen, Rutger Oldenzaal, Niek van Deelen and Chris Verstegen during the validation session

5.1.2 Validation process

Instead of showing the results to the experts and asking their option, another methodology has been used. The 25 untangling options were written down on a large sheet of paper together with a few additional robustness increasing measures that had been mentioned in the workshops used as data input. These extra measures were:

- ***Not using double switches and switches with EBI switch machines***
- ***Avoiding the use of re-used materials***
- ***Improving the approach of handling incidents***

The question asked to them was; '*If you had to redesign Utrecht station and you could pick five measures to increase its robustness, which options would you choose?*' It was a deliberate choice to refer to Utrecht station instead of asking the question in a more general way because of the involved rail system engineer's expertise. A possible drawback of this was that the experts could come up with specific solutions for specific robustness problems only present in Utrecht, but on the other hand it also gave them the opportunity to imagine the effort it would take to install a certain option and take this in consideration when choosing between the options.

All five experts were given a set of five small papers with numbers 1 to 5 written onto them, representing points they could give to the explained options. This means that in total 75 points could be appointed to the different measures. Table 5.1 shows the ranking of the untangling options according to the approach used in this research and how many points each option was given by the experts.

Untangling option	Rank	Expert credits	Untangling option	Rank	Expert credits
(6) Removing switches	*1*	*3*	**(16) Power supply infra**	*16*	*0*
(19) Flank protection	*2*	*25*	**(21) LCE**	*17*	*0*
(17) Relay houses	*3*	*7*	**(12) Terminal power grid**	*18*	*0*
(10) Tunnels & Bridges	*4*	*0*	**(4) Tensioning system**	*19*	*0*
(3) 1500V power stations	*5*	*0*	**(5) Overhead wire gantries**	*19*	*0*
(2) Subsidiary circuits	*6*	*4*	**(15) Signal gantries**	*19*	*0*
(14) Signal control cables	*7*	*0*	**(23) EBP**	*19*	*2*
(7) Switch control cables	*7*	*0*	**(24) PRL**	*19*	*0*
(22) Power supply signal box	*9*	*0*	**(25) Signaller**	*19*	*0*
(13) Station hall evacuation	*10*	*0*	**(20) Safe working area**	*19*	*9*
(1) Contact lines	*11*	*0*	**Avoiding re-used materials**	-	7
(11) Elevated junctions	*12*	*0*	**Not using double switches**	-	8
(9) Switch heating	*13*	*0*	**Not using EBI switches**	-	0
(8) Power supply switches	*14*	*0*	**Improve incident management**	-	8
(18) Interlocking	*15*	*2*			

Table 5.1 Points given by the experts to the various robustness measures including all untangling options considered in this research

It is convincing to see that the points given by the experts are generally consistent with the results found in this research, as the options that were ranked highly also got points from the experts. A few differences can be spotted though, which will be discussed here.

As stated before, untangling option 20 – that was given 9 points by the experts – was actually estimated to have a lot more potential benefit than presented here, but was cancelled as untangling option since the dependency on other untangling options was too large (see section 4.4.2.20). The tunnels & bridges untangling option did not receive any points from the experts, which is sensible as there are no bridges or tunnels close enough to Utrecht station. Together with the fact that all junctions in the Utrecht area are already elevated junctions probably led to the fact that two options (Tunnels & bridges and Elevated junctions) have been ranked significantly lower by the experts. Nevertheless, the approach of validating the general results of this research through a specific case (Utrecht station) most probably caused the experts' underestimation of the two options, but probably also caused that the subsidiary circuit option (2) scored higher with the experts than the power station option (3): As stated before, installing extra power stations is much more expensive than installing (extra) subsidiary circuits. In terms of efficiency, this makes sense.

Probably the most interesting difference between the scores of the experts and the estimation in this research is the difference between option 19, which scored highest with the experts, and option 6, which scored significantly lower. As explained before, the logistical effects of untangling options have not been taken into account, but they can be of great interest, as removing switches influences the ability of a system to operate 'around' incidents which could lead to fewer cancellations of train services (higher robustness). In the develop part of this research the logistical effects will be taken into account to see if removing switches is indeed less efficient than option 19, as stated here by the experts. In the experts' judgement, the logistical effect has probably already been taken into account though their experience in designing stations.

Lastly, it is also striking that the few added non-untangling measures, which have not been included in the research so far, scored so well with the experts. Since the overall research question relates to effectiveness of the untangling options, also compared to other measures, these extra measures should be taken into consideration as well in some way. In chapter 7, where the various scenarios will be created, this matter will be further dealt with.

5.2 Discussion

In sections 4.4.2 and 4.5 the results and used estimation method have been presented and elucidated complemented with many comments on the validity, relevance and accuracy of the found results. This section will try to summarise the most important points of discussion so that the final conclusions that are drawn at the end of this report can be regarded as genuine. Since the parts of the research are all very different, each with their own considerations and dilemmas, the discussion is split in five parts: Railway Service Model, scoping process, generation of untangling options, related incident type selection and the benefit estimation process.

5.2.1 Railway Service Model

There was a need for a clear and comprehensive description of the railway system to facilitate the scoping, exploration and description of untangling possibilities. After having studied various system-descriptive models it was clear none of them could meet the requirements set for the description of the untangling principles. A new model, partly based on other models, was developed but as expected, it is still not perfect.

One of the main requirements was that the model had to support the division of the railway system into subsystems to allow for differentiation in the untangling options. The chosen methodology was to use the railway functions mentioned in an internal ProRail document after it had been verified if they were actual functions: of the eight mentioned functions, only six were actually functions.

Two side effects of this approach are worth discussing, starting with the overview these six selected functions provide: they seem to form the end users' most basic requirements for rail transport, but the list is not complete. Requirements on comfort, speed, protection from wind and rain, physical space and noise are not covered for example. So, it is suggested that the functional subsystems provide an overview of the functions that need to be covered for rail transport, while actually it is only a part of the most basic requirements. Besides that, all of them are oriented on the infrastructural (non-moving) part of the railway system, not explicitly excluding the moving part though, but to some extent neglecting it. As a result of that, together with the split of the model in an infrastructure side and train side, the focus of the whole research was laid on infrastructure and potentially interesting untangling options in the logistical or train field were not considered.

5.2.2 Scoping process

In the scoping process described in section 4.1, the Railway Service Model developed in the previous chapter is used to describe which forms of untangling will be taken into account and which not.

A process that also takes place simultaneously is the identification of the degrees of freedom related to system untangling. As stated before, some variables follow directly from the scope that is chosen for the previous variable, such as ‘division strategy’ which in its described form only exists for the untangling ‘type’ ‘vertical’. If ‘horizontal’ would have been chosen as ‘type’ of untangling to investigate, the variable ‘division strategy’ would not have contained the same options. Besides that, it is unsure whether the list of variables mentioned is complete. Since describing and explaining the untangling mechanism is part of this research, the applied fast scoping process has stand a thorough exploration and description of the degrees of freedom in the way.

Although the Railway Service Model explicitly mentions a single railway network in which both TOCs and FOCs have a place – after all they use the same tracks – freight transport is excluded from the scope. Multiple reasons are mentioned for this, the most important of them being the different characteristics and needs that could lead to a different research approach, which is time wise not allowed. Nevertheless, the impact of untangling on the freight traffic, which does not tend to flow in fixed corridors, would be interesting to take into account as well (Ministry of Transport, Public Works & Water Managment, 2010).

Another small issue that emerged during the scoping process was the impossibility of assigning untangling forms to specific layers of the bottom three layers of the railway service model, since these layers all describe the same physical parts of the railway system, albeit on different levels of detail. The untangling options in these three layers have therefore been combined and have been labelled as ‘level 1’ untangling options. The way the railway service model was designed did not support the description of untangling here.

5.2.3 Generation of untangling options

Generating the untangling options could have been done in many ways, but the large range of untangling possibilities, required detailed knowledge of many technical systems and vital experience in predicting which options could be interesting, the only suitable method seemed to consult experts. Three aspects of this method are worth discussing here, being the composition of the expert group, the way the workshops were organised and the questions asked to the experts.

Utrecht station was the first station built by ProRail where system untangling took a centre stage in the design process (see section 7.1, where this project is described in detail). Using specialists from that project to generate scenarios was therefore a logical choice. Nevertheless, since ProRail is an infrastructure manager and since the project was already in the building phase, the logistical effects related to the untangling options were underexposed once again: the effect of not *fully* untangling the various train routes through the station area or not untangling the staff that is on the trains has not been taken into account, while these options might have a large impact on the robustness of the system (NOS, 2015). After all, if staff from cancelled trains in one corridor is scheduled to switch to a train of another corridor in the untangled station, the delay or cancellation of services will propagate to this other corridor as well and the robustness of the system will decrease. If experts from the operators or the resource allocating level would have been added to the workshops, these options might have been identified as well.

A workshop format has been chosen for the expert consult, because it was assumed that discussions amongst experts would produce more well thought-through untangling options than simple one-on-one questionnaires. After all, whether a certain untangling option could have a positive effect on the robustness on the system had to be gauged by the experts based on their experience and knowledge, which could be different for each expert. A drawback of the chosen process used in the workshop was the fixed discussion frame that was set: various design dilemmas had been preselected by the rail system engineer of DSSU, which pushed the discussion in certain directions. The advantage of this approach was that the expert could discuss the untangling issues on the basis of real and concrete designs, what led to a deeper level of understanding of the untangling dilemmas. On the other hand did it limit the freedom of their mind to think out-of-the-box and come up with ideas that would not directly be applicable to the Utrecht station area. By asking open questions at the end of each session, this disadvantage was attempted to be reduced, but it is inevitable to conclude that the identified untangling options are mostly focused on the Utrecht area.

Linked to this discussion is the power that was given to rail system engineer: besides that the preselected dilemmas limited the discussions in the workshops to the Utrecht area to some extent, these specific topics also gave a lot of influence to the rail system engineer. The way the dilemmas were formulated will have influenced the opinion of the experts to some extent, but it is unsure what other untangling options could have been identified if the dilemmas would have been formulated differently.

5.2.4 Related incident type selection

The related incident types have been selected based on two difference sources: primarily on SAP incident data and checked for completeness with the help of an available FMECA analysis (see section 4.3.2). The methodology used was to first identify for which incident types of the 674 in total the impact could potentially (partially) have been kept within the corridor of occurrence if a certain untangling option would have been applied to some extent.

Selecting the related types was a time consuming and lengthy process that heavily relied on interpretation skills, which does not contribute positively to the accuracy of the analysis. Since the analysis was meant to provide a rough insight in the potential of each untangling option, the method was still regarded suitable though. The difficulty and uncertainty related to this method was to gauge which incident types were related. As guidance, the rail subsystem division ProRail used in the data architecture was used; Table 3.1 provides the links between ProRail’s subsystems and the functional subsystems used in this research. The major disadvantage of the method is that some incident types are not selected for a certain untangling option while they still could be related to this option. For instance the type ‘steel structure train collision’ in the ‘EV1500’ category does probably not only apply to gantries of the catenary system, but also to the signal gantries. Nevertheless, the incident has only been identified for the energy subsystem.

An issue that was encountered with the data was that the incident types do not tell the complete story. Cancelled trains are always blamed to the initial incident type, while for instance the overburdening of a signaller in a disturbed traffic situation could be responsible for the majority of the cancellations. Other reasons could be the complexity of staff or rolling stock schedules, ineffective incident management or a simultaneous occurrence of two incidents.

5.2.5 Benefit estimation

For each incident type and untangling option combination the part of the occurrences of which the impact could potentially have been kept within the corridor of occurrence is estimated. Data of ProRail’s SAP incident management system have been used to determine the yearly occurrences and average incident duration.

The largest uncertainty in the data is the way incidents are logged or categorised. If a switch refuses to change position, the incident would probably be logged as a ‘faulty switch’. After investigation, it could be found out that the problem was not with the switch, but with a fuse in the interlocking installation. The question is then whether the incident type is changed after this discovery, or if the incident type label ‘switch failure’ is kept unfairly. In the latter case, which is likely to have been occurred several times, some incidents are incorrectly assumed to be part of the potential benefits of an untangling option.

The rows of data that have many ‘unknowns’ in them form an additional uncertainty in the data: because investigating the exact reasons for these unknowns in such a large amount of data would be an unfeasible task, these unknowns have therefore been neglected and the rows containing them be regarded as properly registered incidents.

As stated before, the used quantification method was meant for a rough estimation of the potential benefits of each untangling option. In section 4.4.2 it was already explained that the method was not very suitable for untangling options for which the amount of components would significantly increase if they were installed. In these cases, the failure rates of the new amount of components had to be estimated, with a very high uncertainty of results as a consequence.

A key feature of the methodology was the use of sampling; the largest five Dutch stations were used to estimate the frequency of occurrence of incident types. A disadvantage of this approach is that each station is different in size, operation, age and types of systems present. To overcome this disadvantage the occurrences of incidents at each station have been scaled to a fictive average station. The factor used for the scaling was different per incident type, but the choice for this averaging factor leaves room for discussion. It was not always clear which factor would be more suitable, for instance would a faulty pantograph damaging the overhead wires occur more often if the station area is larger, if the amount of trains running through the station is larger, or a combination of both? To know this, a deeper level of understanding of the failure mechanisms is required, which was not in the scope of this research. Other points of discussion related to this averaging technique were the absence of certain infrastructure in specific stations (tunnels or bridges), the fact whether a station was under construction during a significant amount of time and the different ages of the infrastructure at the stations, which all have not been taken into account for determining the average occurrence frequency.

An underexposed error in the applied approach is the neglect of potential negatives. Especially the untangling options related to switches, which have a large logistical effect, do not only have benefits if they are installed. Flexibility and rerouting trains around unavailable pieces of infrastructure will no longer be possible with these untangling options installed. As a result, these untangling options are probably estimated with more benefits than in reality. The second part of this research will take these negatives into account. Besides that the side effects of all untangling options related to safety, comfort, customer preferences have all not be taken into account. For example, whether splitting the traffic control centres and separating the signallers would cause any safety issues – due to less easy communication possibilities – has not been included in the benefit estimation.

Chapter summary

The found results and drawn conclusions in the previous chapter have been validated by a group of experts. Generally, it can be stated that the experts came to the same conclusions, although there were a few differences mainly caused by the fact that this research focussed on effectiveness while the experts seemed to have kept the efficiency of untangling options in their minds. For example, an expensive option such as untangling power stations has therefore scored lower in the expert ranking.

The second part of this chapter discussed the approach and methodology of the whole explore part of this research. Although several comments were made, there were no reasons to believe that the conclusions drawn in this research are not genuine.

Note that this part of the research continues in chapter 10, where the research questions will be answered.

Part 2: Develop

MSc Thesis for Civil Engineering

Introduction ‘Develop’

This report consists of a combination of two separate theses that, although they are closely linked to each other, both have their own objectives, research question and approach. Answering the research questions of both parts will lead to an answer to the single problem statement that was formulated for both parts as a whole. In chapter 1 this process and all details have been described and discussed, in chapter 10 the conclusions from both parts will be presented. Here, a short recapitulation of the research question will be given for the second part (develop part) of the research that is covered in chapters 6 to 9. The report structure and approach are shown in Figure 1.4 the research objectives in Figure 1.2. The research question for this part is repeated below.

> *Which system untangling options are (most) effective in increasing the robustness at large complex stations?*

In the previous part several untangling options have been identified and their potential to isolate incidents within the corridor of occurrence has been estimated. The missing link between the research question for the explore part and the overall research question forms the research question for the develop part: which untangling options are not only effective in isolating incidents but also in increasing the robustness. In this part first the term ‘robustness’ will be defined before a case study of a large complex station will be performed in order to see the effectiveness of several untangling options. Several scenarios will be generated in which these various untangling options are used in the system design and the robustness of these scenarios will be assessed by a modelling tool that has been developed. Finally, the results of the tool will be used to determine the effectiveness of individual untangling options.

These steps contribute to the research objectives for this thesis; determining the effectiveness of untangling options and developing a model that is able to assess the robustness of large complex stations.

6 Literature review

A clear definition of robustness that can be used consistently throughout the research needs to be found. This chapter will review literature in order to come to a comprehensive definition of robustness, see Figure 6.1 for a graphical representation. First scientific literature will be looked at and the various robustness definitions used in research will be identified categorised in three different fields of research. After that, the various definitions for robustness used within ProRail – the Dutch rail infrastructure manager – that have been identified based on internal documents are discussed. Besides a definition of robustness, this chapter will also explore the differences between the terms resilience, availability, reliability and robustness, which will be covered in the third section. Finally, the last section will formulate the comprehensive definition that will be used throughout this report.

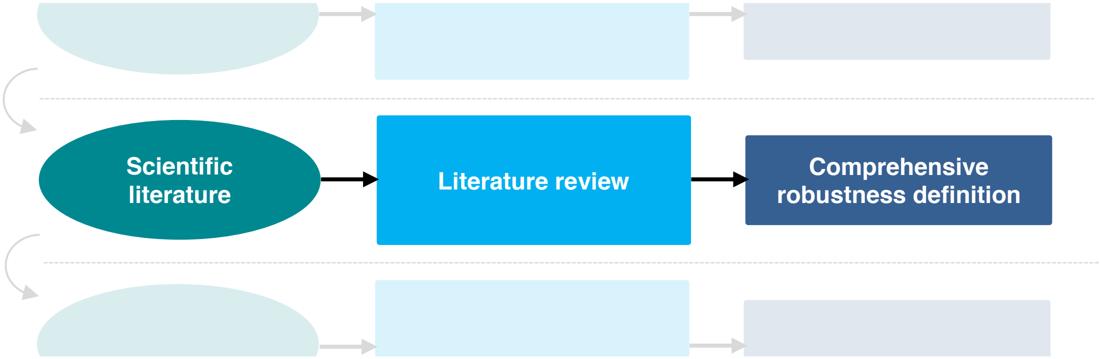


Figure 6.1 Step of the research approach covered in this chapter

So, what is robustness? How is robustness defined in literature? And what are the differences between robustness, resilience and reliability?

> ‘**Robustness** /rə(ʊ)ˈbʌstnəs/ *[Noun]:* 1 The quality or condition of being strong and in good condition’

Definition of robustness by Oxford Dictionaries (Oxford Dictionaries, 2016d)

The Oxford Dictionaries define robustness as either a quality or condition, which means that when a system is called robust this could be permanently (quality of the system) or temporarily (condition of the system). Being ‘in good condition’ seems to imply that the system is able to fulfil its function while ‘being strong’ suggests that the system is not just able to fulfil its function but that it is also not easy to unable it from fulfilling its function; in other words the system is able to resist certain disturbances. Oxford dictionaries emphasise this explanation by adding an extra sentence to the definition given before:

> 1.1 The ability to withstand or overcome adverse conditions or rigorous testing

Definition of robustness by Oxford Dictionaries (Oxford Dictionaries, 2016d)

The last part of this extra sentence in the definition given by Oxford dictionaries –'ability to withstand or overcome rigorous testing'- is quite interesting as it implies yet another meaning of robustness: a form of reliability. When for instance a computer model would be called robust because it has withstood rigorous testing, it could also have been called reliable as it apparently provides reliable results. Further on in this section will be elaborated upon the exact meaning of reliability, robustness and resilience and the differences between them. First definitions of robustness found in scientific literature will be explained.

6.1 Robustness in scientific literature

Many authors in scientific literature discuss the robustness of the (railway) system while all of them are referring to different aspects of the railway system. In this way, the term railway system robustness is used in various contexts and therefore possibly has different meanings. In most articles in scientific literature on the topic of railway systems, robustness is used in relation to timetable design. In order to investigate the differences within literature, papers will be categorised in three different groups according the authors' view on robustness: delay recoverability of the railway system, serviceability and non-timetable & non-railway related robustness. Since this research is about robustness of the railway system, the focus in this literature review will be on railway related articles. In the third category, a brief overview will be given of robustness definitions outside of the railway system.

> *[..] the concept of robustness for scheduling solutions, as well as in other (rail) areas remains vague and not well defined. In fact, it is possible to note different definitions of robustness in scheduling with respect to the different aspects that are taken into account.*

Salido et al. also face the inconsistency in the definition of robustness in scientific literature (Salido, et al., 2008).

6.1.1 Delay recoverability of the railway system

Delay recoverability of the railway system refers to the ability of the railway system, in most cases the timetable, to overcome small disturbances and to return to a normal state. Vromans describes robustness of the railway system as the influenceability of the system by disturbances and states that if a railway system is not robust small external disturbances will cause large delays which propagate quickly through the system (Vromans, 2005). Andersson seems to agree with Vromans since she uses a similar definition in Andersson (2014).

> *We define a robust timetable as a timetable in which [..] trains should also have the possibility to recover from small delays and the delays should be kept from propagate over the network.*

Definition of a robust timetable by Andersson in (Andersson, 2014)

It is interesting to see that Vromans and Andersson link robustness to delay propagation and with that add an extra aspect to the definition of robustness given by Oxford Dictionaries: not only should a robust system be able to overcome adverse condition, it is apparently also supposed to isolate the disturbance.

Vromans and Andersson are not the only ones linking robustness to delay propagation. Fischetti et al. (2008) associate robustness with the ability to prevent delay propagation and favour delay compensation without human interaction (Fischetti, et al., 2008). Salido et al. aimed to find an appropriate robustness measure in timetabling in their research. They state that a timetable is robust if the system is able to return to the initial stage within a certain maximum time after a disruption: delay recoverability of the railway system (Salido, et al., 2008).

Kroon et al. agree with Salido et al. on giving recoverability a key role in the definition of robustness, but provide a much more precise and comprehensive definition. In their chapter of the book 'Railway timetable & traffic' they describe several optimisation models and techniques that can be used for determining railway timetables. The models' and techniques' objective is to find a timetable that is as good as possible in a certain sense, one of them being as robust as possible (Kroon, et al., 2008). To be called robust, the timetable should have three properties. The first one is that the timetable should be able to absorb initial disturbances to some extent so that they do not lead to delays. With initial delay they refer to delays that already existed in the system (previous period) or that trains already have upon their arrival in the system. (Hansen & Pachl, 2008). Secondly the timetable should prevent many knock-on delays from one train to another train, which is similar to the first property. Both could be achieved by placing time supplements appropriately in the timetable, while the last property of Kroon's definition of a robust timetable could be achieved by adding buffer time appropriately between consecutive trains: the last property is that delays should disappear quickly, possibly with light dispatching measures (Kroon, et al., 2008).

So, although they have been comprehensive and more precise in their definition, they have still used many words without strong limits in their meaning such as 'many', 'light' and 'to some extent'. And moreover, they do not conclude whether robustness can be guaranteed by complying with these three properties.

Goverde (2007) uses the word stability to indicate whether a (periodic) timetable has the ability to reduce delays from an earlier period in the next period or in other words if the timetable allows for recovery of delays. As an absolute measure for the stability of the timetable he uses the circulation recovery time of each separate event, an event being for instance a train's departure at a certain station. The circulation recovery time represents the maximum delay that can be absorbed by available slack in the timetable (Goverde, 2007). So, Goverde relates the stability of a timetable directly to available slack time (and indirectly to delay propagation). According to him knock-on delays should be taken into account in the timetabling step or even be used in the objective function. In (Goverde, et al., 2015) timetabling robustness is specified as the ability of a timetable to withstand design errors, parameter variations and changing operational conditions, where the emphasis of the definition seems to be more on imperfections and variations rather than disturbances. On the other hand, disturbances could be seen as changing operational conditions and design errors interpreted as the absence of a sufficient amount of slack time, and therefore also be included in Goverde's definition of robustness.

Dewilde, in his search for a comprehensive definition of robustness, also came across many of these definitions in (Dewilde, 2014) and made a very accurate remark.

> *The major drawback of avoiding knock-on delays is that it solely focuses on delays and leaves passengers aside. This way, knocking on delays to a full train can be preferred above delaying an empty train.*
>
> Drawback of defining robustness by focusing on knock-on delays only (Dewilde, 2014)

His main concern with the authors' definitions previously highlighted is that they are not focused on passengers. Since the scope of this research is on large station areas – as is his – where the users of the railway system are mainly passengers, it makes sense to define robustness from a passengers' point of view. For passengers the (knock-on) delays of individual trains are less important than the total delay of their journey: the time difference between the anticipated arrival time and actual arrival time. A key element that then needs to be reflected in the robustness definition is passenger transfers. (Dewilde, 2014) In the next section, the authors that put passenger centre stage and take transfers into account in the definition of robustness will be discussed.

6.1.2 Serviceability of the railway system

> *Generally, train delays lead to a reduced level of transportation service, and (other authors) [...] have suggested robustness indices based on train delays. Such a concept, however, does not apply from the viewpoint of passengers, as individual train delays do not reflect the reduced level of transportation service that each one suffers.*
>
> Takeuchi et al. express the need to embed serviceability in the definition of robustness (Takeuchi, et al., 2007)

Takeuchi et al. acknowledge the need to incorporate passenger journeys in the definition of robustness and mention the main goal of the railway system between the lines: providing transportation service. So instead of considering the railway system as the operation of trains, many authors refer to the railway system as a system of connections and services. Robustness of the railway system will then obviously be defined differently than previously.

Schöbel et al. suggest a bi-criteria approach for optimising a timetable. They do not only optimise the timetable in undisturbed conditions (nominal objective – smallest possible planned travel times) but also optimise the robustness of the solution – timetable – itself (robustness objective – smallest difference between actual and planned travel times). The difference between the nominal solution and the robust solution is called the price of robustness (Schöbel & Kratz, 2009). The robustness of the timetable is determined by having a close look at the scheduled transfer options in the timetable. For every planned transfer they apply three fixed waiting rules, in other words three rules to when connecting trains should wait for delayed feeder trains. Depending on the preferred settings of these rules, they optimise the timetable again in order to find the timetable that is able to accommodate all the transfers with the highest initial delay (Schöbel & Kratz, 2009). In (Takeuchi, et al., 2007) the passengers' inconvenience is used to optimise the timetable. Crowdedness of the trains, average waiting times and the number of transfers needed form the indicators for the passengers' inconvenience and in their opinion a measure of robustness. Liebchen et al. in (Liebchen, et al., 2007) agree with Takeuchi et al., but use a different way to take passengers' satisfaction into account. Their approach is related to the bi-criteria approach in (Schöbel & Kratz, 2009), as they optimise the timetable for shortest planned travel times while penalising missed transfers.

Paradoxically, some authors see robustness and passengers' satisfaction as opposites of each other and state that the more robust the timetable, the lower the passengers' satisfaction. They associate the serviceability of the network with the time that it takes to get from A to B, and regard robust timetables as slow timetables. In the previous section many authors indeed linked slack time directly to stability and indirectly to robustness (Goverde, 2007). Cacchiani et al. agree with Schöbel et al. on their bi-directional approach and identify two different objectives for each direction: optimising the schedule in terms of operational costs and passenger service (shortest travel times) and avoiding delay propagation as much as possible after small disturbances have occurred. Cacchiani et al. comment that these two objectives are adverse. Maximising the robustness will decrease the passenger service in terms of travel times while maximising the passenger service – meaning removing slack time – will affect the robustness negatively (Cacchiani & Toth, 2013).

Shafia et al. also noticed these opposing objectives, but in a different way. Instead of linking an increase in robustness directly to an increase in travel times and with that a decrease of passengers' satisfaction, they relate a higher level of robustness to longer dwell times and therefore a lower network capacity. The longer dwell times influence the travel times and thus the passengers' satisfaction (Shafia, et al., 2012). Basically, this reasoning is similar to the reasoning in (Cacchiani & Toth, 2013); only Shafia et al. focus more on capacity as a consequence of the increased dwell times instead of passengers' satisfaction.

> *[…] by increasing the desired robustness level, the practical capacity reduces. On the other hand (a maximum dwell time) defines the minimum thresholds to maintain the passengers' satisfactory. Therefore the capacity utilization, i.e. the number of trains going to be scheduled, should be maximised this much so that a certain level of robustness and a certain level of passengers' satisfactory are provided.*

Shafia et al. maximise the utilisation of the capacity and manage the trade-off between robustness and passengers'

But in the light of serviceability, these opposites seem not to exist. Snelder et al. highlight the importance of predictable travel times and conclude that passengers do not mind a slightly longer travel time if they can rely on the expected arrival time (Snelder, et al., 2004). According to their research, serviceability of a system does not relate to the planned travel times and services, but to the actual delivered travel times and experienced services. For example, fast journeys in consumer travel planner tools that hardly ever arrive on time result in the same travel time as slower journeys (with more slack time) that are primarily on time. Taking this into account, there is no trade-off between robustness and travel time or a certain cost for robustness, but an optimum between them: realistic travel times with predictable arrival times, also in disturbed conditions (Vansteenwegen & Van Oudheusden, 2006).

In conclusion, according to these authors the service offered to passengers by the system should take a centre stage when designing or optimising timetables. Robust timetables have a few characteristics: the travel times for passengers are as short as possible while the actual arrival times predictable. Small disturbances during operating should not lead to missed transfers and (extremely) late arrivals. In order to keep the timetable as fast as possible, the minimum amount of slack needed for that should be used. This definition of robustness has an overlap with the definition of reliability which will be discussed further on in this chapter.

6.1.3 Non-timetable & non-railway related robustness

Most of the available scientific literature on railway system robustness is related to the timetable. As a result of that, the literature tends to focus more on train operating companies than rail infrastructure managers, since rail infrastructure managers not only use the term robustness in relation to the timetable but also to their assets. This section attempts to briefly explore in which other rail related contexts the term robustness is used in order to see if those definitions could be adopted in the definition that will be used in this research. Besides that, the definitions of robustness in other research fields will be briefly discussed.

> *Robustness is a widely spread term. A robust railway system can refer to a system with good train and track quality which do not break down easily. It can refer to a system with high safety levels where accidents seldom occur and where few people get injured. It can also mean a system with an extensive network and many lines where passengers easily can be rerouted if there is a disruption.*

Andersson hits the nail on its head by stating the three most used contexts of robustness besides the timetable

Andersson has provided a good starting point by naming three other rail system contexts in which robustness is mentioned in literature apart from timetables: safety, connectivity and assets.

Safety appears to be an outlier amongst the other contexts in the first instance, since safety is a quality of a system rather than something that can be either robust or not. But this is not true, as several authors mention the concept of robust safety. Bahr provides us with a clear definition of this concept and explains that the safety of a technical system can be increased in several manners. One of the ways to do so is by reducing the impact of human errors. According to him robust safety refers to the reduction of the likelihood that human errors will occur or the reduction of the severity of the human errors' effect on the system (Bahr, 2015). Comparing Bahrs definition to definitions of robustness in relation to timetabling reveals an alignment between the two. While timetable related robustness definitions often comprise resisting or overcoming system disturbances, the robust safety definition could be rephrased as resisting or overcoming system disturbances in the form of human errors.

Another context in which robustness is used is connectivity. As discussed before, Snelder et al. in their paper on describing and defining robustness point out that robust systems often have buffer capacity (slack time) to be able to handle disruptions. They briefly explain on what level and in what ways this buffer capacity can be built into the system, one of them being by linking multimodal transport networks and services together so that if one modality suffers a bad service from disruptions, other modalities can take over and still provide a good service for customers (Snelder, et al., 2004). A completely different field, where the robustness of a system is often defined as the number of available alternative routes, is biology. László Barabási addressed the question why damaged human cells often do not affect any function of the body. He compared the human body to a system of links and nodes in which the damaged cells are represented as removed nodes and links. The body will be able to fulfil its functions as long as the network of links and nodes remains connected. He used the percolation theory that mathematically describes the chance that a certain network will fragment into isolated networks if random links and nodes are removed, and assessed the impact of node removal (see Figure 6.2). The lower the chance of isolated networks by the removal of a certain amount of nodes, the more robust the network is (László Barabási, 2014). Indirectly, László Barabási defines robustness as the number of rerouting options available in a system.

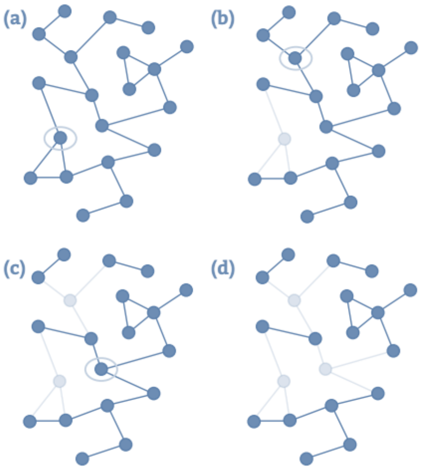


Figure 6.2 Simplified visualisation of the method the percolation theory uses. In step (c) the network becomes fragmented (László Barabási, 2014)

Although Andersson mentioned the robustness of railway assets briefly in (Andersson, 2014), not much literature is available on this specific topic. Norrbin devoted his research to providing a holistic overview of railway infrastructure robustness in order to support rail infrastructure managers. For his literature review he read 350 scientific papers on system robustness, and he concludes by the following sentences:

> *The approaches to robustness studies include: 1) statistics driven models from input to output (e.g., operations research, […]); 2) physical characteristics driven design or optimisation of a complex system or an item (e.g., […] biology); and 3) their integration […] None of the results from the literature can be directly used for railway infrastructure robustness.*
>
> Norrbin concludes that the 350 papers on the topic of system robustness he investigated do not directly relate to rail infrastructure robustness (Norrbin, 2016).

So, none of the definitions he came across in literature seemed directly suitable for infrastructure managers. It is interesting to see that he attempted to summarise the definitions of robustness in each of the eight research fields he defined. Often he either used the common parts of the various definitions within the field or a definition that occurred most frequently in the papers (see Table 6.1).

Research field	General definition of robustness	Source
Biology	Ability of the human system to perform while affected by perturbation and uncertainty	(Stelling, et al., 2004), (László Barabási, 2014), (Kitano, 2007)
Economics	Extent to which models remain valid under different assumptions	(Kuorikoski, et al., 2007)
Decision making theory	Ability of a system to maintain its function when some aspect of the system is subject to perturbations	(Walsh, et al., 2013)
Operations research	Solution that remains functional with changing operational scenario	(Kanai, et al., 2011), (Burdett, et al., 2012)
Statistics	To which extent a system is influenced by small deviations in the assumptions	(Huber & Ronchetti, 2009)
Computer science	The error tolerance of a program	(Rabinowitz & Spilker, 2005)
Control engineering	Insensitivity to uncertainty of a control system in input and model assumptions	(Doyle & Zhou, 1997), (Monje, et al., 2008)
Product development	Small variability in a system's function under various disturbances	(Montgomery, 2008)

Table 6.1 A general summary of robustness' definitions occurring in various research fields. Adjusted from (Norrbin, 2016)

While most of this table has been taken from (Norrbin, 2016), some definitions have been rephrased after reassessing Norrbin's sources and including the sources previously discussed in this chapter.

The same conclusions drawn in the sections on timetable related robustness seem to be valid here. The common part in the definitions is that the system should be able to function to some extent when facing disturbances or uncertainties of a certain severity. The system can represent many different things such as a model, timetable, human body or piece of railway infrastructure and the definition of disturbances varies from delays to uncertainties. For the formation of a comprehensive definition that will be used in this research it is important to take into account these common parts of the robustness' definitions in literature.

6.2 Robustness within ProRail

With such differences in defining robustness found in scientific literature, it is to be expected that the same differences will exist within a large organisation such as ProRail. In order to map the different definitions used within the organisation, several documents and internal reports have been investigated.

There are currently a few projects related to the robustness of the railway system. The 'Beter en Meer' programme – 'Better and More' – has the philosophy that the robustness of the system should improve (better) before extra trains can be added to the timetable (more). In the document called ‘Concept version of Long Term Operational Measures within Beter en Meer’, a clear definition of robustness is not provided, but the need for robust infrastructure is more than once stated. According to the program the core characteristic of a robust infrastructure is that technical failures simply do not occur (ProRail & NSR, 2013).

The Dutch Knowledge centre of Mobility (KIM) conducts independent researches for the Ministry of Infrastructure & Environment, which is responsible for ProRail as organisation. In their research on railway system reliability and robustness they also emphasise the various definitions that exist in literature. According to them robustness is a part of reliability: a robust system contributes to a reliable system. The definition they choose for robustness is different than any other seen before and comes very close to definitions seen in other ProRail internal documents: To which extent extremely large travel times caused by incidents, weather, engineering works or events can be prevented. (Kennisinstituut voor Mobiliteitsbeleid, 2010).

Although Goverde is not directly linked to ProRail, his paper contributing to the Dutch ‘Colloquium of transport & planning’ in 2012 is tailored to the specific conditions of the Dutch railways where ProRail acts as infrastructure manager. In the paper he addresses the benefits of ERTMS for the robustness of the railway system (Goverde, 2012).

> *A robust railway system keeps functioning even when the timetable is not completely feasible, the availability of the infrastructure or process times deviate from the planned availability or process times, or during poor weather conditions. A reliable railway system is popularly known as a system where actual journeys do not deviate from planned journeys: trains do not get cancelled, […] passenger connections are made […]. To do so, a robust system is required.*
>
> Another definition of robustness by Goverde; timetable robustness (previously) versus system robustness (here) (Goverde, 2012).

This definition of robustness is in line of reasoning with the definitions seen before in literature, but Goverde mentions a specific characteristic of a robust system: trains do not get cancelled. For ProRail the prevention of cancelled trains is highly important as they get penalised for delays and cancellation by the Ministry of Infrastructure and Environment.

6.2.1 KPI of a train path

It seems inevitable that a relevant definition of robustness for ProRail would relate to technical failures of the infrastructure or cancellations and delays of trains. But what are the threshold values for delays? And when is a train called cancelled? In this section a small side step is made to investigate when a train path is successfully delivered according to ProRail so that this can be incorporated in the robustness definition.

Two documents are of interest here, one explaining the threshold values of delayed trains and one explaining in what cases a train path can be regarded as having been delivered. To start with delays; according to ProRails website a train is called delayed when it arrives at one of the 50 preselected stations 3 minutes behind schedule. Delayed intercity trains will therefore probably have a greater impact on the punctuality numbers than delayed local trains, as intercity trains pass through multiple large stations. If a train is cancelled, it is not counted as a delayed train: it is either delayed or cancelled. Another delay measurement that is used by both NS and ProRail is passenger delay. Passenger punctuality is defined as the percentage of passengers that arrives with less than 5 minutes delay at one of the 50 preselected stations. This performance indicator takes both missed connections and individual train delays into account and assumes that connections to other transport systems are still feasible with a delay below 5 minutes (ProRail, 2016a).

On first sight, the question of when a train is being called cancelled seems trivial, but in many situations the answer is not that simple. What to do with diverted trains, or trains that skipped a few stations? ProRail has defined very specifically in what situations a planned train path is considered as having been delivered. Train path realisation possibilities are categorised in six different groups and within each group further specified into a few plausible occurrences or situations (ProRail, 2015e). The full description is depicted in appendix E. To summarise, a train path is considered successfully delivered if one or several trains have run over the total length of the planned route, where the specific route in station areas is irrelevant. Skipping stations is allowed, as long as the train passes through the station area.

6.3 Differences between robustness, reliability, availability and resilience

In literature, the definitions of reliability, availability and resilience differ likewise the various definitions of robustness described in the preceding sections. A whole new literature study can be executed for variations in definitions of these terms as well, but this is not within the scope of this research. In this section a commonly used definition of reliability, availability and resilience will be given and the relation to robustness will be explained.

6.3.1 Reliability

The first of the three to be discussed is reliability, from which the definition by Oxford Dictionaries is given below:

> ‘**Reliability** /rɪlʌɪəˈbɪlɪti/ *[Noun]:* 1 The quality of being trustworthy or of performing consistently well’

Definition of reliability by Oxford Dictionaries (Oxford Dictionaries, 2016b)

The most relevant part of the definition is quality of performing consistently well: a reliable rail system is always – or very often – able to fulfil its function: bringing passengers from A to B by train. Robustness seems to be a mean to achieve this quality; if the system is able to withstand or overcome disturbances, in other words if the system is robust, the function of the system will be maintained in these disturbed conditions. This will lead to a more reliable system. The reliability of a system could be expressed in variables such as the number of failures or number of cancelled trains, while for robustness this is more challenging.

6.3.2 Availability

The availability of infrastructure relates to the amount of time that a piece of infrastructure can be used. Oxford dictionaries define availability similarly:

> ‘**Availability** /əveɪləˈbɪlɪti/ *[Noun]:* 1 The quality of being able to be used or obtained’

Definition of availability by Oxford Dictionaries (Oxford Dictionaries, 2016a)

A main difference compared to the terms robustness and reliability is that availability does not say anything about the state of the system or the quality of the performance of the system. For instance if a track from A to B can be used at a maximum speed of 40 km/hr, the track can be called available but you will probably not be able to run all your planned trains. So even though an availability of 100% can be achieved, this will not automatically mean that the performance of the system is also 100%: many trains could still have been cancelled or delayed due to technical failures in the infrastructure. This makes availability not suitable for this research.

6.3.3 Resilience

The last term to be discussed is resilience. Once more, Oxford Dictionaries' definition is shown below:

> '**Resilience** /rɪˈzɪlɪəns/ *[Noun]:* 1 The capacity to recover quickly from difficulties; toughness'

Definition of resilience by Oxford Dictionaries (Oxford Dictionaries, 2016c)

While robustness, availability and reliability describe how well or how much time a system is able fulfil its function or withstand disturbances, the term resilience is used to describe how well or fast a system can recover from disturbances that caused the system to fail. Nevertheless, there are correlations between the terms. In theory a resilient system will have a higher availability than the same less resilient system, since the amount of time the system is not functioning due to disturbances is smaller. As seen before, one of the definitions for a robust system was that disturbances did not spread across the system: the more resilient the system is, the smaller the chance that disturbances spread. Procedures and the effectiveness of the train operating companies play a large role in the resilience of the railway system, which is currently an important topic within ProRail (SpoorPro.nl, 2015a).

6.4 Comprehensive definition of robustness

Several definitions of robustness in various fields of expertise have been discussed in the preceding sections and from all these slightly different ones a suitable comprehensive definition needs to be formed. Below a high level summary of the previously discussed definitions is given.

- ***Delay recoverability of the railway system***
  In scientific literature many authors use robustness to describe the ability of the timetable or railway system to recover from delays by for instance preventing of knock-on effects.
- ***Serviceability of the railway system***
  Some authors agree with the definitions related to recoverability, but would like to add another aspect: passengers. They defined robustness as the difference between average actual arrival times and planned arrival times of journeys. The main difference is the focus on journeys instead of trains so that passenger transfers are taken into account. Surprisingly, some authors are convinced that robust timetables contribute to a high serviceability because of the predictability of the arrival time while others think that the more robust a timetable is, the lower the serviceability is due to the long journey times (slack time has been added to the timetable).
- ***Non-timetable related robustness***
  The variety of contexts in this category is fairly large since it does not only contain railway related robustness definitions. And although the actual definitions are very different for every field of expertise, the underlying way of reasoning is surprisingly consistent: the system should be able to function to some extent when facing disturbances or uncertainties of a certain severity.
- ***Robustness within ProRail***
  A clear unambiguous definition of robustness seems not to be used within ProRail, but the common part of most definitions comprises to which extent disturbances cause longer travel times. By stating larger travel times they refer to cancellations of trains or severe delays of trains for which they are penalised by the government. Appendix E explains in detail when a train can be called severely delayed or cancelled.
- ***Reliability, availability and resilience***
  Summarily recapturing the definitions of reliability, availability and resilience:
  - *Reliability*: chance or time a system is able to fulfil its function
  - *Availability*: amount of time a system or asset is able to be used
  - *Resilience:* time a system needs to recover from a disruption

The purest thinkable definition of robustness, which is also incorporated in all the various definitions above, is that robustness is a measure for the relation between a disturbance of a system and the effect of the disturbance on the performance of the system. In a completely robust system there is no relation at all and disturbances have no influence on the performance, which is, obviously, not realistic. For ProRail the performance of the system refers to the performance of their product, which is in the narrow sense of the word, the supply of train paths to the operator. Naturally the robustness must be quantifiable hence the necessity to take the KPIs of these train paths defined by ProRail into account. Based on these arguments, the robustness of a large complex station is expressed as:

> *The amount and percentage of train movements cancelled as a result of disruptions or incidents.*
>
> Definition of robustness used in this research

Although delays are inconvenient, when services operate as frequently as in the Netherlands it is thought to be sufficient to take only cancellations into account when trying to capture the performance of the system.

Frankly, with this definition of robustness, the research is also interested in the reliability of untangled systems in large station areas because the chance of the occurrence of disturbances inherent to the system design is also important for the success of the system untangling philosophy. Nevertheless, since the focus is on the performance of the system even while being affected by incidents and disturbances, robustness remains the right term to use.

Chapter summary

In chapter 6 a comprehensive definition of robustness has been formulated based on definitions found in literature. Not only have definitions used in research be investigated, also various definitions for robustness used within ProRail – the Dutch rail infrastructure manager –have been discussed. Eventually it was decided to express the robustness of a large complex station in this research as *the amount and percentage of train movements cancelled as a result of disruptions or incidents*, because it was both in line with most definitions found in scientific literature and usable for ProRail.

7 Scenario generation

As has become clear in the explore part, system untangling knows many degrees of freedom and the effectiveness of untangling options heavily depend on the local situation. Since modelling a fictional large complex station would leave way too many design options open, a case study will be performed to assess the effectiveness of system untangling. This chapter consists of multiple steps that will lead to concrete scenarios with explicit system designs, for which a model that will assess the robustness and thus the effectiveness of untangling can be developed.

First the selection and description of Utrecht station as suitable large complex station will be explained, which will be handled in section 7.1. Based on this station and potential benefits of untangling options estimated in the explore part, six untangling options will be selected that are taken into account in this part of the research. This can be regarded as a form of scoping, since the list of 25 options found in section 4.5 is reduced further. In the last two sections of this chapter, the system design of the selected station, the untangling options and other robustness increasing measures will be translated into several relevant scenarios. Eventually, this will lead to 50 selected scenarios that will be modelled in the next chapter to determine the effectiveness of the untangling options.

7.1 Case description

As stated before, a case study will be performed in this part of the research to be able to incorporate the logistical effects of untangling options. To execute this study a case first needs to be selected that is suitable to test the various untangling options and representative for a complex station in the Netherlands (see Figure 7.1).

Figure 7.1 Step of the research approach described in this section

It would only be logical to select a station from the five largest stations – based on train movements – that have been used for the data analysis in section 4.4.1, as they all are both large and complex. Choosing a station from which the subsystems have not been untangled at all would result in a case study with many degrees of freedom: the effects of individual untangling options would be difficult to determine and answering the research question would therefore be more difficult.

Utrecht station is the largest of the five and has just completely been remodelled in the 300 million costing project DSSU in which the system untangling philosophy had a centre stage in the design principles. An incident at this station from which the impact was not contained within the corridor, despite all installed untangling options, formed the direct trigger for this research. Utrecht station has therefore been selected as case study and will be described in detail in this section.

Officially, the DSSU project only comprised approximately 90% of the works carried out at Utrecht, while other projects (Vernieuwing Buurtsporen, UtARK and U-Centraal) also delivered a part of the design shown and described in this section. Nevertheless, the design will be referred to as the DSSU project for the sake of simplicity (ProRail, 2014b).

7.1.1 DSSU design philosophy

The design of Utrecht station or DSSU (Flow Through Station Utrecht) is based on a number of design principles of which the most important ones will be discussed here.

As the name of the project suggests, the design is optimised for train services that do not have Utrecht as their final destination but continue after they have passed through Utrecht. This design principle has mainly been used to increase the capacity of the station because it facilitates shorter headways between trains since the time a continuing train occupies a platform (dwell time) can be shorter than that of a terminating train that has to turn around. Together with the use of long stretches of straight tracks with few switches, which enables trains to enter and leave the station faster, the time a train needs to pass through the station area is minimised (ProRail, 2014b). Figure 7.2 shows the train services that NS operates around Utrecht in 2017 and indeed, most of the services run passed Utrecht, although a few of them still appear to terminate in Utrecht.

Figure 7.2 NS' train services in 2017

The four terminating train services in the upper right corner use a part of the station that was excluded from the DSSU project (platforms 1 to 4) and therefore has not been designed with the same design principles as the rest of the station (platforms 5 to 21). Tracks and other rail infrastructure in the area around tracks 1 to 4 have been renewed, but the original design has been left (mostly) unchanged (ProRail, 2014b). Two other train services worth mentioning are the dark yellow and pink lines in the bottom left corner. These direct services run between the Western part and Northern/ Eastern parts of the Netherlands but still require trains to turn around in Utrecht because of the geographical position of the tracks (the lines from the West and North/East both enter the station from the North side).

The second design principle worth discussing is more directly linked to system untangling: passenger train services should run in predefined, fixed, train corridors and use dedicated platforms and rail infrastructure in the station area (ProRail, 2014b). Figure 7.3 shows the passenger train corridors that have been set by ProRail, NS and the Dutch Ministry of Infrastructure and Environment (Ministry of Transport, Public Works & Water Managment, 2010), a further explanation given in Table 7.1. The names of the corridors can refer to motor ways they run parallel to (A2 and A12), the cities they connect (VleuGel, ICLedn, SPRBkl-Db) or the parts of the country they run to (NO). As explained before, some local trains use a separate part of the station that has not been remodelled (platforms 1 to 4); these train services are indicated in orange in Figure 7.3 (Buurt). As a result, intercity services from Eindhoven will always continue in the direction of Amsterdam and never in the direction of Gouda, and local trains from Driebergen-Zeist always to Breukelen. Passengers wishing to travel in other directions need to change in Utrecht.

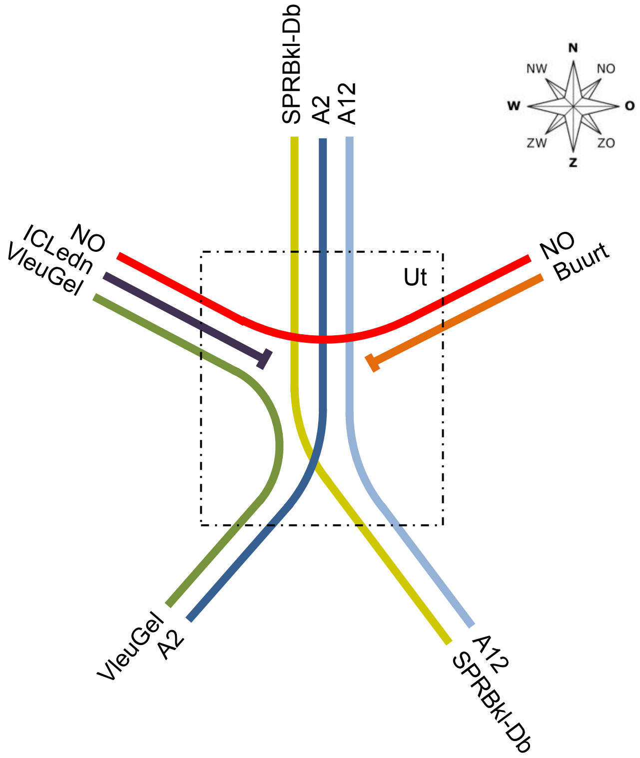


Figure 7.3 Identified fixed passenger train corridors that run through Utrecht

Corridor name	Colour in figure 7.3	Route of the shared part of the corridor	Service type
A2	Dark blue	Eindhoven – Amsterdam	Fast (Intercity – IC)
A12	Light blue	Schiphol – Arnhem	Fast (Intercity – IC)
North-East (NO)	Red	Gouda – Amersfoort	Fast (Intercity – IC)
IC Leiden (ICLedn)	Purple	Utrecht – Leiden	Fast (Intercity – IC)
VleuGel	Green	Woerden – Geldermalsen	Local (Sprinter – SPR)
SPRBkl-Db	Yellow	Breukelen – Driebergen-Zeist	Local (Sprinter – SPR)
Local area (Buurt)	Orange	Utrecht – Hilversum/Den Dolder	Local (Sprinter – SPR)

Table 7.1 Characteristics of the defined passenger corridors through Utrecht

The third important design principle is that switches only have been installed when they fulfil one of the three selected purposes: needed for regular operations, needed for traffic management adjustments in the timetable or needed to reach and leave one of the three yards at Utrecht station (Cartesiusweg, Landstraat and Opstelterrein Zuid). Switches for other purposes, such as crossover switches that enable trains to overtake each other at platforms with 2 sides (a and b side) and switches that would result in a more flexible platform use during disturbances have not been installed.

A design principle that is more focused on the areas around Utrecht is that the station should fulfil the function of a so called ‘timetable disconnection point’ if there is an incident at a neighbouring station. It implies that if for instance a faulty train North of Utrecht blocks the tracks, the (reduced) train service South of Utrecht should be able to continue. The timetable is then, as it were, disconnected from the disrupted piece of the line. The required quality of the disconnected service in terms of frequency has unfortunately not been specified (Movares, 2015).

With these design principles many technical designs options for the station and all its subsystems have been made, but eventually one of them has been selected and actually been built. The next section will discuss the design of DSSU and its subsystems relevant for this case study.

7.1.2 Track layout and operation

The chosen alternative of the track layout design was named ‘4x4’ because of the OZ yard’s position (Opstelterrein Zuid) to the main line tracks: four run East of the yard and also four run West of it. The trains of each corridor run mostly on dedicated tracks with dedicated platforms, but a few exceptions have been made: the A2 and A12 share tracks North of Utrecht and the ICLedn shares tracks with both the NO and VleuGel trains and platforms with the VleuGel trains. From this it can be concluded that, keeping in mind that the rest of the corridors have a dedicated track per direction, eight tracks must run South, four West, four East and four North from the station. The full track layout, platform layout, including the corridor they belong to, and the locations of the yards are depicted in appendix G. The ICLedn corridor has only been marked (in purple) at two specific locations: the point where its trains switch from the NO tracks to the VleuGel tracks and the dedicated tail track where its trains turn around.

A striking fact about the design is the installation of switches that allow trains to switch between corridors at 13 different locations. Nevertheless, this is not a high amount regarding the fact that five corridors (A2 and A12 seen as one) all use dedicated infrastructure: on average each corridor is connected once per direction to a neighbouring corridor.

Another notable feature of the design is the large spacing of the tracks of the A2 and A12 corridors per direction: northbound tracks and southbound tracks are not located next to each other but are separated by the SPRBkl-Db corridor. This automatically implies that trains at the station are not able to turn around in the own corridor without running in the opposite direction for a long period of time. If trains in the A2/A12 corridor are forced to turn around in Utrecht due to a disruption downstream the line, they have to make use of or cross another corridor’s infrastructure.

Lastly, freight trains also make use of Utrecht station but do not always run in the same corridors as the passenger trains. Two freight routes that not follow the train corridors still have to be facilitated by the track layout. The first freight route that deviates from the fixed passenger routes runs from Amersfoort to Meteren and forces freight trains to switch between the NO or Buurt corridor and the A2 corridor. Due to the position of the SPRBkl-Db corridor, switching between the A2 and NO corridors for southbound trains is only possible by also crossing the SPRBkl-Db corridor.

The second route runs from Meteren to Amsterdam and vice versa. The combination of the facts that the A12 and A2 merge North of Utrecht and that the speed differences between intercity A2/A12 trains and freight trains are large, requires freight trains for capacity reasons to use to the local train tracks of the Bkl-Db corridor North of Utrecht. For this reason, freight trains in this route need to switch from the A2/VleuGel corridor South of Utrecht to the SPRBkl-Db corridor North of Utrecht. In appendix G the locations where freight routes are supposed to switch between corridors are indicated by a pink line.

7.1.3 Technical design

Naturally, not all details of the design are relevant for this research, plus not all can be discussed here as the DSSU project is too large and complex; the complete redesign of the largest station area (in terms of passenger trains) has taken many years to plan, design and build. This section will discuss the significant technical details, based on the identified untangling options in section 4.2.2, categorised per subsystem and level as defined in chapter 3.

7.1.3.1 Guidance subsystem

Most of the track layout details, as part of the guidance subsystem have been discussed in section 7.1.2. An interesting side effect of the reduction of switches in the new design compared to the old situation in Utrecht is the reduced accessibility of the yards: the Landstraat yard can only be reached from platforms 1 to 7, OZ from platforms 7 to 15 and Cartesiusweg from platforms 15 to 21. Together with the limited possibilities to switch between corridors this means that the yards are also somewhat untangled: each corridor is connected to one (or sometimes two) yard(s).

Switch control and power cables run to the interlocking installation in the relay houses via dedicated cable tubes alongside the tracks and are not bundled with cables from switches in other corridors. If a pair of switches connects two corridors, spare control cables from each switch run in the cable tubes of the corridor the individual switch does not belong to. This all has to do with the flank protection principle, explained in section 4.4.2.19, which sometimes requires a certain position of a switch that is not part of the corridor, but located near the switch that is part of requested route. By having this redundancy, if an incident in another corridor's cable tube damages the cables, the required position of the neighbouring switch in that corridor can still be obtained through the spare control cables in the cable tube of the own corridor. Directly beneath the platforms the situation is different: three large cable tunnels have been excavated of which two house all cables that run from East to West and one houses all cables from North to South (under platform 20/21). Investigating in detail which cables exactly run through these tunnels is unfortunately out of the scope of this investigation. Selecting untangling options to be modelled that untangle the cables of Utrecht would therefore not be feasible.

The electric switch heating installations are located in separate, small building and have a dedicated power connection to the national grid in order to facilitate the large amounts of power that are required during winter and to exclude the possibility of a power failure that could also affect the operation of the switches, ATB system and signals . These heating installations have not been built per corridor but per group of (neighbouring) switches.

7.1.3.2 Energy subsystem

The design of the energy subsystem will be discussed in two parts: the physical part, which comprises the construction of the catenary system, and the electrical part, which comprises the design of the power supply to the overhead wires and electric diagram.

To start with the physical part, for which the major design considerations were which type of gantries to use and where to install the tensioning systems. With the design of the track layout, the contact lines scheme is automatically fixed since each track, including switches, needs to be equipped with an overhead wire. Different types of gantries have been used across the area, but the reason for the usage of various types is not directly linked to the untangling considerations. ProRail's design guidelines prescribe that the overhead wire design should strive to 'keep as much steel and copper (gantries, tension systems, poles and contact lines) in the own corridor', discouraging the combined use of large gantries or tensioning system installations (ProRail, 2015a). On the other hand, for construction phasing purposes it is very convenient to use large gantries that only need to be built once but remain flexible in their use, namely in the sideway position of the contact lines on the upper bar. If the tracks under the gantry are for instance moved, the contact lines can easily be shifted with them on the same bar. The choice of where to use which gantry type has therefore mainly been based on the construction phasing plan of the project rather than on robustness or untangling principles. Generally, the Southern part of the station area, between stations Lunetten and Vaartsche Rijn, is mainly equipped with a catenary system with individual poles, while most of the tracks North of Vaartsche Rijn share the gantries with tracks in neighbouring corridors (Movares, 2015) (ProRail, 2014b).

The second part of the energy subsystem design comprises the design of the systems that feed power to the catenary system, which is depicted in appendix H. The philosophy that has been used here is that two independent power stations are constructed which together feed the catenary system while each is capable of supplying the full area by itself. Each power station is constructed at one side of the area (one North, one South), and elongated subsidiary circuits connect the two power stations. It is strived for to include all tracks in an elongated subsidiary circuit that is fed by both the Northern and Southern power station, but nevertheless extra subsidiary circuits have been installed in both power stations to feed the parts of the infrastructure that are not included in these elongated subsidiary circuits, such as extra platforms and yards. These isolated subsidiary circuits (fed by only one power station, indicated by the letter X in the circuit ID), could in case of a power loss still be connected to the other power station by electrical switches, but this will be accompanied by an initial power disconnection of that specific circuit.

Appendix H shows the design of the subsidiary circuits, where numbers 1 to 6 are the elongated circuits that are directly connected to both power stations. Circuit IDs starting with ‘S’ are fed by the southern power station and IDs with ‘N’ from the northern power station. The letter ‘E’ (External) in the ID indicates that the circuit is located (partly) outside of the scope.

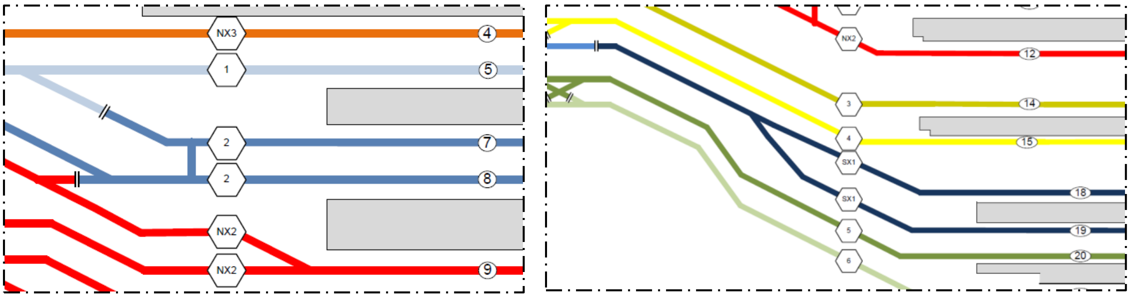


Figure 7.4 Subsidiary circuit tangling of the A2 corridor with the NO at platforms 7 and 8 (Left) and with the A12 at 18 and 19 (Right)

Generally it can be concluded that the subsidiary circuits mostly follow the train corridors, with a few exceptions. The largest tangling occurs where the A12 and A2 stop using dedicated infrastructure and start to share infrastructure (and vice versa), see Figure 7.4. Because the A12 and A2 South of Utrecht are in separated subsidiary circuits, the circuits either have to merge at the tangling point (which makes them one single subsidiary circuit) or one of the circuits needs to continue on a track of another corridor. Both solutions have been applied, the first at the Northern side of platforms 18 and 19 (where southbound A2/A12 trains halt – right side of Figure 7.4) and the second at the Northern side platforms 5 and 7 (where northbound A2/A12 trains halt – left side of Figure 7.4). At that latter location the A2’s subsidiary circuit (number 2 in Appendix H/Figure 7.4) connects to platform 8, which is part of the NO corridor. A short circuit caused by a faulty pantograph on one of these tracks will lead to a power loss in both the A2 and NO corridor (in one direction though) (Movares, 2015).

7.1.3.3 Safety subsystem

The safety subsystem, as defined in section 3.1.2.4, is a broad subsystem with very different design dilemmas of which the choices are hard to capture in a single design philosophy. The location of the signals for instance has been a trade-off between (amongst others) optimal visibility, optimal spacing for capacity reasons and minimal required distance to a switch or crossing to avoid additional flank protection measures (Movares, 2015). The locations and amount of relay houses on the other hand have been determined based on costs, technical capacity and accessibility. Regarding the untangling options identified in section 4.2, it is relevant to discuss the switch pairs with required positions for flank protection reasons, relay houses, the applied signal gantries and the interlocking system.

As discussed several times before, switches that are directly connected to each other, such as a pair of switches in a crossover, are for safety reasons connected to each other. ProRail identifies three levels of connections between switches: connected switches (unable to move independently), ‘requiring’ switches (unable to be run over if not both are in the correct position) and ‘requesting’ switches (switches that when operated once request – not require – a certain position of the other switch) (RIGD-LOXIA, 2013). Connected switches have not been applied in the design of DSSU; most of the switches installed are ‘requiring’ switches, which are indicated by an orange line in appendix I. ‘Requesting’ switches have been indicated by a yellow line.

Four relay houses in the Utrecht area contain the interlocking installation which is based on B-relay technique. The Northern section, middle section and Southern section of the area each have a single, dedicated relay house with exception of the infrastructure next to platforms of Utrecht station that forms the border between the northern and middle section, which can be operated and controlled from both the Northern and middle relay house. In that way, the destruction of failure of one of the relay houses will at least keep Utrecht accessible from one side of the country. In appendix G the locations of the relay houses have been drawn as well and the borders of the area under their control have been depicted by dotted lines.

Even though the division of the station area into these three control areas has not been done according to the train corridors, the equipment itself in the relay houses has been split corridor wise: the several racks with equipment, installed in the relay houses, have all been categorised per corridor. A reason for this, according to the designers, is to reduce repair times as mechanics now know more precisely where they need to search if a certain switch or section is not working correctly (Movares, 2015). As explained before, a pair of ‘requiring’ switches between two corridors has equipment for both individual switches in both corridors: relays in the racks of both corridors and cables in cable tubes from both corridors. The failure of a certain rack will therefore not lead to a disruption in the other corridor. The relay houses are connected to each other through two separate redundant sets of cables (ProRail, 2016k).

Similar design principles as for the gantries of the catenary system and the switch control cables described in section 7.1.3.1 have been used for the signal gantries and signal control cables. The first have been optimised for construction phasing and the latter have been bundled per corridor as much as possible.

7.1.3.4 Support subsystem

The tracks and other track-bound infrastructure have not been built at ground level, but lay on embankments or viaducts throughout the city. This slightly elevated position makes it easier to get roads passed the tracks, as no deep tunnels or high bridges with long slopes are necessary to create enough height between cars and trains. A side effect of this shared support subsystem is that a (suspected possibility of) failure of the viaduct, for instance caused by a crashing car, will result in unavailability of tracks in all corridors. Nevertheless, the untangling option identified by the experts in section 4.2.2.3 focusses on the untangling of tunnels and bridges and their systems, and not on viaducts. In the design of Utrecht are no tunnels present, only two bridges that are near yet out of the station area scope that has been set for this research.

The other identified untangling option comprised the use of elevated junctions so that trains of different corridors do not have to cross each other. Although it might have been rather for capacity reasons than untangling reasons, the two largest junctions have been built as elevated junctions with four fly-overs (North) and two dive-unders (South). Passenger trains in regular service do therefore not have to cross trains in other corridors at any point in the area. Another small junction, South of platforms 7 to 15, that provides access to the OZ yard has been constructed as a flat junction. Besides shunting trains to and from the A2 and NO that have to cross the SPRBkl-Db corridor, also freight trains in regular service from Amersfoort to Meteren (southbound, from NO to A2) have to cross with northbound trains of the SPRBkl-Db corridor at this junction. Finally, a small flat junction is located North of tracks 1 to 4 which causes shunting trains from the A2/A12 corridor (platforms 5/7) to the Landstraat having to cross the tracks of the Buurt corridor. See appendix G for the locations of the junctions.

7.1.3.5 Access subsystem

The access subsystem in the Utrecht area consists of four separate stations: Utrecht, Utrecht Vaartsche Rijn, Utrecht Overvecht and Utrecht Lunetten. The last three are small stations that have no station building and are only served by local trains and therefore only have platforms at the tracks in the Buurt, VleuGel and SPRBkl-Db corridors. These three stations are only within the scope of this research because they are located between Utrecht station and important junctions or switches that have to be taken into account for evaluating the logistical effects of untangling options and thus the robustness of the station.

The most interesting station obviously is Utrecht station, of which the rectangular station hall has been built completely on top of the platforms. Besides the station hall two subways connect the platforms to each other and allow passengers to transfer. Regarding the identified untangling options, separate power grids and evacuation options per corridor, the station hall has not been equipped with these options. Although the station has a separate power grid for so called train service critical equipment, such as information screens and escalators and one for non-rail infrastructure equipment such as bars and shops, the grids have not been split per train corridor.

The same holds for the evacuation plans that allow the station hall to be evacuated per groups of four platforms: 1 to 4, 5 to 9, 11 to 15 and 18 to 21. Unfortunately, the last three groups all consist of platforms from two different corridors (U-Centraal, 2015). An interesting fact about these evacuation plans is the human side of the feasibility of untangling options, which in general is overlooked in this research. During an incident that requires evacuation of a part of the hall, alarms ring and announcements are made in that specific area informing passenger to leave the station as fast as possible. Passengers often have no clue which part of the station is actually being evacuated and either do not respond to the alarm at all or are also evacuated from the parts of the station that are not required to be evacuated (Algemeen Dagblad, 2016b).

7.1.3.6 Information subsystem

The way the information subsystem has been designed in Utrecht has not been investigated, as no potential untangling options for this subsystem have been identified in the previous chapters.

7.1.3.7 Resource allocation level

The equipment belonging to the systems of the resource allocation level physically mainly consists of cables, computers and people and uses the signalling system of the safety subsystem to communicate the allocation train path to train drivers. In Utrecht, the design of the systems at this level is straight forward: there is one traffic control centre, one EBP for the area and one LCE per rack in the relay house.

A notable characteristic of the design of the new traffic control centre, from where the signallers set routes and monitor the local traffic, is that it no longer houses the computers for, amongst others, the EBP and PRL systems. These computers have been moved to a dedicated data centre in Nieuwegein (Datacenterworks, 2012). Although this form of horizontal untangling is not within the scope of this untangling research, it is a new development in the Netherlands to prevent the possibility of a simultaneous evacuation of both the control room and IT-rooms that would cause a stop of all traffic in the area. Another horizontal untangling option that has been applied is the new location of the traffic control centre, which is outside the largest planned evacuation range of Utrecht station (SpoorPro.nl, 2015b).

Vertical untangling has not so much been applied at this level, probably also because this level was not in the scope of the DSSU project. The two signallers though that are responsible for Utrecht station have been untangled: one signallers handles trains in the NO and Buurt corridors (which all need to turn around in Utrecht), while the other handles trains in the A2, A12, VleuGel, ICLedn and SPRBkl-Db corridors (ProRail, 2014d).

The choice to use a Local Control Unit (LCE) per rack in the relay houses, which are untangled per track and thus corridor, automatically untangles these LCEs as well. A faulty LCE will always only have an effect on the specific track which safety and guidance equipment is in that rack. Power supply and communication between the various relay houses, control room and the data centre all have been made redundant: only large, network wide incidents could now cause multiple corridors to be disrupted (ProRail, 2016k).

Section summary

This section has described the design and (intended) operation of Utrecht station that will serve as large complex station for the case study. In general it can be concluded that the systems at Utrecht have already been untangled to a large extent.

7.2 Untangling options selection

In the explore part of this research various untangling options have been identified with the help of experts and the potential benefits of these untangling options have been quantified with data. A major difficulty that was faced with the applied method is that the actual benefits of the options heavily depend on the local situation, which made quantifying general benefits impossible. For example the logistical effects of the options, which form the heart of the robustness definition (see section 6.4), have not been taken into account there. The potential benefits quantified in section 4.4 produced a ranking of promising untangling options that will now be used for selecting which untangling options will be modelled. Six untangling options have been selected and will be translated into concrete scenarios in the next section. Figure 7.5 shows this step of the research approach that will be described here.

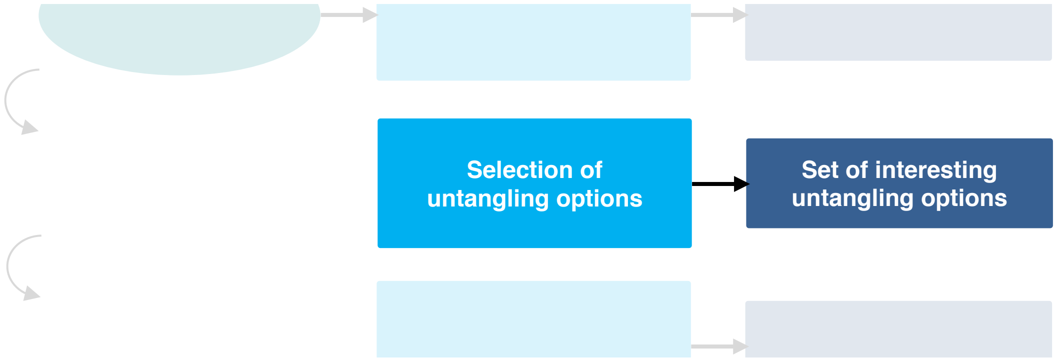


Figure 7.5 Step of the research approach described in this section

A straight forward method for selecting the untangling options that will be included in the scenarios for further modelling here, would be to take the first few from Table 4.14. After all, in general these options do have the largest potential to be most effective. On the other hand, as explained in 5.2.5, the applied quantification method appeared to be less suitable for some options, especially the ones where (much) more equipment would have to be installed for an untangled system than for a tangled system. For this reason and on request of ProRail, who considered to develop and implement a few of these ‘hard to quantify' options, some of the lower ranked options have been selected as well, besides some of the top ranked.

This section describes the selected untangling options shortly together with the reason of their selection, starting with the first option.

- ***Removing all crossovers between two corridors including switches (A)***
  The first selected untangling option is the removal of switches between corridors, which is an untangling option within the guidance subsystem. Not only has this option been quantified with the highest potential benefit, it is also an option that has a great logistical effect that could both be positive or negative for the robustness. As discussed in section 4.4.2.6, these effects have not been taken into account yet, which makes modelling this option in a case study very relevant. Some caution is in order when it comes to drawing general conclusions: benefits gained with this option might be very specific for the local situation in the case study.
- ***Installing procedures or systems that enable the safe use of a switch that requires a position of another switch that is out of control (B)***
  This option was ranked second in Table 4.14 and seems similar to the previous one, but actually untangles the safety subsystem instead of the guidance subsystem. A major advantage of this option is that it can still gain some of the benefits that the previous option has, while not having the potential negative logistical effects that come with the removal of switches. Because of this potentially high effectiveness, this untangling option has already been under investigation at ProRail for some time.
- ***Building separate relay houses for each corridor (C)***
  Also in the top 5 of highest ranked potential benefits, this option differs from the previous ones because of its related incident types' low chance of occurrence. If one of these incidents occurs though, the damage and the duration of the infrastructure's unavailability would be huge. The combination of these two (small chance, large effect) resulted in the high ranking for potential benefits. By modelling this option, some logistical effects can be taken into account and moreover the unavailability of the infrastructure could be nuanced: an unavailability period of several days could perhaps transcend after some time in a period where the infrastructure is only partly available.
- ***Installing subsidiary circuits for every corridor (D)***
  Two options of the energy subsystem scored high in the potential benefit ranking: building separate power stations for each corridor and installing subsidiary circuits for each corridor. The first option cancels out the latter and has a greater potential benefit, but on the same time requires a far larger investment than the last option. For efficiency reasons is it therefore probably more interesting to investigate the last option.

These four options discussed so far are the options with a high ranking that have been selected; another option that scored very high, untangling bridges and tunnels, can simply not be taken into account due to the lack of tunnels and bridges in the selected case study. Two other untangling options, which have not scored so high, have been selected as well.

- **Developing and using interlocking devices that operate independently per corridor (E)**
- **Using a separate EBP system for the control each corridor's infrastructure (F)**

The reason for selecting these two untangling options despite their low score is threefold. As explained before, the method used in chapter 4 is less suitable for untangling options where more equipment needs to be installed to untangle the system as with the installation of more equipment the chance of failures increases. Estimating how much these failure rates increase comes with great uncertainty. These two options are amongst this group of untangling options and have been selected because modelling them could lead to a more precise estimation of the benefits. The other reason is that in addition to the previous reason, the experts during the validation process of the results in chapter 5 agreed that the estimated potential benefits of this option were indeed too low: modelling them would be appropriate. The third reason is that ProRail is already thinking about applying these untangling options and has stated its preference for these two options (amongst many others) to be modelled (ProRail, 2017a).

Section summary

Six untangling options that have been selected from the identified untangling options in the explore part of this research, mostly based on their potential benefit score, have been described: removing crossovers between corridors (A), lifting the position requirements of unavailable requiring switch pairs (B), building relay houses per corridor (C), installing a subsidiary circuit per corridor (D), using a separate interlocking device per corridor (E) and using a separate EBP system per corridor (F).

7.3 Possible variations

With all the untangling options to be taken into account now known, the next phase of the scenario generation can commence: which variations should be modelled to be able to answer the research question? The word ‘effectiveness’ in the research question has an implication that is twofold: on the one hand which untangling option amongst the possible untangling options is most effective, and on the other hand which untangling option amongst other robustness increasing options is most effective. These ‘other robustness increasing options’ have not been identified as thoroughly and with the same care as the untangling options, as they are not the main topic of this research but simply an alternative to reflect the effectiveness of the untangling options with. The alternative options that have been found in the literature review in chapter 2 are redundancy, use of elements/materials with higher performances, decreasing the duration of an incident and maximising the use of remaining availability during incidents.

This section will set a framework for all these possible variations that in combination with the previously selected untangling options will lead to a list of specific scenarios that will be modelled in the remaining part of this research. The framework will be described in two parts, of which the first part will handle the variations in physical system layout that forms the input of the model. with the creation of a total system layout, the chances and types of incidents that will occur in the station area become clear and fixed. After all, when it has been decided how many switches there will be installed, the number of switch failures can then be predicted and becomes a fixed chance of occurrence.

The impact of incidents and with that the robustness of an area though, has not become fixed with the formation of a total system layout: that also depends on the way incidents are handled. The second part of this section will describe which variations of the impact will be modelled to answer research question. Together with section 7.4, this will lead to a set of relevant and coherent scenarios that will be further assessed. Figure 7.6 shows the step of the research approach taken in these two sections.

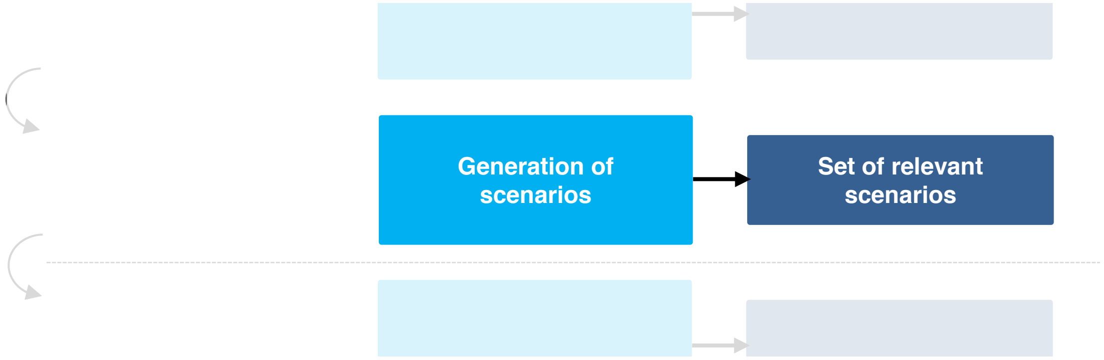


Figure 7.6 Step of the research approach described in the coming two sections

7.3.1 System design variations

As has been seen before, untangling is a broad concept with many different degrees of freedom such as type, location, extent and level. In section 4.1.3 most of these variables have been scoped down, what resulted in the identified and selected untangling options, but one of these variables is still unlimited and takes a centre stage in answering the research question: the extent of untangling. Obviously the variation in the scenarios should therefore be linked to the extent of untangling, but once again this leads to a large amount of possible scenarios.

A solution for this that will reduce the number of variations drastically while still expressing the effects of applying untangling options to various extents is to use the current extent of untangling in the DSSU design as a point of reference. The effectiveness or actually the change in effect, could be calculated by modelling one scenario where the extent is larger and one scenario where the extent of the untangling options is smaller. Section 9.5 will elaborate on the advantages and disadvantages of this approach. Figure 7.7 graphically shows the range of the extent that will be modelled.

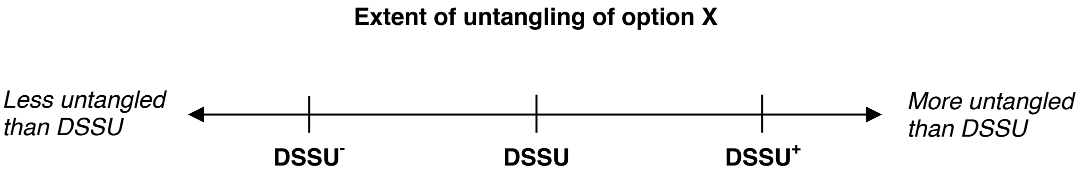


Figure 7.7 The modelled range of the extent of an untangling option visualised

As discussed previously, the word effectiveness in the research question has a meaning that is twofold. In section 2.1, theory about system untangling has been gathered which also discussed alternative measures to increase a system's robustness besides system untangling. An interesting straight forward measure that could be applied instead of untangling but also in combination with untangling is decreasing the functional failure rate of elements by for instance intensifying the maintenance frequency or installing equipment with better failure rates. The experts who were consulted in chapter 4.2 for the identification of untangling options also have stated multiple times that using more robust (with lower failure rates) elements would increase the robustness as much as certain untangling options would and sometimes be significantly cheaper. Besides that, even if an untangling option is installed, decreasing failure rates of individual elements by intensifying maintenance is often strongly advised by these experts, because the dependency on individual elements often increases when a system is untangled (see section 2.1.1.3): operating trains around the failing element, such as a switch, becomes (almost) impossible, or in other words the level of redundancy decreases as the extent of untangling increases. See chapter 2.1 for the full explanation of this theory.

This measure for increasing the robustness could be modelled in the same way as the untangling options: with the failures rates of the current elements used in DSSU as point of reference. By modelling scenarios of Utrecht with increased and decreased element failure rates, the effect of this alternative to untangling can be determined. See Figure 7.8 for a visualisation of the range.

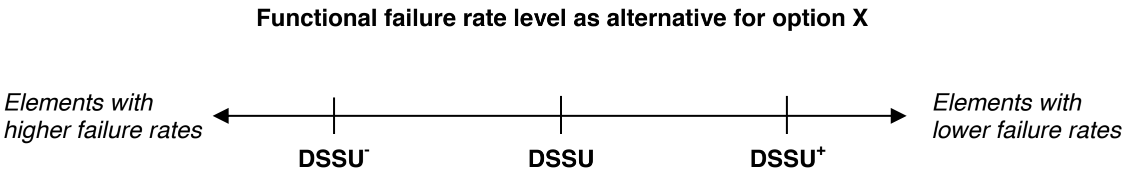


Figure 7.8 The modelled range of the element failure rates as an alternative for an untangling option visualised

Modelling various scenarios of the untangled system and various scenarios of the system with improved failure rates is relevant for answering the research question, but the interaction between the two might also be interesting in relation to the effectiveness of increasing robustness. After all, in appendix B2 the experts clearly stated that decreasing the failure rates of elements is crucial to increase the robustness in an untangled system, as most switches, more than in the tangled situation, have become essential for executing the timetable.

Extra scenarios should therefore be generated in which the system layout has been altered in both the failure rates of the elements and the extent of untangling. Figure 7.9 shows the possible system design scenarios if both the element failure rates and extent of untangling are varied with reference to the current situation in DSSU. The first small symbol in the upper right corners of the scenario options in Figure 7.9 indicates if the extent of untangling is smaller than (-), equal to (0) or larger than DSSU (+), while the second symbol does the same for the failure rates of the elements. Each scenario was given a number between -4 and 4 to make references to specific scenarios in this framework easier.

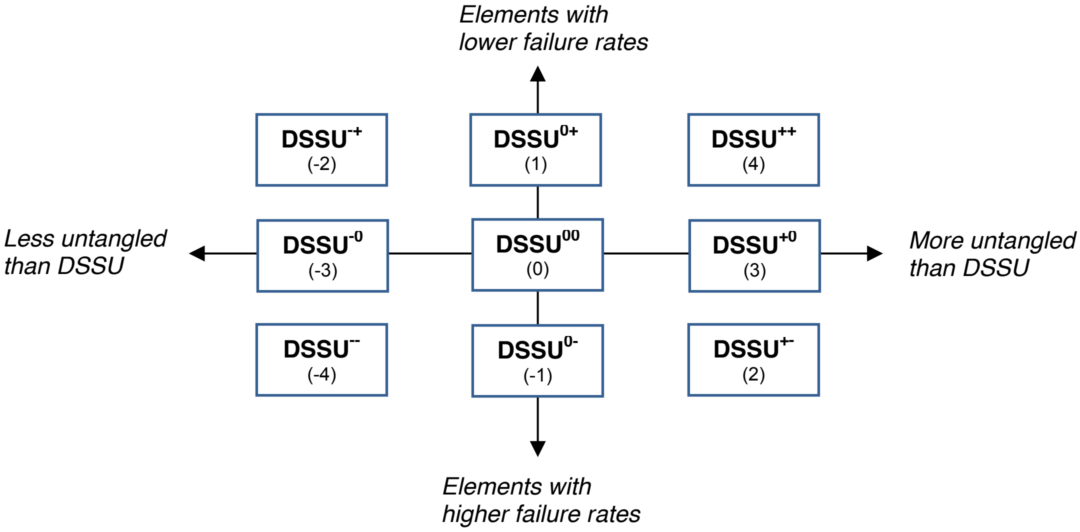


Figure 7.9 Possible system design variations per untangling option

This framework with 9 variations in system design will form the basis in the scenario generation process, but two steps have to be taken yet before the selection of scenarios can commence. After all, what the exact system layout is in a DSSU+ or DSSU- scenario has not yet been determined. It has only been concluded that the system layout is more untangled (+0), less untangled (-0), has lower failure rates (0+) or higher failure rates (0-) than DSSU. Besides that, not all of these nine possibilities exist for every untangling option. For instance for the untangling options removing switches between corridors (A) in the guidance subsystem and lifting the required position principle of a pair of switches in the safety subsystem (B) both have the same alternative of applying elements with other failures rates – installing better/worse perfuming switches – since the incident types related to these untangling options fully overlap. In section 7.4 the possibilities per untangling option will be inventoried and the found variations will be more specifically defined to eventually select relevant scenarios.

7.3.2 Effect variations

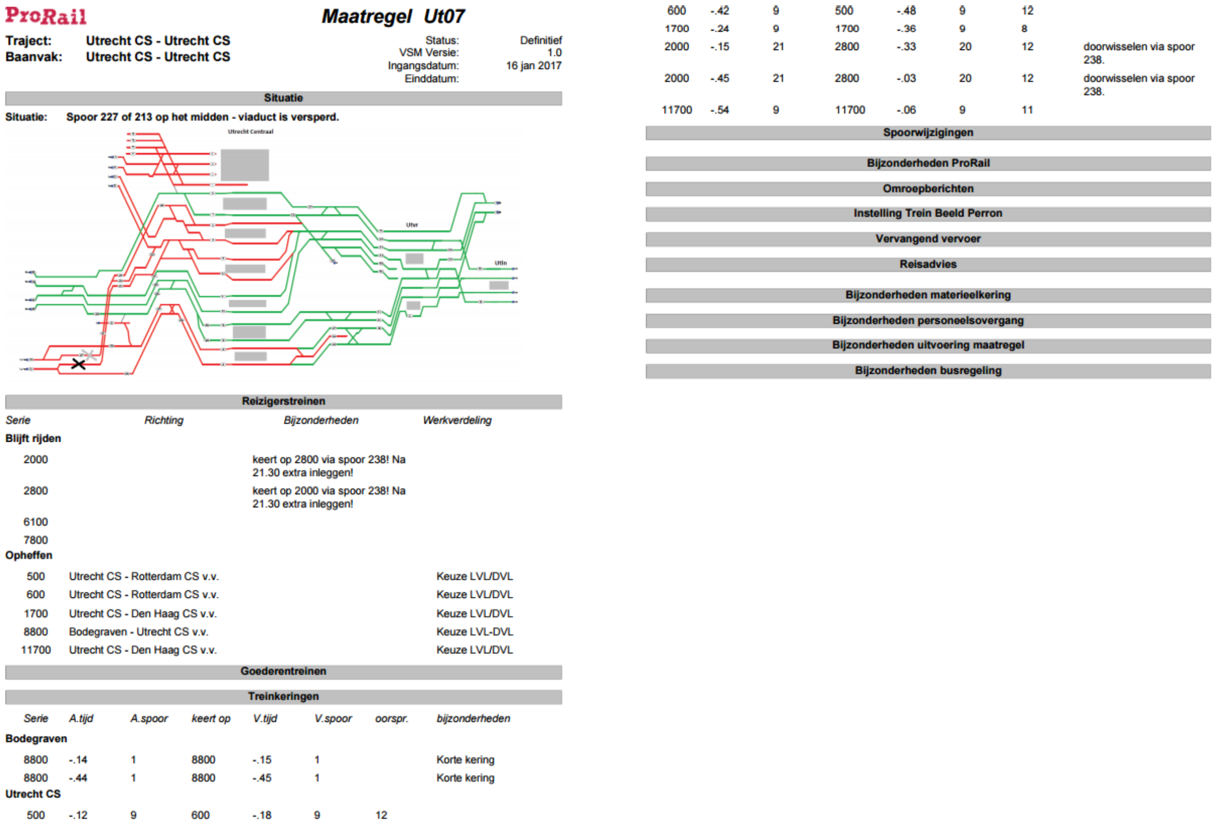
With the formation of a system design or system layout in combination with the planned timetable, the types and frequencies of incidents that will most probably occur in the system become predictable. Based on the number of elements used, the types, their failure rates and the way they are all connected to each other, the unavailability of each section of track can be predicted. However, there is a difference between unavailability of infrastructure and the robustness of the system; the latter is defined as the effect of the unavailability on the performance of the timetable, or in other words the percentage or number of cancelled trains because of infrastructure unavailability. Obviously the way these effects are modelled is key in determining which system design is more robust.

This section focuses on the possible variations in effects on the timetable that could be modelled and will try to incorporate the alternative measures for untangling that have been found in the literature study (see section 2.1). One of the alternative measures, using elements with lower failure rates, has yet been incorporated in the system design variations, but the others, such as decreasing the duration of an incident and maximising the use of remaining availability during incidents, are related to the effect of unavailable infrastructure and should therefore be incorporated in scenario variations here.

7.3.2.1 Logical effect calculation regime (α)

To limit the impact of incidents, ProRail and NS have developed detailed plans for how to adjust the timetable in case of specific incidents. These VSMs (contingency plans) are available for almost any possible scenario and accelerate the decision making process in the traffic control centres so that they can focus on monitoring and supervising the traffic in the area. The most logical method to calculate the effects of a certain unavailability would therefore be to apply the matching VSM that describes the adjustments to the timetable. After all, these adjustments (cancelled trains) are the adjustments that will actually be made by the traffic control centre in case of an incident. For an untangled station as Utrecht with limited number of switches between corridors, the VSMs are fairly straightforward, as the number of possibilities for adjusting the timetable is limited.

For Utrecht twelve different scenarios have been defined which are named Ut01-Ut13 (Ut03 does not exist anymore). Each VSM consists of three main sections: which trains services are cancelled, which should continue to run (including how), and which train services need timetable adjustments in other stations (including which). Figure 7.10 shows an example of a VSM in Utrecht (OCCR, 2017).



ProRail

Maatregel Ut07

Traject: **Utrecht CS - Utrecht CS**
Baanvak: **Utrecht CS - Utrecht CS**

Status: Definitief
VSM Versie: 1.0
Ingangsdatum: 16 jan 2017
Einddatum:

Situatie

Situatie: **Spoor 227 of 213 op het midden - viaduct is versperd.**

Reizigerstreinen

Serie	*Richting*	*Bijzonderheden*	*Werkverdeling*
Blijft rijden			
2000		keert op 2800 via spoor 238! Na 21.30 extra inleggen!	
2800		keert op 2000 via spoor 238! Na 21.30 extra inleggen!	
6100			
7800			
Opheffen			
500	Utrecht CS - Rotterdam CS v.v.		Keuze LVL/DVL
600	Utrecht CS - Rotterdam CS v.v.		Keuze LVL/DVL
1700	Utrecht CS - Den Haag CS v.v.		Keuze LVL/DVL
8800	Bodegraven - Utrecht CS v.v.		Keuze LVL-DVL
11700	Utrecht CS - Den Haag CS v.v.		Keuze LVL/DVL

Goederentreinen

Treinkeringen

Serie	*A.tijd*	*A.spoor*	*keert op*	*V.tijd*	*V.spoor*	*oorspr.*	*bijzonderheden*
Bodegraven							
8800	-.14	1	8800	-.15	1		Korte kering
8800	-.44	1	8800	-.45	1		Korte kering
Utrecht CS							
500	-.12	9	600	-.18	9	12	
600	-.42	9	500	-.48	9	12	
1700	-.24	9	1700	-.36	9	8	
2000	-.15	21	2800	-.33	20	12	doorwisselen via spoor 238.
2000	-.45	21	2800	-.03	20	12	doorwisselen via spoor 238.
11700	-.54	9	11700	-.06	9	11	

Spoorwijzigingen

Bijzonderheden ProRail

Omroepberichten

Instelling Trein Beeld Perron

Vervangend vervoer

Reisadvies

Bijzonderheden materieelkering

Bijzonderheden personeelsovergang

Bijzonderheden uitvoering maatregel

Bijzonderheden busregeling

Figure 7.10 Ut07, an example of a VSM, which is used when a track from Gouda is blocked or unavailable (OCCR, 2017)

7.3.2.2 Increased utilisation effect calculation regime (β)

One of the alternatives that have been discovered in chapter 2 to increase the robustness is the improved use of remaining infrastructure during incidents. The use of VSMs has as main disadvantage that the VSMs are not flexible. If the incident slightly deviates from the pre-specified incident the VSM is based on, it is not possible to use this extra part of the infrastructure that is not unavailable. By using the remaining available infrastructure to its maximum, the effect of the incident could probably be limited, which could be more effective than untangling the systems (any further).

Examples of increased utilisation are temporary allowing shorter turn-around times for trains, allowing trains to have scheduled red signal approaches or letting trains leave the station before the scheduled departure time.

Calculating the effects of incidents under this β regime will mean that instead of applying a VSM a tailored made adjustment to the timetable will be used based on the optimal usage of remaining available infrastructure. This means that the regular timetable is maintained as much as possible with as main purpose to run as many trains as possible. The following rules have been used:

- ***Trains will not be cancelled if they could be rerouted or given a delay of 5 minutes maximum with small impact to other trains instead.***
  In that case trains will need to consume their buffer times downstream the line.
- ***Trains could leave the station two minutes ahead their schedule as long as their dwell times allow this.***
- ***The standard train planning rules are used.***
  Meaning a five minute turnaround time, three minute follow up time (four at the platform) and a one minute crossover time (time between arrival and departure of a train over the same track in the opposite direction) (ProRail, 2015d).

7.3.2.3 Shorter (functional) repair time effect calculation regime (γ)

Another alternative to increase robustness which could also easily be combined with system untangling measures is decreasing the time needed to resolve incidents. This alternative too has been found in literature, but investigating the various ways how to reduce the duration of an incident and the actual time reduction they will lead to, could be a full research by itself. How this reduction is achieved is less relevant: the purpose of calculating the effect of incidents under this regime is to see if striving for incident time reduction is more effective than applying the various untangling options. Also the combination of both applying untangling options and reducing the duration of incidents might be interesting, as it will show the range of robustness increase that can be achieved rather easily (in comparison to, for example, developing switches that never fail).

Under this γ regime it is assumed that all incidents are resolved 20% faster than found in the historical data, aligning with the necessary reliability increase of 20% originally stated in the Better and More program (Ministry of Infrastructure & Environment, 2014a).

7.3.2.4 Absence of safe working space effect calculation regime (δ)

Although all alternative measures found in literature have yet been incorporated in either the system design variations or in one of the previously discussed effect calculation regimes, another interesting variation can be thought of. Identified untangling option 20, creating safe working areas around corridors so that repair works can be carried out without hindering other corridors, appeared to be so fundamental that its benefits could not be quantified in the same way as the other untangling options: for many other untangling options, having a safe working area around each corridor was simply a requirement in order to have any potential benefit (see section 4.3).

But, in order to quantify the effect of safe working distances between the corridors on the robustness of the station area, another approach would be to calculate the effects of incidents under a regime that does not allow repair works on a track without taking the neighbouring track out of service. Effects of incidents under this regime could be the result of corridors that are spaced too closely, absence of facilities between corridors such as fences and walls, or the tightening of safety regulations. The latter seems to have been a trend over the past few years (Andersson Elffers Felix, 2016). The results of the robustness under the δ regime could trigger solutions for creating safe working areas that can be an alternative to further untangling the system.

7.4 Scenario selection

In the previous section a framework has been developed that describes the various variations that should be taken into account in the scenario generation process. Together with the selected untangling options of section 7.2, this scenario generation process can now be finished, with as result a list of scenarios to be modelled. This conclusive phase of the process will be described in this section.

First the framework of variations will be plotted onto the untangling options to see if all variations exist for each untangling option and to determine the total number of possible scenarios. Unfortunately, due to time restrictions not all of these scenarios can be modelled. In the second part a selection will be made of the most relevant scenarios and a more detailed description will be given of the used system design variations.

7.4.1 Overview of generated scenarios

One of the key aspects of this research is the fact that it focuses on *total* system untangling, which is compared to the current system analyses found in literature and within ProRail, a new approach. Total system untangling means that not simply a single subsystem or level is under investigation, but that all options in multiple subsystems and levels and their interaction is taken into account. The way the variations have been defined in the previous sections supports this approach.

The basic total system design that will be modelled is the current DSSU situation as described in section 7.1 and the robustness found there will serve as point of reference. The six selected untangling options A to F, all can be varied. The variations used for the various untangling options in a scenario will be denoted with a value of parameter V_x between -4 and 4, where x represents options A to F and the values -4 to 4 correspond to the variation framework explained in Figure 7.9. Formula (7.1) shows the notation format of the scenarios, the basic scenario would be denoted as six vertical zeros.

$$V = \begin{bmatrix} V_A \\ V_B \\ V_C \\ V_D \\ V_E \\ V_F \end{bmatrix}, -4 \leq V_x \leq 4 \tag{7.1}$$

The regime under which the scenarios are modelled is denoted similarly by variable R_x, which can have the 'values' α, β, γ, or δ, referring to the regimes described in the previous sections (see formula (7.2)). The square brackets used in formula (7.2) represent the square brackets of formula (7.1) and have been used to show that the modelled regime indication is denoted in the top right corner of the V matrix. Both formulas (7.1) and (7.2) do not represent a mathematical operation of any kind.

$$R = [\ ]^{R_x}, \quad R_x \in \{\alpha, \beta, \gamma, \delta\} \tag{7.2}$$

While a system design can consist of various variations and combinations of system untangling options (V_x), there can only be a single regime under which the effects are modelled (R_x). Combinations of regimes are imaginable, such as a combination of the improved usage of available infrastructure and absence of safe working space (β & δ), but this is not in line with the research question. After all, it is not the most effective way to increase robustness that is under investigation, but the effectiveness of untangling options in relation to variations of untangling and other alternatives.

Not every V_x exist and as stated before, the details of the variations have not yet been determined. Table 7.2 shows the range of the variations (second column), the relevant regimes (third column) and details of different of the various directions of V_x (columns 4 to 7). The letters in the first column refer to the untangling options as selected in section 7.2. As alternative failure rate increase and decrease 20% has been chosen, since the program 'Better and More' originally foresees a necessary infrastructure reliability increase of 20% to cope with the future train frequencies (Ministry of Infrastructure & Environment, 2014a). Formula (7.3) translates the indicated range in Table 7.2 into the scenario notation format introduced before.

Option (*x*)	**System variation range (V_x)**	**Relevant regimes (R_x)**	**More untangled (DSSU^{+0}) *or* (3)**	**Less untangled (DSSU^{-0}) *or* (-3)**	**Less failing elements (DSSU^{0+}) *or* (1)**	**More failing elements (DSSU^{0-}) *or* (-1)**
A	-4 ↔ 4	α, β, γ, δ	No switches between corridors	Switches to both neighbouring corridors	Switch failure rate -20%	Switch failure rate +20%
B	0, 3	α, β, γ, δ	Only requesting switches	-	-	-
C	-4 ↔ 4	α, β, γ,	Separate relay house per corridors	Single relay house for Utrecht	Relay house failure rate -20%	Relay house failure rate +20%
D	-3, 0, 3	α, β, γ, δ	No connections between corridors	Merging A2/A12 and directions	-	-
E	-1 ↔ 4	α, γ	Separate interlocking per corridor	-	Interlocking failure rate -20%	Interlocking failure rate +20%
F	-1 ↔ 4	α, γ	Separate EBP per corridor	-	EBP failure rate -20%	EBP failure rate +20%

Table 7.2 Details and range of variations per untangling option

$$x \in \{A, \dots, F\}, \qquad V \in \left\{ \begin{bmatrix} -4, \dots, 4 \\ 0, 3 \\ -4, \dots, 4 \\ -3, 0, 3 \\ -1, \dots, 4 \\ -1, \dots, 4 \end{bmatrix} \right\}, \qquad R \in \{\alpha, \beta, \gamma, \delta\} \tag{7.3}$$

Based on Table 7.2 or formula (7.3) the total number of possible scenarios can now be calculated taking into account the range of all untangling options. As the calculation in formula (7.4) shows, the total number of scenarios is over 69,000, which is obviously too large for all to be modelled. The number has been found by multiplying the internal product of the ranges of *V* by 4, which then pretends that each system design variation is relevant to be run under all 4 regimes of R_x. Since this is not true, the amount of scenarios in which only variations in C, E or F are made, which are not relevant under the β and/or δ regime, is subtracted from the total number (in two batches, one for the δ regime and one for the β regime).

$$N_{scenarios} = (9 \cdot 2 \cdot 9 \cdot 3 \cdot 6 \cdot 6) \times 4 - (1 \cdot 1 \cdot 9 \cdot 1 \cdot 6 \cdot 6) \times 1 - (1 \cdot 1 \cdot 1 \cdot 1 \cdot 6 \cdot 6) \times 1 = 69{,}624 \tag{7.4}$$

A further selection is necessary to come to an acceptable amount of scenarios, but to do so the details of all variations need to be explained. The following subsections discuss the variations and range of each untangling option and provide the necessary details.

7.4.1.1 Generated scenarios for option A (Switches)

Option A fully exists in the possible range of system design variations (V_x) and is also relevant under all regimes, with the single exception that the standard VSMs cannot be applied directly if the track layout has changed by the extra or removed switches. In that case some adjustments to the VSMs will need to be made without changing the philosophy of the current VSMs. Obviously, under the β regime these adjustments are always made for every untangling option and will not follow the standard VSM philosophy. In the standard VSM philosophy trains cannot deviate from their regular slot and are cancelled if a conflicted route cannot be avoided. Intentionally delaying trains or letting trains depart ahead of schedule is not allowed (Ministry of Infrastructure & Environment, 2014b), (ProRail, 2014c).

In the more untangled system all switches between corridors have been removed, see Figure 7.11 in which the removed switches are shown in red and see appendix G in which the train corridors have been plotted onto the track layout of Utrecht. If a crossover is located *between* two corridors, it is removed in the more untangled variant. If the crossover is located *within* a corridor, it is not removed.

In the less untangled scenario switches have been added to the DSSU design (green in Figure 7.11) and the red switches have been kept. The applied rule was that an extra switch pair is added (if it was not already present) between two neighbouring corridors in *both directions* (for trains running from North to South and from South to North) both North and South of the platforms of Utrecht. Therefore in some cases four switches have been installed between two corridors, as was the case between the VleuGel and A12 corridors.

Naturally, an increased/decreased functional failure rate of switches is used as alternative measure.

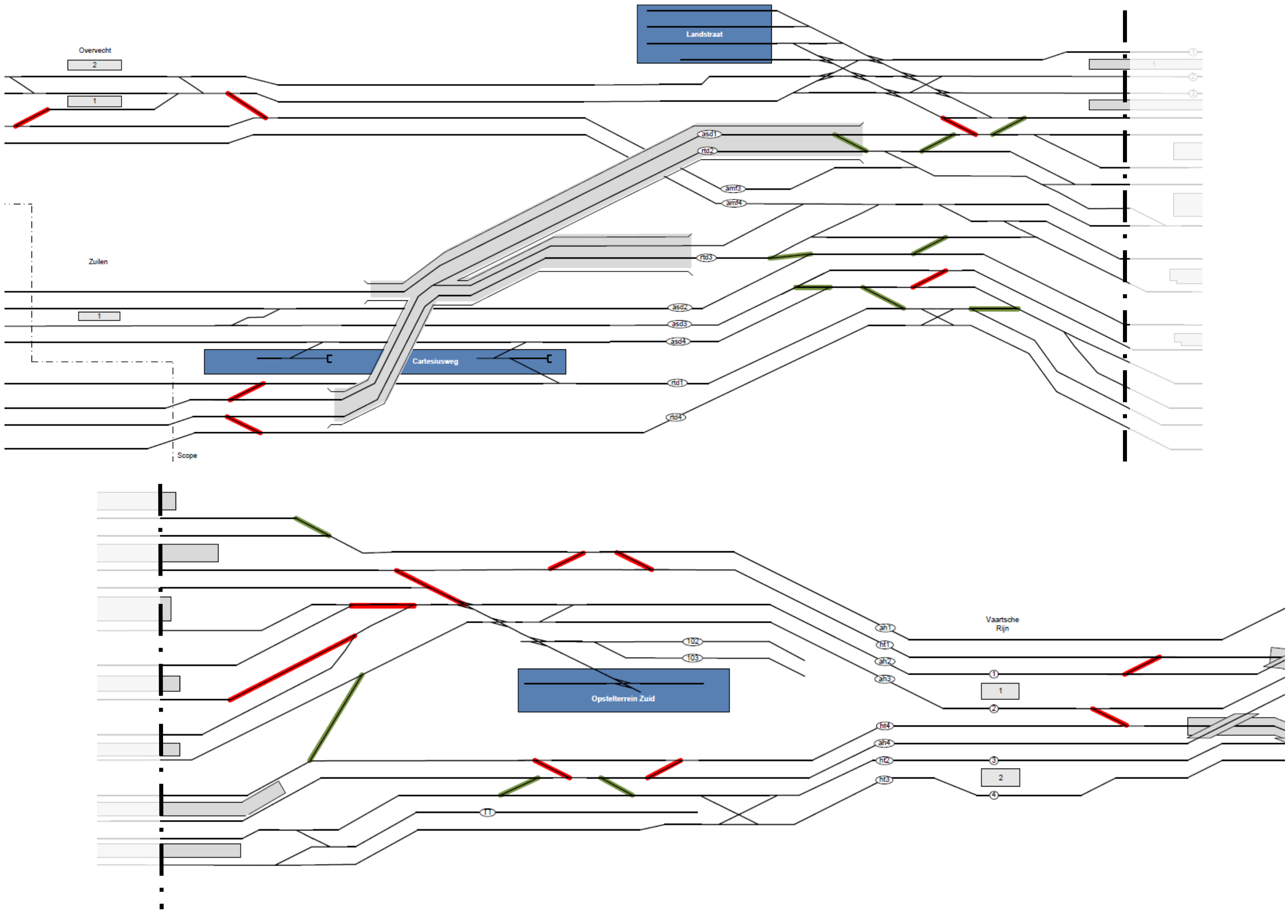


Figure 7.11 Location of removed switches (red) and extra installed switches (green) at both the northern side (top) and southern side (bottom) of Utrecht

7.4.1.2 Generated scenarios for option B (Requiring switches)

Option B is strongly related to option A as it is cancelled out by A due to the way option B has been defined in section 4.2: removing the ‘required position relation’ of a switch pair between two corridors. Obviously, if the switches between corridors are removed, this option does not make sense anymore. But, an additional advantage of this option is that it also has an effect on the switches that lie within the corridor. This makes a scenario with the combination of fully untangled option A and a variant of B still possible, even though technically option B would not be an untangling option anymore then, but an element failure rate reducer (It reduces the amount of time a switch cannot be used up to 50%).

Untangling option B therefore on the one hand tends to be more similar to a modelling regime than an actual untangling option, but on the other hand the design of the interlocking requires modification if this option is used, which makes it a system design variation and thus a true untangling option. The amount of system design variations is limited though, the system is either tangled (current situation, pairs with required positions) or more untangled, but never more tangled. The failure rate decrease alternative does not exist either: as explained before the relief of the required position relation between two switches functions as an element failure rate decrease for the switches that lie *within* the corridors. A clear alternative measure would be a decrease in the failure rate of the switches in general, which has already been used as alternative for option A. See appendix I for an overview of all switches that require positions of neighbouring switches.

7.4.1.3 Generated scenarios for option C (Relay houses)

The third selected untangling option exists in all possible variations, but not under all regimes. Relay houses are located next to the tracks and executing engineering works on them does not require tracks to be taken out of service to create a working area. Modelling this variant under the δ regime would therefore not be relevant.

As untangling variations, the more untangled scenario consists of six relay houses, one for every corridor – except for freight trains and ICLedn, as they do not have any dedicated infrastructure – and the less untangled scenario consists of a single house which holds all relays of the station area. Assumed is that the distance between this single relay house and the infrastructure elements does not exceed the maximum cable length. The alternative measure is trivial and comprises the decrease relays house failure rates, which could for example be achieved by installing extra protective elements such as poles in front of the house that prevent damage caused by vehicle collisions.

7.4.1.4 Generated scenarios for option D (Subsidiary circuits)

In DSSU the subsidiary circuits more or less follow the train corridors, but a few exceptions have been made due to technical reasons. The exact scheme of Utrecht can be found in appendix H.

In the more untangled system design variation, each corridor in each direction forms its own subsidiary circuit, of which most are fed from both the southern and northern power station. The NO and Buurt corridors are supplied by only the northern power station. To overcome the physical distance between the A2/A12 merging points and the northern power station, two extra cables are assumed to be installed: one to the end of platforms 5 & 7 and one to the end of platforms 18 & 19, where the A12/A2 tracks merge/split. In the less untangled variation the circuits are merged per 2 tracks, the merged subsidiary circuits are shown in Table 7.3.

Southern side	Northern side
1+2	2+NX2
3+4	3+4
5+6	NX1+SX1
	5+6

Table 7.3 Overview of merged subsidiary circuit IDs

A solution that would decrease the failure rate of the related incidents seems not directly available, so unfortunately these variations do not exist for this untangling option. The scenario is relevant under all effect calculation regimes.

7.4.1.5 Generated scenarios for option E (Interlocking)

The current interlocking based on relay technology is one large electrical chain of components that sends electrical signals to the infrastructure elements based on the position of relays and control signals send from the EBP. In the more untangled variation 6 separate smaller interlocking devices are installed that exchange information through the EBP or separate cables, instead of through the wires that are part of the interlocking's electric circuit. A less untangled alternative does not exist, there is already only one interlocking for the whole area. The variations of system designs with different functional failure rates consist of the use of different interlocking types (such as VPI (Alstom, 2015)) that have a lower or higher failure rate.

Because the unavailability of the interlocking leads to the unavailability of the whole station area, effect calculation regime β is not relevant: no trains can be run. For option C, where the failure of a complete relay house also leads to the unavailability of a large part of the station area, the β regime is still interesting: due to the long repair time of the related incident types, a very much reduced train service might be possible over the uncontrollable tracks, which are not described in the VSMs (WDR, 2016). For the shorter interlocking failures, the start-up of this extremely reduced service is not plausible.

For the same reason as explained in section 7.4.1.3 regime δ is not relevant, namely the absence of the necessity for the related incident types to carry out repair works near the tracks.

7.4.1.6 Generated scenarios for option F (EBP)

The variation possibilities for this untangling option are similar to the variations described for option E. It is even discussable if this option can be installed without installing option E, or in other words if multiple EBPs can send signals to the same interlocking. Because this division of corridors over various EBPs has never been done before, this cannot be verified; the two options are therefore treated here as independent of each other.

Again, only a more untangled variation exists, namely having six EBPs instead of one. Less than the current one EBP is not possible. Measures to decrease the failure rate of the EBP represent the alternative system design variations, and could for example consist of a modernisation program for the relatively old software. From the regimes under which the effects could be calculated, only α and γ are relevant, because of the exact same reasons as described for option C.

7.4.2 Selection of scenarios

The amount of possible variation combinations is unfortunately too large and not all of them might be evenly interesting to be modelled. This section will select the set of scenarios that will be modelled in the next chapter. Although not every possible scenario will be modelled, the model will be built in this way that it is capable of processing every thinkable combination of untangling options and variations under every regime. If the results from the selected scenarios will trigger the need for more scenarios to be modelled, this can easily be done. Besides that, an objective of this thesis is to develop a modelling tool that can be used for assessing the effectiveness of untangling in large station areas, which therefore requires a tool that can model all possible combinations.

Easily indicating which scenario is discussed or shown in a picture or graph requires an unmistakeable scenario notation. Following the variation framework defined in section 7.3, the scenarios are identified by a matrix with six numbers that correspond to the used variation for each of the six untangling options. The meaning of each number (between -4 and 4) is shown in Figure 7.9. To denote the calculation regime the effects of the scenario are modelled under, the corresponding Greek letter is added to the right top corner of matrix.

Please beware that the notation does not represent any mathematical formula or operation. As example, the IDs of the three scenarios that will be discussed in the next paragraph have been written down below.

Base scenario: $\begin{bmatrix}0\\0\\0\\0\\0\\0\end{bmatrix}^{\alpha,\beta,\gamma,\delta}$ Maximum scenario: $\begin{bmatrix}4\\3\\4\\3\\4\\4\end{bmatrix}^{\alpha,\beta,\gamma}$ Minimum scenario: $\begin{bmatrix}-4\\0\\-4\\-3\\-1\\-1\end{bmatrix}^{\alpha,\delta}$

7.4.2.1 Base, minimum and maximum scenario

The starting point is a base case which will function as a point of reference for the other scenarios. A logical base case would be the current situation of DSSU modelled under all four effect calculation regimes, previously represented as six zeros.

Besides a base case, defining a maximum and minimum scenario could be useful as well in order to get an idea of the range of the results. The problem is that it is not yet known which variation combinations will give the minimum and maximum value of robustness. For the element failure rate system variation, the combination that will give the optimum and worst result can easily be reasoned: installing elements with low failure rates and all elements with high failure rates. For the untangling extent variation this is not so easy, hence the need for this research, but for consistency reasons the maximum extent and minimum extent of untangling are assumed to be most robust. If this is a false hypothesis, it will show in the results of other scenarios and a new maximum or optimum could be defined. In the (assumed) maximum scenario the δ regime is irrelevant: not having working space will never lead to a more robust system. On the contrary, the same holds for the β and γ regimes in the minimum scenario: shorter incident repair times or better use of remaining infrastructure will also never lead to a less robust system.

7.4.2.2 Other scenarios

The other scenarios should first of all focus on identifying the individual variations' influence or effects on the robustness of the system. A straightforward method of investigating these individual effects is modelling the effects of a single change made in the system's design. In order to make the amount of scenarios manageable, it is decided to only create scenarios in first instance, in which single variations have been made in reference to the base scenario. This will be sufficient for answering the research question and leave the option open to model combinations of variations that seem promising based on the first results of the set of single variation scenarios.

A variation direction that is probably not the most interesting to investigate immediately is the use of elements with increased failure rates. Complex stations often function as a large and important node in the rail network and if they are redesigned the best possible techniques and elements are most likely to be used there. The scenarios containing a variation of elements with increased failure rates (-1) are therefore in first instance excluded.

With these two selection criteria, the number of scenarios besides the base, maximum and minimum scenario has been limited to 41 (with the base, minimum, maximum scenarios under all regimes 50 in total). The matrix of six digits (V) that indicates the variations used in the scenarios therefore always contains five digits with a value of 0 and one with -3, 1 or 3. No selection has been made on the effect calculation regimes these variations could be modelled under, as no clear indications are present which ones are most relevant or interesting. An overview of the 41 selected scenarios besides the base, maximum and minimum scenarios is shown in Table 7.4. The right column indicates the number of single variation scenarios per untangling option which has been calculated by multiplying the number of variations by the number of regimes.

Untangling option (x)		Selected variations for single variation scenarios (V_x)			Regimes (# (R_x))	Scenarios (#)
A	**Switches**	More untangled	Less untangled	Decreased failure rate	x 4 (αβγδ)	= 12
B	**Required positions**	More untangled			x 4 (αβγδ)	= 4
C	**Relay houses**	More untangled	Less untangled	Decreased failure rate	x 3 (αβγ)	= 9
D	**Subsidiary circuits**	More untangled	Less untangled		x 4 (αβγδ)	= 8
E	**Interlocking**	More untangled		Decreased failure rate	x 2 (αγ)	= 4
F	**EBP**	More untangled		Decreased failure rate	x 2 (αγ)	= 4

Table 7.4 Overview of single variation scenarios that will be modelled in this research

Section summary

From all the untangling options selected in the previous section, 50 scenarios have been created that can be modelled to assess their robustness. The scenarios vary in extent of untangling per untangling option, element failure rate, incident management measures, presence of safe working areas and incident duration. The current design of DSSU functions as point of reference, therefore in every scenario the extent or related failure rates of only one untangling option is adjusted. Table 7.4 provides an overview of the modelled scenarios besides the maximum, minimum and base scenarios depicted on page135.

8 Model development

In this chapter an existing model found within ProRail is modified in order to assess the robustness of previously created scenarios. The approach of this chapter is split in two basic parts, first the specifications for the model will be deduced (section 8.1) before the actual model will be developed (sections 8.2 and 8.3). In Figure 8.1 these two steps of the research approach are visualised once again.

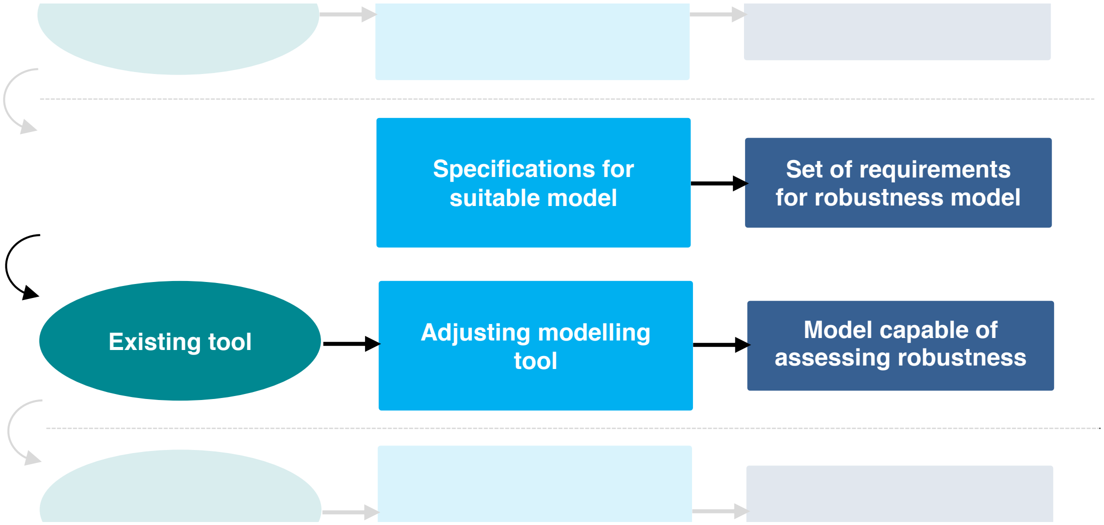


Figure 8.1 Steps of the research approach described in section 8.1 and in sections 8.2 and 8.3

8.1 Model requirements

From the scenarios developed in the previous chapter the robustness needs to be determined, which will be done by calculating the expected number of cancelled trains since robustness has been defined as such. This section will state what capabilities the model should have in order to facilitate this calculation and will elaborate on which incident types need to be included.

8.1.1 General modelling mechanism and requirements

In chapter 4 a methodology has been used to translate incidents into infrastructure unavailability and to see if, based on this infrastructure unavailability, a partition could be made between relevant untangling options with high potential benefits and less relevant untangling options with low potential benefits. In this stage of the research, this approach needs to carried one step further and the logistical component of the untangling options, which in general has been ignored previously, will have to be taken into account to some extent now. Figure 8.2 shows a visualisation of the three steps this model has to take: incidents will (could) lead to unavailability of infrastructure which will (could) lead to the cancellation of trains.

Figure 8.2 Steps to be followed by the model

The challenging part of this research on the one hand is that changes in the system layout can lead to changes on both the incidents side as well as on the unavailability of infrastructure side, while on the other hand the effect the infrastructure unavailability has on the robustness strongly depends on the way incidents are handled. These interdependencies need to be captured and be adjustable in the model to assess all specified scenarios. Each of the three steps of Figure 8.2 will be discusses below.

8.1.1.1 Incidents

The impact the various scenarios have on the incident side is mostly limited to the incidents' frequency of occurrence. For instance the removal of switches will obviously lead to a reduction of the frequency of switch failures. Another impact of the scenarios could be on the average duration of an incident, especially scenarios in the γ regime for which the reduction of repair time take a centre stage. The model requirements for the incident side are therefore defined as *the presence of the functionality in the model to adjust the incident frequency and average duration* per incident type.

8.1.1.2 Infrastructure unavailability

The way the system is designed influences which parts of the infrastructure become unavailable when an incident occurs. For example the design of the subsidiary circuits in the energy subsystem determines which tracks will be powerless when a faulty pantograph causes a short circuit at a certain location. A different design in a different scenario will therefore lead to a different unavailability, which will need to be adjustable in the model. A requirement of the model is therefore that *the tracks in station area have to be dividable in to smaller sections, at least to the level of 'links'*, meaning a piece of track between two switches or between a platform and a switch that forms a single unit (on which there is only one route possible per direction). In Figure 8.3 two of these 'links' have been indicated by a blue line, the word 'section' could be confusing here as a link can consist of multiple track detection sections. The word 'link' has been chosen in reference to a link-node representation of networks.

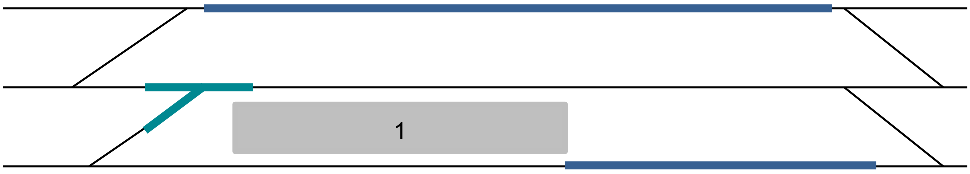


Figure 8.3 Two 'links' (Dutch: spoortakken) visualised in blue, and a switch section visualised in green

A switch or pair of switches in this case could be regarded as a link as well – it is actually a node – taking into account that the 'connecting' track between the switches by itself cannot be a link, as it shares the safety envelope and track detection section with the part of the 'straight' track around the switch.

For each of these links the availability has to be adjustable and combinable so that the various incident types can be translated into infrastructure unavailability. Some variations between the scenarios can then be modelled by adjusting the link combinations and their unavailability.

Another group of differences between the scenarios, in particular related to the switch untangling options, will be covered by adjusting the track layout or introducing a new one. The model should therefore facilitate adjustments in the infrastructure.

8.1.1.3 Logistical effect

As stated before, the logistical effect of the various scenarios, or in other words the expected amount of cancelled trains is most important to be taken into account. The model should *identify which trains are affected by a certain unavailability in the infrastructure and allow for or even suggest an adjustment of the timetable*. These adjustments should in the first instance be based on ProRail's VSMs, but since the difference between α and β regimes in the scenarios is that the latter does not use VSMs, these adjustments should be amendable. The required output of the model is straight forward: the (expected) number of cancelled trains.

8.1.2 Scenario compliance check

In the previous paragraphs the required mechanism for a general modelling tool that should be able to find results that will help answering the research question has been explained. Developing a model that can assess the robustness of a system and can help in providing insight in the untangling strategy is only a part of the goal of this research. The other part is finding an answer to the question which untangling option is most effective, for which Utrecht station has been selected as case study. In the previous section the compatibility of the modelling mechanism requirements with the developed scenarios for Utrecht station has already been mentioned briefly at some points. In this paragraph, the coverage of the requirements that follow from the generated scenarios in the previously introduced modelling mechanism will be discussed and checked.

Scenarios for options A and B are related to the location, amount and interrelation of switches, see section 7.4.1. The requirements that follow for the model are adjustable track layouts (extra or fewer switches), adjustable switch failure rates (better or worse performing switches) and breakable simultaneity of unavailable switches (removing the connection of switches through the safety subsystem). The first must be handled through variation options in the track layout, the second could be implemented through amendable incident frequencies while the third is related to which unavailability of infrastructure occurs simultaneously. Concluding, for the scenarios of options A and B there does seem not to be more requirements for the model than mentioned in the previous section.

Scenarios for options C, D, E, and F are comparable, as the track layout of the system design is not influenced by these scenarios but only the frequency and duration of incidents and the parts of the infrastructure that will be unavailable simultaneously. The functionality in the model that is needed for that has been covered in the previously described mechanism.

8.1.3 Required incident types & compliance check

Besides the requirements for the model that follow from the developed scenarios, the types of incidents that need to be modelled could influence the requirements for the modelling tool as well. Before it can be assessed whether the requirements for the model that follow from these incident types have been covered in the previously described requirements, a decision has to be made on which incident types the model should be able to handle.

A logical decision would be to include the incident types that have been related to the selected untangling options in chapter 4. For some of these incident types it would be of no use to distinguish between certain 'subtypes', such as a faulty switch caused by a motor fire and a faulty switch that is simply labelled as 'out of control'. Merging these two related incident types into 'faulty switch' would only make sense and moreover reduce the complexity of the model.

The left columns Table 8.1 show the incident types related to the selected untangling options as they were identified in Table 4.11 and in the right columns the simplified incident group the individual incident type could be covered by. The middle columns refer to the untangling option these incidents types are related to. Grouping these incident types has led to a reduction of incidents from 16 to 7, taking into account that that the same incidents types related to option B are also related to option A and therefore should not be counted twice.

Related Incident type	Option	Modelled incident	Related Incident type	Option	Modelled incident
Contact line - damage	D	Partial power loss	**Relay house – Damage**	C	Relay house failure
Lightning damage	D	Partial power loss	**Relay house – Damage**	C	Relay house failure
Short circuit	D	Partial power loss	**B-relay failure**	E	Interlocking failure
Power switch failure	D	Partial power loss	**Faulty fuse**	E	Interlocking failure
Faulty train	A	Faulty train	**General ATP failure**	E	Interlocking failure
Switch out of control	A	Faulty switch	**Switch out of control**	B	Faulty switch
Switch motor fire	A	Faulty switch	**Switch motor fire**	B	Faulty switch
Snow/Ice in switch	A	Faulty switch	**Snow/Ice in switch**	B	Faulty switch
ES weld failure	A	Section failure	**POST21 – EBP failure**	F	Operation failure
Fire damage	C	Relay house failure			

Table 8.1 Related incident types found in chapter 4 and the corresponding incident groups that will be used in the model

A point of discussion that should be mentioned here, is that these incident types have been selected based on a different criterion. An incident type was labelled as relevant if the impact of an incident type could have been kept within the corridor of occurrence when the untangling option in question had been installed (see section 4.3). This way of reasoning is actually focused on the preventing the spread of *infrastructure unavailability* to other corridors instead of preventing the spread of *train cancellation.* As a result of that, there are incident types from which the logistical impact is certainly influenced by the concerned untangling option, even though they have not been identified as related. An example of this situation is the incident type ‘broken cable due to construction works’, which has not been flagged as related to untangling option A (Removal of switches between corridors), while its logistical impact is certainly influenced by this option. When this broken cable leads to the unavailability of a train corridor in the station area, the amount of trains that will be cancelled because of this strongly depends on the fact whether these trains can be rerouted over the infrastructure of neighbouring corridors. Taking this into account, the right approach to neutralise this point of discussion is to model all thinkable incident types, which is impossible due to time restrictions. In the recommendation section this matter will be elaborated on.

The second goal of this section is to check whether the identified incidents that will need to be modelled for the case study are covered in the model requirements as stated in section 8.1.1. On first sight, all seven incidents could indeed be represented by a simultaneous unavailability of several infrastructure links or nodes, which is in line with the previously stated requirements.

8.2 Available risk analysis tool within ProRail

Developing a modelling tool from scratch is a lengthy process and requires extensive programming skills. For the sake of efficiency and to enhance the usability of the tool within ProRail, several existing modelling tools within ProRail have been assessed to see if one of them meets the requirements stated in the previous section. In this way, the focus can be laid on modelling the large amount of scenarios instead of programming the basic functionalities of the modelling tool. Besides that, the barrier for ProRail to use the modelling approach again in other case studies will be lifted as well.

Unfortunately, none of the assessed modelling tools within ProRail did meet all the requirements. Nevertheless, it was discovered that one model named ‘RA-tool’ (Risk Analysis tool) uses a similar modelling mechanism as was proposed in section 8.1.1 and did meet some of the requirements as well. It was developed for ProRail to quantify the reduction in switch related incidents, affected trains and caused knock-on delays if a certain switch in a station area would be removed. By knowing these impacts per switch in a station area, it supports ProRail to decide which switches are most interesting to remove, to upgrade or to maintain more intensively (CQM, 2016).

Adjusting this tool in a way that it is able of modelling the scenarios is assumed to be easier than completely building a model from scratch. The RA-tool has therefore been selected as preferred modelling tool and will be explained in this section in further detail. Figure 8.4 shows the RA-tool that has been developed for ProRail by a company called CQM.

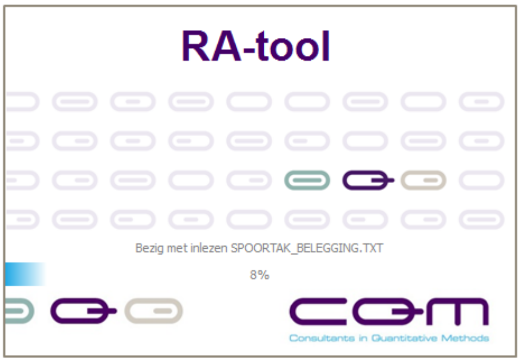


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Figure 8.4 RA-tool that was developed for ProRail by CQM

8.2.1 Modelling mechanism

The RA-model consists of five different steps in which the user has to provide input or state the preferred settings of the model. Figure 8.5 shows these five steps, which will be discussed step by step in this section. The (external) input, the transformation that takes place in a step and the output that is passed on to the next step will be described per step.

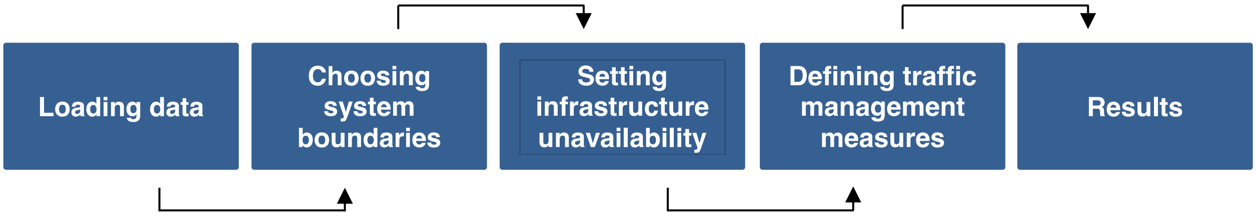

Figure 8.5 Five steps of the RA-tool

8.2.1.1 Loading data

Naturally, the first step of the tool is to load the necessary data into the model. The RA-tool needs four different input files: infrastructure (DONNA - InfraAtlas file), timetable (DONNA – BU timetable file), a list of switches that form pairs (text file composed by ProRail Asset Management department) and passenger numbers (text file composed by ProRail Timetabling department). Not all information in these input files will be used, the tool filters the information to create a node-link representation of the infrastructure that consists of a sequence of switches and track detection sections. The routes of the train series found in the timetable are plotted over the infrastructure and the individual sections and switches they use are linked to these train series. An average number of passengers is also attached to each of these train series.

Summarising the output of this step; the tool created a link-node representation of the infrastructure and a list of train series in which all used infrastructure elements and the average number of passengers are stated. The infrastructure representation or track layout becomes fixed in this step, making it impossible to change it in a later modelling stage. This is not in line with the requirements set for modelling the DSSU scenarios and therefore needs to be solved before the modelling work can commence.

8.2.1.2 Choosing system boundaries

From both the created infrastructure representation and the train series that use the infrastructure a physical scope needs to be selected. Boundaries should be set for the infrastructure in such way that the full scope of the intended project is covered, which sometimes requires to include more tracks than the geographical code ProRail uses for location represents. For the train services a selection needs to be made from the list of train series that run in the selected area and for all these series the general hourly frequency has to be confirmed. The selection is required because ECS trains, night services, freight train paths that exclude each other and services that only run occasionally are also included in the list. Depending on the purpose the tool used for these trains can be included or excluded. In principal, the tool could use the frequencies of train series as stated in the timetable, but since the number of train paths found in the BU file sometimes can deviate from real frequency, they have to be confirmed manually.

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The output of this stage is similar to the output of the previous stage, only has the area and included train series been scoped down from nation-wide to a suitable project scope.

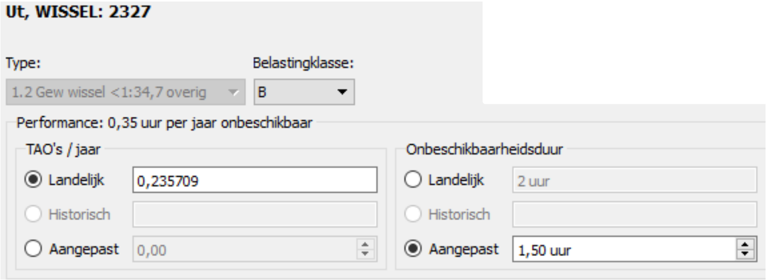
8.2.1.3 Setting infrastructure unavailability

Setting the unavailability is an extensive process and one of the most crucial stages of the model. The RA-tool has identified all switches and asks the user to specify for all of them how many hours per year they are unavailable. The unavailability is calculated by the product of the frequency of switch failure occurrences and average duration of these failures which both can be set manually. Formula (8.1) shows the definition of unavailability U of infrastructure element k as the product of failure rate ρ and average incident time *FR (Functional repair time)* which both (can) vary per infrastructure element.

$$U^k = \rho^k \times \overline{FR}^k \tag{8.1}$$

For the failure frequency this manual setting is not necessarily required, as unavailability data of all switches in the Netherlands from the period 2013 to 2015 is available in the tool. When a specific switch is available, the tool will in first instance use this historical data, which unfortunately is not present for relatively new switches such as most of the switches in Utrecht station. In that case, a national average failure rate based on the type of switch and the quantity of trains that runs over it should be used. These failure rates are also available in the tool, but unfortunately need to be selected manually per switch.

Switches that form pairs through the safety subsystem (requiring switches), are automatically grouped in the tool, and the unavailability of the pair is calculated by summing up both switches' individual unavailability. If a group of two switches has been formed with a combined unavailability, the unavailability of the individual switches is no longer included in order to prevent counting the unavailability twice. Figure 8.6 shows the unavailability specification screen of the RA-tool, unfortunately in Dutch. In the picture, the national average failure rate for a 'standard switch with a smaller crossing angle than 1:34.5' with a load class 'B' has been selected for switch 2327 in Utrecht, with an adjusted average incident duration of 90 minutes.


Ut, WISSEL: 2327

Type: 1.2 Gew wissel <1:34,7 overig

Belastingklasse: B

Performance: 0,35 uur per jaar onbeschikbaar

TAO's / jaar
● Landelijk 0,235709
○ Historisch
○ Aangepast 0,00

Onbeschikbaarheidsduur
○ Landelijk 2 uur
○ Historisch
● Aangepast 1,50 uur

Figure 8.6 Unavailability specification screen of switch 2327 in Utrecht

Besides switches, the RA-tool offers the possibility to specify unavailability of sections. Unfortunately, no automisation has been implemented there, so the failure rate and average incident duration have to be set manually for all sections. Utrecht consists of more than 200 sections, which illustrates the amount of effort it will take. The output of this stage is a list of sections, switch pairs and individual switches with their annual unavailability (hours per year).

8.2.1.4 Manually defining traffic management measures

Since the timetable and thus the indivual train routes has been developed with the same software as where the infrastructure input file has been delivered from (both DONNA), the RA-tool exactly knows which trains use which switches and sections. In the traffic management measure definition stage, the tool shows all trains that have been selected in the second stage and lists per train which sections and switches, when unavailable, block the route of the train. Only the switches, switch pairs and sections to which an unavailability has been assigned are listed including the ones that affect the train route in the opposite direction. For example, a switch that lies in the route of a train from Amsterdam to Nijmegen is also listed for trains from Nijmegen to Amsterdam (to prevent a rolling stock shortage/overflow at the end of the lines).

The user is asked to specify measures, which can consist of two types: cancelling the train, which has been defined as a delay of 60 minutes for all passengers, or delaying the train. If the latter is chosen, the delay can be specified in minutes including the possibility of a delay of 0 minutes to model rerouted trains. Each unavailable switch (group) or section that was listed to this train then needs to be assigned to one of these measures. This process needs to be repeated for all selected trains.

There are two main disadvantages attached to this way of defining the traffic management measures, besides the fact that it is extremely time consuming. The first is the lack of consistency between measures of different train series for the same unavailability. For example, the unavailability of switch 2327 in Utrecht is flagged as relevant for six different train series. For each of the six, the switch is assigned to a specific traffic mangement measure for that train, so the unavailability of switch 2327 asks for six measures for six train series. But, there is no consistency check between these six measures, resulting in the possibility that the six measures combined lead to an infeasible timetable. A more logical approach would be to specify measures per unavailability instead of per train series. Related to this disadvantage is the second disadvantage: the measures are not modelled at all and therefore not checked on infrastructure or timetable compliance in any way. For instance if a rerouted train meets the required platform length and train planning rules or if no other trains are hindered by the rerouted trains. It is up to the user to chechk this compliance before a train is flagged as rerouted or delayed. In general it can be concluded that there is a difference in level of detail between the very specific infrastructure and timetable input and the very rough way these traffic management measures need to be defined

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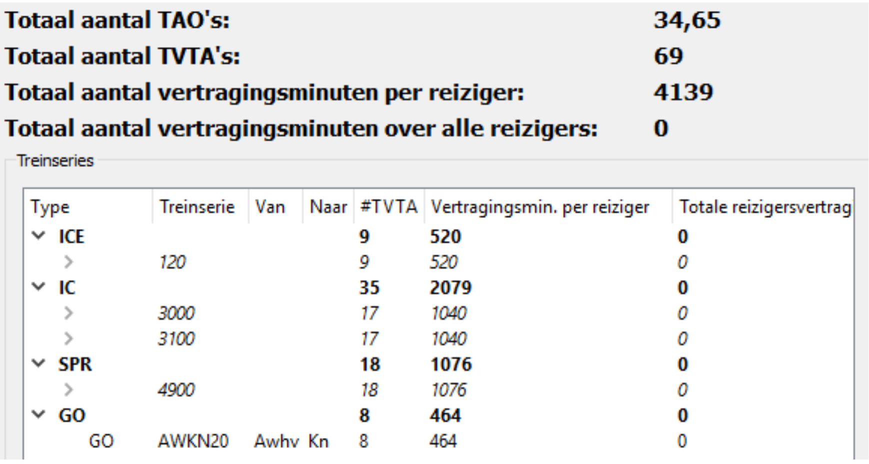
The output of this stage is a set of traffic management measures for each train series-unavailability combination that specifies exactly which trains are delayed or cancelled if a certain unavailability occurs.

8.2.1.5 Results

In the result stage the unavailability of infrastructure is multiplied with the corresponding traffic management measures and a single value for the system's robustness is produced. Formula (8.2) illustrates how this single value for robustness (*R*), the number of expected cancelled trains per year, is calculated. The yearly unavailability *U* (in hours) of infrastructure element *k*, which can be either a switch, section or switch pair, is divided by the service interval *f* between trains in corridor *c* and multiplied by the specific traffic management measure *M* for trains in corridor *c* in case of an unavailability of infrastructure element *k.* If trains of corridor *c* do not use infrastructure element *k*, $M^{c,k}$ will have a value of zero as it will not have been defined then. This process is repeated for all corridors in *C* and for all infrastructure elements in *K*. Accumulating the results leads to the number of expected cancellations *R.*

$$R = \sum_{k=1}^{K}\sum_{c=1}^{C} M^{c,k}\frac{U^{k}}{f^{c}} \qquad (8.2)$$

The tool is capable of exporting an extensive report exactly stating which train is delayed when and for how long. For larger stations though this table becomes very large and impractical to use. Figure 8.7 shows the summary of results generated by the RA-tool, unfortunately this overview is in Dutch. The first line shows the TAO's (Train Service Affecting Unavailability) or hours of yearly unavailability in the whole system (accumulated *U* for all infra elements *k*). TVTAs (Explainable Timetable Deviations) are the number of trains that was affected by these TAOs, the actual robustness R multiplied by 60 (cancelled train is counted as 60 minutes delay) is shown in the third line. Since the effects of timetable adjustments are not modelled only primary delays are taken into account, with exception of secondary delays caused by the fact that train series are always cancelled in both directions to prevent accumulation of rolling stock at one end of the line.



Totaal aantal TAO's: **34,65**

Totaal aantal TVTA's: **69**

Totaal aantal vertragingsminuten per reiziger: **4139**

Totaal aantal vertragingsminuten over alle reizigers: **0**

Treinseries

Type	Treinserie	Van	Naar	#TVTA	Vertragingsmin. per reiziger	Totale reizigersvertrag
ICE				**9**	**520**	**0**
	120			*9*	*520*	*0*
IC				**35**	**2079**	**0**
	3000			*17*	*1040*	*0*
	3100			*17*	*1040*	*0*
SPR				**18**	**1076**	**0**
	4900			*18*	*1076*	*0*
GO				**8**	**464**	**0**
GO	AWKN20	Awhv	Kn	8	464	0

, Figure 8.7 RA-tool result overview with fictional numbers

8.2.2 Time and incident component

In section 8.1 the modelling mechanism that would be needed to answer the research question has been specified. An important difference with the mechanism of the RA-tool is that the tool skips the incident step and starts with unavailability. The frequency of occurrence and duration of incidents has directly been translated into a failure rate and average infrastructure unavailability duration. As a result of that the way time is modelled requires extra attention.

To start with an example, if the unavailability of a certain infrastructure element has been defined as 24 hours per year, when do these hours occur? Are those 24 peak hours, hours during the night, off-peak hours or a combination? The RA-model makes a certain distribution between peak hours (all trains run according to specified frequency) and nightly hours (no trains run), but this distribution is not linear: the first 18 hours are counted as peak hours, the next 8 as nightly hours, the following 18 as peak hours again and so on. As a consequence of this method, there is no difference between an unavailability of 19 and 23 hours while there is a difference between 17 and 19 hours of unavailability, which is rather strange.

Another interesting result of the way incidents are (not) modelled in the RA-tool is the assumed additivity of incident impact. An incident or failure that blocks the track for two hours will probably have a much larger impact than four independent incidents that block the track for 30 minutes (not simultaneously of course). When a track is blocked for two hours a VSM will have been put into practice with the result that staff rosters and the rolling stock planning have been subjected to many changes. Returning to an operation according to the timetable will take longer than when simply one or two trains had to be delayed or cancelled as a result of a 30 minute incident. These differences in impact per incident do not come to expression in the RA-tool in any way.

8.3 Model modification

In the previous sections the model requirements needed for answering the research question have been specified and an existing tool has been described that met most of these requirements. Nevertheless, at some points this RA-tool will need to be adjusted or reprogrammed as there were discovered some insurmountable deviations from the specified model. This section will describe the adjustments that have been made to the RA-tool in three different categories: general adjustments, adjustments to model the incidents and adjustments to model the scenario variations. In the last section the developed state and usability of this adjusted model will be explained.

8.3.1 General modifications

The only general modification that needs to be made is related to the time component that is used in the tool, which has been discussed in section 8.2.2. Instead of using the time component the way it is used now, the number of peak hours per day is set to 24 hours. By doing so there is no longer a differentiation in hours across the day and the difference between 10 and 15 hours of unavailability becomes equal to the difference between 20 and 25 hours; in both cases now the difference is five peak hours and the amount of affected trains thus five times the hourly frequency of the related trains. To compensate for the fact that not all incidents occur during peak hours an extra term (p_{peak}) is added to formula (8.2), see formula (8.3).

$$R = \sum_{k=1}^{K} \sum_{c=1}^{C} M^{c,k} \frac{U^k \cdot p_{peak}}{f^c} \tag{8.3}$$

This term reduces the unavailability U of an infrastructure element k to the unavailability of an infrastructure element during peak hours (U^k x p_{peak}). The theory behind this is that all train frequencies during the night are zero and therefore any unavailability would not have an effect on the robustness. This effect is modelled by nullifying a part of the unavailability. By carefully balancing the value of the time factor p_{peak}, the peak period, off-peak period and night period can be simulated. The difficulty with estimating the time component is that there is a strong relation between the amount of trains and the amount of incidents. After all, the more a switch for example is operated, the higher the chance it will get out of control. On the other hand, a lot of failures are discovered during nightly checks which would implicate a smaller value of p_{peak}. Besides the distribution of incidents over the day the difference in frequency of trains in peak hours and off-peak hours also influences the time factor. The greater the difference, the smaller the time factor should be.

Since the difference in peak hour train frequencies and off-peak hour train frequencies is limited in Utrecht, and no information is available on the distribution of incidents over the day, the share of the nightly hours in the day is simply used as time component: 5/24 (00:00-05:00 AM) is equal to approximately 20%, which would implicate a time factor p_{peak} of 0.8.

8.3.2 Incident related modifications

The RA-tool is capable of modelling the unavailability of switches and sections, but to assess the robustness of the previously defined DSSU scenarios this is not sufficient. After all, the incident types that should be modelled have been summarised in Table 8.1 and comprise more than only section and switch failures. This section will describe how each of the incident types will be modelled, except for the switch failures, since there is no modification necessary.

The basic solution to use this tool for all other incident types was discovered when the RA-tool formed switch pairs to model requiring switches. Since the tool does not model incidents but directly translates them to infrastructure unavailability, specific groups of infrastructure elements could actually represent an unavailability that occurs simultaneously and thus mimic the impact of an incident. If any section and switch can be grouped and a specific unavailability can be assigned to that group, basically all incident types can be modelled.

Grouping sections and switches can be done by coding an input file that specifies which infrastructure elements to combine, similar to the way the switch pairs were formed. In contrary to the requiring switches, the individual infrastructure elements of a group should not be neglected but exist alongside the group. For example, if twenty sections form one subsidiary circuit that is unavailable for one hour per year, a group ‘subsidiary circuit X’ is composed with an unavailability of ‘1’. The individual sections also have unavailability as a consequence of possible ES-weld failures and therefore also need to be modelled as individual sections. For combined switches this is different: if one switch fails, the other one automatically fails as well through the requirements set in the safety subsystem. In that case, the individual switches no longer exist and should therefore be replaced by the switch pair.

8.3.2.1 Section failure

Track clear detection sections can fail for difference reasons, but the most common failure is an ES-weld failure (ProRail, 2016l). In that case, the safety systems detect a train on an empty track and prohibit setting a route for another train, with a red signal as a consequence.

Modelling a section failure in the RA-tool is probably the easiest incident type, since this functionality is already present in the tool. Nevertheless, an increase in efficiency can be made by grouping the sections per a link (link-node representation, see Figure 8.3), and considering these links as weighted sections. Without this step, the amount of work required to define the traffic management measures – which need to be defined per section unavailability – would be very large.

The blue lines in the bottom half of Figure 8.8 show how sections between switches can be grouped. The amount of sections, compared to the original shown in the upper half, is reduced. Depending on how many sections and switches there are, this reduction can easily reach levels of 70%. Although the sections are grouped, this is not achieved through the grouping mechanism as was explained in the previous section. In this case, the increased unavailability of one section in the group simply represents the unavailability of all the other sections as well, which can therefore be ignored. For the dark blue lines, one of the two sections is given an unavailability of zero (it will therefore not appear in the traffic management measures defining stage), the other one an unavailability twice as high as the section unavailability found in the incident data. For the light blue line three sections are given a value of zero and one an unavailability four times higher.

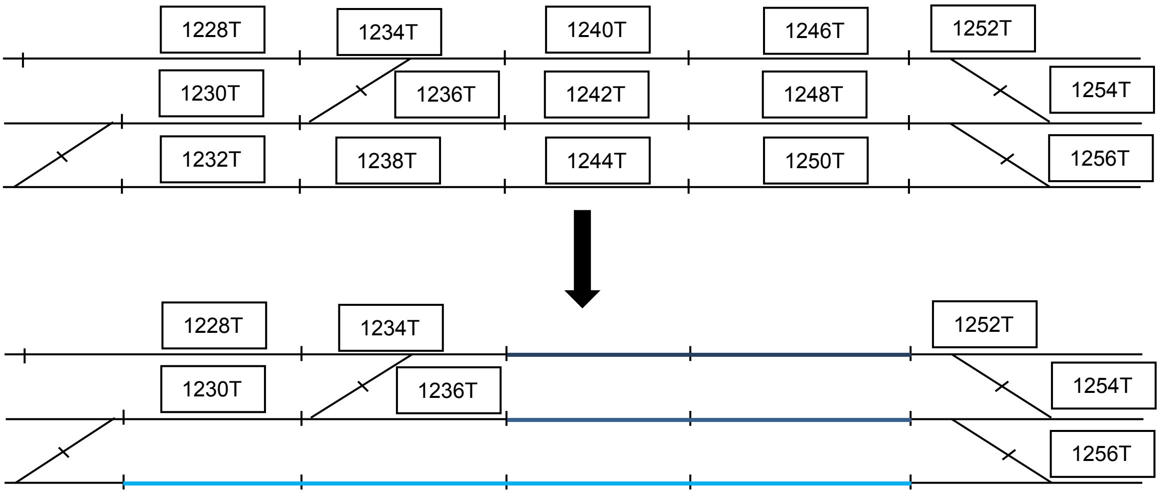


Figure 8.8 Reduction of number of sections. The blue lines represent three groups of sections

8.3.2.2 Partial power loss

The partial power loss incident is a collection of incident types that all lead to the same unavailability: one of the subsidiary circuits loses power. Although the way the subsidiary circuits have been designed should actually be represented by the infrastructure input in the model, the infrastructure input only comprises a track layout built from coupling switches and sections together. Therefore, the design will be represented by the combination of simultaneously unavailable switch sections.

Figure 8.9 shows four switch sections that form the representation of subsidiary circuit three in that area. By modelling them as simultaneously unavailable, the line of the subsidiary circuit becomes visible and all trains that need to use those switches are flagged as affected by this unavailability. Because the switch sections are used instead of the switches itself, switch pairs that require certain positions of each other remain effective during this unavailability.

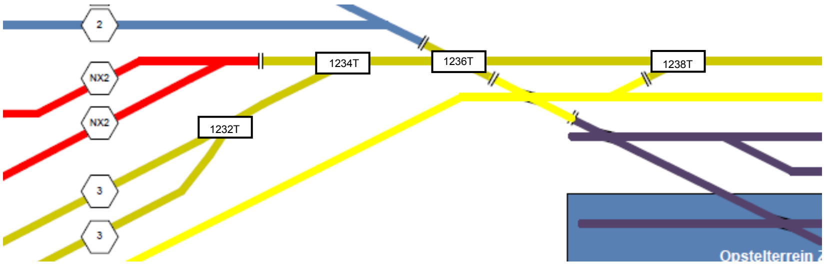


Figure 8.9 Part of the simultaneously unavailable switch sections that represent subsidiary circuit 3

In contrary to the previous incident, there is no weight added to these groups since there is no dominant failure mechanism here as was the case with section failures predominantly caused by ES-weld defects. Whether the size of the subsidiary circuit, the amount of crossing contact lines or the number of trains using it should be leading in determining the unavailability, is unknown. All circuits will therefore been given the same unavailability.

So, three separate steps, namely the system design, incidents that occur in that system and the unavailability of the infrastructure they lead to, are all modelled in a single step here. In the discussion section this matter will be elaborated on.

8.3.2.3 Relay house failure

A relay house failure is defined as an incident type that leads to the unavailability of all the equipment inside the building. Operation of switches and signals, track clear detection and communication on switch positions to the traffic control centre becomes impossible for the whole area under control by a relay house. To model this incident type, the same approach is used as for the previous incident. An input file needs to be written that groups sections that can represent the full reach of the relay house, or in other words flag all trains that run through the relay house control area as 'affected by this unavailability'.

Figure 8.10 shows an example of a relay house group (sections within the red lined plane). Likewise the approach for the subsidiary circuit group, the unavailability for each relay house group is equal, since the specific variables that determine the unavailability a relay house are unknown.

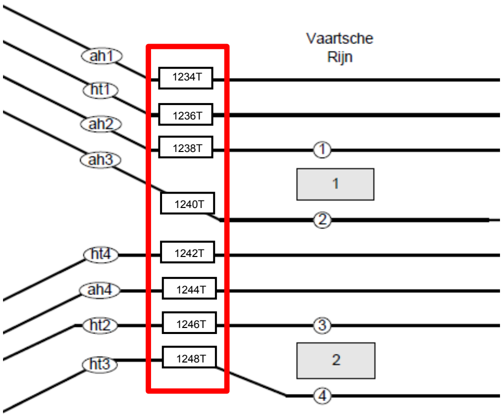


Figure 8.10 Example of a relay house group (DSSU South)

8.3.2.4 Interlocking failure and operation failure

An interlocking failure is a collection of incidents that have the unavailability of the interlocking as a whole as a consequence. An operation failure is defined as a problem with the PRL system that results in the impossibility of operating switches and signals from the traffic control centre. The incident types relay house failure, interlocking failure and operation failure can all be modelled in a similar way; by grouping sections that are unavailable simultaneously. Since the approach and required RA-tool modification for relay house failure have already been explained in the previous section, the interlocking and operation failures will not be discussed in further detail here.

8.3.2.5 Faulty train

Probably the most difficult incident type to model with the quite static RA-tool is the unavailability caused by a faulty train. In contrast to the previous incident types, this incident type is fully dependent on the logistical components of the system, or in other words the trains that use the station.

The most sensible way to represent a faulty train would again be a group of sections that is temporarily unavailable, but unfortunately the composition of these groups is not fixed, as was the case with the previous incident types. Each faulty train blocks a set of track sections during the incident, but which sections these are depends on the location, route and length of the train. A pragmatic methodology would be to explore all possible groups of sections contingent on the infrastructure layout and train routes in the timetable, and determine the unavailability of each of these groups based on the train frequencies. However, given that in chapter 4 was found that 83% of all faulty trains stood at the platform, which can simply be modelled by a single unavailable section, the added value of the proposed pragmatic methodology does probably not outweigh the large amount of required extra effort. An alternative methodology is therefore proposed which consists of two separate parts.

Approximately 83% of the faulty trains can be modelled by an unavailable single platform section. The value of the unavailability will be connected to the amount of trains that will use the platform. Seventeen percent of the faulty trains, which do not stand at the platform, will be modelled by assigning an extra unavailability to the track sections defined for the section failure incidents (see paragraph 8.3.2.1). Both parts have been visualised in Figure 8.11, in which the red section labels represent the platform sections and the white section labels the 'regular' sections (actually links – grouped sections – and switch sections) outside the platform area.

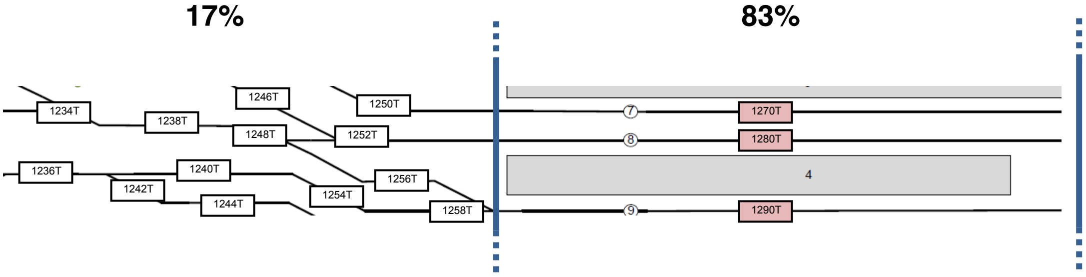


Figure 8.11 Faulty trains are modelled in two parts: 83% by dedicated unavailability in platform sections (red section labels, right side) and 17% by an unavailability addition assigned to section failures (white section labels, left side)

The amount of this addition to the 'regular' track sections' unavailability is independent of the frequency of trains that run over them, even though this is technically incorrect. Since the incorporation of the frequency is expected to lead to only very small differences in the results, this simplification is considered to be legitimate.

Another effect that is not modelled correctly by this methodology is that trains are often longer than a single section and faulty trains therefore also block more than one section. Representing 17% of the faulty trains as single section failures is too optimistic, but the effect is fortunately partially compensated by the fact that most sections are grouped in a link.

8.3.3 Scenario related modifications

This last section of the chapter focuses on the necessary modifications to the RA-tool that follow from requirements to assess all the scenarios specified in chapter 7. The scenarios vary on two different aspects: the system design and the regime under which the scenario is modelled. All regimes and system design variations will shortly be discussed.

8.3.3.1 Modelling the various regimes

The four modelling regimes – logical effect (α), increased utilisation (β), shorter repair times (γ) and absence of safe working space (δ) – all need to be modelled by the RA-tool. In the previous sections, the α regime has been assumed to be the standard and the compatibility with the use of VSMs in the traffic management measure stage of the tool has already been shown. The β regime is not so different from the α regime besides the fact that pragmatic traffic management rules are used instead of VSMs. Since the traffic management measures of the RA-tool are completely adjustable for the user and need to be set manually anyway, this will not trigger the need for a modification. Also the γ regime can easily be handled by the RA-tool, since this regime will simply lead to a reduction of the unavailability which is manually specified to the tool.

The only regime that requires a model modification is the δ regime, for which the unavailable infrastructure elements caused by incidents that require line-side repair works need to be grouped with neighbouring infrastructure elements. The incident types that require a safe working area are switch failures, section failures, faulty trains and partial power losses. For these types input files need to be written that add the neighbouring sections to unavailable infrastructure elements, which is equal to the way sections have been grouped to model incidents.

8.3.3.2 System design variations

In section 7.4.2 in Table 7.4 an overview has been displayed of the various scenarios that will be modelled for this research. The variations in system design shown there can be placed in two different categories: increased/decreased failure rates and more/less untangled. The first category can be modelled in the RA-tool by simply adjusting the unavailability of the related infrastructure elements and is therefore comparable to the approach taken to model the γ regime. The second category on the other hand cannot (fully) be modelled in that way and requires a different approach.

Most of the system design variations from the second category do not require a model modification. The system design variations of B, C, D, E and F scenarios have already been discussed in the previous sections: it was stated there that the explained modifications translate the system design, incidents that occur in the system and unavailability of infrastructure they lead to, into a group of simultaneously unavailable elements. Variations in the system design can therefore simply be handled there.

For the A scenarios this is a different case, as the system design is related to the track layout of the system, which is inserted into the model as input file. Unfortunately, the RA-tool offers no opportunity to adjust the track layout and advises to create two separate RA-tool files with each their own track lay-out, if two layouts need to be compared (CQM, 2016). However, this requires infrastructure input files and corresponding timetables, which have not been generated for the scenarios of group A. To overcome this impossibility another methodology is used, which again consists of two parts.

To remove switches, the unavailability of these switches (or switch pair) is set to zero and a new timetable input file needs to be created (if there are trains that use these switches). The latter can be done by the tool Inframonitor, an internal ProRail tool that can read the DONNA infrastructure and timetable files, modify the route through a station area and times of a train path and export a file in the right format. The feasibility of this adjusted timetable is not checked at all (for example no conflict detection).

To add a switch pair, a group of two sections with a standard switch unavailability is formed that represents this switch pair. The added switch pair can only be used by trains in the traffic management measure stage of the RA-tool (during 'incidents') as there can no timetable with trains using these switches be generated in Inframonitor: it will not recognise this possible route over these switches because the set of possible routes is based on the inserted DONNA infrastructure files.

Figure 8.12 shows a visualisation of a removed switch pair (in red) and an added switch pair (in green). In the first case the unavailability of switch pair 1238-1240 will be set to zero, and trains using the switch pair will be rerouted in the timetable file. In the case of an added switch, a new group of two sections will be formed (1234T-1236T) that will be given an unavailability equal to the unavailability of a standard switch pair. Trains that can use this new switch pair can be specified in the traffic management measure stage.

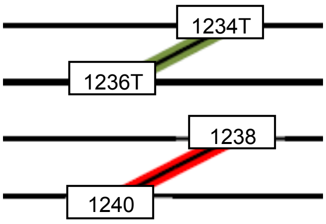


Figure 8.12 An added switch pair (green) and a removed switch pair (red)

8.3.4 State and usability of the modified RA-tool

In the previous sections the RA-tool has been introduced and modified to fulfil the requirements set in section 8.1 in order to enable it to assess the robustness of the generated scenarios. This section will shed light on what the modified tool includes and how it can be used in other studies.

The RA-tool has been developed for the purpose of providing insight in the impact of individual switch failures in order to show which switches should be removed, improved or maintained more intensively. For the representation of requiring switches, the tool has been given the functionality of grouping infrastructure elements through input text files. The modifications made in this research have stretched the tool beyond its current limits and introduced possibilities to use the tool for a system robustness analysis, without changing the code of the existing RA-tool. By taking advantage of the possibility to group elements in a way the tool was originally not intended for, and adjusting the settings of the tool, it can now be used for such an analysis.

To use the modified RA-tool for other case studies, the original RA-tool can simply be used together with a few input files that need to be written specifically for each case study. These input files tell the RA-tool which sections need to be grouped in order to represent a system design, incident types and the unavailability of infrastructure they lead to. In section 9.2 the modelling process is described step-by-step and a few examples of these input files are shown. If a user has access over the current RA-tool and follows the steps described in 9.2, the tool can be used for any other case study.

Nevertheless, working with these input files is not user friendly and very time consuming. In fact, the modified RA-tool is currently only a proof of concept consisting of the current RA-tool with instructions how to write extra input files that give functionalities to the current RA-tool that have been described as functionalities of the modified RA-tool. In the recommendation section, the proof-of-concept state of the modified RA-tool is discussed and recommendations are made on how the functionality of modelling incident types (other than switch failures) and different systems designs can be incorporated in the RA-tool, so that writing these input files is no longer necessary.

Chapter summary

In this chapter the model has been described that will be used to assess the robustness of all generated scenarios. The model comprises an improved version of an existing modelling tool within ProRail named the RA-tool and has five different stages: loading data, choosing system boundaries, setting infrastructure unavailability, defining contingency measures and exporting results.

The key modifications made consist of extra input files that order the tool to group certain infrastructure elements together and represent them as elements that are unavailable simultaneously. This functionality has enabled the modified RA-tool to model various system designs and incident types and therefore assess the system robustness of scenarios. The modified RA-tool has been described in a general way so that it can also be used in other case studies.

9 Modelling scenarios

This chapter will first describe the data collection and preparation processes (section 9.1) before the actual modelling process of the 50 scenarios will be discussed (section 9.2). See Figure 9.1 for a visualisation of this step of the research approach. The results produced by the improved RA-tool will be presented, validated and discussed further on in sections 9.3 to 9.5.

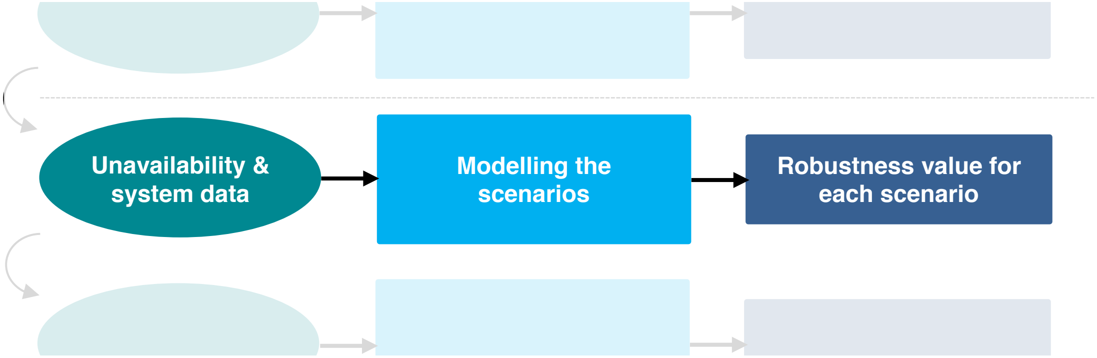


Figure 9.1 Step of the research approach described in the first two sections

9.1 Data collection and preparation

As is shown Figure 9.1, 'Unavailability & system data' is required in this phase of the research, which corresponds to the required input for the improved RA-tool. The four input categories have been summarised in Figure 9.2, and as can be seen there is one extra category added compared to the required input of the RA-tool: infrastructure unavailability data. In the RA-tool the infrastructure availability data is available in the model, but only for switch failures. For all the other incident types extra unavailability data is therefore required. The reason why there are still just four input categories shown, just as many as required for the RA-tool, is because the infrastructure input file and requiring switch pair input file have been merged into one category here: physical infrastructure data. The input for the DSSU case study in all four categories will be discussed in this section, in the same order as shown in the figure.

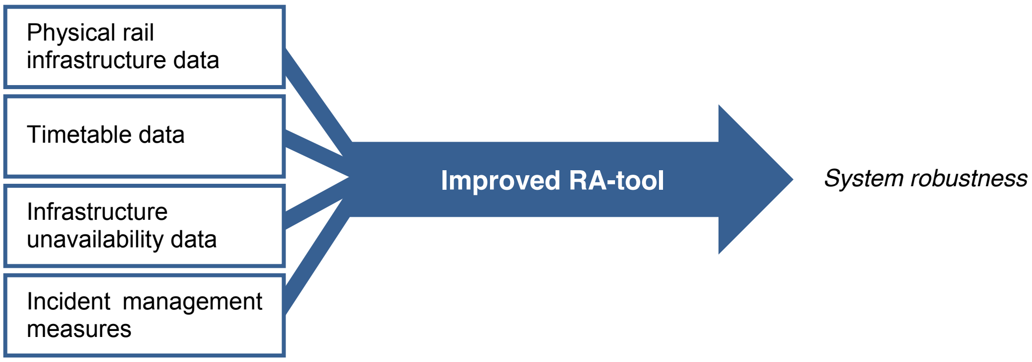


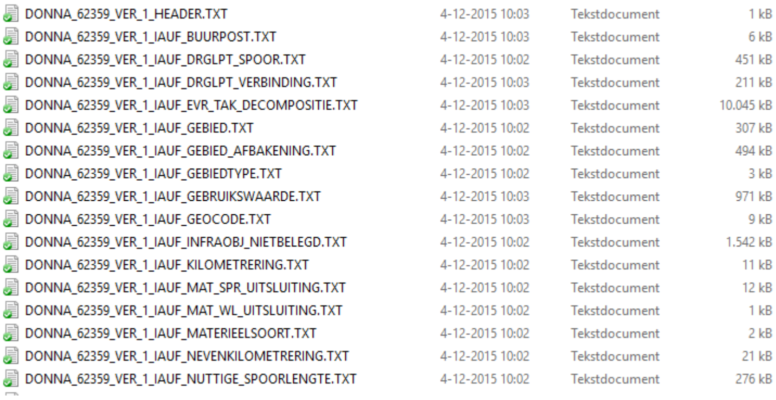
Figure 9.2 Input categories for the improved RA-tool

9.1.1 Rail Infrastructure

A representation of the rail infrastructure forms the basis of the RA-model and already contains some choices for untangling options such as the amount and position of the switches. The first section of this paragraph will discuss the data source and format that has been used in the model while the second paragraph elaborates on the content of the infrastructure data and the potential differences with the system as described in section 7.1.2.

9.1.1.1 Infrastructure data collection

The DONNA system that is used to (microscopically) design the timetable is fed by InfraAtlas, a ProRail system that contains information on the basic rail infrastructure managed by ProRail (ProRail, 2016m). After all, without an accurate representation of the infrastructure it is impossible to design the timetable microscopically and to detect potential conflicts if anything is changed or added to the timetable. The DONNA system is able to generate a set of text files in which the full infrastructure is described in a way that it is compatible with the timetable file it also generates. This compatibility (in format, structure, labels and so on) is important for the RA-tool, since it needs to project the routes of trains in the timetable onto the infrastructure. Figure 9.3 shows the first part of the list of files generated by DONNA. Unfortunately the file names are in Dutch, but to get an idea what kind of files is in the list it would be relevant to translate a few names in English: ‘geo code’, ‘area’, ‘track length’, ‘mileage’, and ‘connection’.

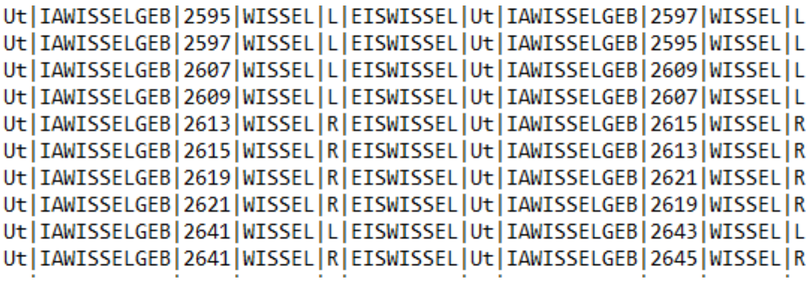


DONNA_62359_VER_1_HEADER.TXT	4-12-2015 10:03	Tekstdocument	1 kB
DONNA_62359_VER_1_IAUF_BUURPOST.TXT	4-12-2015 10:03	Tekstdocument	6 kB
DONNA_62359_VER_1_IAUF_DRGLPT_SPOOR.TXT	4-12-2015 10:02	Tekstdocument	451 kB
DONNA_62359_VER_1_IAUF_DRGLPT_VERBINDING.TXT	4-12-2015 10:03	Tekstdocument	211 kB
DONNA_62359_VER_1_IAUF_EVR_TAK_DECOMPOSITIE.TXT	4-12-2015 10:03	Tekstdocument	10.045 kB
DONNA_62359_VER_1_IAUF_GEBIED.TXT	4-12-2015 10:02	Tekstdocument	307 kB
DONNA_62359_VER_1_IAUF_GEBIED_AFBAKENING.TXT	4-12-2015 10:02	Tekstdocument	494 kB
DONNA_62359_VER_1_IAUF_GEBIEDTYPE.TXT	4-12-2015 10:02	Tekstdocument	3 kB
DONNA_62359_VER_1_IAUF_GEBRUIKSWAARDE.TXT	4-12-2015 10:03	Tekstdocument	971 kB
DONNA_62359_VER_1_IAUF_GEOCODE.TXT	4-12-2015 10:03	Tekstdocument	9 kB
DONNA_62359_VER_1_IAUF_INFRAOBJ_NIETBELEGD.TXT	4-12-2015 10:02	Tekstdocument	1.542 kB
DONNA_62359_VER_1_IAUF_KILOMETRERING.TXT	4-12-2015 10:02	Tekstdocument	11 kB
DONNA_62359_VER_1_IAUF_MAT_SPR_UITSLUITING.TXT	4-12-2015 10:02	Tekstdocument	12 kB
DONNA_62359_VER_1_IAUF_MAT_WL_UITSLUITING.TXT	4-12-2015 10:02	Tekstdocument	1 kB
DONNA_62359_VER_1_IAUF_MATERIEELSOORT.TXT	4-12-2015 10:02	Tekstdocument	2 kB
DONNA_62359_VER_1_IAUF_NEVENKILOMETRERING.TXT	4-12-2015 10:02	Tekstdocument	21 kB
DONNA_62359_VER_1_IAUF_NUTTIGE_SPOORLENGTE.TXT	4-12-2015 10:02	Tekstdocument	276 kB

Figure 9.3 List of text files that compresences parts the national rail infrastructure

As explained in the previous chapter, the information in these files comprises the location and characteristics of all track bound assets (ES-welds, platforms, ATB beacons, signals, switches) and the connections between them. Information on for instance cable positions, catenary system assets, subsidiary circuits, relay houses and power stations are not included in this list, as they are less relevant for the timetabling process.

One piece of information that cannot be obtained from DONNA's infrastructure files is the relation switches have with each other in the safety subsystem. Switches that require positions from other switches before they can be run over occur at many points in the design of DSSU (see appendix I), and therefore have to be incorporated into the RA-model as well. These switch relations are not part of the fixed physical rail infrastructure as they are regarded as safety settings that can be changed. A separate text file therefore needs to be inserted that tells the program which switches will be unavailable to be used as well if a certain switch cannot be set in the required position. Figure 9.4 shows the first few code lines of the file that was inserted to cover the relations between switches. The information for this was found in the design of DSSU (Movares, 2015) and the files are also available at ProRail's Asset Management department.



```
Ut|IAWISSELGEB|2595|WISSEL|L|EISWISSEL|Ut|IAWISSELGEB|2597|WISSEL|L
Ut|IAWISSELGEB|2597|WISSEL|L|EISWISSEL|Ut|IAWISSELGEB|2595|WISSEL|L
Ut|IAWISSELGEB|2607|WISSEL|L|EISWISSEL|Ut|IAWISSELGEB|2609|WISSEL|L
Ut|IAWISSELGEB|2609|WISSEL|L|EISWISSEL|Ut|IAWISSELGEB|2607|WISSEL|L
Ut|IAWISSELGEB|2613|WISSEL|R|EISWISSEL|Ut|IAWISSELGEB|2615|WISSEL|R
Ut|IAWISSELGEB|2615|WISSEL|R|EISWISSEL|Ut|IAWISSELGEB|2613|WISSEL|R
Ut|IAWISSELGEB|2619|WISSEL|R|EISWISSEL|Ut|IAWISSELGEB|2621|WISSEL|R
Ut|IAWISSELGEB|2621|WISSEL|R|EISWISSEL|Ut|IAWISSELGEB|2619|WISSEL|R
Ut|IAWISSELGEB|2641|WISSEL|L|EISWISSEL|Ut|IAWISSELGEB|2643|WISSEL|L
Ut|IAWISSELGEB|2641|WISSEL|R|EISWISSEL|Ut|IAWISSELGEB|2645|WISSEL|R
```

Figure 9.4 Part of the file that was inserted to cover the switch relations in Utrecht

9.1.1.2 Infrastructure data characteristics and modifications

The newest infrastructure data file available at the time was a representation of the infrastructure as it should be on 1 May 2017. In this version it is simply assumed that all infrastructure projects will deliver the planned infrastructure according to the schedule they have provided. In other words, if all projects proceed according to schedule and no disasters or any other influences that change the infrastructure occur, the version shows the rail infrastructure as of 1 May 2017. Figure 9.5 shows a schematic view of the left part of Utrecht station, created from the DONNA infrastructure files.

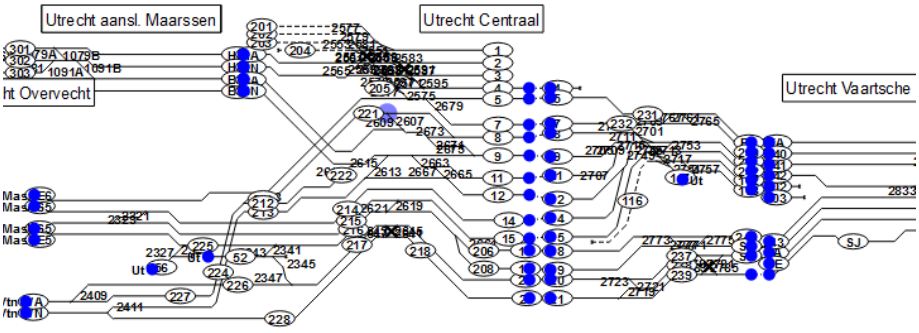


Figure 9.5 Visualisation of the infrastructure used in the model

Unfortunately the UtArk project, which is responsible for the construction of the rtd1 and rtd4 tracks at the Western side of the station (see appendix G), will not be completed by the time the infrastructure in this version becomes reality. However, the UtArk project is part of the new layout of this complex station and therefore needs to be included as well, as explained in section 7.1.2. Adjusting the infrastructure files is too complex, but an alternative way would be to adjust the flagging process of trains during unavailability of infrastructure: train series that run over non-existing tracks rtd1 and rtd4 are no longer flagged if tracks rtd2 or rtd3 are unavailable (in the timetable they run over rtd2 and rtd3 because rtd1 and rtd4 are not present yet).

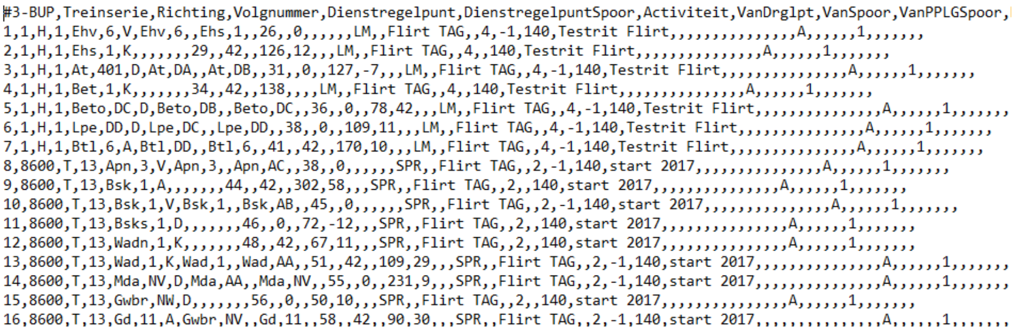
With the infrastructure files inserted, the RA-tool now has information (ID and location) on the switches and sections and knows which switches form pairs through the safety requirements. The next step is to insert a timetable to form connections between infrastructure elements and trains.

9.1.2 Timetable

A timetable is required to model the trains that run through the station area, but timetables are available in many different forms and level of details. As stated before, the RA-tool does not check the timetable itself or adjustments made to the timetable for conflicts or inconsistencies with ProRail's train planning rules, but obviously the timetable should be feasible for the analysis to make sense. The most important information for the tool is the frequency of train series, the service type of train series (for clustering purposes) and the routes trains are supposed to take through the station. Besides that, the tool needs to know which train routes are each other's equivalents in opposite direction to flag trains if the trains in the opposite direction are blocked. If this would not be done, trains could keep on running in one direction, resulting in a train set overflow at one end of the line and a train set shortage at the other end.

9.1.2.1 Timetable data collection

DONNA is the planning system used by ProRail, TOCs and FOCs for both the design of the national timetable and for application for and allocating of rail capacity. A feature of the DONNA system is that it can produce a single text file that contains the complete national timetable including information on train set types and lengths that are intended to be used and routes taken in stations in a standardised format. This feature makes DONNA suitable as data source for the RA-tool. Figure 9.6 shows an extract of a DONNA-file as an example.



```
#3-BUP,Treinserie,Richting,Volgnummer,Dienstregelpunt,DienstregelpuntSpoor,Activiteit,VanDrglpt,VanSpoor,VanPPLGSpoor,
1,1,H,1,Ehv,6,V,Ehv,6,,Ehs,1,,26,,0,,,,,,LM,,Flirt TAG,,4,-1,140,Testrit Flirt,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
2,1,H,1,Ehs,1,K,,,,,,,29,,42,,126,12,,,LM,,Flirt TAG,,4,,140,Testrit Flirt,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
3,1,H,1,At,401,D,At,DA,,At,DB,,31,,0,,127,-7,,,LM,,Flirt TAG,,4,-1,140,Testrit Flirt,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
4,1,H,1,Bet,1,K,,,,,,,34,,42,,138,,,,LM,,Flirt TAG,,4,,140,Testrit Flirt,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
5,1,H,1,Beto,DC,D,Beto,DB,,Beto,DC,,36,,0,,78,42,,,LM,,Flirt TAG,,4,-1,140,Testrit Flirt,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
6,1,H,1,Lpe,DD,D,Lpe,DC,,Lpe,DD,,38,,0,,109,11,,,LM,,Flirt TAG,,4,-1,140,Testrit Flirt,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
7,1,H,1,Btl,6,A,Btl,DD,,Btl,6,,41,,42,,170,10,,,LM,,Flirt TAG,,4,-1,140,Testrit Flirt,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
8,8600,T,13,Apn,3,V,Apn,3,,Apn,AC,,38,,0,,,,,,SPR,,Flirt TAG,,2,-1,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
9,8600,T,13,Bsk,1,A,,,,,,,44,,42,,302,58,,,SPR,,Flirt TAG,,2,,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
10,8600,T,13,Bsk,1,V,Bsk,1,,Bsk,AB,,45,,0,,,,,,SPR,,Flirt TAG,,2,-1,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
11,8600,T,13,Bsks,1,D,,,,,,,46,,0,,72,-12,,,SPR,,Flirt TAG,,2,,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
12,8600,T,13,Wadn,1,K,,,,,,,48,,42,,67,11,,,SPR,,Flirt TAG,,2,,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
13,8600,T,13,Wad,1,K,Wad,1,,Wad,AA,,51,,42,,109,29,,,SPR,,Flirt TAG,,2,-1,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
14,8600,T,13,Mda,NV,D,Mda,AA,,Mda,NV,,55,,0,,231,9,,,SPR,,Flirt TAG,,2,-1,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
15,8600,T,13,Gwbr,NW,D,,,,,,,56,,0,,50,10,,,SPR,,Flirt TAG,,2,,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
16,8600,T,13,Gd,11,A,Gwbr,NV,,Gd,11,,58,,42,,90,30,,,SPR,,Flirt TAG,,2,-1,140,start 2017,,,,,,,,,,,,,,,A,,,,,,1,,,,,,,
```

Figure 9.6 Example of a DONNA output file. Each line represents a location where a train passes by at a given time

There are two different types of timetables that can be produced by DONNA in this format, namely a standard (week) day timetable (BD) and a standard (peak) hour timetable (BU). The first describes 24 hours of a day with all trains departing from 4 AM in the morning until 4 AM the next day, while the second describes all trains that could depart in a randomly selected hour of the day. The latter means that if there are for instance trains that run only a few times a day (peak services, freight trains, international trains), they are still included in the standard hour timetable, even though they might not run in a specific hour. The total number of train paths shown in that timetable will therefore be more than there can possibly be used in a single hour as some of the train paths will even exclude each other: only one of them can be used in a selected hour.

In section 8.2.2 it has been explained that the RA-tool always calculates the impact of incidents on the same hour of the day. A standard hour timetable would therefore be more suitable to be used than a standard day timetable, as there will be made no difference between the various hours of the day. The standard hour DONNA national timetable file for the year 2017 contains 18,500 rows in total that describe 318 different train series in both directions.

If the raw DONNA data would be fed directly into the RA-tool though, many more trains would be flagged as being cancelled due to incidents than in reality, because of the mutual exclusions of some train paths and presence of train services that do not run hourly. The next section will describe the adjustments that have been made to the original timetable as it was published by ProRail and will provide an overview of the timetable that is used in the model.

9.1.2.2 Timetable adjustments

Besides the necessary adjustments that needed to be made to the timetable to get a realistic and representative single hour of the day, more adjustments had to be made for a different reason. A risk exists that the tool is actually showing the robustness of the timetable instead of assessing the robustness of the system layout of Utrecht station.

The design of a large station should not limit the timetable designers to come up with only a single possible timetable, but using train fixed corridors with dedicated infrastructure does not leave much room for variation. A proper robustness investigation should include different timetables to some extent, in order to show and rule out the influence of the differences in timetables. Nevertheless, this was left out in this research, since the list of variations in system designs and modelling regimes was already quite extensive. In the discussion and recommendation sections, this matter will be elaborated on.

After the timetable had been studied, it was found out that in contrary to what was explained in section 7.1.2, the station is operated differently: various ECS paths per hour were discovered that should not be present, freight trains that do not follow the preferred routes, trains that occupy platforms up to 13 minutes and trains that turn around while standing alongside the platform instead of using the tail track. There are various reasons why the timetable planners deviated from the original timetable structure: savings in required rolling stock quantities, small changes in the timetable outside Utrecht and coupling of train series outside Utrecht. If the RA-tool would assess this timetable, the number of cancelled trains and especially the difference in cancelled trains between the various scenarios would be a lot higher. The most efficient robustness increasing measure in that case would probably be to introduce a new timetable.

To still let the model produce results for Utrecht station that provide insight in which untangling options are most efficient without having to model multiple timetables, small adjustments to the 2017 timetable have been made. These adjustments have been made in such way that the timetable is standardised (fixed routes and service intervals) and makes use of the infrastructure the way it was intended as much as possible. Table 9.1 shows the timetable that has been used in the model including references to the adjustments made to the original 2017 timetable. The columns ‘Entry point’ and ‘Exit point’ refer to the tracks on which the train leaves or enters the station area, the location of these tracks can be found in appendix G.

Train series /direction	Corridor	Entry point	Entry time	Platform	Platform time	Exit point	Exit time	Comment
4900E	*Buurt*	-	-	2	:22/:52	amf1	:25/:55	
4900W	*Buurt*	amf2	:01/:31	2	:05/:35	-	-	
5500E	*Buurt*	-	-	3	:06/:36	amf1	:10/:40	
5500W	*Buurt*	amf2	:18/:48	3	:23/:53	-	-	
5600E	*Buurt*	-	-	3	:18/:48	amf1	:22/:52	
5600W	*Buurt*	amf2	:06/:36	3	:11/:41	-	-	
5700E	*Buurt*	-	-	1	:10/:40	amf1	:14/:44	
5700W	*Buurt*	amf2	:14/:44	1	:19/:49	-	-	1)
28300E	*Buurt*	-	-	4	:31	amf1	:34	2)
28300W	*Buurt*	amf2	:11	4	:15	-	-	2)
500E	*NO*	rtd3	:38	11	:42-:48	amf4	:50	
500W	*NO*	amf3	:08	8	:12-:18	rtd2	:20	
600E	*NO*	rtd3	:18	11	:12-:18	amf4	:20	
600W	*NO*	amf3	:38	8	:42-:48	rtd2	:50	
1700E	*NO*	rtd3	:26	11	:30-:36	amf4	:38	
1700W	*NO*	amf3	:20	8	:24-:30	rtd2	:32	
11700E	*NO*	rtd3	:56	11	:00-:06	amf4	:08	
11700W	*NO*	amf3	:50	8	:54-:00	rtd2	:02	
2000E	*NO*	rtd3	:11/:41	12	:15/:45	-	-	3)
2000W	*NO*	-	-	9	:15/:45	rtd2	:17/:47	3)
2800E	*NO*	rtd3	:23/:53	9	:27/:57	-	-	3)
2800W	*NO*	-	-	12	:03/:33	rtd2	:05/:35	3)
8800E	*ICLedn*	rtd3	:04/:24	21	:08-:10/:38-:40	TT	:11/:41	4)
8800W	*ICLedn*	TT	:19/:49	20	:20-:24/:50-:54	rtd2	:27/:57	4)
6000W	*VleuGel*	ht2	:19/:49	20	:26-:27/:56-:57	rtd1	:01/:31	5)
6000S	*VleuGel*	rtd4	:28/:58	21	:02-:05/:32-:35	ht3	:09/:39	5)
6900W	*VleuGel*	ht2	:02/:32	20	:08-:10/:38-:40	rtd1	:14/:44	5)
6900S	*VleuGel*	rtd4	:16/:46	21	:20-:22/:50-:52	ht3	:26/:56	5)
120N	*A12*	ah1	:57	5	:00-:02	asd1	:04	
120S	*A12*	asd4	:54	19	:58-:01	ah4	:05	6)
800N	*A2*	ht1	:17/:47	7	:21-:23/:51-:53	asd1	:25/:55	
800S	*A2*	asd4	:04/:34	18	:07-:09/:37-:39	ht4	:11/:41	
3000N	*A12*	ah1	:03/:33	5	:06-:08/:36-:38	asd1	:10/:40	
3000S	*A12*	asd4	:19/:49	19	:22-:24/:52-:54	ah4	:26/:56	
3100N	*A12*	ah1	:17/:47	5	:21-:26/:51-:56	asd1	:28/:58	
3100S	*A12*	asd4	:01/:31	19	:04-:09/:34-:39	ah4	:11/:41	
3500N	*A2*	ht1	:02/:32	7	:06-:11/:36-:41	asd1	:13/:43	
3500S	*A2*	asd4	:16/:46	18	:19-:24/:49-:54	ht4	:26/:56	
7300N	*Bkl-Db*	ah2	:13/:43	14	:19-:21/:49-:51	asd2	:24/:54	7)
7300S	*Bkl-Db*	asd3	:06/:36	15	:10-:12/:40-:42	ah3	:15/:45	
7400N	*Bkl-Db*	ah2	:29/:59	14	:03-:07/:33-:37	asd2	:09/:39	7)
7400S	*Bkl-Db*	asd3	:13/:43	15	:18-:25/:48-:55	ah3	:28/:58	
AWKN20S	*Freight*	asd3	:01	15	:03	ht4	:06	
BESX10S	*Freight*	amf3	:29	8	:34	ht4	:35	8)
ESBX21E	*Freight*	ht1	:56	7	:59	amf1	:03	9)
FBV11N	*Freight*	ht1	:40	14	:44	asd2	:46	7)
KNAW20N	*Freight*	ht1	:26	14	:29	asd2	:31	7)
LUBV21N	*Freight*	ht1	:10	14	:14	asd2	:16	7)

Table 9.1 Timetable used in the model

The differences between this adjusted timetable and original 2017 timetable are briefly discussed below.

1) In the original timetable trains of the 5700 series arrive in Utrecht at platform 4, after which the train sets are sent to the yard as ECS. Just before a train needs to depart again, the coaches are taken from the yard and sent by ECS to platform 1, from which the train will then depart. In case of an unavailability these ECS paths will be cancelled as well and therefore lead to extra cancellations, which does not represent the robustness of the system in any way. In the adjusted timetable, trains for the 5700 series therefore arrive and depart from platform 1, even though this is not in line with the train planning rules: an arriving 5700 train needs to cross a 5600 series train one minute after it departed, while TPR requires at least 3 minutes. This could be solved by increasing the dwell time at Utrecht Overvecht of arriving 5500 series and 5700 series trains by two minutes. (ProRail, 2015d)
2) Related to the previous adjustment, since platform 4 is now only used by the 28300 series, it can turn around there and get rid of the required ECS paths to the yard. There were no conflicts detected.
3) Rolling stock of arriving 2000 series trains will be used in the 2800 series and vice versa. In this way a cross platform connection can be offered between the 2000 and 500/600 series and the platforms in Utrecht are used as intended. In the actual 2017 timetable the 2000 series is combined with the 8800 series, which lead to the full integration of the ICLedn corridor into the NO corridor. Departing 2000 series will need to depart one minute earlier in the adjusted timetable to comply with train planning rules.
4) As explained under the previous adjustment, the 8800 series trains are no longer combined with the 2000 series trains but are again operated with dedicated rolling stock in a separate corridor. As a result of that the headways between trains of the 8800 and 6000 series become two and three minutes respectively at the platform, while the train planning rules require four minutes. This conflict could be solved by giving 8800 series trains a one or two minute longer dwell time at Woerden (ProRail, 2015d).
5) The 6000 series (Utrecht-Tiel) & 6100 series (Utrecht-Woerden), and 6900 series (Utrecht-‘s-Hertogenbosch) and 7800 series (Utrecht-The Hague) are operated as two single continues train services in the VleuGel corridor, but have been assigned two different administrative service IDs. Since this will lead to a twice as high cancellation rates during incidents, the whole service Tiel-Utrecht-Woerden represented under the single ID 6000 and the service ‘s-Hertogenbosch-The Hague under ID 6900.
6) Southbound ICE 120 was in the original timetable planned on platform 18, while according to Utrecht’s corridor design this should be 19. In the adjusted timetable the southbound ICE departs two minutes earlier, which allows for a departure of the intended platform 19.
7) Northbound trains of the 7400 series have a strikingly long dwell time of 13 minutes in Utrecht in the 2017 timetable, blocking the platforms that are part of the preferred freight routes. By relocating a part of this long dwell time to Driebergen-Zeist and Breukelen stations, the dwell time of 7400 series train in Utrecht can reduced to five minutes and all northbound freight trains can make use of the preferred route through Utrecht. For one of these freight trains, northbound 7300 series trains have to be delayed by one minute as well.
8) Freight services from Amersfoort are supposed to use platform 8, but this results in a headway between westbound 11700 series trains and southbound BESX10 series trains of two minutes, while four minutes are required according to the TPR. By delaying the freight trains with two minutes, the conflict is resolved (ProRail, 2015d).
9) Eastbound freight trains of the ESBX21 series cannot use the preferred freight route through Utrecht, and this cannot be solved easily. Instead of using platform 11 and exit point amf4, these freight trains use platform 7 and exit point amf1, which is in line with the 2017 timetable.

9.1.3 Unavailability of infrastructure

In the first part of this research, the unavailability of the infrastructure has already been estimated to some extent for various incident types. In section 4.4 the frequency of occurrence of all related incident types and their average duration have been determined, based on a sampling exercise of incidents reported at the five largest Dutch stations between 2010 and 2015. The average frequency of occurrence per incident type for an average station was found by dividing the number of reported incidents by 5. However, for the RA-tool the unavailability of an element needs to be expressed in a failure rate and average incident duration. The latter can theoretically directly be taken from Table 4.13 in section 4.4, but the failure rate needs to be deducted from the data presented in that section. There are a few other incompatibilities as well between the values used in the first part and in the values required for the RA-tool. This section will discuss how the values for the unavailability of the infrastructure elements have been determined.

9.1.3.1 Incident groups versus incident types

Incident types found in the SAP incident registration system were categorised in a specific way, for instance per responsibility (third party versus ProRail) or per cause (technical versus weather). As has been explained in section 8.1.3, this categorisation is unnecessary for the purpose of this modelling exercise and these incidents types can therefore easily be grouped in incident groups (or still named incident types, but then on a lower level of detail then the incident types used in the first part) with an equal effect. How these incident types should be grouped has already been explained in Table 8.1. In the next paragraphs the frequencies of occurrence and average duration of *individual incident types* will be transformed in failure rates and unavailability duration *per incident group*.

9.1.3.2 Frequency of occurrence versus failure rate

As was stated in the introduction of this section, the frequencies of occurrence found in the first part need to be transformed into element failure rates. An important input that is used for this is Table 4.12, in which the quantities of the various elements at the five largest stations are shown. The table has been used before to scale the amount of reported incidents found in the data to the size of the station the incidents occurred at in order to define a ‘general frequency of occurrence at an average large complex station’. The quantity of elements at this fictional average station is of great importance for determining the failure rate. After all, if for example a section failure at this average station occurs 50 times per year and the quantity of sections at the station is 100, a failure rate of 0.5 for each section can be deducted. A summary of these average large station element quantities is also shown in Table 9.2.

Formula (9.1) shows this deduction. The deducted failure rate ρ_d of incident group g is calculated by dividing the average number of occurrences Q of incident type y at a fictional average large station by the amount of related infrastructure elements $n_{elements}$ present at this station, and repeating this for all incident types y belonging to this incident group g and summing up the results. The related incident types in an incident group can be found in Table 8.1 and the average number of occurrences per incident type in Table 4.13. The average number of elements at Utrecht ($n_{elements}$) and the results are shown in Table 9.2. The incident group ‘faulty train’ has been split in groups ‘platform faulty train 83%’ and ‘non-platform faulty train 17%’, see section 8.3.2.5. The average Q_y of the incident type ‘faulty train’ is therefore multiplied first by 0.83 or 0.17 respectively.

$$\rho_{dg} = \sum_{y=1}^{Y} \frac{\bar{Q}_y}{\bar{n}_{elements}} \tag{9.1}$$

The applied approach in the first part – a sampling exercise of incident occurrences at the five largest stations – has been used because of a lack of data on infrastructure element failure rates. During this research, ProRail has come up with a new yearly incident report that does include failure rates of some elements, which are obviously more accurate than the deducted approximations (ProRail, 2016l).

Differences can for instance be explained by the fact that these failure rates are based on the whole infrastructure, not only on infrastructure in the five largest stations. Especially for switch failures the failure rates are more accurate, since both the type of switch and usage of the switch are taken into account when determining a switch's failure rate. If a more accurate failure rate is therefore available, it will be used instead. In Table 9.2 these more specific failure rates have been called 'Reported failure rates' (ρ_r).

Incident group (g)	Related Elements (k)	Average quantity of elements ($n_{elements}$)	Deducted failure rates (ρ_d)	Reported failure rates (ρ_r)	Average duration [min] ($\overline{FR}$)	Rounded duration [min] ($\overline{FR}$)
Switch failure	Switches	145	0.70	0.01-3.72	63	120
Section failure	Sections	170	0.14	0.09	130	180
Partial power loss	Subsidiary circuits	7	1.47	-	75	120
Relay house failure	Relay houses	2.8	0.18	-	3788	3840
Interlocking failure	Interlocking installations	1.6	0.88	0.67	101	120
Operation failure	EBPs	1	0.10	0.06	508	540
Platform faulty train 83%	Trains	46	0.97	-	16	60
Non-platform faulty train 17%	Sections	170	0.06	-	121	180

Table 9.2 Unavailabilty values used in the RA-tool

9.1.3.3 Incident duration versus unavailability duration

Similar to the failure rate deduction process, the incident type average durations need to be accumulated to get incident group average durations. Unfortunately, these durations cannot simply be averaged since the share of each incident type in the incident group is not equal. For example, if incident group 'switch failure' consists of two underlying incident types of which one occurs on average one time per year with an average duration of 100 minutes and the other occurs twenty times per year with an average duration of twenty minutes, the incident group average duration is not 60 minutes: the durations need to be weighted according to the failure rate share of individual incident types.

Formula (9.2) describes how the average functional repair time (or incident duration) $\overline{FR}$ for incident group g is determined. The deducted failure rates ρ_d for incident types x, y and z, all belonging to group g have been calculated with the help of formula (9.1). Each failure rate is multiplied with the corresponding incident type average functional repair time $\overline{FR}$, which can be found in Table 4.13, after which the sum of these products is divided by the sum of the individual incident type failure rates (which is equal to the deducted failure rate of the group ρ_{dg}).

$$\overline{FR}_g = \frac{\rho_{dx} \cdot \overline{FR}_x + \rho_{dy} \cdot \overline{FR}_y + \rho_{dz} \cdot \overline{FR}_z}{\rho_{dg}} \qquad (9.2)$$

After an incident has been reported as 'repaired', it will take a short while until the infrastructure element can actually be used. Several checks for instance need to be carried out first. Besides that, the average incident time $\overline{FR}^k$ of infrastructure element k can only be specified in the tool in steps of 30 minutes. For that reason and to partly compensate for the fact that the RA-tool models unavailability instead of incidents (see discussion section), the incident group average functional repair times $\overline{FR}_g$ have been rounded up by a maximum of 60 minutes, until they reach the first whole hour.

As has been discussed in section 8.1.1.2, the unavailability of an infrastructure element (U^k) in the RA-tool is specified as the product of the element failure rate ρ of element k (ρ^k) and average incident time FR of element k (FR^k), see formula 8.1.

The relation between ρ_g and FR_g on one side and ρ^k and FR^k is straightforward: all reported ρ_{rg} (or deducted ρ_{dg} if no reported failure rates are available, see Table 9.2) need to summed up and FR_g averaged (with weights corresponding to the share of the deducted failure rates ρ_{dg}), for all incident groups g that use the same element k in the RA-tool representation. As can be seen in the second column of Table 9.2 this only applies to the groups 'section failure' and 'non-platform faulty trains 17%'. In formulas (9.3) and (9.4) the ρ^k and FR^k for this infrastructure element are calculated, for all other infrastructure elements holds that the ρ_g and FR_g are equal to ρ^k and FR^k. All results can be found in Table 9.2.

$$\rho^{sections} = \rho_{d,non-platform\,ftrain} + \rho_{r,section\,failure} = 0.15 \tag{9.3}$$

$$FR^{Sections} = \frac{\rho_{d,non-platform\,ftrain} \cdot \overline{FR}_{non-platform\,ftrain} + \rho_{d,Section\,failure} \cdot \overline{FR}_{Section\,failure}}{\rho_{d,non-platform\,ftrain} + \rho_{d,Section\,failure}} = 180 \tag{9.4}$$

9.1.4 Incident management measures

As explained in section 7.3.2, the effect of unavailable infrastructure on the timetable, which will lead to the determination of the robustness of the system, will be modelled with the help of ProRail's VSMs (contingency plans for the timetable). These VSMs form the last part of the input that is required by the RA-model, even though the model is not yet able to use it automatically. The user of the model will need to interpret the VSMs and translate them into cancelled and delayed train series. In the recommendations this matter will be addressed in further detail. The 12 relevant VSMs are available from the OCCR website (OCCR, 2017). Scenarios modelled under the β regime will not use the VSMs but pragmatic traffic management rules instead, see section 7.3.2.2.

Another problem emerges when the system design is significantly altered in a scenario, as is the case in the A scenarios in which (extra) switches are removed and installed. In those cases, the VSMs cannot directly be applied anymore, so an alternative approach must be found for this. The 'rules' behind the VSMs seem not to be very complicated and have been summed up below.

- ***Only reroute train series without the violating a single train planning rule***
  If a newly proposed train path conflicts with an existing train path, either one of the two series using these paths needs to be cancelled.
- ***Turn-around times must be greater than 10 minutes***
- ***Reduce affected train series' frequencies by approximately 50%***

If a certain system design in a scenario leads to the incompatibility or unfitting of a VSM, these VSM rules will be used in the α regimes instead of the VSMs. In the next section, examples of the use of VSMs and VSM rules will be shown, together with examples of the incident management measures applied under the β regimes.

9.2 Modelling various scenarios

The input as explained in the previous section has been loaded into the improved RA-tool, which has been described in the previous chapter. Recapturing the five modelling stages that can be identified for the improved RA-tool shown in Figure 8.5; the first two steps (*loading data* and *choosing system boundaries*) have already been explained in detail in the previous section and chapter. The third and fourth step though (*setting infrastructure unavailability* and *defining traffic management measures*) have not been discussed in detail yet and will therefore we addressed here by taking the base scenario as an example. However, there will also be spent some words on other scenarios and a larger emphasis will be laid on the β-regime, since modelling under that regime is subject to the user's creativity. The fifth step (*results*) will be discussed in the result section.

In the base scenario the current situation of DSSU is modelled as a reference scenario. The track layout, switches, sections and timetable all follow from the data input and are loaded into the model automatically. The first step to take then is to set the infrastructure unavailability.

9.2.1 Setting infrastructure unavailability

In section 8.3.2 all incident types that need to modelled are listed and the exact way how they are modelled is explained. The unavailability of switches is the easiest to start with; per switch the average failure rate and average duration needs to be specified in the RA-tool. For requiring switches, groups have been formed that are listed in the RA-tool instead of individual switches. The unavailability of the group is twice as high as the unavailability of the individual switches (if one fails, both are unavailable).

In principle, the actions to be taken for the section failure are similar, nevertheless a more efficient approach is taken since the total amount of sections is significantly larger than the number of switches. All sections between two switches, previously called a 'link', are used by the exact same trains. After all, a train has only route that it can take since there are no switches on the link (the links lie *between* switches). By giving one section in the link the regular average duration of a section failure, but an accumulated failure rate corresponding to the amount of sections in the link, the unavailability of the other sections can be kept at zero, which is more efficient (see section 8.3.2.1). To model faulty trains, a surcharge is added to the unavailability of individual sections. This surcharge is not treated differently and accumulated in the same way as the section failure rates.

The other incident types – partial power loss, relay house failure, interlocking failure and operation failure – are all modelled similarly. A group of sections needs to be formed per part of the system that can become unavailable as a result of the occurrence of one of the selected incident types. For example one group per subsidiary circuit, one per relay house, one per EBP system and so on. This grouping of sections is done in order for the RA-tool to know which trains are affected by a certain unavailability. This 'flagging' of trains occurs when one of the used infrastructure elements by a train route is part of the group. Therefore, not all sections in the unavailable area need to be part of the group. See Figure 8.10 in section 8.3.2.3 for an example, in which eight sections are grouped to flag all trains running South of Utrecht.

As an example, an input file has been written that would group sections 0001T, 0002T, 0003T, 0004T and 0005T in Utrecht, see Figure 9.7. For each group a similar input file needs to be written that could be named '*Relay house South*', '*Subsidiary circuit SX1*', or '*Interlocking VPI A2',* depending on which system design part (that could become unavailable) it represents. For each of these formed groups an average failure rate and average incident duration is specified, which follows directly from the data input (Table 9.2).

At the end of this step, all the quantity and locations of unavailabilities are known to the RA-tool (and thus TAOs, which will be introduced in the result section) including the trains affected by them.

```
Ut|IAWISSELGEB|0001T|SECTION|GROEPEER|Ut|IAWISSELGEB|0002T|SECTION
Ut|IAWISSELGEB|0002T|SECTION|GROEPEER|Ut|IAWISSELGEB|0003T|SECTION
Ut|IAWISSELGEB|0003T|SECTION|GROEPEER|Ut|IAWISSELGEB|0004T|SECTION
Ut|IAWISSELGEB|0004T|SECTION|GROEPEER|Ut|IAWISSELGEB|0005T|SECTION
```

Figure 9.7 Dummy RA-tool input file that would group sections 0001T to 0005T in Utrecht

9.2.1.1 Untangled, tangled and decreased failure rate scenarios

Modelling a scenario with a decreased failure rate is not too difficult in the RA-tool: simply reduce the failure rate of the individual switches or other groups of unavailable infrastructure. For more untangled and more tangled scenarios the composition of the formed groups has to change. For example, the sections that used to represent a subsidiary circuit that no longer exist in a certain more tangled scenario are added to various other groups (depending on which parts of the original subsidiary circuits are merged with other subsidiary circuits). In this way, all thinkable variations can be modelled.

An exception is the track layout, which has automatically been read by the model from the data input files and cannot be changed. There are two actions to be taken which together solve this issue: a removed switch is modelled by setting the failure rate of the switch to zero while an extra switch pair is modelled by creating a group of two sections at the location of the switch and assigning a switch failure rate and average switch incident duration to that group. The formation of such a group has been explained through the example input file in Figure 9.7.

9.2.1.2 Γ and δ regimes

Two of the effect regimes are modelled in the unavailability step. The γ regime, which assumes shorter incident duration, is modelled in the RA-tool by simply reducing the average incident duration of each switch and other group of unavailable infrastructure. The δ regime requires more effort, but is modelled by adding a section of the neighbouring track to all specified groups of unavailable infrastructure (switches, sections and subsidiary circuits), see section 8.3.3.1. This extra section in the group will flag all trains on the neighbouring track as ‘affected’ by the unavailability. In the next stage of the RA-tool these trains will then either be cancelled or rerouted.

9.2.2 Define traffic management measures

With a list per train series of unavaibilities hindering the train series, the RA-tool now asks per unavailability what to do with this specific train series. The scenarios have been modelled under two different regimes: α and β, which both will be discussed here. See section 8.3.3.1 for details on the content (rules, differences) of these regimes.

9.2.2.1 Effects under the α regime

For each unavailability a suitable VSM needs to be selected, which is not too difficult since the VSMs clearly specify the situation they are valid for. A problem emerges when the track layout is altered in a scenario or if an unavailability has not been captured by a suitable VSM. In those cases the same approach has been used as under the β regime, with different rules though (see section 9.1.4). Explaining the β regime will be handled in the next section.

9.2.2.2 Effects under the β regime

Modelling under the β regime leaves room for the user’s creativity in how to handle the incident. For every unavailability a suitable timetable solution needs to be created. But, since the RA-tool is oriented per train series instead of incident or even unavailability, it very difficult yet important for the user to keep in mind which timetable adjustments are made per unavailability in order to guarantee the feasibility of the produced contingency plan; the RA-tool will not check for conflicts. Luckily solving such a complex puzzle is possible due to the current extent of untangling at DSSU that does not leave much room for variation. In a completely tangled station in which many different routes and platforms are thinkable, this puzzle would be a lot more difficult to solve.

To illustrate the process of the modelling under the β regime and to show the differences between the α and β regimes, two examples of situations found in Utrecht will be explained. Obviously differences between the α and β regimes are not present everywhere, moreover, for most unavailabilites no better contingency plan was found than proposed in the VSMs. The two selected situations (and slightly different situations that have been handled the same way) instinctively represent the largest part of the differences in TVTA score between the α and β regimes.

9.2.2.2.1 Blocked track in A12 and A2 corridors South of Utrecht

In appendix G the full track layout of Utrecht and the corridors in the area are shown. The numbers of the train series and the corridor they belong to can be found in Table 9.1. Figure 9.8 shows a schematic representation of the platforms 14 to 19. The red cross indicates the track that is unavailable, for example because of a faulty train at platform 19 or a ES-weld failure.

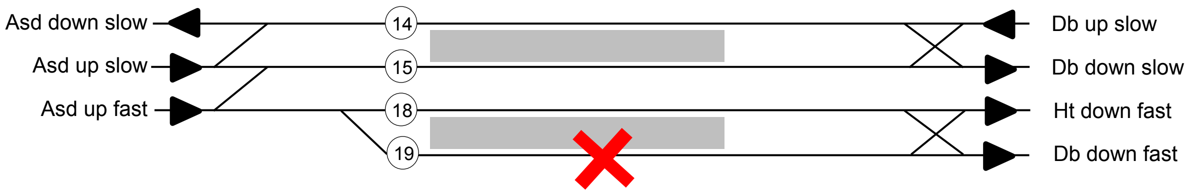


Figure 9.8 Schematic representation of the platforms 14 to 19

Under the α regime, VSM UT09 dictates that in this case IC trains planned from the Asd up fast track towards the Db down fast track (train series 3000 and 3100) are altered. Train series 3100 is cancelled in both directions and southbound trains of the 3000 series are handled at platform 15 and then rerouted over the Db down slow track. To free up capacity, train series 7300 is also cancelled in both directions. As a result, the impact of a faulty train at platform 19 is eight TVTAs per hour: two northbound 7300 and 3100 trains per hour and two southbound 7300 and 3100 trains per hour as well.

A different contingency plan is used under the β regime; southbound trains of both the 3000 and 800 series are rerouted to platform 15 and use the Db down slow track to leave Utrecht (800 series trains are able to switch back to the Ht down fast track at Utrecht Vaartsche Rijn, see appendix G). Due to the platform switch of the 800 series, the 3100 series trains can now use platform 18. The long dwell time of the 7400 train series at Utrecht is shifted towards Utrecht Zuilen, since platform 15 needs to be used by other trains as well now. In this way, a faulty train at platform 19 does not lead to any TVTA.

9.2.2.2.2 Blocked track in A12/A2 corridor North of Utrecht

In another case the Asd down fast track is unavailable, causing trains from platform 5 and 7 to be unable to proceed. Figure 9.9 shows a schematic representation of the platforms 5, 7, 14 and 15 and relevant tracks and switches. Again, the full track layout and corridor plan can be found in appendix G.

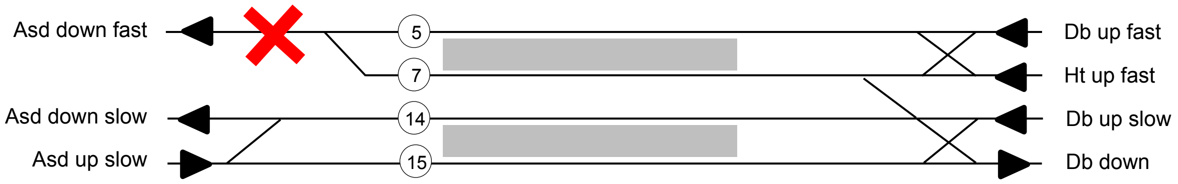


Figure 9.9 Schematic representation of the platforms 5, 7, 14 and 15

According to VSM UT05, which describes the adjustments that need to be made to the timetable if this situation occurs, the 3100 and 3500 series trains are cancelled in both directions. The 7300 series trains and 7400 series northbound trains are also cancelled to free up capacity at platform 14, which will handle the northbound 800 and 3000 series trains originally planned at platforms 5 and 7. These intercity trains will be rerouted to Amsterdam over the Asd down slow track instead of the Asd down fast track. Trains of the 7400 series arriving via the Db up slow track will use platform 15 to turn around. In total, this unavailability leads to 14 passenger train TVTAs per hour: two northbound 3100, 3500, 7300 and 7400 series trains (eight in total) and two southbound 3100, 3500 and 7300 trains (six in total).

Under the β regime all northbound intercity trains (800, 3000, 3100 and 3500 series) use platform 14. By ordering an early departure of one minute for the 800 and 3000 series trains and allowing a one minute late departure of the 3100 and 3500 series trains, both can easily use the same platform. 7300 Series trains arriving via the Db up slow track will use platform 7 to turn around and depart six minutes later (according to schedule) as southbound 7400 series train via the Db down slow track. The same holds for 7400 series trains arriving on the Db up slow track, they will also turn around at platform 7 and return south as 7300 series train via the Db down slow track. From the other side, 7400 series trains arriving on platform 15 via the Asd up slow track, will be brought to the OZ yard as ECS where they can turn around and depart from platform 14 again. These northbound 7400 series trains need to depart five minutes ahead of schedule and compensate this by a longer dwell time in Maarssen though, in order to make room for 800 series trains at platform 14. Northbound 7300 series trains will be cancelled. Under the β regime, this unavailability leads to only 2 passenger TVTAs per hour: two northbound 7300 trains.

Section summary

In the past two sections the input used in the improved RA-tool has been discussed and some steps of the modelling process itself have been described. The input of the RA-tool consisted of four categories: infrastructure data, timetable data, unavailability data and contingency plans (VSMs). In the next sections, the outcomes of the model will be presented, interpreted, validated and discussed.

9.3 Results

This section will present and interpret the results produced by the improved RA-tool per scenario group (A to F) and draw the first conclusions. In the next section, the results will be validated (in a minor way, with the help of incident data) and discussed (see Figure 9.10).

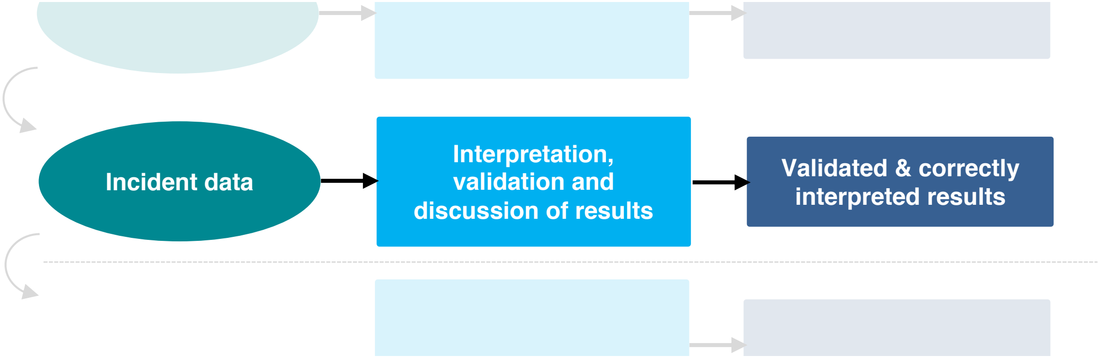


Figure 9.10 Steps of the research approach described in the coming three sections

The RA-tool generates three types of output for every scenario that are of interest for this research: TAOs, TVTAs and traffic management measures overviews. TAO stands for ‘Train Service Affecting Unavailability’ and is a measure for the number of incidents that occurs yearly. For example, if 25 TAOs have been logged at a certain location, it means that during the year 25 incidents took place that affected trains. To which extent though, cannot be deducted from the number of TAOs only. TVTAs (Explainable Timetable Deviations) express the number of trains that was affected by the TAOs, which is equal to the number of cancelled trains in this research, since delays are not taken into account. In other words, the TVTA captures the impact and duration of the TAOs on the train services, which is exactly the indicator needed for this research. To complete the overview, the RA-tool generates a table which states exactly per unavailability if a train is cancelled and if so how often it is cancelled. Table 9.3 shows a part of this overview for train A3100, which is part of the A12 corridor.

Train ID	Unavailability	Cancel/ Reroute	TAOs	TVTAs
3100, IC, A3100 Nm-Shl	Circuit 1 failure	Cancel	1.47	2.94
	Circuit NE5 failure	Cancel	1.47	2.94
	EBPInterlockTotal failure	Cancel	0.76	1.52
	Faulty train platform 5	Cancel	4.37	4.37
	Relayhouse Centre failure	Cancel	0.18	11.52
	Relayhouse North failure	Cancel	0.18	11.52
	Section N3-5 failure	Cancel	0.75	2.25
	Section P5-3 failure	Cancel	0.45	1.35
	Section S3-8 failure	Reroute	1.20	0
	Ut, SWITCH: 2677	Cancel	0.385	0.77
	Ut, SWICTH: 2761	Cancel	0.45	0.9
	Ut, SWITCH: 2763	Reroute	0.385	0

Table 9.3 Example of the overview output generated by the RA-tool

With fifty scenarios under investigation it is obvious that multiple combinations of scenario results are interesting to discuss. First the results of the base scenario will be assessed before these interesting combinations, which are captured in various comparison frames (maximum & minimum, A, B, C, D and E & F scenarios), are discussed.

9.3.1 Base scenarios

The base scenarios form the point of reference for all other scenarios and the results should therefore in first instance be used for comparison purposes and less for the exact values. Nevertheless, to get a feeling for the meaning of the exact values, in the validation section a comparison will be made between these values and actual incident data.

Table 9.4 shows that 171 TAOs are to be expected for the current DSSU system design and shows that TVTAs for the base scenarios vary between 3462 and 1949 cancelled trains per year. Although 3462 cancelled trains seems to be a lot, in relation to the 330,000 yearly passenger train departures in Utrecht it is just over 1% (NDOV Loket, 2017).

KPI	Base Scenario (Base-α)	Improved infrastructure usage (Base-β)	Duration reduction (Base-γ)	Absent safe working areas (Base-δ)
TAOs	171	171	171	171
TVTAs	2437	2138	1949	3462

Table 9.4 TAOs and TVTAs calculated for the base scenarios

Differences between the α and β regime, a possible reduction of TVTAs without changing the system, could not be found on a large scale since the fairly untangled system did not allow for many other traffic management measures alternatives than already used in the VSMs. The difference between these regimes found in the base scenario is only due to the simultaneity in the timetable of arriving trains in the A2, A12 and SPRBkl-Db corridors, which in the VSMs immediately leads to cancellations if one of the tracks becomes unavailable. After all, as was stated in 9.1.4, trains hindered by unavailable infrastructure elements can only be rerouted if the newly proposed train path (which timewise has to be equal to the original train path) does not conflict with existing train paths. With three trains arriving simultaneously – A12, A2 and SPRBkl-Db, each on their own tracks – rerouting one of these train over another train's infrastructure immediately leads to a train path conflict. Under the β regime, which allows small timetable deviations, these trains can be rerouted over the same tracks, hence the lower TVTA score.

The γ TVTA score is used to see if it would not be more effective to focus on incident time reduction instead of system untangling and represents therefore nothing else than an indication for a possible strategy. After all, an incident duration reduction of 10%, 15% or 19% are all proportionally as effective as the value shown in the γ scenario. Since 20% was mentioned as target in the Better & More programme, the TVTAs calculated in the γ scenario are regarded as the maximum realistic values.

It is interesting to see that the δ scenario led to a TVTA value that is almost 50% larger than the value found in the α scenario. In section 4.4.2.20 it was already concluded that the influence of the safe working areas is very large, as it affects the impact of multiple incident types. The impact area of section failures, switch failures, faulty trains and circuit failures (partial power losses) at least doubles or sometimes triples compared to the α scenario. As a consequence, not only more trains are affected, but also the rerouting options are reduced. Obviously, these extreme cases in which either all elements or no elements have a safe working area around them only form the boundaries of the robustness loss/increase that can be gained by (not) installing these areas. Assessing the influence of a safe working area around a particular element could therefore be even more relevant and due to the made modifications the RA-tool now allows for this type of assessments. In this chapter the results of the δ scenario are only used to indicate what the robustness increase (or sometimes even decrease) of an untangling option as a whole would be if it is installed without a safe working area.

9.3.2 Maximum and minimum scenarios

Figure 9.11 shows the calculated TVTA values for the maximally untangled and minimally untangled scenarios as they were defined in section 7.4.2.1. The variations used in these scenarios have been recaptured below, the meaning of this notation can be found in formula (7.1) and Figure 7.9.

$$\text{Base scenario: } \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}^{\alpha,\beta,\gamma,\delta} \quad \text{Maximum scenario: } \begin{bmatrix} 4 \\ 3 \\ 4 \\ 3 \\ 4 \\ 4 \end{bmatrix}^{\alpha,\beta,\gamma} \quad \text{Minimum scenario: } \begin{bmatrix} -4 \\ 0 \\ -4 \\ -3 \\ -1 \\ -1 \end{bmatrix}^{\alpha,\delta}$$

The result of the RA-tool is remarkable. It was expected that the maximum scenarios would have the highest system robustness (and thus the lowest amount of TVTAs) and the minimum scenarios the lowest system robustness (highest amount of TVTAs). But, as can be seen in the graph in Figure 9.11, both have a higher TVTA score than the base scenario and the maximum scenario even has the highest score of the three. Where these scenarios were initially meant to indicate the borders of the robustness increase and decrease under investigation, it now becomes clear that the selected combinations of variations in these two scenarios do not produce such an optimum and minimum value. The range of TVTA found until now is around 600 TVTA, which means a difference in cancellations of 0.2 percentage points. The calculated amounts of TAOs though are in line with the expectations: 171 TAOs for the base scenario, 154 for the maximum scenario and 194 for the minimum scenario. Nevertheless, the impact of the TAOs in each system design appeared to be very different.

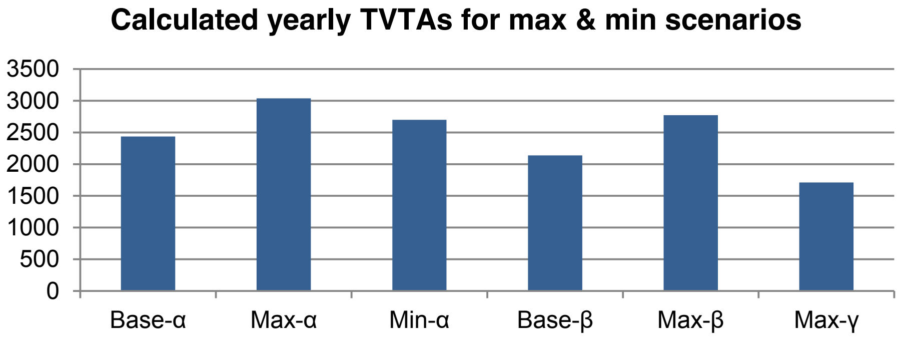


Figure 9.11 TVTA scores of the minimum and maximum scenarios

The question is why this maximum and minimum value is not found, is strongly related to the main research question: which untangling option is most effective? Apparently one, multiple or the combination of the untangling options used in the maximum scenario resulted in a worse robustness than the current situation in DSSU. Consequentially it can be concluded that only striving for a more untangled system does not always lead to a more robust system. Which options are effective in increasing the robustness should be concluded then from the individual option scenarios (A to F).

9.3.3 Results of the A scenarios

Three different system designs have been modelled in which untangling option A (removing/adding switches) has been varied. In the first system design (more untangled) switches between corridors have been removed, in the second (less untangled) extra switches have been added between corridors and in the third system design (decreased failure rates) the original base system design has been used, only with 20% lower switch failure rates.

The three different A scenarios have all been run under all four regimes and the TVTA values are shown in Figure 9.12. The red line represents the TVTA value of the Base-α scenario.

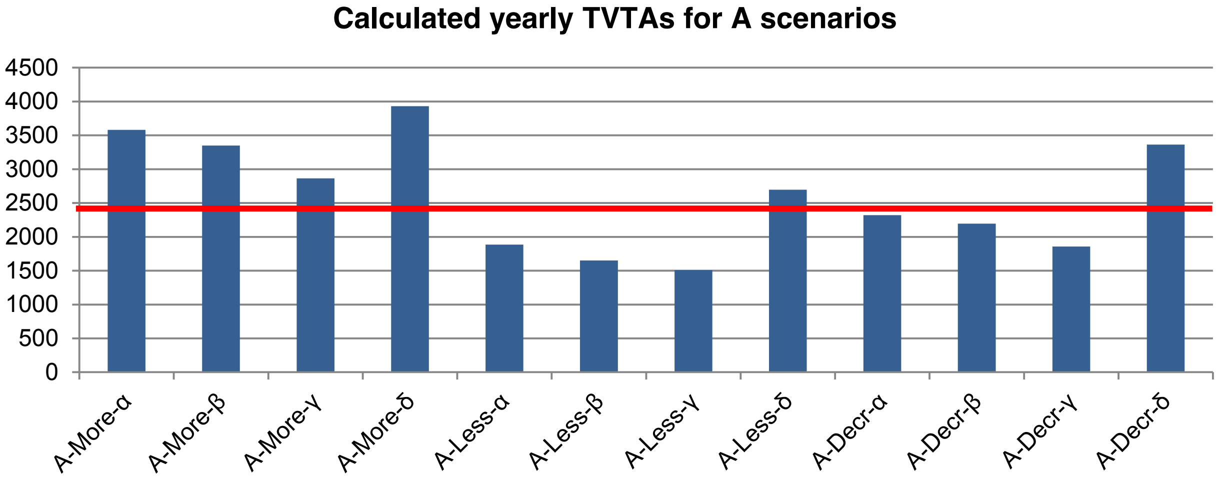


Figure 9.12 TVTA scores of the A scenarios. The red line represents the TVTA score of the Base-α scenario

It immediately becomes clear that untangling option A is one of the options that contributed to the fact that the maximum scenario scores lower on robustness than the base scenario. By just looking at the α scenarios, it can clearly be seen that the more untangled variant leads to a TVTA increase of more than 1000, the less untangled variant to a decrease of approximately 500 TVTA, and the decreased failure rate variant to a marginal reduction of 100 TVTA.

The TVTA increase in the more untangled variant is caused by limitations in the traffic management measures as a result of the new system design: without the presence of switches between corridors, every TOA within the corridor will inevitably lead to a full suspension of services. The reduction in TAOs as a consequence of the removal of switches (approximately 7 TAOs) is not large enough to compensate for this effect, hence the increase in TVTAs. A special feature of DSSU is that trains in the A2, A12 and SPRBkl-Db corridors need to make use of each other's infrastructure in order to turn around in Utrecht. Without these switches, turning trains around in case of an unavailable infrastructure element on one side of the station and sending them back in the direction they came from, is impossible. This side effect amplifies the impact of more untangling the physical tracks in a negative way. In the last subsection this matter will be elaborated on.

Adding extra switches between corridors or in other words less untangling the system seems to have a positive impact on the robustness: the extra TAOs that emerge from these extra switches are well overcompensated by the extra flexibility in the traffic management measure generated by these switches.

On the other hand, the score of scenario A-Decreased switch failure rate-β shows that by simply trying to reduce the switch failure rates by 20% and improving the usage of the remaining infrastructure during incidents, the TVTA score of the base scenario can also be slightly reduced. But, in general it must be concluded that the decreasing failure rate approach seems less effective than the untangling strategy (in this case).

Having said that, the three generated scenarios around untangling option A do not necessarily represent the optimal extent or use of untangling option A: the removed switch pairs (every pair between corridors), the added switch pairs (at some locations, see section 7.4.1.1) and the decreased failure rate (20%) are all possible variations out of a scope of thousands of possibilities around options A. The three scenarios only indicate if more or less untangling in reference to the base scenario given the current case study will lead to a lower or higher robustness and if this robustness increase/decrease is significant compared to a solution currently under investigation at ProRail: reducing the TAOs with 20% (Ministry of Infrastructure & Environment, 2014a).

Once again it can be concluded that the impact of the presence of safe working space, which is a form of untangling, is large; the δ variants all scored significantly lower than the α variants. Even the less untangled scenario, for which a higher robustness was calculated, shows a lower robustness under the δ regime than was calculated for the base scenario. In other words, adding these switches if less effective than creating safe working areas around infrastructure elements. As stated before, there are also many variations possible between complete absence (δ) and full presence (α) of these working areas, the developed model can be used to assess the impact of each individual safe working area.

9.3.4 Results of the B scenarios

Strongly related to the previous untangling option are the scenarios modelled for option B. Again, the only variation modelled here is the removal of all 'requiring' relations between switch pairs. From a safety point of view, an assessment per switch pair (safety risk versus impact on robustness) could be relevant, which can easily be done with the help of the developed model.

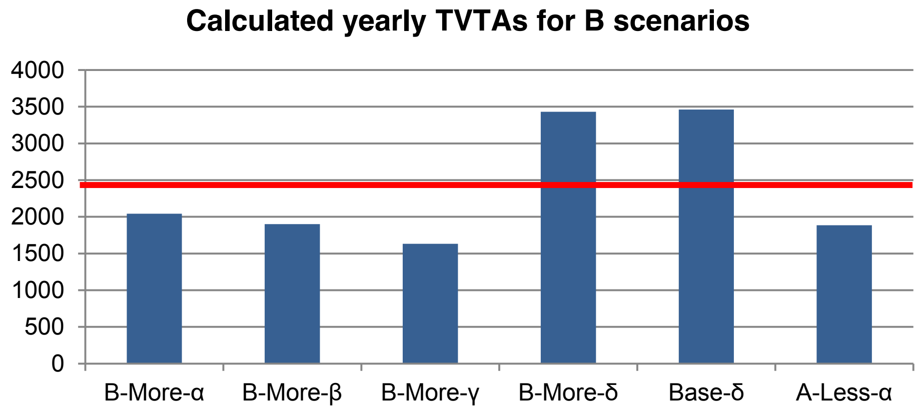


Figure 9.13 TVTA scores of the B scenarios. The red line represents the TVTA score of the Base-α scenario

Figure 9.13 shows the scores of the B scenarios, and the main conclusion that can be drawn from this directly is that this untangling option has a positive effect on the system robustness: a reduction of approximately 500 TVTAs compared to the base scenario. Another interesting characteristic of this untangling option is that does not only work for switch pairs between corridors, but also for switch pairs within corridor. Due to that, one of the two tracks in a corridor could remain available and allow for a reduced train service in that corridor instead of a complete suspension, which has a huge impact on the robustness.

The B-more untangled-δ and Base-δ scenarios should not show a large difference in TVTA score, after all if switch pairs between two corridors are no longer simultaneously unusable because of the flank protection requirements (B scenario), but still both need to be taken out of service because of the safe working area, the effect is the same. As can be seen in Figure 9.13, this is indeed the case.

On the right side of the figure, the result of the A-Less untangled-α scenario has been depicted to show the small difference in results between this scenario and the B scenarios. Instead of installing new switches, the same TVTA result can be achieved by untangling the requiring switch pairs (only in case of unavailability of one of the switches) or perhaps in combination with improved infrastructure usage (β). Although costs are not part of this research, this B scenario alternative seems to be much cheaper and therefore of high interest.

9.3.5 Results of the C scenarios

The main differences of the C scenarios compared to the A and B scenarios is the low chance of occurrence of related failures, the high duration of the unavailability as a result of these failures and the large area of impact. A failure of a relay house will automatically lead to a complete suspension of train services in that area.

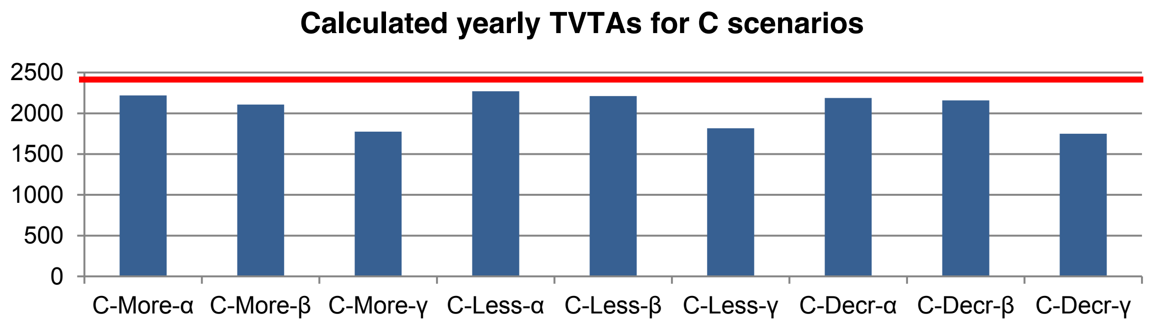


Figure 9.14 TVTA scores of the C scenarios. The red line represents the TVTA score of the Base-α scenario

Figure 9.14 shows the results of the C scenarios, and what stands out immediately is that both the more untangled and less untangled variants score better than the base scenario. Because the amount of

TAOs related to relay house failures is only 0.18, the predicted number of TAOs for both scenarios (171 and 170 respectively) does not deviate significantly from the base TAO score (171). A difficulty faced before in this research seems to be responsible for the decrease of TVTAs in both scenarios: the number of relay houses increases from 4 to 6 in the more untangled scenario and decreases from 4 to 1 in the less untangled scenario, but the failure rate of a relay house remains equal regardless of its size. So, where an A2 corridor train service can be interrupted by the unavailability of three different relay houses in the base scenario, in the less untangled variant it is only interrupted by the unavailability of a single relay house: a reduction of 66%. The real question here is whether the data used for relay house unavailability is still valid for such a large relay house, after all the extra components in this larger house perhaps increase the repair time significantly. On the other hand, the same way of reasoning in the opposite direction can be applied to the smaller relay houses, where fewer components could lead to a reduced unavailability. In the discussion section this matter will be addressed once again.

In general can be concluded, based on the TVTAs calculated, that untangling the relay houses is not very effective. Decreasing the failure rate (C-Decrease failure rate-α) or improving the usage of infrastructure during incidents (Base-β) is as effective as untangling the relay houses and probably easier and cheaper to accomplish. Nevertheless, a key aspect that is not covered well in the used definition of robustness is the hindrance cancelled trains cause for passengers. In the tangled situation (Base-α), trains in several directions are cancelled simultaneously during the unavailability of a relay house, which requires passengers to use alternative modalities. In the untangled situation, either the local trains or the intercity trains – since they each have their own corridor – remain operable resulting in the possibility for passengers to use the other service with only a minor delay of their journey as a consequence. This very positive effect of untangled relay houses is not quantified in the model though.

9.3.6 Results of the D scenarios

In the D scenarios the design of the subsidiary circuits in the overhead wires have been altered, even though the subsidiary circuits are already almost lined up with the corridors. Figure 9.15 shows the results generated by the RA-tool for the more untangled scenarios and the less untangled scenarios.

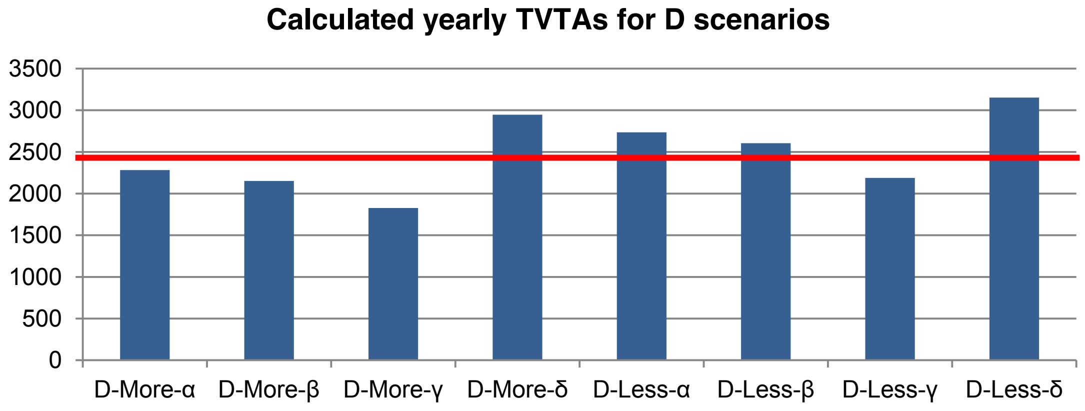


Figure 9.15 TVTA scores of the D scenarios. The red line represents the TVTA score of the Base-α scenario

The result is clear: a more untangled system leads to a TVTA reduction and a less untangled system to a TVTA increase. At the same time it must be concluded that the difference in results with the base scenario is small, which was to be expected since the subsidiary circuits were already largely designed corridor wise.

It is interesting to see the range between D-less untangled-α and D-more untangled-α, which is approximately 500 TVTAs. The question is whether these 500 TVTAs, a reduction which also could be achieved by (simply) increasing the usage of the remaining infrastructure during incidents (Base-β) could justify the effort and cost to create these subsidiary circuits.

9.3.7 Results of the E and F scenarios

The E and F scenarios are similar in many ways: both consist of a single system that controls the whole modelled area in the base scenario and in the untangled scenario both systems are split per corridor. It is not a surprise that the results will therefore be similar too, hence this combined result discussion section. Figure 9.16 shows the TVTA scores for both the E and F scenarios compared to the Base-α scenario (red line).

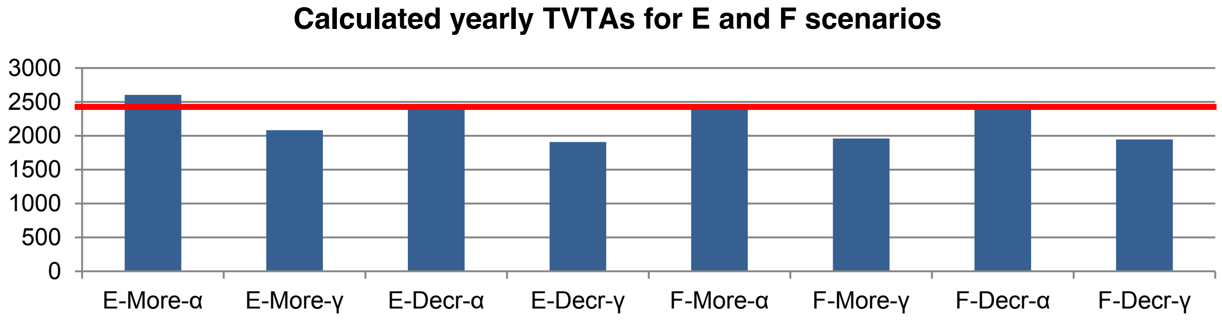


Figure 9.16 TVTA scores of the E and F scenarios. The red line represents the TVTA score of the Base-α scenario

A clear pattern can be seen in the results: the more untangled scenarios score slightly worse than the non-untangled scenario and the decreased failure rate scenarios score slightly better than the base scenario. The worse score can be explained by the increased amount of TAOs caused by the multiplication of total number of systems (from a single interlocking or EBP to multiple interlocking devices or EBPs). The failure rate of each of these smaller systems is kept equal to the failure rate of the current single system, which in combination with the increased amount of systems led to the TOA increase. The correctness of these failure rates can be argued.

The deviation from the base scenario is greater for the E scenarios than for the F scenarios, which can be explained by the difference in related infrastructure unavailability. The E scenarios adjust a system (interlocking) that has a yearly unavailability of 1.3 hours, while the F scenarios adjust a system (EBP) that has a yearly unavailability of 0.5 hours.

In general can be stated that the effectiveness of these two scenarios is low, mainly because of the low unavailability that is related to the scenarios. A huge untangling benefit though, that is not captured in the TVTA score, is the passenger hindrance. In the tangled situation (Base-α), trains in all directions are cancelled simultaneously during the unavailability of the interlocking or EBP, which requires passengers to use alternative modalities. In the untangled situation, either the local trains or the intercity trains – since they each have their own corridor – remain operable resulting in the possibility for passengers to use the other service with only a minor delay of their journey as a consequence.

9.3.8 General findings

The previous sections have discussed the results of specific scenario groups (Base, min, max and A to F) predominantly in reference to the TVTA score of the Base-α scenario. Besides the TVTA scores, several other findings were made during the modelling process that are worth taking into account. This section will describe these findings.

9.3.8.1 Result pattern in α, β, γ, and δ scenarios

It is interesting to see how the other robustness increasing measures scored that were posed as alternative (or addition) to system untangling. Table 9.5 presents some characteristics of the β, γ and δ scenarios in relation to the α scenarios that will be discussed below.

	Maximum TVTA difference	Average TVTA difference	Minimum TVTA difference	Base TVTA difference
β-scenarios	-13%	-7%	-2%	-12%
γ-scenarios	-20%	-20%	-20%	-20%
δ-scenarios	+68%	+32%	+7%	+42%

Table 9.5 Relative scores of the β, γ, and δ scenarios in relation to the α scenarios

The right column of Table 9.5 shows the TVTA differences in terms of percentages between the Base-β, Base-γ, Base-δ and the Base-α scenario. The middle three columns express the minimum, average and maximum difference in TVTA score between a β/γ/δ regime and α regime of the same variant, for example the difference between A-More-α and A-More-β or between C-Decr-α and C-Decr-γ.

By only increasing the usage of current infrastructure during incidents (definition of the β regime) a TVTA reduction of 12% can already be realised, which is more than the benefits of some untangled scenarios. In the base scenario the effectiveness of β is quite high though, since the β measure in addition to untangling options only results in an average TVTA reduction of 7%. Nevertheless, especially allowing departure times of trains in disturbed situations that deviate from the timetable appeared to be a very effective robustness measure that can be implemented without changing any infrastructure. For example departing local trains five minutes ahead of schedule to free up scarce platform capacity and prolonging their dwell time at Utrecht Zuilen, Leidsche Rijn or Vaartsche Rijn made a large difference in the TVTA score.

For the γ scenarios this TVTA reduction is trivial: a reduction of the infrastructure unavailability duration by 20% automatically leads to a reduction in TVTA of 20%, see formula (8.3). What is interesting to see though, is that a 20% reduction of incident time in the base scenario, so without changing anything to the system's design, leads to the third best TVTA score. Only scenarios A-Less-α and B-More-β have a better score (apart from the other γ scenarios). Striving for incident duration reduction seems therefore a very effective measure, especially in the light of the infrastructure unavailability approach used by the model instead of an incident based approach (see validation section, where this will be explained in further detail).

The δ scenarios have been introduced with a different purpose: quantifying the impact of not having safe working areas around infrastructure elements that could require physical repair (switches, faulty trains, ES-welds). This safe working area (or in other words physical track untangling in the safety subsystem) has been identified in the explore part of this research as separate untangling option, but has soon been flagged as too correlated to other untangling options. Therefore it has been modelled as a regime here, so see the damage in terms of TVTA if a safe working area is not installed. From Table 9.5 it becomes clear that the impact is huge: 42% more cancellations in the base scenario if no safe working areas are installed. In the other scenarios this varies largely, between 68% and 7% with an average difference in TVTA score between the α and δ regime of 32%.

9.3.8.2 Differences in performance between corridors

Although it is not part of the research question, it seems to be a fruitful exercise to analyse the performance per corridor to see if there are differences that can be explained. Table 9.6 shows the number of TVTAs and the corresponding TVTA share per corridor together with the share in train frequency. Theoretically, if each corridor performs equally well, the share in TVTA and the share in trains should be equal. A positive difference in TVTA share indicates a worse performing corridor (more cancellations per unit of train frequency) and a negative difference in TVTA share indicates a better performing corridor (fewer cancellations per unit of train frequency).

Corridor	TVTAs	TVTA share	Train share	Difference
A2	335	14%	13%	+1%
A12	405	18%	16%	+2%
SPRBkl-Db	344	14%	13%	+1%
VleuGel	267	11%	13%	-2%
North-East	413	17%	19%	-2%
Buurt	373	14%	14%	0%
ICLedn	52	2%	3%	-1%
Freight	270	11%	10%	+1%
Total	2437	100%	100%	0%

Table 9.6 TVTA share and train frequency share of corridors in the Base-α scenarios

In the fifth step of the model, the traffic management measures, which are based on VSMs, need to be specified for each infrastructure unavailability train series are affected by. Executing this time consuming process teaches inside knowledge on which characteristics of a corridor play an important role in the relation between TAOs and TVTAs, or in other words between unavailability (incident) and train cancellations (impact).

From Table 9.6 it can be seen that the VleuGel, North-East and ICLedn corridors scored better than average while the A2, A12, SPRBkl-Db and Freight corridors scored worse than average. Which differences between these corridors could explain the difference in performance?

- ***Policy to avoid Utrecht station in disrupted circumstances***
  For one specific train series (ICE in A12) and for one corridor (Freight) the policy stated in the VSMs is to reroute these trains around Utrecht as much as possible in disturbed conditions. This policy has been made on the one hand to free up capacity at Utrecht (freight) and on the other hand to allow international passengers to reach their final destination (ICE). ICE services could be rerouted over Arnhem-Deventer-Amersfoort-Amsterdam or Arnhem-Ede-Wageningen-Amersfoort-Amsterdam and vice versa. From Utrecht's point of view though these trains are then cancelled – see appendix E – resulting in a higher TVTA score for the A12 and freight corridors.

- ***Infrastructure that allows trains to turn around easily and rapidly in the corridor***
  Although turning trains around in stations is nothing more than the train driver who needs to walk from one cabin in the train to the other cabin, the turnaround capacity of a corridor is mainly determined by the infrastructure. To explain the performance difference between the A2 and A12 on one side and the VleuGel on the other side, Figure 9.17 shows a schematic visualisation of the track layout around the platforms 14 to 21. The VleuGel corridor Tracks 14 and 15 are used for the SPRBkl-Db corridor, track 18 for the A2 (southbound) trains, 19 for the A12 (southbound) trains and 20 and 21 for the VleuGel and ICLedn corridors. See appendix G for details.

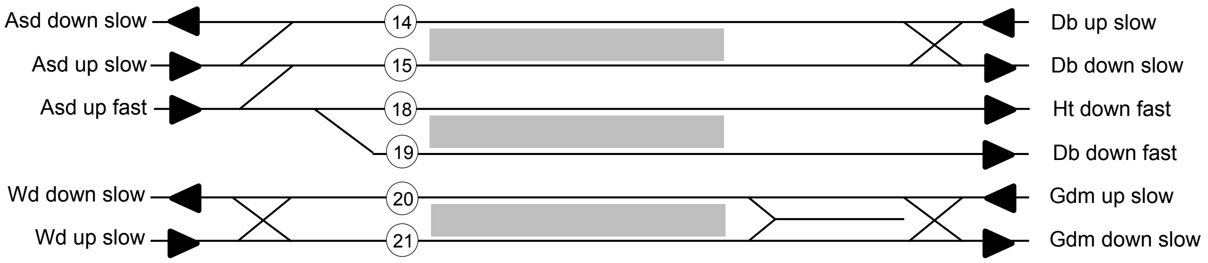


Figure 9.17 Schematic representation of the track layout around platforms 14 to 21 in the base scenario

In the case of an infrastructure unavailability in the VleuGel corridor on one side of the station, trains in the VleuGel corridor arriving on the up track can, with the help of the two crossovers on both sides of the platform, turn around at both platforms and quickly be guided towards the down track once they have departed again. Moreover, a tail track has been installed for trains arriving from the North, which for these trains could even lead to a dwell time reduction from 6 minutes (time required to turn around) to 1 minute (time required for passengers to disembark), as the turnaround process now takes place on the tail track instead of at the platform. This high flexibility means that all train services can continue to operate in one direction in case of a disruption on one side of the station.

For the A2 and A12 corridors this is not possible: as can be seen from Figure 9.17 trains arriving on the Asd up fast cannot be guided towards an Asd down track if they have to turn around in Utrecht. Trains arriving on the Asd up slow track can only use platform 14 to turn around. If trains have to be sent back over an up track, the capacity of that up track is drastically reduced, since only one track will then be available for both directions. In the VSMs it is stated that in case of an infrastructure unavailability on the southern side of the station (right side in the figure), trains from the A2 and A12 arriving on the Asd up fast track need to use platform 15 to disembark passengers and will then be sent to the OZ yard where they will turn around and be sent to platform 7 to reach the Asd down fast track.. With 9 trains per hour arriving on the Asd up fast track and 5 on the Asd up slow track, a disruption in the South will immediately lead to the cancellation of southbound services *and* a reduction of Northbound services. Besides that, if the OZ yard is also unavailable, for example due to a centre relay house failure which also controls the OZ area, the reduction in northbound services will even be greater.

A similar situation exists around platforms 5 and 7 for northbound A2 and A12 services which cannot turn around easily in southern direction. This corridor characteristic – absent infrastructure to turn around easily – played an important role in the performance difference between the A2, A12 and VleuGel corridors.

- **Spare *platform***
  Another important infrastructure aspect of a corridor that contributed to a relative high performance was discovered in the North-East corridor, which scored 2 percentage points higher than average. Platform 9 is only used for the departures of the 2000 series (The Hague – Utrecht) and this train service could also be handled on platform 20 and 21 if the rolling stock roster is coupled to the rolling stock roster of the ICLedn. By doing so, platform 9 can be freed up without any cancellations to facilitate trains that cannot use their planned platform due to an incident. As a result of that, a faulty train at platform 8 for example did not lead to any cancellations.

9.3.9 Overview of found results

Table 9.7 shows the percentage difference between the TVTA score of the α scenario of each untangling option with the lowest TVTA score and the TVTA score of the Base-α scenario. The third column states whether the more untangled or less untangled α scenario scored better (thus lower TVTA score) and the fourth column whether the alternative measure ‘decreasing failure rate’ was more effective than untangling. At the bottom the comparison is made between the average TVTA score of scenarios run under the δ regime and the TVTA score of the Base-α scenario.

Untangling option	Highest robustness increase	Untangling extent in reference to DSSU	Decreasing failure rate more effective?
(A) Removing switches	23%	Less	No
(B) Flank protection	16%	More	-
(C) Relay houses	10%	More	Yes
(D) Subsidiary circuits	6%	More	-
(E) Interlocking	-7%	More	Yes
(F) EBP	-1%	More	Yes
(δ) Safe working area	32%	More	-

Table 9.7 Summary of the α scenario TVTA results, percentage scores all in reference to the Base-α scenario

Besides untangling option A, all more untangled scenarios scored better than the less untangled scenarios, even though the scores of options E and F are negative (robustness decrease instead of increase). The latter will be elaborated on in the discussion section. The top three most impactful untangling options are removing switches (A), lifting flank protection requirements from unavailable switches (B) and creating safe working areas next to each track (δ). In the conclusion chapter all conclusions that have been drawn in this section will be repeated and summed up. First, the results will need to be validated though.

9.4 Validation

Validating the results of the improved RA-tool is a difficult matter, since both the modelled infrastructure and timetable do not yet exist. Most of the infrastructure of DSSU has been put into service in December 2016, but some parts of the infrastructure will not be ready until 2018 (UtArk project). The chosen timetable was therefore the 2017 timetable, since it needed to fit the future infrastructure. At the time of this research this timetable had barely started and relevant incident or performance data was not yet available. In order to get a feeling for the correctness of the model, this section will address two small validation processes that have been executed.

9.4.1 Tool validation

In the previous chapters many comments have already been made on how the RA-tool can be used, what its limitations and advantages are and which effects and aspects are not represented in the most optimal way. In the discussion section (Section 9.5) some of them will be repeated and most probably more will be added.

An interesting validation to the improved RA-tool that not has been mentioned previously is to see whether the chosen incident types form a representative set of incidents. The selection of the incident types to include in the model followed directly from the choice of untangling options; in the first part of this research, incidents types have been linked to untangling options based on a single criterion. This criterion – select incident type if the untangling option could potentially limit the impact area of the incident to the corridor of occurrence to some extent – was very suitable for the estimation of the untangling options' potential in the first part, but the validity of this criterion in the second part of the research is questionable. Because the logistical effect of an incident, which was not taken into account in the first part, has an important role in the RA-tool, the impact of incident types that have not been linked to a certain untangling option in the first part could be influenced in the RA-tool by that same untangling option.

Ideally, all incident types should be modelled in the RA-tool to assess the robustness of a system, but due to practical reasons this is infeasible. To make the model as representative as possible, the modelled incidents types should comprise as much of the total number of incidents as possible. Figure

9.18 shows the shares of incident categories in the total number of reported incidents in the Netherlands in 2015. Unfortunately, the incident categories do not completely match with the incident types found in the used data source (ProRail, 2016l).

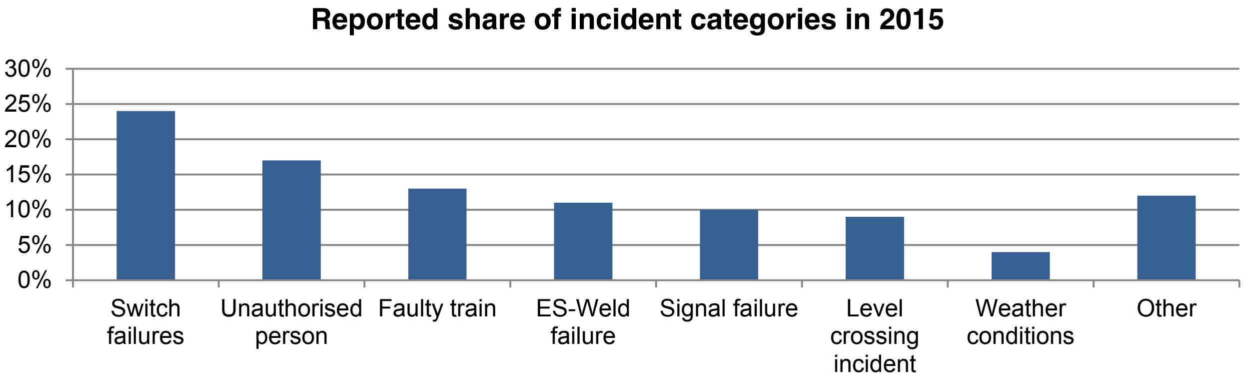


Figure 9.18 Reported share of incident categories in the total number of reported incidents in 2015 nationally (ProRail, 2016l)

Very recognisable incident categories are ‘Switch failures’, ‘Faulty train’ and ‘ES-Weld failure’, which have been incorporated in the improved RA-tool. Suicide incidents and people spotted walking alongside the tracks illegally belong to the category ‘Unauthorised person’, which often do not occur at large complex stations where there is a lot of surveillance (ProRail, 2016l). The same holds for the incident category ‘level crossing incidents’, but then for the reason there are no (public) level crossings located in large complex stations. It is not clear which failure results in an incident of the category ‘signal failure’, as this could comprise an interlocking failure, a broken light bulb, EBP failure or many other failure types. The same holds for ‘Weather conditions’, from which it is also unsure to which extent they have been taken into account (which sub categories). For example ‘Snow/Ice in switch’ and ‘EBP failure’ have been identified as related incident types (See Table 4.11), while a broken light bulb or a fallen tree have not.

What can be concluded from Figure 9.18 is that at least 74% of the reported incidents have been modelled in the RA-tool, which despite the mentioned invalid criterion of incident type section indicates that the found results would not change much with more incident types modelled.

9.4.2 Result validation

As has been stated before in the result section, the absolute values of the TVTAs produced by the RA-tool are not of great interest, it is the proportion of TVTA values between scenarios that is most important for answering the research question. Nevertheless, it might be relevant to put the results of the base scenario into context and see whether they could be linked to actual numbers found in other data sources.

Performance indicator	Modelled Base-α	Reported in 2016
TAOs in Utrecht area	171	139
Cancelled trains at Utrecht (TVTAs in model)	2437	5792
Number of train departures at Utrecht (yearly)	419,000	382,487
Percentage of cancelled trains	0.6%	1.5%

Table 9.8 System performance indicators calculated by the RA-tool and found in incident data reports (ProRail, 2017b)

Table 9.8 shows the results of the RA-tool (left) and data abstracted from incident reports (right) (ProRail, 2017b). A large difference has been found between the reported TAOs in Utrecht and the calculated TAOs for Utrecht, which are much lower. An explanation for this discrepancy could lie in the time periods that have been used for both results. The reported result was obviously measured in 2016, but the calculated result has been based on the average frequency of occurrence in the years 2010-2015 (see chapter 4). In the years 2010-2015 Utrecht station was fully under construction for the DSSU project with as result that the used infrastructure was still the old infrastructure that at the time was probably even more heavily used due to construction phasing.

Cancelled trains in Utrecht cannot be compared to TVTA values in the report, since delayed trains – which have not been taken into account in the model – are also flagged as TVTAs. Fortunately, the data also reports cancelled trains. The amount of cancelled trains due to an incident in Utrecht is more than two times higher in the reported incident data than calculated by the RA-tool, even despite the lower amount of TAOs. An aspect that plays an important role, is that the scenarios are modelled under the α regime, which implies that all switches, sections and faulty trains can be repaired without closing down the neighbouring tracks. This safe working area is not always present though, and sharply deviating results from the δ scenarios (absent safe working area everywhere) shows the sensitivity of having/not having this safe working area. The actual amount of cancellations will therefore be higher than the presented TVTAs under the α regime.

Another aspect has already been mentioned in chapter 8, but will be explained here through the assessment of two incidents occurred in Utrecht in 2015. To analyse the relation between the number of cancelled trains and the reported duration of the incident, three different categories have been made: trains that were cancelled during the reported duration in the affected corridor, trains that were cancelled during the reported duration in non-affected corridors and trains that were cancelled after the incident had been reported as ‘solved’. Figure 9.19 shows the shares of these three categories in the total number of cancelled trains due to the incident.

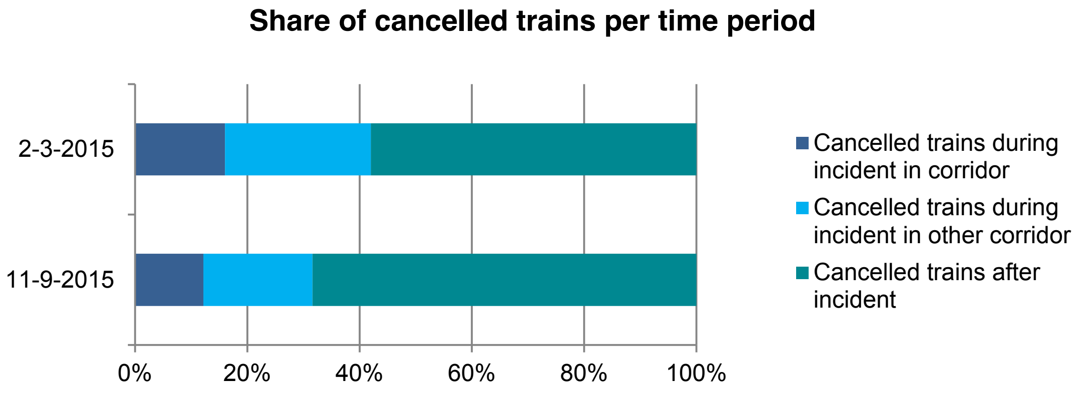


Figure 9.19 Share of cancelled trains in two different time periods of an incident

It is interesting to see that the blue areas represent only around 40% of the total cancellations and that the most cancellations are reported after the incident has been solved. This could be explained by the logistical complexity of the timetable, staff rosters and rolling stock roster that challenges the operation to cope with disturbed conditions and deviations from the original (complex) plan. The time needed after a disruption to have all trains running according to schedule again is therefore large and has (from an infrastructure point of view) unnecessary cancellations as a consequence.

The RA-tool only models cancellations in the blue areas of Figure 9.19, which – based on these two incidents – only represent 40% of the total cancellations. Related to this is an issue that has been discussed before: the RA-tool does not model individual incidents, but accumulates the infrastructure unavailability caused by incidents. For example, three disruptions of 1 hour or a single disruption of 3 hours that both have the same impact on the infrastructure unavailability, are represented in exactly the same way in the RA-tool, namely as an infrastructure unavailability of 3 hours. Keeping in mind that each incident has a certain ‘timetable restart phase’, as shown in green in Figure 9.19, the impact of each

case on the number of cancellations is very different. In the recommendations section a possible solution for this discrepancy is proposed.
From the comparisons between real incident data and the results of the improved RA-tool can be concluded that the exact values given by the RA-tool are not representative. The results should therefore only be used to compare scenarios, not to predict the exact hindrance or robustness a system design will produce.

9.5 Discussion

In the previous sections and even in the previous chapter, many comments on the modelling mechanism, validity and results of the improved RA-tool have already been discussed. In this section some of these issues will be discussed in further detail and a few new points of discussion are to be introduced. The discussion is, in line with the two objectives, split in a tool discussion part and a result discussion part.

9.5.1 Tool discussion

The improved RA-tool has produced results that are used to draw conclusions on the effectiveness of certain untangling options. But, there are some characteristics of the tool that and should be kept in mind when drawing these conclusions.

One of them is the bad representation of safety rules and regulations. The importance of safe working areas around infrastructure elements has been emphasised multiple times and has been quantified through the introduction of the δ regime. In standard conditions, the tool does not take these safe working areas into account at all. A striking example of this is the way that double switches are modelled (see Figure 9.20), namely as two separate switches of which one can be repaired while the other is in use. Obviously, this is not possible from a safety point of view, and the negative effect (TVTA increase) of a double switch is therefore underestimated. Fortunately the amount of double switches in the DSSU case is limited with exception of the Buurt corridor.

Figure 9.20 Example of a double switch

Another aspect that is not taken into account properly is the fact that the robustness of a system design is also influenced by incidents outside the modelled area. For example, if a faulty train stands between Utrecht and Geldermalsen, the TVTAs caused by the fact that the infrastructure in Utrecht does not allow all 4 intercity trains per hour from Amsterdam to turn around is not incorporated. To account for these effects in a correct way, all incidents between the station under investigation and the surrounding large stations should be modelled.

In general the way faulty trains are modelled in the model is too optimistic. While faulty trains in reality can have a large effect on the performance of the system because they block multiple sections and switches, in the model they (only 17% of faulty trains) never block more than one section. Rerouting trains around this faulty train is therefore easier than in reality. Since Utrecht has fixed infrastructure corridors in which trains cannot vary their routes much, this effect can be neglected.

The VSMs form the backbone of traffic management measures that need to be taken in disrupted situations. The RA-tool flags trains that are affected by the incidents and asks the user what to do with them. Trains that are not flagged cannot be altered which sometimes led to the impracticability of VSMs: trains that should be cancelled could not be cancelled as the RA-tool did not foresee the relation between that train and a certain unavailability. To solve this issue, sometimes the wrong trains have been cancelled, simply to keep the TVTA score as it should be. Especially the A12 train series have been cancelled several times favouring the SPRBkl-Db trains. A more basic issue that underlies the previously mentioned problem is that the RA-tool does not model incidents, but infrastructure unavailability. Because of that, the 'collateral damage' in train cancellations that occurs in the restart phase of the timetable, is not taken into account resulting in a too optimistic number of yearly cancellations. This has already been shown in the validation section and the exact values for the robustness have therefore been concluded to be invalid, demanding to use the RA-tool only for comparative purposes. To compensate for this non-incident based modelling approach, the durations of the incidents as found in the data have already been rounded up with a maximum of 60 minutes (see Table 9.2), increasing the yearly unavailability time. Nevertheless, this was not effective as was shown in the validation section, in the recommendations chapter a new proposal to handle this matter will be presented.

The last aspect of the RA-tool that requires discussion is the way time is taken into account. If a switch is unavailable approximately 2 hours per year, when will these two hours occur? In the night? During peak hours? The RA-tool assumes that all infrastructure unavailability happens during the peak hours, but in reality this is not the case. By adding a time factor p_{peak} with a value of 0.8 to formula 8.3 it is assumed that 80% of the unavailability emerges during peak hours and 20% during the night. Some incidents tend to occur more in peak hours, such as faulty trains (there are more trains in peak hours), while other tend to occur during the night, such as EBP failures (systems are updated during the night). In (ProRail, 2017c) is stated that in January 2017 9% of all incidents was reported between 00:00-05:00 AM, which would call for a time factor of 0.91 instead of 0.8. Nevertheless, since the reduced services in off-peak hours – especially between 08:00-12:00 PM when the frequency in almost every direction is reduced by 50% – will also contribute to a lower TVTA score, a lower time factor of 0.8 seems more realistic. However, since the improved RA-tool in its current format cannot be used yet for its exact values but only for comparative purposes, this time factor is not of any influence on the results as the factor is equal for all scenarios.

9.5.2 Result discussion

Besides discussions on the way the improved RA-tool determines the robustness of system designs, the data used in this specific case study can also lead to discussion.

An important aspect has already be mentioned several times: the failure rates of larger systems that are split up in smaller systems, such as the interlocking installation, relay houses and EBP system. The smaller systems will probably have a different failure rate than the original larger systems but only a single failure rate has been used for all systems. For example splitting up an EBP system that is unavailable 2 hours per year into six EBP systems that are each 2 hours per year unavailable, will show a negative effect on the robustness. Nevertheless, if the failure rate of these six smaller EBP systems is much lower than the original failure rate, the effect on the robustness can be much more positive. The effectiveness of untangling the relay houses, EBP system and interlocking device is therefore too pessimistic.

Another failure rate related issue is the absence of a distinction between types of subsidiary circuits. There have not been used different failure rates and unavailability durations for subsidiary circuits fed by two power stations (such as circuit 1), fed redundantly by one power station (such as circuit SX2) and fed non-redundantly by one power station (such as circuit SX1), see appendix H. A difference in failure rate could theoretically lead to a different untangling effectiveness and would also pose the question which type of subsidiary circuit is more robust and whether changing the circuit type would not be more effective than untangling.

An aspect that not has been mentioned so far is the influence of the timetable. In the explore part of this research it was already concluded that the effectiveness of untangling options heavily depends on the local situation such as the used timetable. The β regime has been an attempt to cover the influence of the timetable to some extent, as it showed the difference in TVTA score between the contingency plans linked to the current timetable (α) and using contingency plans linked to a slightly adjusted timetable (β). But ideally, a sensitivity analysis should be carried out to explore the full range of TVTA that can be attributed to the timetable. However, since the list of variations in system designs was already quite extensive and the sensitivity of the timetable partly covered by the β scenarios, a full sensitivity analysis was not executed.

Lastly, another timetable related issue that not has been mentioned yet. In contrary to train paths granted to passenger trains, train paths granted to freight trains are not always used. For example, there are three freight train paths per hour reserved from Amsterdam to Meteren, while there is only one hourly freight train path from Meteren to Amsterdam. Practically, freight trains to the North will use the one train path and trains to the South will choose one of the train paths available. As a result the other freight train paths to the South will be used less frequently, but this has not been taken into account in the model. Together with the fact that freight trains are either rerouted or (extremely) delayed, but hardly ever cancelled, the TVTA results for the freight trains calculated by the RA-tool are not representative (OCCR, 2017).

Section summary

In the past three sections the results of the modelled scenarios have been presented, interpreted, validated and discussed. It appeared that the improved RA-tool's results should not be used for its exact values, since the design of the model and the assumptions made have led to a deviation from actual train cancellation quantities which is considered to be too large. However, the tool is usable for comparison reasons and could be used to express the effectiveness of the modelled untangling options in increasing the robustness.

Compared to the current DSSU system design and operation, the top three most impactful untangling options are removing switches (A), lifting flank protection requirements from unavailable switches (B) and creating safe working areas next to each track (δ). It has to be stated though that for scenarios A the more tangled scenario (adding switches) scored significantly better than the untangled scenario. Besides these scores, other findings were made on when a corridor scored high: the presence of spare platforms and infrastructure to turn around trains easily appeared to play an important role.

Note that this part of the research continues in chapter 10, where the research questions will be answered.

Conclusions & Recommendations

MSc Thesis for Transport, Infrastructure & Logistics
MSc Thesis for Civil Engineering

10 Conclusions

In the previous 9 chapters two separate studies have been described each with their own research objectives and research questions. The added value of this combined report is that both parts form the answer to an overall research question, which explains the choice for merging the individual conclusion sections into this general conclusions and recommendations chapter. In this way, the conclusions can be drawn, explained and visualised in a more consistent and constructive way. As a result of that, this chapter belongs to both the explore and develop parts and the step of the research approach shown in Figure 10.1 appear in both parts their research approaches (see Figure 1.3 and Figure 1.4).

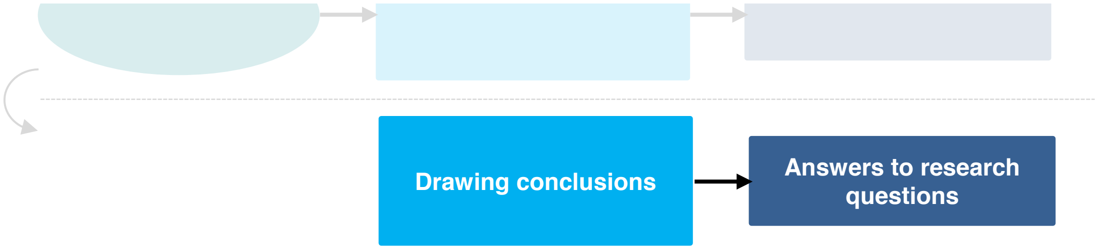


Figure 10.1 Step of the research approach described in this chapter

Besides the conclusions that will be drawn and the answers that will be given to all research questions in the first part of this chapter, the second part of this chapter provides the recommendations for further research, recommendations for adjustments at Utrecht station and recommendations for the development of the RA-tool.

10.1 Conclusions

This section presents per research part the conclusions that have been drawn and provides answers to the research questions in a fixed format: first general findings will be presented in a slightly summarising way in which all sub questions will be answered, after which the research question will be answered and the achievement of the research objective will be checked. When both the explore part and develop part have been discussed in this way, the last section will answer the general research question of this research.

10.1.1 Conclusions of the explore part

The explore part of this research has a more exploratory character and strived to get a deeper understanding of the untangling principle and to investigate what untangling options there are and what their potential is.

10.1.1.1 Findings throughout the research and answers to the sub questions

In the literature review the phenomenon *system untangling* was under investigation. It became clear that forms of rail system untangling are used for multiple purposes such as capacity increase (fly-overs), cost reduction or space scarcity and disruption spread decrease (new design of Utrecht station), only the latter obviously within the research scope. Many examples of untangling projects have been examined and with the help of a developed rail system describing model, a few degrees of freedom or characteristics of the untangling strategy could be identified.

> *(1B) How can this system be defined or modelled and which subsystems can be identified in order to describe system untangling?*

This Railway Service Model, depicted in Figure 10.2 has been developed with the main purpose to facilitate the description of the untangling strategy's degrees of freedom so that a selection could be made to narrow down the scope. The model is based on several existing models and has been applied to the Dutch railway system in various ways.

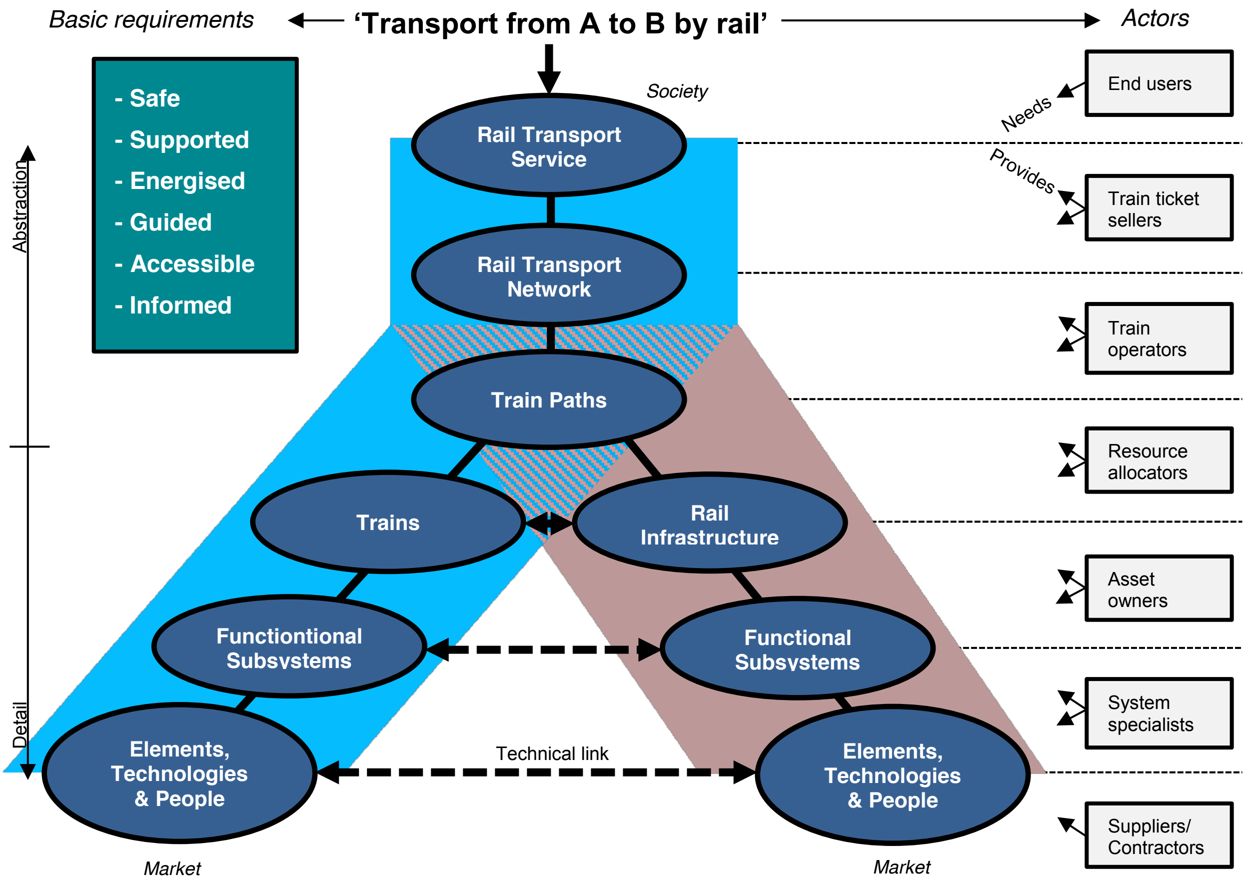


Figure 10.2 Railway Service Model developed in chapter 3

> *(1A) What is system untangling and which variables are of interest?*

The system untangling strategy and its degrees of freedom have been identified in the literature review and with the help of the Railway Service Model. System untangling has been defined as *the creation of multiple parts within the railway system that have less interaction with each other and therefore prevent irregularities from spreading and increase the system's robustness.* The identified related degrees of freedom are: '*type*' (untangling between subsystems or between corridors), '*level*' (splitting up transport systems or untangling within a single system), '*division strategy*' (untangling per direction or per TOC), ‘*geographical strategy*’ (untangling in complex stations or on the line) and ‘*extent*’ (untangling fully or just at some points).

(1C) Which forms of system untangling are interesting to take into account?

For each of these variables a suitable range was chosen that lead to the following demarcation; *untangling the subsystems of the railway system at complex stations per train corridor to all possible extents*.

(1D) Which (relevant) untangling options can be identified?
(1E) What is the (potential) effectiveness of these options?

With a deeper understanding of untangling and a delimited research direction, workshops were held with experts of different fields (within the railway sector) in which possible untangling options have been explored. This resulted in a list of 25 options from which the potential benefits have been quantified in a very general way with the help of incident data, see Table 10.1. The results show large differences in effectiveness between untangling options which unfortunately were not always easy to interpret.

Untangling option	Potential benefit [min]	Rank [#]	Untangling option	Potential benefit [min]	Rank [#]
(6) Removing switches	4938	*1*	**(8) Power supply switches**	161	*14*
(19) Flank protection	4334	*2*	**(18) Interlocking**	141	*15*
(17) Relay houses	1890	*3*	**(16) Power supply infra**	135	*16*
(10) Tunnels & Bridges	1549	*4*	**(21) LCE**	70	*17*
(3) 1500V power stations	1054	*5*	**(12) Terminal power grid**	6	*18*
(2) Subsidiary circuits	775	*6*	**(4) Tensioning system**	0	*19*
(14) Signal control cables	426	*7*	**(5) Overhead wire gantries**	0	*19*
(7) Switch control cables	426	*7*	**(15) Signal gantries**	0	*19*
(22) Power supply signal box	414	*9*	**(23) EBP**	0	*19*
(13) Station hall evacuation	337	*10*	**(24) PRL**	0	*19*
(1) Contact lines	324	*11*	**(25) Signaller**	0	*19*
(11) Elevated junctions	321	*12*	**(20) Safe working area**	0	*19*
(9) Switch heating	188	*13*			

Table 10.1 Ranking of identified untangling options with highest potential benefits

- ***Some options were too correlated to estimate an individual potential benefit***
  This was the case with the safe working area untangling option, which in order to quantify it has been taken into account in the second part of this research in a different way.
- ***Some options led to the increase or decrease of elements that are susceptible for failures***
  For that reason the assumed frequencies of occurrence of related incidents type were not representative anymore. Some of these options, such as the interlocking untangling option, have been included in the set of untangling options in the second part to see if they could be quantified there.
- ***Some options were more detailed than the incident data used to quantify their potential***
  Because the workshops were organised per subsystem, sometimes similar untangling options were identified of which the potential benefit could not be distinguished from one another. An example is the untangling options ‘untangle element control cables’ and ‘untangle switch control cables’.

- ***For one option no incident data was available***
  The untangling option to have a single signaller per corridor could not be quantified because the 'failure' of signallers or incident spread caused by a work overload of the signallers is not measured by ProRail.

10.1.1.2 Answering the research question

A research question has been formulated in the first chapter that now can be answered based on the results and findings in this thesis.

> *Which system untangling possibilities are (most) effective in limiting the impact of single incidents?*

Seven untangling options have been identified as a high potential in isolating the impact of incidents within the corridor of occurrence. Table 10.2 shows these untangling options and their potential benefits, expressed in minutes of infrastructure unavailability that could potentially be isolated from neighbouring tracks if the option was installed (TB_z). It is important to say that these results do not represent the system robustness, as the logistical effects and potential negatives of the untangling options have not been taken into account.

Untangling option (*z*)	Potential benefit [min] (TB_Z)	Rank (*#*)
(6) Removing switches	4938	*1*
(19) Flank protection	4334	*2*
(17) Relay houses	1890	*3*
(10) Tunnels & Bridges	1549	*4*
(3) 1500V power stations	1054	*5*
(2) Subsidiary circuits	775	*6*
(20) Safe working area	0	*19*

Table 10.2 Seven untangling options that scored a high potential benefit value

The first two are related to switches and have both scored so high because *switch failures have a large share in the total number of reported incidents*. Especially the fact that neighbouring switches are often also taken out of service during a switch incident – for safety reasons or because of the required flank protection – contributed to high score of these untangling options. It is important to mention that *the removal of switches has a huge logistical effect that has not been taken into account* here, but which could result in a *lower robustness*.

Untangling the relay houses is also effective (even though the result shows a large difference with the previous two) because *the loss of relay house leads to a prolonged unavailability of the area*, which usually comprises a large part of the station area. The frequency of occurrence though is low, but the combination of both led to this high score.

Tunnels & bridges, mostly tunnels, have a *high unavailability due to the strict safety requirements* and the presence of sensitive tunnel installations that follow from these requirements. The large number of fire alarms found in the data for Schiphol Airport station (the only large station with a tunnel taken into account) resulted in the conclusion that having a *form of physical separation in the tunnel will lead a large reduction of impact spread*.

The options *untangling the power stations* and *untangling the subsidiary circuits* are *strongly correlated* and therefore both scored high. However, the *difference in potential benefit is small* while the difference in cost and effort to install both options is large. In terms of effectiveness the power stations are wiser to untangle, but *in terms of efficiency the subsidiary circuit untangling option is much more interesting*.

Lastly, the *safe working area between tracks* that allows for repair works to one track without causing hindrance to the neighbouring track is probably the *most important untangling option*, even though the score in Table 10.2 is zero. There is a strong correlation with almost all other untangling options: even when all switch pairs between corridors have been removed, if a failure in one track requires the neighbouring track to be taken out of service, the impact of this incident will not be contained in the corridor of occurrence. For this reason, this untangling option has also been taken into account in the second part.

10.1.1.3 Research objective

The research objective for this part of the research has been defined as *to gain insight in the untangling strategy and provide an overview of untangling possibilities and their potential*.

By the given definition of system untangling and the identification of the variables related to system untangling, which have been gathered in the literature study and with the help of the Railway Service Model, the first part of the objective has been met. The second part of the objective is closely related to the research question and with the answer given to the research question in the previous section, that has been produced with the help of expert workshops and extensive incident data analysis, this part of this objective has also been met.

10.1.2 Conclusions of the develop part

The second part of this research builds on the results and conclusions from the first part. The logistical effects of untangling options have not been taken into account in the first part, but for the robustness of a system these effects play a key role. A model has therefore been developed that is capable of incorporating these effects to some extent, and with this model the most promising untangling options have been assessed in a case study.

10.1.2.1 Findings throughout the research and answers to the sub questions

The research started with answering the first sub question.

> *(2A) What is a proper definition of robustness for this research?*

In the literature review a comprehensive definition of robustness has been formulated out of the many different interpretations that were found in literature: the amount and percentage of train movements cancelled as a result of disruptions or incidents. Although delayed trains are also a (smaller) form of hindrance for customers, they were intentionally left out of the definition because of the macroscopic character of the research question.

> *(2B) Which large complex station is suitable to select as case study?*

The selection process for a case study was short since Utrecht station, which had been the trigger of this research, proved to be very suitable due to system untangling philosophy that had already been used in the design.

> *(2C) Which untangling options identified in the first part should be taken into account?*

Based on the case study choice and the potential benefits estimated for every untangling option in the explore part, six untangling options were selected: removing/adding switches between two corridors (A), enabling the safe use of a switch that requires a position of another switch that is out of control (B), building separate relay houses for each corridor (C), installing subsidiary circuits for every corridor (D), developing and using interlocking devices that operate independently per corridor (E) and using a separate EBP system for the control each corridor's infrastructure (F).

> *(2D) What system variations are relevant to include for assessing the effectiveness of system untangling?*

From the alternative robustness increasing measures mentioned in the literature review of the explore part scenarios were generated in which the current situation of DSSU took a centre stage. A distinction was made between incident quantity changing variations, for which the six untangling options and associated *element failure rate decreasing measures* were used, and effect only variations or modelling regimes, for which *improved usage of infrastructure*, *incident time reduction* and *safe working space regulations* have been selected.

In every scenario each untangling option (of the six) has a position in the scheme shown in Figure 10.3, and every scenario can also be modelled under the four different effect regimes, which led to a total number of possible scenarios of almost 70,000. From this impossible amount 50 scenarios have been selected in which each time only one untangling option is moved to another position in the scheme of Figure 10.3 and the five others are kept at position '0' (Current DSSU situation).

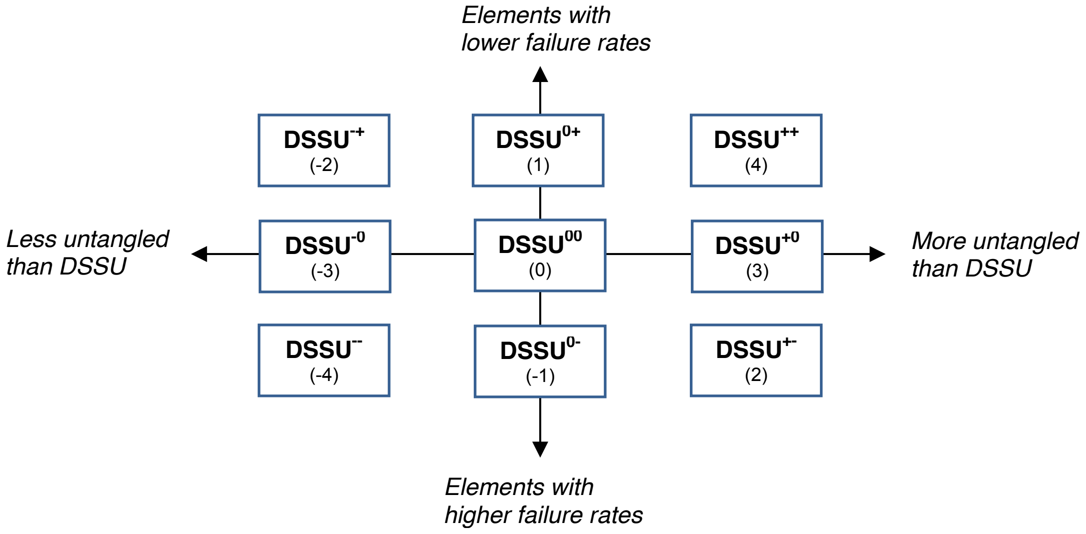


Figure 10.3 Scheme used to describe the incident quantity changing variations in the scenarios

> *(2E) What should the model look like to assess the total system robustness for all generated scenarios?*

To assess the robustness of these scenarios, requirements for a model were specified, an existing ProRail risk analysis tool was selected and modifications to this tool were made to meet the specified requirements. The most basic mechanism this tool has to follow had been specified as depicted in Figure 10.4. The system design (scenario) determines which incidents are likely to take place and to which infrastructure unavailability they lead. The tool needs to translate infrastructure unavailability into cancellations, which has been called the 'logistical effect' several times in the explore part.

Figure 10.4 Modelling mechanism the to be developed tool had to follow

The developed tool (a modified existing tool) combined the first two blocks of Figure 10.4 into one step by asking the user how frequently (failure rate) and how long (incident duration) a certain group of infrastructure elements is unavailable on a yearly base. For each unavailability, the model asks to specify what traffic management measures have to be taken for trains that are affected by this unavailability. The developed tool is therefore unavailability based instead of incident based, although the latter would be preferred. As a result of that, the values produced by the model can only be used for comparison purposes.

(2F) What can be concluded from the robustness values calculated by model?

The results generated by the tool for all 50 scenarios have been discussed extensively in section 9.3. A few interesting conclusions can be drawn from these results besides the strict answer to the research question, will be given in the next section.

- ***Only striving for a more untangled system does not always lead to a more robust system***
  This was assumed in the explore part, but the results showed clearly that this 'logistical effect' can have a huge impact. Especially the option to untangle the system by removing all switches between corridors did not lead to a more robust system than a system in which some connections were kept. Having these switches proved to be beneficial for incidents such as faulty trains or section failures, which have a limited area of infrastructure unavailability, as trains were able to temporarily leave their dedicated tracks and be rerouted around the incident.
- ***Having safe working areas is very important***
  Although it has not been modelled as a separate untangling option (due to the correlation with other untangling options) the δ regimes showed what the difference could be between not having these safe working areas and having them around each switch and track. On average the difference in robustness is 32%, which is far greater than the most effective untangling option that has been modelled.
- ***Decreasing failure rate of elements appears to be effective***
  As an alternative robustness increasing measure decreasing the failure rate of switches, relay houses, ES-welds and others have been modelled, and in some case this led to a higher system robustness than the related untangled scenario. Especially for infrastructure elements with relatively high unavailability, such as the relay houses, this measure is more effective than untangling.
- ***Using the remaining infrastructure more intensively during incidents is cheap and effective***
  This modelling regime β showed the robustness increase that could be gained by simply increasing the usage of available infrastructure during incidents by adjusting the contingency plan. This measure seems to be a real low-hanging fruit, as it can be implemented without any system design changes. On average a robustness increase of 7% could be realised.
- ***Important characteristics of untangled corridors were found***
  Two important infrastructure characteristics of untangled corridors were found that have a positive influence on the robustness of this corridor: the presence of a spare platform and the presence of infrastructure to turn trains around easily. In corridors where one of these characteristic was present, the robustness was 2% higher than on average.

10.1.2.2 Answering the research question

A research question has been formulated in the first chapter that now can be answered based on the results and findings in this thesis.

> *Which system untangling options are (most) effective in increasing the robustness at large complex stations?*

Six untangling options, or actually seven if the safe working areas are regarded as untangling options as well, have been modelled to see their effectiveness in increasing the robustness at Utrecht station and have been compared to three alternative robustness increasing measures. Table 10.3 shows a summary of the results.

Untangling option	Highest robustness increase	Untangling extent in reference to DSSU	Decreasing failure rate more effective?
(A) Removing switches	23%	Less	No
(B) Flank protection	16%	More	-
(C) Relay houses	10%	More	Yes
(D) Subsidiary circuits	6%	More	-
(E) Interlocking	-7%	More	Yes
(F) EBP	-1%	More	Yes
(δ) Safe working area	32%	More	-

Table 10.3 Summary of the α scenarios TVTA results, percentage scores all in reference to the Base-α scenario

Removing switches or adding extra switches has the second greatest effect on the robustness: 23%. The model showed that in the *DSSU* case *adding extra switches between corridors*, or in other words tangling the corridors, would lead to a *more robust* system. Untangling the corridors further by removing switches had a negative effect on the robustness. These negative effects could perhaps be overcome by *installing infrastructure to turn around trains easily* and *adding spare platforms*.

Related to this untangling option is untangling option B that *lifts the requirements one switch has towards the position of a neighbouring switch in case of a switch failure*. For this option holds that further untangling DSSU leads to a *robustness increase of 16 percent*, which is substantial regarding the fact that the *functionality of the switch pair is maintained*.

Untangling the *relay houses* also proved to be increasing the robustness, even though the *effectiveness is only 10%* and a *greater robustness increase* could be gained by *decreasing the failure rate by 20%*. An important benefit that is related to robustness from a passenger perspective, but which not has been captured in the definition used here, is that *untangling the relay houses* will ensure that *trains in every direction continue to operate during a relay house incident*, since the five directions in Utrecht will always be handled by two different relay houses (one for the local train corridor and one for the intercity train corridor).

The *subsidiary circuits* even showed a *smaller robustness increase*, partly because the system design difference between the current DSSU situation and the fully untangled design is small. Untangling the *interlocking installation* or the *EBP* led in both cases to a *robustness decrease*. As has been explained in section 9.3, the failure rates used for the untangled systems should actually be recalibrated, which could lead a more positive impact on the robustness. Event then the effectiveness of these untangling options will probably remain small due to the low related infrastructure unavailability. However, the remark made for relay house untangling on the *robustness from a passenger point of view*, is also valid for these two untangling options.

The last untangling option, creating *safe working areas* around tracks and switches, appeared to have the *greatest impact on robustness*. It has to be stated though that the difference between system designs (between α – completely absent – and δ – present everywhere) is more extreme than the difference in system designs between the base scenario and the other scenarios (A to F) which could explain the larger increase (32%). Nevertheless, there is no doubt that even the best scoring untangled system is *significantly less robust without having these safe working areas*.

10.1.2.3 Research objective

The research objective for this part of the research has been defined as *to develop a model or methodology to assess the robustness of large complex stations and determine the effectiveness of untangling options in increasing this robustness*.

The model that has been used for the assessment of the options' robustness is a modified existing modelling tool (RA-tool) that has been used beyond its current capabilities: by writing input files the model's functionalities have been extended. However, the state of this modified model is regarded as a proof of concept state, since the usability is very low and the effort required to model a station high. In the recommendations section several improvements to the usability of the tool and incorporation of various functions into the code of the tool will be suggested. Nevertheless, with this report and the current RA-tool, the tool can be used to assess the robustness of large complex stations (not for its exact values though, but to compare various scenarios).

The second part of the objective is closely related to the research question and with the answer given to the research question in the previous section, that has been produced with the help of the improved RA-tool this part of this objective has also been met.

10.1.3 General research question

Previously in this chapter the research questions for both the explore and develop parts have been answered. The answer to the general research question, which is shown below, is nothing more than the combination of these two answers. This section will be used to comment on the differences in conclusions between the explore and develop parts.

> *Which total rail system untangling options are (most) effective in limiting the impact of single incidents and in increasing the robustness at large complex stations?*

It is comforting to see that most of the conclusions drawn in the explore part based on the untangling options' potential estimation are also drawn in the develop part based on the results generated by the improved RA-tool. Unfortunately, also some of the issues that were faced in the explore part were faced in the develop part, for example the difficulty to estimate the failure rate of untangled 'single systems' such as a relay house or EBP, from which the effectiveness has now been modelled too pessimistically.

There is one main difference between the conclusions that is worth to be discussed: untangling the guidance subsystem by removing switches between corridors. While the explore part concluded that this would have the greatest potential in limiting the impact of incidents within the corridor of occurrence, the develop part concluded that this has a counterproductive effect on the robustness of the system. The difference in conclusions is mainly caused because the develop part takes more incident types and the logistical impact (to some extent) into account. However, it must be stated that this negative effect was found when the already untangled DSSU design was untangled to a larger extent. Since the impact of this untangling option on the robustness is large, it is imaginable that applying this untangling option to a smaller extent could still result in a higher robustness than when this untangling option is not applied at all (such as in Figure 4.14). In the next section, a recommendation will be made on this matter to find out where the optimal extent of this impactful untangling option lies, in combination with the discovered robustness increasing corridor characteristics.

In general, it can be concluded that system untangling is an effective measure to increase the robustness of a large complex station. The effectiveness however strongly depends on which untangling option is installed and how, and for some of these options more effective robustness increasing measures are available as alternative. The developed modelling technique in this research can be a powerful tool in assessing the effectiveness of untangling options in specific situations.

10.2 Recommendations

Research always triggers new research as there will be issues or results that ask for a closer look or an improvement of the developed model. This chapter will make a few recommendations that have been organised in three different categories: recommendations on system untangling research, recommendations on the further development of the RA-tool and recommendations for the development of complex stations specifically.

10.2.1 Recommendations on system untangling research

The first recommendation is to model scenarios that *combine untangling option variations*, to see if the two interfere and possibly create higher effectiveness in increasing the robustness. For modelling capacity reasons, these combinations have not been taken into account here, but the developed tool is capable of handling these scenarios.

In addition to that, a *new maximum robustness scenario* could be developed and modelled, since the used maximum scenario appeared not to provide maximum robustness. In line with that is the conclusion that removing and adding switches has a large impact on the robustness, but that the optimal balance between them has not been found in generated scenarios. With the current insight another scenario could be developed in which this optimal configuration for Utrecht can be found keeping in mind both robustness increasing corridor characteristics; infrastructure to turn trains around and spare platforms.

The failure rates used in this research have been based on historical data which often concerned data from older infrastructure and sometimes even infrastructure in areas that were under construction. As a result of that, the failure rates might not be in line with the failure rates that can be expected from new infrastructure. Besides that, the used failure rates for systems that decrease in size but increase in number of installations in an untangled scenario (Interlocking, EBP, relay houses), have not been based on these new sizes. With these new failure rates, the effectiveness of these three options could appear to be higher. Concluding, it is recommended to investigate which *specific failure rates* should be used to quantify the effects of certain untangling options, since the used generic failure rates did not distinguish between various states of infrastructure and used types of equipment.

The scope in this research has been limited to system untangling in large complex stations and has not investigated the influence of system untangling under another geographical strategy. An issue with Utrecht station was that the assumed dedicated infrastructure for corridors shown in the model often merged into shared infrastructure further down the line, resulting in remaining dependencies between corridors. It is therefore recommended to carry out *research on system untangling from a network perspective* to see whether the robustness benefits gained at an untangled complex station are not nullified or changed by the way the rest of the network has been designed.

10.2.2 Recommendations on the further development of the RA-tool

The RA-tool has shown to be a helpful model to gain insight in the effects of system design on the robustness of the station. In this research various extensions and improvements to this tool have been described which enable a more generic and complete view on the system design, since the original RA-tool only takes switch failures into account. However, these improvements have been presented as a proof of concept and have not been built in to the tool in a user friendly way. On the contrary, using the tool the way it was used in this thesis has been very time consuming and laborious.

Naturally not all of the improvements can be implemented in the tool in a user friendly way, as it will make the tool more reliant on data input which conflicts with its approachable character to use it for short researches. Besides that also the cost of implementation will play a part in the consideration whether a modification is worthwhile. In this section a selection of four recommendations for the further development are described.

One of the most important stages in the model is the definition and application of the traffic management measures, which are usually based on VSMs or traffic management guidelines. These VSMs and guideline documents are textual documents that describe how the timetable for a limited number of infrastructure unavailabilities changes and which train series have to be altered. The RA-tool on the contrary simply needs to know per train series for which infrastructure unavailabilities it is cancelled or delayed. The incident based VSM format and the train series oriented RA-tool do not match at this specific point with the consequence that the user needs to solve a logistic puzzle again and again for each unavailability. A valuable recommended improvement for the RA-tool is to *implement a module in which the user is able to define the VSMs* which are then automatically linked to the concerned unavailabilities. Besides the efficiency increase, this will also solve the problem that only train series that use the unavailable infrastructure element can be affected, while in reality non-related train series are often cancelled to free up capacity for the directly affected train series. In a separate VSM module the unavailability can be linked to a VSM (each infrastructure unavailability triggers exactly one VSM in which is stated which trains are cancelled) instead of linking unvailabilities to train series (each unavailability is listed multiple times under various train series), see Figure 10.5.

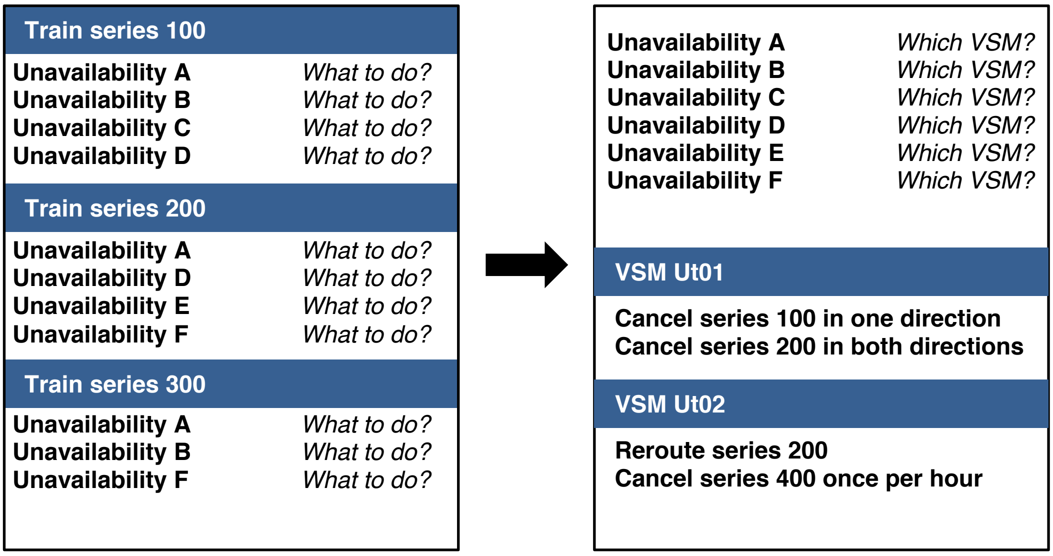


Figure 10.5 Current traffic management format (left, train series oriented) and recommended traffic management format (right, VSM oriented

The second recommendation is to *implement the modelled incident types in the software and interface* of the RA-tool, so that these common incident types no longer have to be modelled through the input files as groups of sections. The work carried out in this research has extended the RA-tool beyond its intended capabilities by making use of an existing functionality in the tool. This functionality though, grouping sections through input files, has not been developed for this purpose – it was developed only to model requiring switches – and is therefore far from user friendly. These modifications should therefore be considered as a proof of concept since the way it has been modelled decreases the usability of the tool significantly. By implementing the incident types 'power loss', 'section failure', 'relay house failure', 'faulty train', 'EBP failure' and 'interlocking failure' in the dashboard likewise the switch failures currently, the tool incorporates the improvements shown through a proof of concept in this research.

As has been stated in the validation section, the absolute values of robustness calculated by the improved RA-tool are not comparable to incident data reported by ProRail. As a probable cause for the underestimated number of cancellations, the non-incident based character of the RA-tool is mentioned; during incident analyses it appeared that after the incident has been declared as 'solved' it took a while before all trains ran according to schedule again, which resulted in a significant amount of extra cancelled trains. Sometimes this amount went even up to twice as much as during the period the infrastructure was actually unavailable. The improved RA-tool does not take this period after the incident was solved into account, as it only includes the average repair time of an infrastructure element. Transforming the RA-tool in an incident based model would be such a fundamental change that is not realistic to carry forward. An alternative approach to incorporate the period of cancellations after the incident is recommended in the form of an *unavailability duration surcharge.* A more realistic average unavailability duration can be deducted by surcharging the individual incident durations by a fixed amount. The graph in Figure 10.6 is a fictive example of how such a surcharge chart could look like, more research on the values and pattern would be required though.

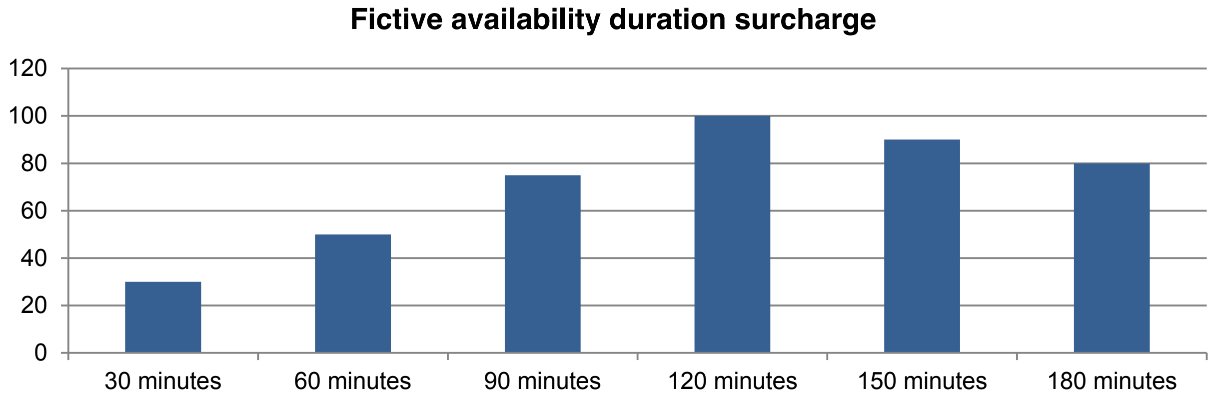


Figure 10.6 Fictive surcharge structure that could be applied to individual incident durations to compensate for the uncovered timetable restart time after an incident

If an infrastructure element on the route of a train is unavailable, the train cannot run over that specific infrastructure element. This has been modelled for many infrastructure elements in Utrecht station but what happens if this unavailable infrastructure element is located further down the line outside Utrecht? It would still require trains to turn around in Utrecht and the effect of unavailability outside Utrecht is then still dependent on the system design of Utrecht station. It is therefore recommended to *introduce a residual unavailability value per track leaving/entering the modelled area.* The value should depend on the length, installed infrastructure elements and number of trains running over the track between the modelled station and the first timetable decoupling location, as they have been specified by ProRail and NS (Ministry of Infrastructure & Environment, 2014b).

10.2.3 Recommendations for the development of complex stations

Knowledge on robust complex stations, predominantly related to system untangling, has been gathered throughout this research and a few specific recommendations on how to design them can now be made. These recommendations are based on the findings for Utrecht station, but are relevant for large complex stations in general.

Having a safe working area around potentially failing infrastructure elements such as switches has proven to have a large and positive impact on the robustness. However, the space needed for these areas is often scarce and expensive, which forces the designers to make difficult choices. The impact of individual working areas strongly depends on the unavailability of the involved infrastructure element, the amount of trains that uses this element and the surrounding system design that determines whether trains can easily be rerouted around the unavailability or not. As a result of that, the impact of different safe working areas varies. Although this research has only investigated scenarios in which safe working areas were either installed everywhere or installed nowhere, the developed tool is capable of assessing the benefit of individual working areas. It is therefore recommended to *include the implementation of safe working areas in an early stage of the design* and evaluate the individual benefit with the help of the improved RA-tool.

System untangling to some extent has proven to be effective for the robustness at a complex station. However, in the results a difference in performance has been found between various corridors that were untangled similarly, which led to the discovery of an important robustness increasing factor: the presence of infrastructure to turn train services around easily. In corridors where trains could switch from the up track to the down track easily and preferably use multiple platforms to turn around in case of a disruption on the line at one side of the station, the number of cancellations lies below average, despite the extra unavailability as a consequence of the switches. It is therefore strongly recommended to *install infrastructure to facilitate that all train services in the corridor at a large station can turn around* if a disruption occurs further down the line. In the current situation of Utrecht many train services are already cancelled upstream the line in case of a disruption and only a handful reaches Utrecht and turns around there. An improvement for Utrecht station would be to install two switch pairs directly north of platforms 14 and 15 and to connect platform 5 to the Db down slow track, see Figure 10.7 and appendix G.

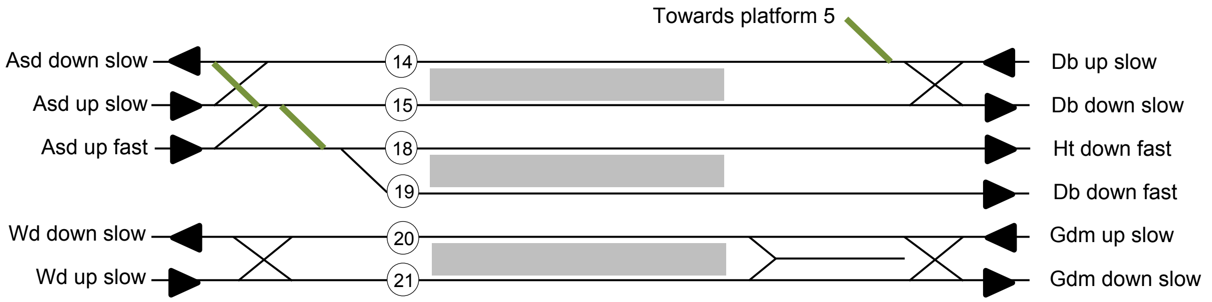


Figure 10.7 Switches recommended being installed (green) in order to increase robustness at Utrecht station

The last recommendation is to *remove the requirement switches have for the position of neighbouring switches in disrupted situations,* during which the neighbouring switch is unavailable and unused. This untangling option is not only very effective, it also does not lead to a reduction in flexibility and rerouting options or to high investment costs, which makes it a better alternative than removing switches. Besides that, this untangling option is also beneficial for switch pairs which are located within a corridor and outside stations, and on itself could lead to a reduction of 16% in yearly cancelled trains at Utrecht station.

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Appendix A

In this appendix the operation process of the traffic in the Netherlands is explained. Switches are part of the guidance subsystem and amongst other things enable trains to travel to the intended direction. Setting switches in the right positions and giving route clearance in the optimal order are all tasks that are handled in the ProRail's resource allocation and steering process, which comprises two levels and some subsystems of the railway system.

Figure III shows a simplified version of ProRail's Traffic management chain in order to provide an overview of the interaction all the mentioned ProRail systems. The meaning of all used abbreviations in the figure can be found in the glossary on the first pages of this report. The layers indicated by the dashed lines are the layers distinguished by ProRail. According to the Rail Service Model though, which is explained in chapter 3, most systems in the chain belong to the resource allocation level. Systems and elements that belong to a functional subsystem have been put in a coloured plane with a dash-dotted line around it.

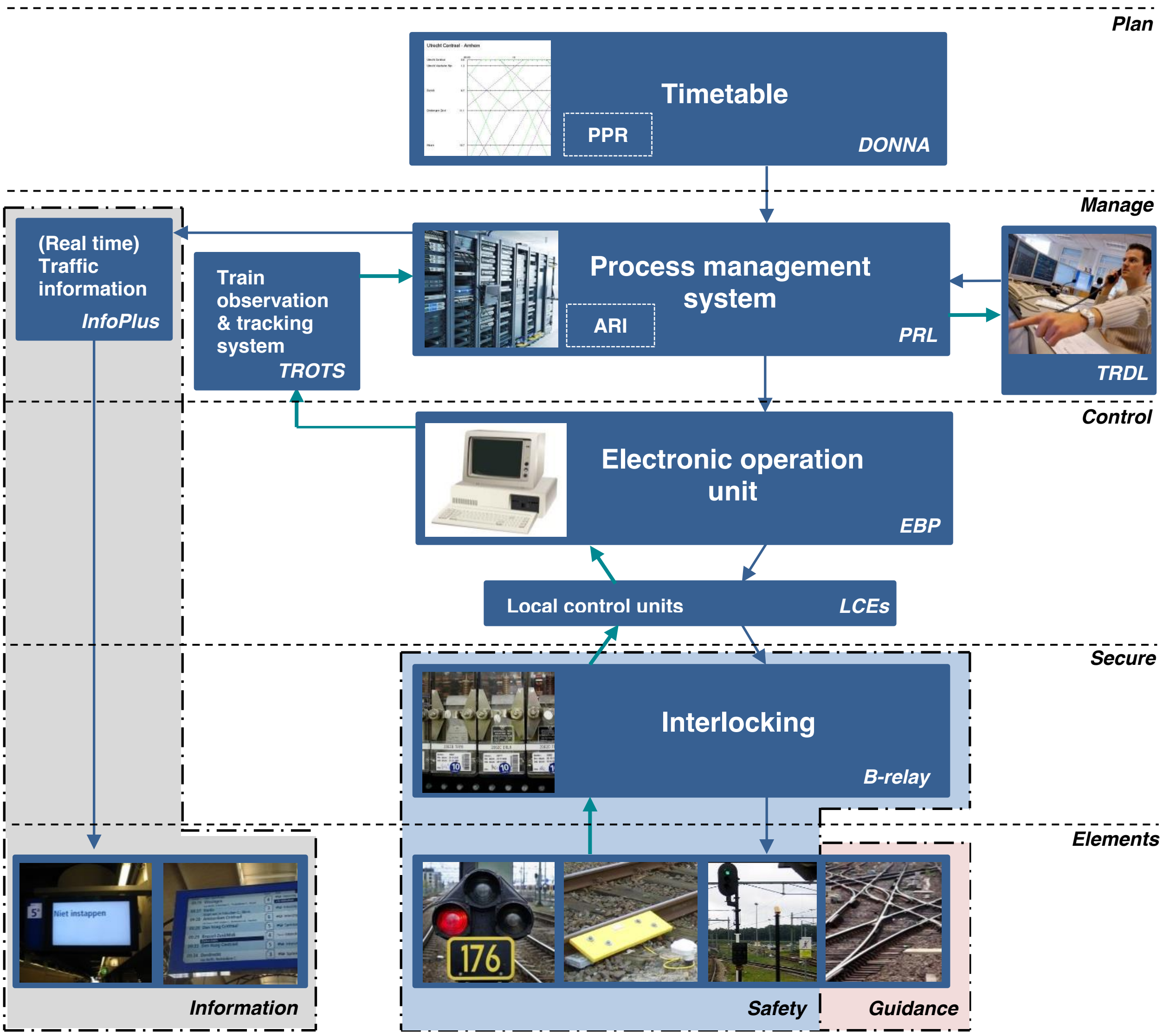

Figure III ProRail's traffic management chain (Railinfra Opleidingen, 2014)

Appendix B

To generate untangling options six workshops have been organised with various experts mostly from ProRail, but also from contractors involved with the DSSU project. Every workshop took two hours, included three fixed members and progressed according to a predefined framework. The full workshop reports, framework and attendees are described in this appendix.

Besides the author this thesis, whose role was to guide the workshops and ask the questions, the attendees always included a senior system architect and the rail system engineer responsible for the DSSU project. The senior system architect F. Bokhorst MSc is experienced in assessing the holism and consistency of large system designs while rail system engineer Van Deelen MSc knows the DSSU project thoroughly, enabling him to link and denominate issues and options that transcend the workshops' topics. Besides them, on average three experts were present, whose specialisms were thought to be contributory to the topic of the workshop.

The framework used in the workshops consists of two different parts: one part with questions about untangling options and one part discussing the reasons for using or not using the various untangling options. Both parts were focused on the design of DSSU, the first large station project of ProRail with a focus on system untangling (Movares, 2015).

The workshop topics were energy supply, civil engineering & switches, PT terminal, signalling system, operations & construction phasing and IT & connectivity. The answers, comments and solutions in the second part of the workshops are categorised in three different groups, but this division is irrelevant for this research. The split was made because the workshop results were also used by a taskforce within ProRail that is trying to evaluate and improve the DSSU design, with whom the workshops were in cooperation. Answers, comments and solutions given in the first category are successful and have been implemented in DSSU. The ones in the second category are successful but have not (yet) been implemented and the ones in the third category are promising, but are not ready for implementation (yet).

B.1 Energy supply

The workshop was held on the 4th of July 2016 and the attendees besides Frank Bokhorst and Niek van Deelen were Hugo van Veen (Tractive effort specialist at ProRail) and Johan van Heusden (System engineer at ProRail). The results of part one can be found in Table III and the results of part two in Table IV.

Question	Answers given by experts
Without restrictions in time, money, space or current techniques, how would you adjust the design Utrecht station?	- Do not use any wire struts. - If a certain overhead wire has been repaired or connected to another wire over and over, the whole line should be replaced to increase the robustness. - Do not re-use materials; only use new materials at such an important location. - Untangle the system simultaneously with the design of other subsystems. - Space is the major bottleneck.
In a perfect world, how would you untangle this part of the system?	- Apply corridor division also to the power schematics and circuits. - Lose some functionality by not installing certain assets in favour of a better and more robust design for instance by not installing wires over switches inside the station. - Maybe do not untangle the gantries: the effects of material failures have to be minimised and not untangling might be a better solution. - Use experts of all fields to start the design process to help generating new solutions and come to optimal designs for all subsystems. - Do not use high-voltage cables underground.
If you were asked to change one thing in the design of DSSU to increase the robustness, what would you change?	- Apply corridor division also to the gantries and contact wires: not all experts agreed on this statement, Niek states that the use of single gantries for all corridors increases the robustness.
What would you consider as the key system untangling improvement that was realised within the DSSU project?	- We used 3 directions of optimisation: Untangling the technique, optimise to the predicted use and install redundancy. We installed circuits per corridor.

Table III First part of the results of the energy supply workshop

	Should the catenary systems of all corridors be on one gantry or on multiple?	How to apply subsystem untangling when a switch between corridors has been installed?	Optimal electrical scheme versus feasibility: Why do the subsidiary circuits not always follow the train corridors?	How to design robust energy supply for the elements such as switches and signals?	Could the design not be optimal due to construction phasing?
1	-	-All switches have been equipped with stand-alone overhead wires in separated electrical sections, which are not part of the main electrical lines that supply energy to other sections. -No switches in areas with limited space for the overhead wires.	-Three directions of optimisation used: Untangling the technique, optimising to the predicted use and installing redundancy. Each corridor is a subsidiary circuit.	-A large cable connects the two power stations to make sure that the switch heating power is redundant.	-
2	-Not untangling the gantries leads to a lower collision risk; there are fewer pillars.	- Create more than one entrance to the yard: by having one entrance automatically system untangling becomes difficult, creating a huge single point of failure in the design.	-Always build power stations on two sides and connect all corridors to both sides. -Make sure that all cables are thick enough to power the full system, also the ones that are only used during incidents.	-	-Renewing the overhead wires after all the construction phases will prevent that all wires are full of welds. -The choice whether to untangle the gantries was also based on planned construction phases.
3	-Using battery power in trains at large stations would allow the lack of overhead wires and thus the need for untangling. -Fully untangled gantries would be a hindrance for signal visibility. -Using one gantry would leave the option to avoid collision risk by placing the columns away from the tracks.	-	-	-	-

Table IV Second part of the results of the energy supply workshop

B.2 Civil engineering & switches

The workshop was held on 29 June 2016 and the attendees besides Frank Bokhorst and Niek van Deelen were Eric Terwolbeck (Switch specialist at ProRail), Harry van Iersel (Civil engineer at Movares) and Onno Hazelaar (System architect at ProRail). The results of part one can be found in Table V and the results of part two in Table VI.

Question	Answers given by experts
Without restrictions in time, money, space or current techniques, how would you adjust the design Utrecht station?	- Improve the foundation of the 1:29 switches - Design from a vision, philosophy or policy instead of design rules. The design rules do tell you 'how' but not 'when' to use certain techniques. - Move the columns of the Waterlinieweg viaduct further away from the tracks.
In a perfect world, how would you untangle this part of the system?	- Evaluate the accessibility of yards and then balance between the required accessibility and the number of extra switches needed to achieve that. - Design including the extra switches need to handle incidents: if the design would have changed a bit, maybe the untangling could have been improved. - Use switches that have a preferred position and always automatically return to this position.
If you were asked to change one thing in the design of DSSU in order to increase the robustness, what would you change?	- Do not use pairs of switches with 'demanded positions' but 'requested positions' instead. - The double switches behind the Gouda-Utrecht-Amersfoort corridor: that should have been untangled.
What would you consider as the key system untangling improvement that was realised within the DSSU project?	- Most of the tracks have been fully untangled resulting in a huge capacity and robustness increase. Nevertheless, fewer switches asks for a higher intensity of maintenance because most of the switches have become essential for executing the timetable

Table V First part of the results of the civil engineering and switches workshop

	How can the accessibility of elements that are likely to fail on a regular basis be increased?	How to handle older pieces of infrastructure that do not meet the latest standards in design?	How to cope with scarcity of space?	How could the track lay-out be fully untangled?
1	-Using a different strategy: if a switch is out of control try to fix a position as soon as possible and postpone the repair works until the night	-Not automatically replacing older bridges and tunnels: assess on the basis of their remaining life expectancy and current performance.	-	-
2	-	-Replace the less robust EBI switch machines with NSE2 switch machines that have a higher availability.	-In earlier versions of the DSSU design it was proposed to move the southern yard of the station to create better untangled tracks. This design options was not chosen though, mainly because of money issues.	-
3	-Possibility to remotely fixate a switch in a certain position to prevent that someone needs to get onto the tracks -Locating the switches outside the station areas, at specific locations that are easily accessible	-Pieces of infrastructure that need a plan to withstand heave rainfall such as tunnels and dykes, a plan should be made in cooperation with the government to include all effects of flooding.	-Do not use too many stand-alone solutions that just cover a single problem: these problems are the symptom of choices made in the design. Solve problem integrally.	-Use robustness, availability and reliability as primary design criteria. -Design with an integral view. Clear priorities and design choices will help. -Report all the design philosophies in documents to assure that the design is well used in the future. -Reason from a network instead of a project point of view.

Table VI Second part of the results of the civil engineering and switches workshop

B.3 Operations & construction phasing

The workshop was held on 29 June 2016 and the attendees besides Frank Bokhorst and Niek van Deelen were Bruno van Touw (Rail traffic engineer at ProRail), Wim Roos (Safety manager at ProRail) and Adrie van Eck van der Sluijs (Manager of signallers at ProRail). The results of part one can be found in Table VII and the results of part two in Table VIII.

Question	Answers given by experts
Without restrictions in time, money, space or current techniques, how would you adjust the design Utrecht station?	- Do not start two projects simultaneously at the same location: the terminal and tracks were built as separate projects. For a robust system design one party should be in charge. - Signallers were often not willing to think outside the box and refused some of the proposed construction phasing plans.
In a perfect world, how would you untangle this part of the system?	- Construction phases were too short with the result that the signallers were not able to get familiar with the current situation. - The use of large gantries simplifies the construction phasing process.
If you were asked to change one thing in the design of DSSU to increase the robustness, what would you change?	- Solving the restrictions of requiring switch pairs.
What would you consider as the key system untangling improvement that was realised within the DSSU project?	- 'Regular' operation of passenger trains requires fewer than 10 switches to be operated.

Table VII First part of the results of the operations and construction phases workshop

	How to build a untangled system from a tangled system?	How to balance working efficiently versus minimising hindrance?	How to run as many trains as possible without compromising on safety?	How could a smooth train service be maintained when some elements fail?	How to increase the visibility of signals?
1	-Start with creating small areas from which the overhead wires can be switched off electrically -Phasing of the catenary system seems to be leading in the phasing design. -Take the flexibility into account of the various systems that need to be implemented, to prevent large out-of-service areas per phase.	-	-	-Maintain switches with higher intensity if the importance of the switch increases in a construction phase.	-Use simulation software to visualise the design before it is built.
2	-Use visualisation of the design in an early stage to get a clear image of the design right away: this will reduce the amount of adjustments that have to be made during construction.	-Large construction phases seem to be more efficient. Sometimes errors were made because there was a lack of situation awareness. -Extreme construction phases require more replacement buses, but the situation is clearer for customers.	-Decision making based on specific cases instead of general rules: adjust rules if safe to do so. -Not everything is perfect: phases are sometimes declined because they do not meet all standards, even though the phase is safer than the current situation.	-Design a process that instructs the traffic controllers how to cope with certain incidents in a specific construction phase.	-Smaller signals would significantly improve the visibility of signals. -Allow margin when building the signals so that they can be moved without violating guidelines.
3	-	-	-	-	-Develop one-light signals -At large stations do not use the standard design guidelines. -When designing leave space for future techniques.

Table VIII Second part of the results of the operations and construction phases workshop

B.4 Signalling system

The workshop was held on 28 June 2016 and the attendees besides Frank Bokhorst and Niek van Deelen were Jan van Keulen (System architect at ProRail) and Erik van der Meer (Asset manager at ProRail). The results of part one can be found in Table IX and the results of part two in Table X.

Question	Answers given by experts
Without restrictions in time, money, space or current techniques, how would you adjust the design Utrecht station?	- Use one interlocking system that is supplied by multiple suppliers to have flexibility - Find a way to couple to interlocking devices without an uncontrolled area in between. Then, the use of smaller interlockings such as PLC and VPI becomes possible. -.Build a relays house for each corridor instead of per section.
In a perfect world, how would you untangle this part of the system?	- Equip all switches with NSE2 switch machines instead of EBI switch machines - Base the switch machine choice on robustness specifications.
If you were asked to change one thing in the design of DSSU to increase the robustness, what would you change?	- Solving the restrictions of requiring switches. - Find a way to split the EBP 'horizontally' or in other words one EBP per corridor.
What would you consider as the key system untangling improvement that was realised within the DSSU project?	- Untangling of all systems outside the relays houses. Although the use of single relay houses for all corridors means that they are not untangled, within the relays houses each corridor has its own, separated location.

Table IX First part of the results of the signalling system workshop

	How to assure future adjustments do not tangle the system again?	How could the train signalling system be untangled if switches are present between corridors?	Can a safe working area installation increase robustness?	When to build two separate buildings and when to untangle systems within a building?	How to deal with flexibility and legal aspects when choosing an interlocking system?
1	-Also untangle cables. -No relays houses that are completely tangled: every corridor its own rack. -Create a signalling installation file with all details included. -All design guideline documents have be assessed for possible improvements	-	-	-The untangling of systems has been applied in the design until the relays house, which holds the critical equipment of all corridors.	-.
2	-The philosophy used in the design has not well been documented. Therefore future adjustments may not use the same philosophy and by that tangle the systems.	-Sooner fixate the position of switches that are out of control: less impact on the operation of trains.	-Switches for the safe working area installation should be located at accessible locations -Only install safe working area installations at high risk locations. -Together with fences safe working area installation will reduce the amount of tracks that will have to be taken out of service during incidents or maintenance.	-	-
3	-Design guideline documents seem outdated and may lead to non-optimal design choices. -Create guidelines for how to design certain functionalities: now every project uses different solutions. -Untangle all technical building: each corridor should have its own buildings.	-Redesign the restrictions for using switches that are out of control. -Better instruct the signallers what to do when switches are out of control. -Install switches with a preferred position. -Presence of mechanics that can easily fix switch failures.	-	-The robustness could be increase if within the buildings themselves a physical separation (walls) could further untangle the systems.	-Flexibility of an interlocking system should be a main criteria in the tender process. -Find a way to couple to interlocking devices without an uncontrolled area in between. Then, the use of smaller interlockings such as PLC and VPI becomes possible.

Table X Second part of the results of the signalling system workshop

B.5 Public Transport terminal

The workshop was held on 27 June 2016 and the attendees besides Frank Bokhorst and Niek van Deelen were Hugo van Veen (Asset manager at ProRail) and Hans van Ham (Structural engineer at U-Centraal). The results of part one can be found in Table XI and the results of part two in Table XII.

Question	Answers given by experts
Without restrictions in time, money, space or current techniques, how would you adjust the design Utrecht station?	- Build the terminal without travellers - Also untangle the freight trains, which now use the tracks meant for passenger trains.
In a perfect world, how would you untangle this part of the system?	- Separate power grid for infrastructure related purposes and non-infrastructure purposes. - Create level crossings for emergency services to increase accessibility and decrease the time an incident disrupts the train services.
If you were asked to change one thing in the design of DSSU in order to increase the robustness, what would you change?	- All cables for operating the switches and signals are not redundant. - Several entrances of the terminal are not well secured. - Building next to the terminal both contains the energy supply and emergency energy supply installations.
What would you consider as the key system untangling improvement that was realised within the DSSU project?	- Partial evacuation of the terminal possible.

Table XI First part of the results of the PT terminal workshop

	What is the best way to get cables passed the station building?	How to deal with multiple contractors working at one location?	How to cope with different users of the electricity network?	How to cope with existing vertical ascents in the terminal?	How could the terminal be split per corridor during disruptions such as a fire alarm?
1	-Construct a dedicated tunnel in which the cables are connected to the ceiling: This will prevent damage during floods. Control the access of this tunnel.	-	-Split the infrastructure related power grid from the non-infrastructure related power grid.	-	-Compartmented evacuation per two predefined platforms and per quarter of the terminal. Unknown yet how to communicate this to passengers.
2	-	-Decrease risk levels by making sure that there is a good communication between the two contractors: often they do not know what the other one has already done/made.	-	-Shifting vertical ascents to the endings of the platforms will facilitate smoother evacuations during incidents.	- Compartmented evacuation per platforms depending on the location and type of incident.
3	-	-Combine the infrastructure and public transport terminal in a single project. In this way only one construction phasing plan is required.	-Maintaining the installations should not be under the responsibility of a third party. -Each group of users should maintain its own power grid. -Limit the accessibility of technical buildings: sometimes all mechanics have access to all buildings. -Strictly maintaining the own grid by a single department.	-	-Redevelop the fire alarm policies: when the fire alarm rings first inspect the validity before starting the evacuation. -Construction materials that are difficult to replace should be a lot more fire resistant than the current standards.

Table XII Second part of the results of the PT terminal workshop

B.6 IT & connectivity

The workshop was held on 7 July 2016 and the attendees besides Frank Bokhorst and Niek van Deelen were Rutger Oldenburg (System architect at ProRail), Klaas van Smeden (IT specialist at ProRail), Paul van der Lee (Interlocking expert at ProRail) and Marcel Ritzema (Connectivity expert at Movares). The results of part one can be found in Table XIII and the results of part two in Table XIV.

Question	Answers given by experts
Without restrictions in time, money, space or current techniques, how would you adjust the design Utrecht station?	- Develop a possibility to still use pairs of switches with demanded positions that are out of control - IT and the cable department should be able to see each other's administration. - Signallers should be able to see current states of the assets on their screens.
In an ideal world, how would you untangle this part of the system?	- When starting a project, also regard the architecture of the IT infrastructure as part of the project. - Use buildings for IT equipment with the same safety standards as the buildings used for the signalling system.
If you were asked to change one thing in the design of DSSU in order to increase the robustness, what would you change?	- The old signal box has become unused in the new design of Utrecht, but it still houses a main IT infrastructure node. Relocate this node to a safer building. - Largest risk occurs after software or hardware has been updated. - There is a need for a document that does not only describes the IT infrastructure functionally, but also indicates where all the cables physical position is.
What would you consider as the key system untangling improvement that was realised within the DSSU project?	- Many redundancies built in systems. LCEs can be reached by two separate networks. - Removal of critical equipment out of the signal box.

Table XIII First part of the results of the IT & connectivity workshop

	How could a split of the whole traffic control chain contribute to a higher robustness?	Is it beneficial to split the element control systems of a station?	How has the robustness been taken into account when designing the geographical layout of the IT infrastructure?
1	-The untangling of LCEs has been executed in the design and leads to clear and organised relays houses where each corridor has its own location. -The failure rate of the EBP is almost zero and has not led to any disruption of train services in the last few years. Updates on this system have though.	-	-Systems have been untangled up and until the LCEs or relays houses (depending on perspective). -Critical systems have been separated from the signallers so that an evacuation of the signal box will not lead to a complete stop of train operations. -Broken cables can be detected which decreases the incident time heavily.
2	-	-	-
3	-IT systems should facilitate the safe use of switch pairs with demanded positions of which one of them is out of control. -A guideline on how to set up the architecture of the full command chain would be most welcome. -A new layer in the command chain will need to facilitate the setting of train path in more than one EBP area.	-The EBP area is regarded as the area of a station where the switches are. Future use of horizontal boundaries with an EBP for every corridor could increase the robustness.	-

Table XIV Second part of the results of the IT & connectivity workshop

Appendix C

The untangling options have been treated as if they were completely independent of each other, each with their own potential benefits and related incident types. But actually, several relations between untangling options can be described and are also important to be described, as they may reveal exclusions or options that require other options to be installed. Especially the latter has a great influence on the determination of the efficiency of an untangling option. After all, if an untangling option's stated potential benefits can only be gained by installing another option, the costs and effort to actually get the benefits (installing both options) will be larger.

Table XV shows seven different types relations between all possible combinations of untangling options. Untangling options can require other options to have been installed (+) or be required to have been installed by other options (&). On the other hand options can also cancel out other options (X) or be cancelled out by others (0). Options can be similar (≈) or equal (=) to each other or have no relation at all (-). On the vertical axis the relation of an untangling option with all other untangling options is indicated and the matrix is per definition mirrored about the diagonal axis.

The high dependency of the options on untangling option 20 is clearly visible and has led to the cancellation of option 20 as such: without this option almost none of the options could gain the stated quantified potential benefits. In a later stage of the research, where some logistical effects are modelled, scenarios have been generated with the absence of option 20 in order to see the difference.

Besides the interdependencies related to option 20, only option 1 requires other options to be installed. In this case because of technical reasons, as tracks of different corridor could not cross or be connected to each other in order to make the physical untangling of the overhead contact lines possible.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1		-	-	-	-	+	-	-	-	-	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-
2	-		0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	X		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-
4	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-		-	-	-	-	-	-	-	-	-	≈	-	-	-	-	+	-	-	-	-	-
6	&	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-
7	-	-	-	-	-	-		-	-	-	-	-	-	=	-	-	-	-	-	+	-	-	-	-	-
8	-	-	-	-	-	-	-		-	-	-	-	-	-	-	≈	-	-	-	+	-	-	-	-	-
9	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	+	-	-	-	-	-
11	&	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-	-
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20	&	-	&	-	&	-	&	&	-	&	-	-	-	&	&	&	-	-	&		-	-	-	-	-
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24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

Table XV Various identified relations between untangling options

Appendix D

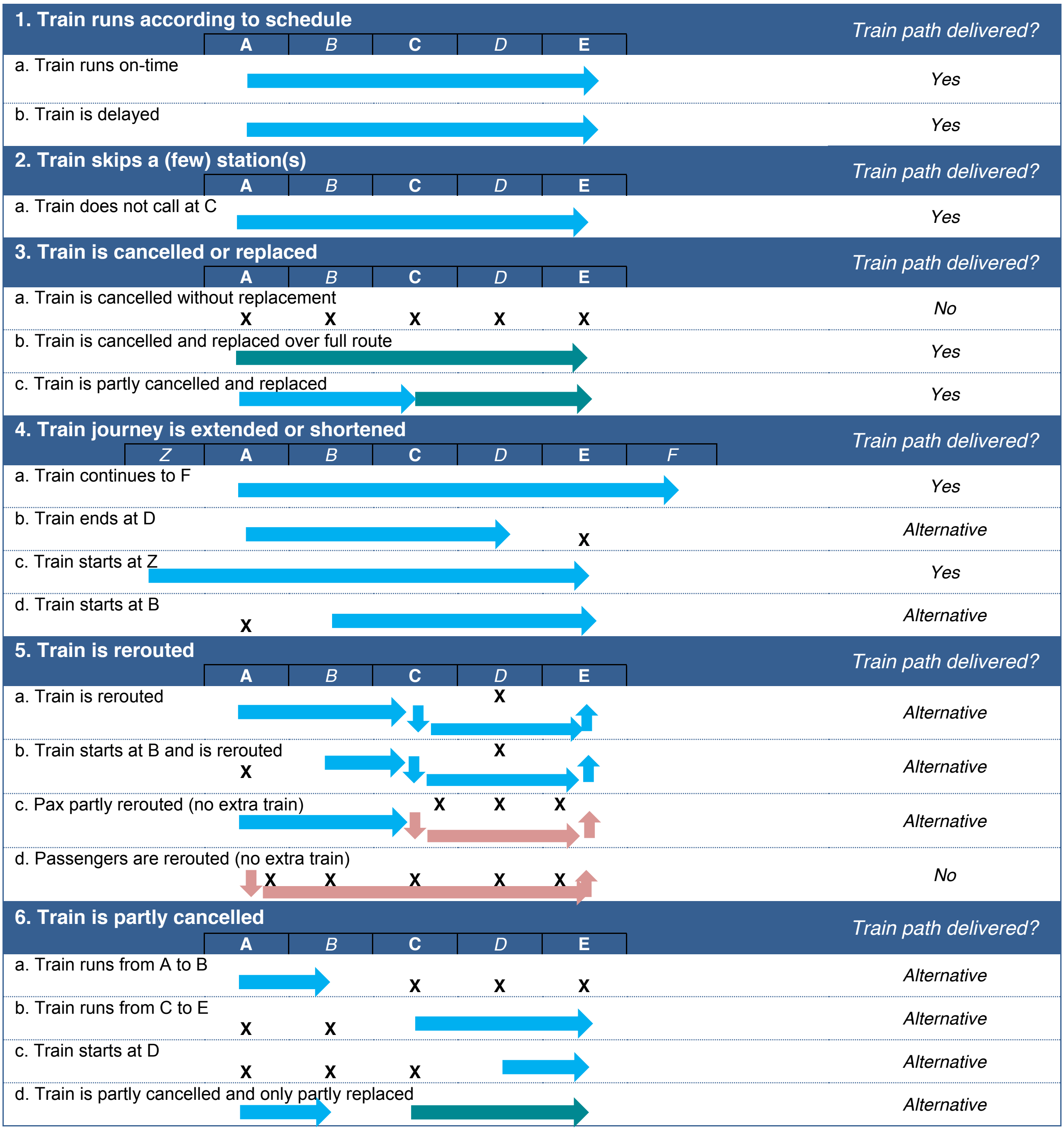
In Table XVI a result overview of all untangling options is shown. The frequencies of occurrences of individual related incident types have been summed up per untangling option, after they had been multiplied by potential factors indicated in Table 4.13. The outcome is an indication of the yearly amount of incidents that could potentially be isolated by the untangling option. The average incident duration follows from a weighted (towards occurrence frequency) accumulation of the repair times (again multiplied by potential factors indicated in Table 4.13) of individual related incidents types. Multiplying the average duration and the amount of incidents will give the potential benefit per untangling option as they were presented in Table 4.14 (expressed in minutes of unavailable infrastructure that can be isolated within the corridor of occurrence).

Untangling option	Yearly potentially affected incidents	Average incident duration [min]	Potential benefit [min]
(6) Removing switches	77.2	*64*	4938
(19) Flank protection	68.3	*63*	4334
(17) Relay houses	0.5	*3780*	1890
(10) Tunnels & Bridges	25.5	*100*	1549
(3) 1500V power stations	11.3	*93*	1054
(2) Subsidiary circuits	10.3	*75*	775
(14) Signal control cables	2.1	*203*	426
(7) Switch control cables	2.1	*203*	426
(22) Power supply signal box	4.5	*92*	414
(13) Station hall evacuation	11.6	*29*	337
(1) Contact lines	0.2	*1621*	324
(11) Elevated junctions	2.6	*123*	321
(9) Switch heating	2.7	*70*	188
(8) Power supply switches	1.8	*89*	161
(18) Interlocking	1.4	*101*	141
(16) Power supply infra	2.2	*61*	135
(21) LCE	3.9	*18*	70
(12) Terminal power grid	0.2	*32*	6
(4) Tensioning system	0	*0*	0
(5) Overhead wire gantries	0	*2288*	0
(15) Signal gantries	0	*1891*	0
(23) EBP	0	*508*	0
(24) PRL	0	*189*	0
(25) Signaller	0	*194*	0
(20) Safe working area	-	-	0

Table XVI Overview of the amount of incident occurrences and the average duration of these incidents that are potentially affected by the untangling option

Appendix E

This section explains in which situations ProRail considers a train path as delivered, which is important for the definition of robustness chosen in this research. One of the key findings is that even a heavily delayed train that has run along its complete route is still considered as a successfully delivered train path. An internal document describes 6 scenarios of an example train's course that is supposed to run from A, via B, C and D to E only calling at A, C and E. The train paths can be considered as delivered, not delivered or partially delivered (ProRail, 2015e). See Table XVII.



	Z	A	B	C	D	E	F	
1. Train runs according to schedule		**A**	*B*	**C**	*D*	**E**		*Train path delivered?*
a. Train runs on-time								*Yes*
b. Train is delayed								*Yes*
2. Train skips a (few) station(s)		**A**	*B*	**C**	*D*	**E**		*Train path delivered?*
a. Train does not call at C								*Yes*
3. Train is cancelled or replaced		**A**	*B*	**C**	*D*	**E**		*Train path delivered?*
a. Train is cancelled without replacement		X	X	X	X	X		*No*
b. Train is cancelled and replaced over full route								*Yes*
c. Train is partly cancelled and replaced								*Yes*
4. Train journey is extended or shortened	*Z*	**A**	*B*	**C**	*D*	**E**	*F*	*Train path delivered?*
a. Train continues to F								*Yes*
b. Train ends at D						X		*Alternative*
c. Train starts at Z								*Yes*
d. Train starts at B		X						*Alternative*
5. Train is rerouted		**A**	*B*	**C**	*D*	**E**		*Train path delivered?*
a. Train is rerouted					X			*Alternative*
b. Train starts at B and is rerouted		X			X			*Alternative*
c. Pax partly rerouted (no extra train)				X	X	X		*Alternative*
d. Passengers are rerouted (no extra train)		X	X	X	X	X		*No*
6. Train is partly cancelled		**A**	*B*	**C**	*D*	**E**		*Train path delivered?*
a. Train runs from A to B				X	X	X		*Alternative*
b. Train runs from C to E		X	X					*Alternative*
c. Train starts at D		X	X	X				*Alternative*
d. Train is partly cancelled and only partly replaced								*Alternative*

Table XVII Six scenarios of a train's course with train path delivery KPI. Blue arrows indicate the original train, green a replaced train and red rerouted pax

Appendix F

In addition to section 9.3, in which the results have been presented and discussed, this appendix shows an overview of all modelled scenarios. See Table XVIII for the exact values of the TAOs and TVTAs and Figure IV for a graph of the TVTA results.

Scenario	TAOs (# incidents per year)	TVTAs (# cancelled trains per year)	Scenario	TAOs (# incidents per year)	TVTAs (# cancelled trains per year)
Base-α	171	2437	**C-More-α**	172	2220
Base-β	171	2138	**C-More-β**	172	2107
Base-γ	171	1949	**C-More-γ**	172	1776
Base-δ	171	3462	**C-Less-α**	170	2271
Max-α	154	3038	**C-Less-β**	170	2212
Max-β	154	2772	**C-Less-γ**	170	1817
Max-γ	154	2430	**C-Decr-α**	170	2188
Min-α	191	2699	**C-Decr-β**	170	2158
Min-δ	191	3086	**C-Decr-γ**	170	1750
A-More-α	164	3580	**D-More-α**	171	2283
A-More-β	164	3350	**D-More-β**	171	2152
A-More-γ	164	2864	**D-More-γ**	171	1827
A-More-δ	164	3930	**D-More-δ**	171	2948
A-Less-α	177	1886	**D-Less-α**	166	2736
A-Less-β	177	1652	**D-Less-β**	166	2606
A-Less-γ	177	1509	**D-Less-γ**	166	2189
A-Less-δ	177	2697	**D-Less-δ**	166	2913
A-Decr-α	168	2321	**E-More-α**	173	2603
A-Decr-β	168	2196	**E-More-γ**	173	2083
A-Decr-γ	168	1857	**E-Decr-α**	169	2385
A-Decr-δ	168	3363	**E-Decr-γ**	169	1908
B-More-α	170	2042	**F-More-α**	171	2450
B-More-β	170	1901	**F-More-γ**	171	1960
B-More-γ	170	1633	**F-Decr-α**	171	2433
B-More-δ	170	3430	**F-Decr-γ**	171	1946

Table XVIII TAO and TVTA scores of all modelled scenarios

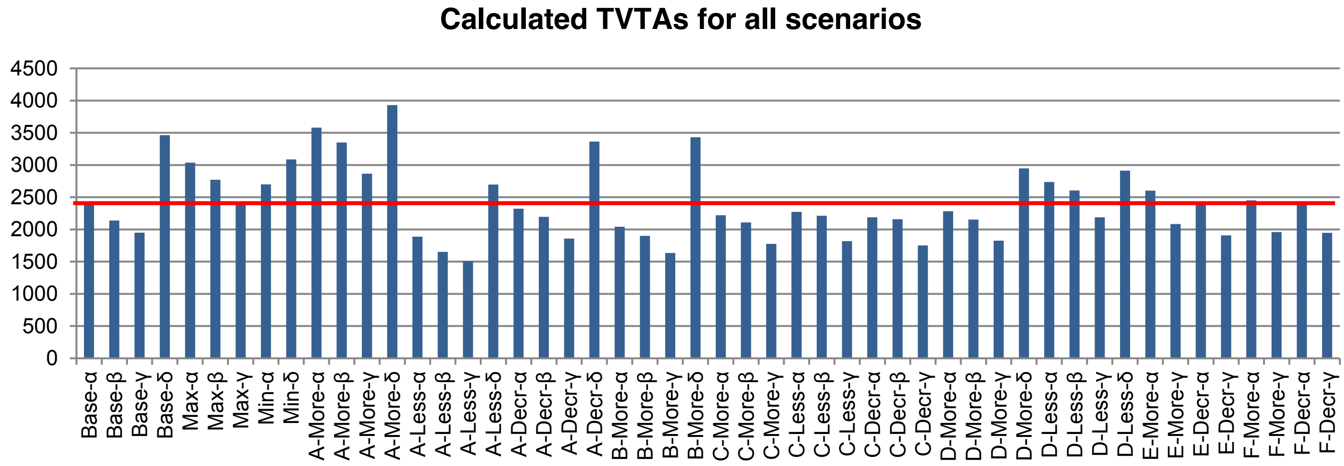


Figure IV TVTA scores of all scenarios. The red line shows the result of the Base-α scenario

Appendix G


Design of the Utrecht Central station area
Corridors & element IDs
Train corridors
A2
A12
Bkl-Db
North-East (NO)
IC Leiden (ICLedn)
VleuGel
Freight trains Amersfoort – Meteren
Buurtsporen
Legend
Signal for main, uninterrupted operation
Signal for traffic management purposes
Automatic signal
Signal with speed indicator
Pre-signal
L H Signals for heavy freight trains
asd1 Track name
1 Platform with number
Relay house
Power station
Traffic control centre
Planned direction of operation
DSSU + UtARK
Size 11xA4
Scope
Overvecht relay house control area
Northern relay house control area
Centre relay house control area
Utrecht Central
Amersfoort
Overvecht
Landstraat
Zuilen
Amsterdam
Leidsche Rijn
Gouda
Cartesiusweg
Power station North
Opstelterrein Zuid
Vaartsche Rijn
Lunetten
Bunnik
Arnhem
Houten
Geldermalsen

Appendix H


Design of the Utrecht Central station area
Subsidiary circuits & power stations
Legend
Subsidiary circuit
Isolator
ah1
Track ID
H
Connection to power station
1
Platform with number
Power station
SE1
Subsidiary circuit ID (S=South, N=North, X=Extra, E=External, B=Bunnik)
DSSU + UtARK
Size
11xA4
Scope
Overvecht
Amersfoort
amf1
amf2
amf3
amf4
Zuilen
Amsterdam
asd1
asd2
asd3
asd4
Leidsche Rijn
Gouda
rtd1
rtd2
rtd3
rtd4
Landstraat
Cartesiusweg
Power station North
Utrecht Central
Opstelterrein Zuid
Vaartsche Rijn
Power station South
Bunnik
Power station Bunnik
Arnhem
Lunetten
Houten
Geldermalsen
ah1
ah2
ah3
ah4
ht1
ht2
ht3
ht4
102
103

Appendix I

Design of the Utrecht Central station area

Switch pairs with required and requested positions


1417
1409B
1413A
1403B
1405A
1419
1413 B