UNIVERSITY OF TWENTE

FACULTY OF BEHAVIOURAL, MANAGEMENT AND SOCIAL SCIENCES

Providing Insight In The Impacts Of Removal And Replacement Decisions Of Existing Track Switches On Cost Of Train Diversion Routes During Possessions

Master thesis at ProRail

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Orientation	*Supply Chain and Transportation Management*

Preface

This thesis serves as the result of half a year research at ProRail and marks the end of my master Industrial Engineering and Management at the University of Twente. Even though the research was performed at home because of the pandemic, I still learned a lot of my colleagues of ProRail.

At ProRail, many people have contributed to my research some way or another. I would like to thank my supervisor Dennis Wittenberg in particular, for his time and the possibility to ask questions any time. I learned a lot during our meetings and often got helpful insights.

From the University of Twente, I would like to thank Peter Schuur for his guidance during the whole research. I enjoyed your enthusiasm and stories during all our meetings. I also would like to thank Engin Topan for being my second supervisor and for providing feedback in the final phase of my research, which has been very useful.

Finally, I want to thank my family and friends for their support during my whole study. I am thankful for the great time and I am excited to start with the first steps of my professional career.

I hope you enjoy reading this thesis!

Ellen Thijs

November 2021

Management Summary

Please note that some costs are excluded from this public version.

Research motivation

This research is performed on behalf of the PreVAB department of ProRail. Within ProRail, there are several visions about the design of the infrastructure of the railway system.

Figure 1 Example of track switches. Source: ProRail

On the one hand, the Infrastructure Development Department wants to reduce the asset costs and the risk of a defect on track sections and track switches that are barely used, by creating an infrastructure that is as robust as possible. An example of track switches is visualized in Figure 1. Over the past three years, each track switch that has reached the end of its life-cycle, has been checked to see whether the switch should be replaced or removed. Replaced means here that the old track switch is replaced by a new track switch. In the event that a track switch is replaced, the current diverting routes can still be used. Furthermore, a one-time replacement cost and yearly maintenance costs must be paid. Removed means that the old track switch is eliminated from the railway track, which leads to a new track section. Removing track switches results in a one-time removing cost that must be paid and in some cases, the current diverting routes can no longer be used, which results in higher diverting costs. To make a decision, the Infra Development Department uses a standard methodology where four aspects are taken into account: (i) current timetable, (ii) future timetable, (iii) 24/7 set up to shunt trains from their carriage siding and (iv) traffic adjustments when unexpected breakdowns occur. In the event that the switch track is not used in for at least a few times in one of these four situations, the switch will be removed. At this moment, the consequences for removing these track switches are not known.

On the other hand, ProRail made agreements with Railway Undertakings (RUs) regarding the distribution and handling of BTD "Buitendienststellingen" (possessions). One of the agreements made is that freight trains cannot be cancelled. Therefore, the PreVAB team (a division of the Capacity Management Department) wants to enable as much train traffic as possible under all circumstances.

During BTD, some track switches and railway sections are needed that are normally not used. At places where track switches are removed, the PreVAB has great difficulty in finding new diverting routes.

Therefore, the central research question of this thesis is:

What are the impacts of removal and replacement decisions of existing track switches on costs of train diversion routes during possessions and how can these decisions be made properly?

Research approach

To give a clear insight in the problem, interviews were held with various stakeholders. To get an impression of the consequences for the RUs, various passenger and freight carriers were interviewed. Furthermore, various departments within ProRail were interviewed such as the PreVAB, Infrastructure Development Department, Asset Management Department and the Department that is responsible for the compensation rates during BTD. They were consulted for their motivations behind the current policy and the data about the costs of diverting and the costs of asset.

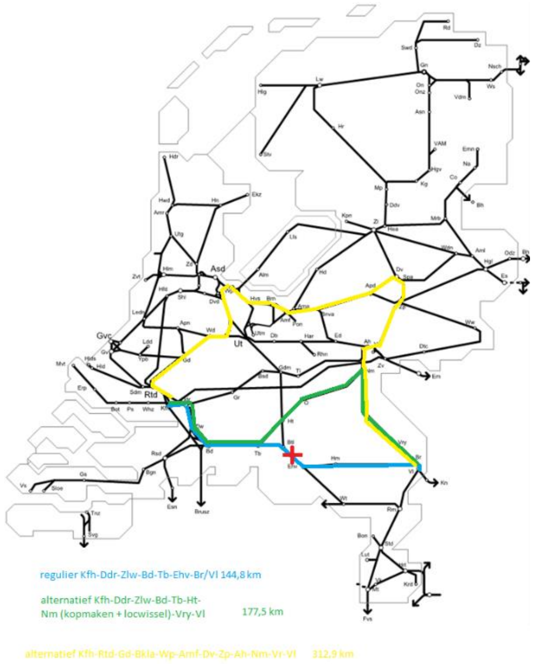

Figure 2 Direct result of changes in the infrastructure at emplacement Nijmegen. Source: Wittenberg, 2021

After this, we performed a case study for the changes at emplacement Nijmegen. At this emplacement, extra train tracks are being built for passenger traffic, which is at the expense of the four freight track sections that are located there currently. As a result, during BTD between Boxtel and Eindhoven, the diverting route from the port of Rotterdam to Venlo will be significantly longer (from 117.5 km to 321.9 km). This is visualized in Figure 2, the blue route is the normal route from Rotterdam to Venlo. If there is a BTD between Eindhoven and Boxtel (red cross) the green diverting route is used. After the changes at emplacement Nijmegen the yellow route becomes the new diverting route.

Unfortunately, ProRail does not record the compensation rate that is paid to the freight RUs in the past. Besides that, also the number of trains that were affected during BTD between Eindhoven and Boxtel is not known. Therefore, we made an estimation based on the current compensation rate of €770 per affected train and the average number of freight trains that are affected and use this for the diverting route through emplacement Nijmegen. Each weekday approximately 10 trains are affected and between 2018 and 2021, there is only one weekday that there is a BTD between Eindhoven and Boxtel. Which means that yearly 10 trains are affected.

The compensation rate depends on the extra kilometers of the diverting route, the number of times that the train needs to change direction and the number of non-commercial stops and the costs of rescheduling the timetable of the train. ProRail expects that the compensation rate will increase by at least 300% when the diverting route will change to the new yellow route.

With the information gathered from the interviews and the case study about emplacement Nijmegen an ILP model is made to decide whether the track switches should be replaced or removed. The model calculates the minimal costs over the next 20 years of diverting and the asset costs after replacing and removing the track switches. In the event that the switches will be replaced, the BTD costs will remain the same since the same diverting routes can be used. However, a one-off replacement cost for the track switch and the switch heater and a yearly maintenance cost must be paid. When the track switches will be removed, the BTD costs will increase since the diverting routes become longer and a removement cost (which is more than the replacement cost) must be paid per track switch. But there are no maintenance costs anymore.

Results

The case study of emplacement Nijmegen is used as input for the ILP model. For the model it is pretended that the decision about removing or replacing the tracks switches is not taken yet. At the four freight track sections, there are 12 track switches of type 80 km/h that have to be removed or replaced within 5 years. Each year there is (on average) one weekday on which there is a BTD between Eindhoven and Boxtel and in that day, 10 trains are affected. With an inflation rate of 1.2%, increasing traffic rate of 3.0%, compensation rate of 300% and an increasing compensation cost of 3.5%, the excel solver decided to remove the track switches in year 1. This decision gives the lowest cost over 20 years of €**X**.

After using the case study as input for the model, a sensitivity analysis is done to give more depth to the findings. Therefore, the switch types, the number of track switches, the heater age, the increasing compensation rate, the increasing traffic rate and the compensation rate are changed, to see how these parameters influence the results of the model. Changes in the switch type, heater age and increasing compensation rate did no gave a different result.

As visualized in Figure 3, when the number of track switches is below 5, it is cheaper to replace the switches in the first year and when there are 6 switches it is cheaper to remove them in year three. However, in the case of emplacement Nijmegen, at least four switches are needed to change the direction of the train ("kopmaken"). When looking at the increasing traffic rate in Figure 4 (for the example of emplacement Nijmegen), only a yearly increase of 10% will change the decision from removing the switches in the first year to replace the switches in the first year. The compensation rate (Figure 5 when the switches are removed have a higher influence, when the compensation rate will increase with 550%, it is cheaper to replace the switches.

X

Figure 3 The costs of removing (R31 and R33) and replacing (R21) track switches is plotted against the number of track switches. If there are only 1 till 5 track switches, replacing in year one gives the lowest objective function. When looking at 6 track switches, they should be removed in year three and when the case has 7 track switches of more, it is more beneficial to remove all the switches in year 1.

X

Figure 4 The objective function for 20 years for the decisions R21 and R31 per increasing traffic rate. For every traffic rate between 0.0% and 9.5% the decision of removing the track switches in year one results in a lower objective function than replacing the track switches in year one. For a traffic rate that is 10.0% or higher, replacing in year one will lead to a lower objective function.

X

Figure 5 The objective function for 20 years for the decisions R21 and R31 per compensation rate. For every compensation rate between 100% and 450% the decision of removing the track switches in year one results in the lowest objective function. When the compensation rate is 500%, removing in year three gives the lowest objective function. For a compensation rate that is 550% or higher, replacing in year one will lead to a lower objective function.

Limitations and recommendation

The model solver is suitable to make a decision whether track switches should be replaced or removed and in which year it is the most profitable to take this decision. The model makes a 20-year cost calculation in which the diverting and asset costs are included. The solution can also be obtained manually by using the DIY-tool. Every possible solution can be entered here, after which the model calculates the costs. In this way it is also possible to check whether the solver provides the best solution. However, to make the model more significant more data is needed:

There is no data available about past BTD. Therefore, information such as the number of affected trains, number of days a BTD takes place and whether the BTD is ad-hoc (BTD is applicated 4 months till 36 hours before execution) or not are estimated. To make the model more accurate, data about BTD needs to be recorded.

Furthermore, the maintenance costs are not accurate. At this moment, ProRail divides the total amount of maintenance through the number of track switches. Then they divide these costs proportionally per switch type. Besides that, all switches of the same type are assumed to have the same life-cycle in the present approach. While in reality, switches that are used more often have a shorter life-cycle. The switches that are involved in this research are barely used and therefore their life-cycle and their yearly maintenance costs might differ from the current values. To improve this, the switches can be divided into three groups according to the usage of the switch: high usage, moderate usage and low usage. After this, the maintenance costs can be divided proportionally among the three groups.

Finally, the compensation cost after removing track switches is estimated to be at least 300% more expensive than replacing the track switches. In order to receive a more accurate compensation cost, data about the new diverting routes is needed. Information about extra kilometers after diverting, extra times that the train needs to change the direction of the train, the number of non-commercial stops and the costs for rescheduling the train should be recorded. Then the compensation rate can be calculated by the average cost of all the freight trains that are affected by the BTD.

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Function maintenance projects – functie handhavingsprojecten, page 13

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Rail – spoorstaaf, page **Fout! Bladwijzer niet gedefinieerd.**

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(Gutter, 2016)

Abbreviations

AUP – “Alternatief Uur Patroon” (Alternative Hour Pattern)

BTD – “Buitendienststellingen” (Possessions)

CM – Capacity Management

CRS – Customer Requirement Specification

IO – "Incidentele onttrekkingen" (Incidental withdrawals)

LPO – "Landelijk Platform Overleg" (National platform consultation)

RU – Railway Undertaking

SRS – System Requirement Specifications

WO – "Wekelijkse onttrekkingen" (Weekly withdrawals)

Concepts

Ad-hoc BTD = BTD that are applicated 4 months till 36 hours before execution.

BTD = Possessions on the railway track that are determined and adjusted 2 till 1 year before execution

Corridor = an important connection between busy areas, over which goods or persons are transported (ProRail, 2017).

Emplacement = an area of the railway infrastructure that has at least one switch and is intended to make trains stop, start, end, overtake, cross, line up or shunting. (ProRail, 2019)

"Kopmaken" = change direction of traffic of the train, whereby the locomotive of the train needs to be placed on the other side of the train.

"Goederenverkeersluwe" periods = periods with freight traffic-calmed, being: weekends, public holidays and days between public holiday and weekend. (ProRail, 2019)

"Reizigersverkeersluwe" periods = periods with passenger traffic-calmed, being: school holidays and public holidays. (ProRail, 2019)

Category 1 or 2 = The compensation rate for passenger Railway Undertakings during BTD of function changing projects (see Section 2.4 and appendix 8A.1)

1 Introduction

This thesis is written in the framework of completing my master study in Industrial Engineering and Management at the University of Twente. The research is performed at ProRail and it provides insight in the effects of changes in the infrastructure on the diversion of train traffic during possession. This first chapter gives an introduction about the organization, the research motivation, the problem description, problem approach, the research problem and research questions.

1.1 Company description

ProRail is the Infra Manager of the Dutch railways and is responsible for the maintenance, renewal, extension and safety of the railway system. Together with the Railway Undertakings (RUs) ProRail ensures that passengers and freight traffic arrive at their destination safely and in time (ProRail, sd).

Furthermore, ProRail allocates the space on the track and arranges all train traffic and builds and manages the railway stations. In 2019, Dutch railway system consisted of 7,000 kilometers of track, 6,500 track switches, 2,400 railway crossings and 400 stations. Furthermore, ProRail employed more than 4,300 employees, collaborated with 27 railway companies, transported 1,1 million passengers a day and arranged 3.3 million train journeys per year for freight traffic (ProRail, 2021).

1.1.1 Maintenance on the railway system

Many trains are running on the track every day and therefore the infrastructure wears out quickly. Especially the freight traffic has a major influence. Each freight train has an average speed between 90 and 95 km/h and consists of on average 30 wagons, where one wagon includes 8 wheels and 4 axles. Each axle has an axle load of 22,500 kg, which causes a point load on the rail of a euro coin. The passenger trains have a lower axle load, but there are more passenger trains than freight trains and the passenger trains have a higher speed (Wittenberg, 2021). Therefore, a lot of maintenance or replacement must be done on the track. When works are carried out on the rail track, mostly the track is taken out of service. In Dutch this is called “Buitendienststellingen” (BTD).

Maintenance of the infrastructure can be divided in two categories. The first one is the regular maintenance that is used for small repairs and it takes a maximum of 4 to 7 hours. Examples of these small repairs are tightening bolts and lubricate or set track switches. Every week on a fixed night a fixed part of the railway system is out of service for this type of maintenance. In Dutch this is called: “Wekelijkse Onttrekkingen (WO)”. During WO maintenance the freight traffic is diverted. When designing or redesigning infrastructure these BTD are (usually) included in the plans. ProRail has contracts with contractors who maintain the railway. In each contract, ProRail defines which requirements the railway must meet. The contractors themselves determine how often and when they maintain the track. Therefore, the contractors could use the WO schedule in which every week, 2 weeks or 4 weeks a part of the railway track is reserved for BTD (Wittenberg, 2021).

The second type is the more complicated maintenance, takes place on an incidental basis. This results in an incidental allocation of a particular part of the railway system. In Dutch this is called “Incidentele Onttrekkingen (IO)”. This type of maintenance is performed when more time or more workspace is needed. The duration of IOs ranges from 8 hours to more than 2 weeks. Examples of IOs are large repairs, renewing of the railway track, replacement of track switches and renewing of the overhead line. Yearly, the Capacity Management department has to allocate approximately 1300 IOs. Each week, the national timetable is adapted and partly redesigned because somewhere in the country there are emplacements and track sections that are partially or entirely out of service. When designing or redesigning infrastructure these IOs are not included in the plans (Wittenberg, 2021).

1.1.2 PreVAB department

This research is conducted at the Capacity Management Department (CM) in the PreVAB team (VAB = Verkeersaanpassingen Als gevolg van Beheer). The organizational chart of the Capacity Management department of ProRail is visualized in Figure 1.1**Fout! Verwijzingsbron niet gevonden.**.

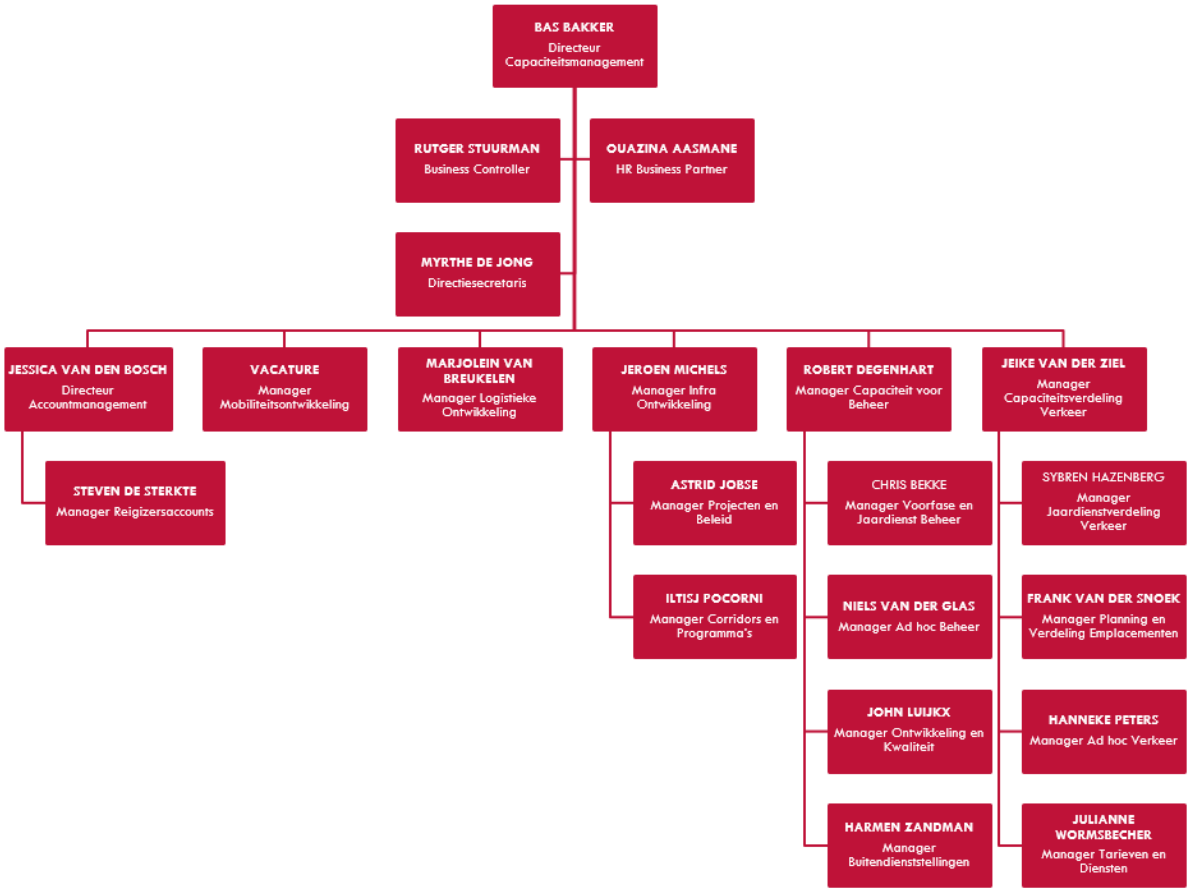


Figure 1.1 Organizational chart capacity management ProRail. Source: (ProRail, 2021)

The PreVAB team is a part of the Ad-Hoc department. The goal of PreVAB is to make a modified transport product feasible in time due to BTD. In this case, the transport product means: all logistical adjustments because of one or more BTD. The transport product should be properly designed with a scoop, without rework (ProRail, 2018).

1.2 Research motivation

During works on the rail track, the handling of the passenger and freight traffic must be able to continue as usual. To make this possible, the limited infrastructure that remains in service at that time is used in a creative and efficient manner. In certain cases, traffic is diverted via alternative routes and the emplacement and track sections are used in a different way.

In recent years, when new infrastructure is designed and existing infrastructure is optimized, the alternative use of emplacements and track sections is not always considered. During BTD, other routes and track sections are used. In addition, some trains also have to change direction whereby the locomotive of the train needs to be placed on the other side of the train. Therefore, in the future, handling of train traffic during BTD is sometimes no longer (fully) possible or the works on the railway track should be carried out in a different way. This results in far-reaching consequences and costs for ProRail, the RUs, contractors and terminals.

One of the matters that should be investigated is whether all considerations are made during the designing and optimizing of the infrastructure. The knowledge of the alternative rail use and to what extent a cost-benefit analysis is properly substantiated in this, should be included in this process (Wittenberg, 2021).

1.3 Problem statement

To investigate the problem definition, a chain of events (Figure 1.2) is made to identify the cause (colored in red) and effects that lead to the core problem. The function maintenance and function changing projects are further elaborated in Section 2.1.

In the current situation, there are two visions about the use and construction of the infrastructure of the railway system. To reduce the maintenance costs of the railway system, the infrastructure will be changed. The department of infra development, that is in charge regarding the infrastructure design, wants an infrastructure that is as robust as possible, with the focus mainly on the optimum during an undisturbed situation. Because the costs of using alternative routes during BTD are not known yet the IOs are not taken into account during this process. Therefore, all track switches and train tracks that are not used during the annual timetable, will be removed.

On the other hand, the PreVAB wants to enable as much train traffic as possible under all circumstances (planned BTD or disruptions). During BTD the infrastructure is used in a different way than was conceived in earlier stages or what is normally the case (Wittenberg, 2021).

Together with the RUs, shippers, governments and abroad, ProRail made agreements regarding the distribution and handling of IOs. Stated in these agreements:

- Canceling freight traffic is not an option, unless the (only connection to the) terminal or relevant border crossing itself is out of service.
- An exception is made for the possessions that only take a few hours, mostly when diverting takes longer than waiting.
- Operating level of passenger RUs at the stations may not fall below a certain level.
- Canceling international passenger transport is not an option, unless the (only) connection to the relevant terminal in the Netherlands or the crossing borders are out of service themselves.
- Contractor supply and return trains (ranging from a single to several per day) must be possible between regular train services.
- Visitors of events must be able to be transported by trains.

PreVAB needs to make sure that these agreements are met while they are diverting the routes during BTD. When a train (planned) cannot run its normal route, for example due to work on the track, it may be decided to partially drive a different route. These different routes are called: diverting routes. Therefore, an AUP is made for each IO. Since multiple IOs are planned every week, national cooperation is always needed. However, at this moment no agreements are made regarding the timetable during possessions. In case that the normal timetable cannot continue, other options will be considered. Each time these timetables are coordinated with the RUs. Furthermore, there is no standard yet that determines whether a particular diverting route is currently too long, making it no longer realistic to use this diverting route.

At this moment, there are two problems that PreVAB encounters. Firstly, although PreVAB can completely redesign the timetable component, this is getting more complicated every year due to the intensification and longer lines in the design of the passenger traffic. Secondly, at places where the infrastructure has changed, more diverting solutions are disappearing. This results in four bottlenecks for the PreVAB, namely:

1. Diverting routes for freight traffic are not possible anymore
2. Diverting routes have become much longer and therefore they are no longer realistic
3. Diverting routes are only possible with significant cuts in the passenger traffic
4. New dependencies of national cohesion IOs, which means that it is no longer possible to have BTD at multiple locations at the same time.

These four bottlenecks result in postponing of the BTD, which has consequences for the quality of the rail track and will increase the maintenance costs. Furthermore, to keep train traffic possible, BTD should be redesigned and moved to periods when less passengers are using the train. Unfortunate, the BTD will take more time and will become more expensive.

To conclude, there are two different visions regarding the design of the infrastructure. The Infrastructure Development Department wants to reduce the maintenance costs and therefore a robust infrastructure that is focused on undisturbed situations. This results in removing parts of the infrastructure that are not used during the annual timetable. On the other hand, the PreVAB wants to continue as much train traffic as possible, during possessions. Therefore, alternative routes and other track switches are necessary during BTD. Since the costs of the alternative routes are not known yet, they are not taken into account when the infrastructure is changed.

Therefore, the problem definition of this research is:

There is a lack of insight about the impacts of removal and replacement decisions of existing track switches on costs of train diversion routes during possessions and how these decisions can be made.

Where removal of an existing track switches means that the old track switch is eliminated from the railway track, which leads to a new track section. Removing track switches results in a one-time removing cost that must be paid and in some cases, the current diverting routes can no longer be used, which results in higher diverting costs. Replaced means here that the old track switch is replaced by a new track switch. In the event that a track switch is replaced, the current diverting routes can still be used. Furthermore, a one-time replacement cost and yearly maintenance costs must be paid.

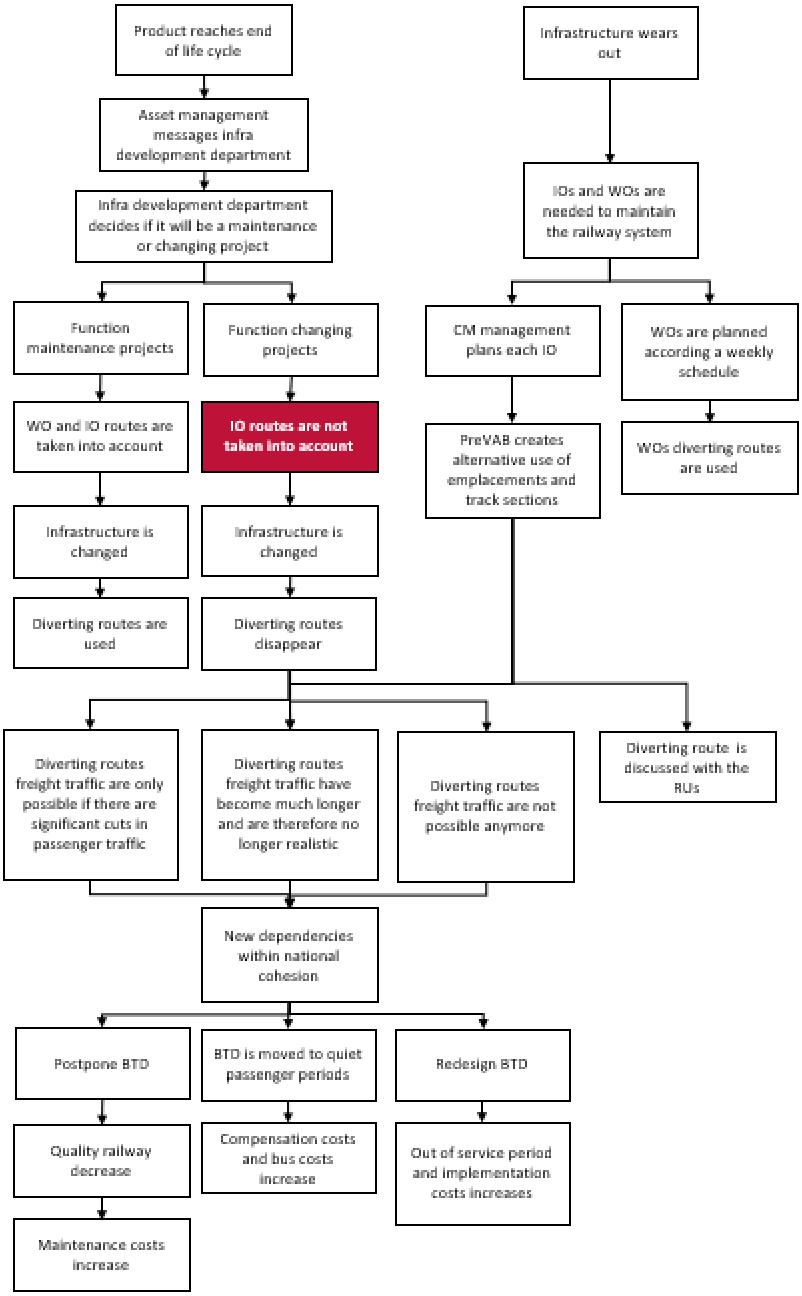


Figure 1.2 Chain of events, in which the cause that leads to the main problem is colored in red.

1.3.1 Examples

To give a clear insight in the problem, three examples of direct consequences of changes in the infrastructure are explained. For these examples the decisions are already made.

Example 1: Emplacement Nijmegen

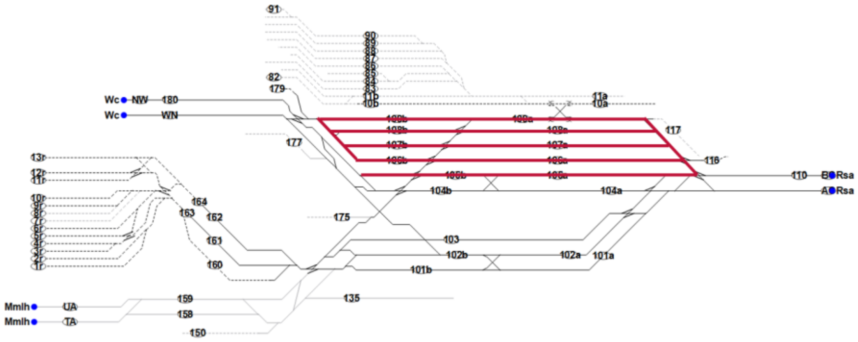


Figure 1.3 Emplacement Nijmegen. Source: InfraMonitor

In 2026 the railway tracks that are colored in red (Figure 1.3) are removed, because these tracks are not used in the normal routes. This change in the infrastructure has no influence on the annual timetable. However, during a BTD between Boxtel (Btl) and Eindhoven (Ehv), normally freight trains are diverted via Nijmegen. At Nijmegen the train needs to change its locomotive to a diesel locomotive and the train needs to switch of direction by placing the locomotive to the other side of the train. By removing a part of the railway track in Nijmegen this is not possible anymore. Therefore, a new diverting route has to be made.

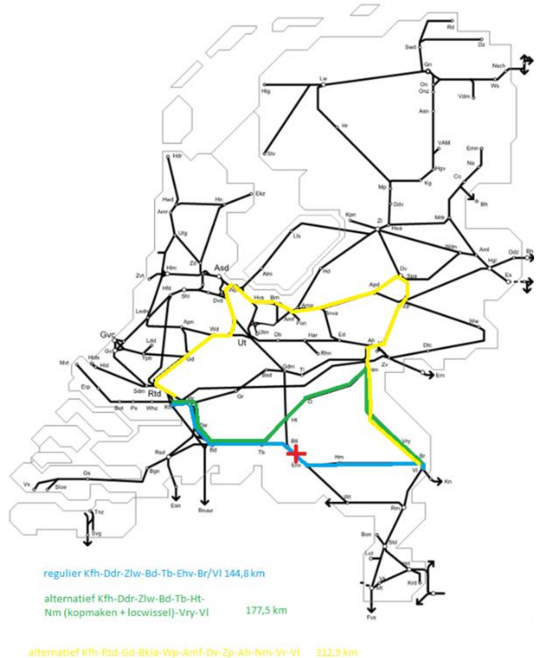


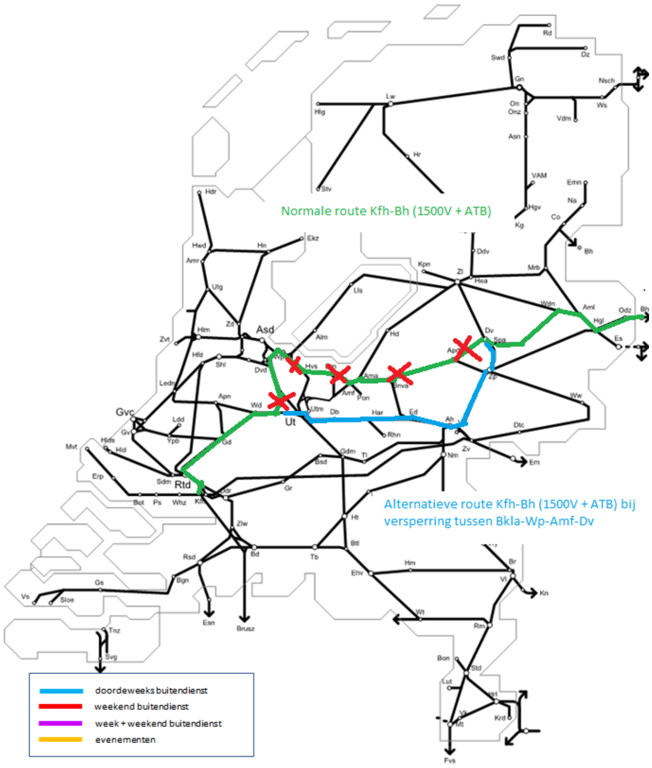
Figure 1.4 Direct result of changes in the infrastructure at emplacement Nijmegen. Source: Wittenberg, 2021

This situation is visualized in Figure 1.4. The normal route, colored in blue, has a length of 144.8 km. During a BTD between Eindhoven and Boxtel this blue route cannot be used. The green line represents the alternative route, which is 177.5 km. After removal of railway sections at Nijmegen, the yellow line come the new alternative route. This new diverting route is 312.9 km. Since the train track between Nijmegen and Venlo does not have electrification, only diesel engines can drive over this track. Diesel engines have less power and have higher running costs than the electric locomotives. Therefore, most of the route is driven with the electric locomotive and a locomotive switch is needed. Changing locomotives takes about half an hour. Besides that, freight RUs buy exact amount of diesel engines that are necessary for the annual timetable. When they need an extra diesel engine during BTD, they have to hire an engine for one month. In 2019 and 2020, there was a BTD six times (in total 16 days) between Boxtel and Eindhoven.

This example is used for the case study in Chapter 4.

Example 2: Emplacement Ede

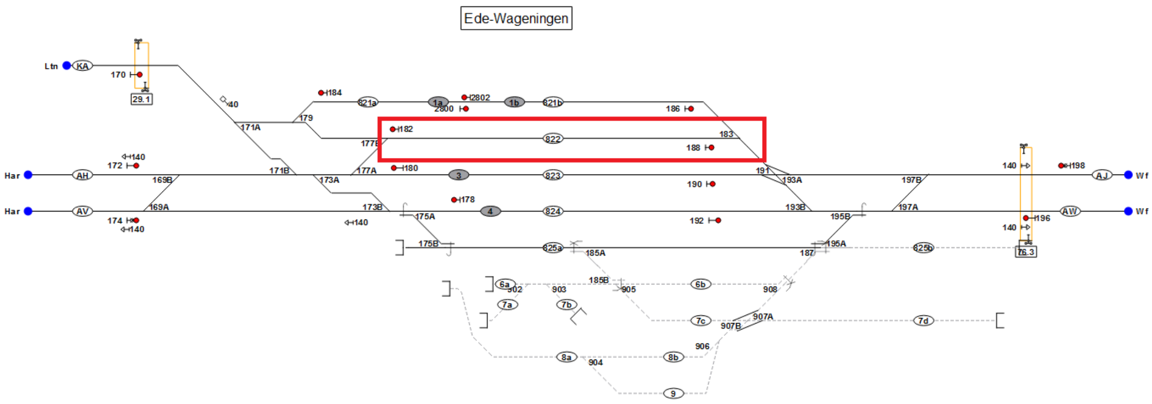
In 2024 a railway track nearby train station Ede-Wageningen (Figure 1.6), will be removed because this track is not used in the normal routes. In the event that there is a BTD at one of the red crosses (Figure 1.5), this railway track is used by freight trains to overtake the passenger trains and fit in the timetable.



By the decision of removing the track section at Ede-Wageningen, the alternative (blue) route can only be used when one or two ICs between Arnhem and Utrecht are canceled per hour. Which results in delays and fuller trains for the passenger transport. In 2019 and 2020 there was 9 times a BTD at one of these red crosses, which resulted in 26 days of possessions.

Figure 1.5 Emplacement Ede-Wageningen. Source: Wittenberg, 2021

Figure 1.6 Track section at Ede-Wageningen that will be removed. Source: (Wittenberg, 2021)



Ede-Wageningen
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197A
192
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140
AW
Wf
175B
825a
185A
187
195A
825b
76.3
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902
903
185B
905
6b
908
7a
7b
7c
907B
907A
7d
906
8a
904
8b
9

Example 3: Emplacement Tilburg Goederenemplacement

During BTD between Roosendaal and Lage Zwaluwe, the alternative route (blue) that is visualized in Figure 1.7 is used. When using the blue route, the direction of the train changes and the locomotive will be placed at the other side of the train at one of the four train tracks at the Tilburg freight emplacement.

ProRail made the decision to decrease the number of train tracks from 4 to 3 tracks in the future (Figure 1.8). Three train tracks are used for passenger traffic and other freight routes. Two tracks are used for trains between Tilburg Universiteit and Weert and two tracks are used for changing directions of freight trains and access routes for contractor trains.

Figure 1.7 Tilburg Goederenemplacement

After removing the extra track section at Tilburg freight emplacement, there are two options when there is a BTD between Lage Zwaluwe en Roosendaal and a freight train needs to drive from Kijfhoef to Sloe (green route): (i) passenger trains have to be canceled or (ii) the longer (yellow) alternative diverting route has to be used.

The current alternative route (blue) is 101,1 km. The new alternative route (yellow) is 149,1 km. In 2019 and 2020 the route between Roosendaal and Lage Zwaluwe was 8 days out of service.

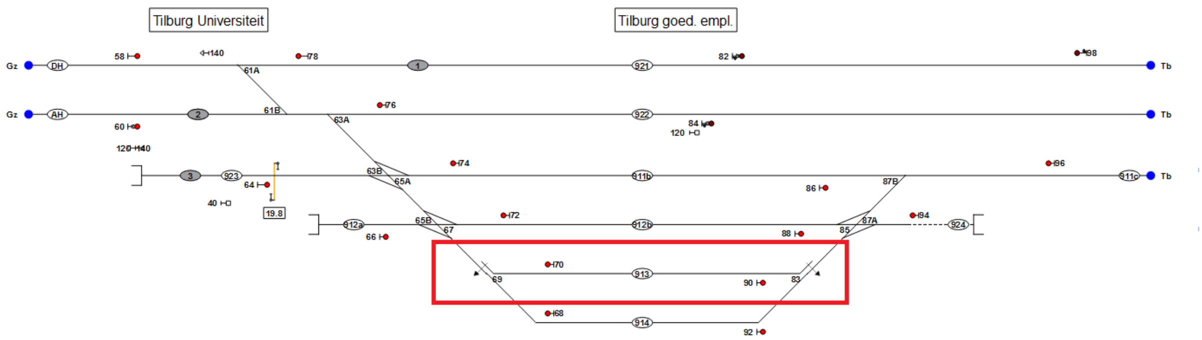


Figure 1.8 Track section at Tilburg goederen emplacement that will be removed. Source: (Wittenberg, 2021)

1.4 Research design

Based on the problem statement, the main research question is set up:

What are the impacts of removal and replacement decisions of existing track switches on costs of train diversion routes during possessions and how can these decisions be made properly?

To give an answer on the main research question, first the following sub questions must be answered. Each chapter represents a sub question.

Chapter 2: Current situation

What is the current situation regarding diverting traffic?

1. *What does the current process of planning IOs and WOs look like?*
2. *How is the traffic diverted during BTD?*
3. *What are the current costs of diverting?*
4. *What KPIs are currently in place?*

What is the current situation regarding the infrastructure development?

1. *What does the current process of infrastructure development look like?*
2. *Who are the stakeholders?*
3. *What does the current cost-benefit analysis look like?*
4. *What KPIs are currently in place?*

In order to investigate the effects of infrastructure development, first the current situation has to be analyzed. Therefore, first more information is needed about the process of traffic distribution, the planning of works on the railway system and the procedure of diverting train traffic during BTD. After this, the process of infrastructure development is described. These research questions will be answered by collecting information from relevant ProRail documents and interviews with the infra development department, the PreVAB department and the RU.

Chapter 3: Literature review

The literature review is divided into three parts:

<u>Process development:</u>

Which methods are described in available literature regarding development processes of infrastructure?

1. *What requirements are needed in a development process of infrastructure?*
2. *Which method is suitable for this research?*

<u>Indicators:</u>

Which indicators are important regarding infrastructure development projects?

<u>Cost-benefit analysis:</u>

Which methods are described in available literature regarding cost-benefit analysis regarding infrastructure development projects and diverting routes?

1. *Which methods are there for cost-benefit analysis of infrastructure development projects?*
2. *Which method is suitable for this research?*

After an analysis of the current situation, a literature review is done. In this chapter first possible process development methods are described. After this the indicators that are used during infrastructure changing projects are described. Next, methods to set up a cost-benefit analysis for infrastructure development projects and diverting routes are discussed.

Chapter 4: Case study

After the current situation is described and the literature review is done, a case study is performed. Therefore, the example of emplacement Nijmegen is chosen (Section 1.3). Based on the following research questions, emplacement Nijmegen is further elaborated:

What is the motivation behind the changes of emplacement Nijmegen?

1. *What does the track around emplacement Nijmegen look like at this moment?*
2. *What will be changed around emplacement Nijmegen?*

What are the impacts of changes at emplacement Nijmegen?

1. *What are the costs of diverting trains before emplacement Nijmegen is changed?*
2. *What are the costs of diverting trains after emplacement Nijmegen is changed?*
3. *What are the asset costs before emplacement Nijmegen is changed?*
4. *What are the asset costs after emplacement Nijmegen is changed?*
5. *How often is there are BTD between Boxtel and Eindhoven?*

Chapter 5: LP model

How can a model be developed to calculate a cost-benefit analysis regarding infrastructure development projects and diverting routes?

To answer this question, first the research questions regarding the literature of the cost-benefit analysis should be answered. Together with the information that is gathered in chapter 2, a model can be performed.

Chapter 6: Results

This chapter describes the results.

Chapter 7: Discussion and limitations

In chapter 7 the discussion and limitations of this research are described.

Chapter 8: Conclusions and recommendations

In the last chapter the conclusions and recommendations are described.

1.5 Deliverables

The deliverables of the study are this report with new insights in the effect of infrastructure development on the diverting routes of train traffic.

Furthermore, a decision tool will be proposed to determine whether the switch(es) on a certain location on the railway track should be replaced or removed.

2 Current situation

All processes that are relevant for this research are analyzed and described in this chapter. First, Section 2.1 describes how maintenance on the railway track is planned and it describes the costs of maintenance. Section 2.2 describes the development of the infrastructure, who initiates the development and who are consulted for the projects of infrastructure development. Then the process of capacity distribution of the train traffic is described in Section 2.3. This section also gives the timeline of the of PreVAB department, it explains when the maintenance activities are scheduled and the diverting process during BTD "Buitendienststellingen" (posessions) is explained. This section also includes the effects and costs of diverting train traffic during BTD and. After this, the stakeholders of ProRail are described in Section 2.4. In Section 2.5, the KPIs that are in place are explained. Finally, chapter 2 is concluded in Section 2.6.

2.1 Maintenance

In this section the process of maintenance planning is described. As described in Section 1.1.1, maintenance on the railway system can be divided into two categories, namely; WOs (weekly withdrawals) and IOs (incidental withdrawals). Where WOs is the maintenance for the small repairs that takes a maximum of 4 to 7 hours and IOs are performed when more time or more workspace is needed.

2.1.1 WO planning

For WOs, every week on a fixed night a part of the railway system is taken out of service. (Some WOs take place during the day, but these WOs never cause out of services). During these hours, contractors have the opportunity to perform maintenance. In contracts with ProRail is defined what requirements the railway must meet. Contractors themselves determine how often and when they maintain the railway track. When contractor decide to work on a part of the railway system, they have to sign in two weeks in advance. Even though there may not be a single contractor working on the track on a given night, the freight Railway Undertakings (RUs) are not allowed to use these tracks.

At Friday night, no WOs can be planned and at Sunday night, most of the railway tracks are out of service to perform WOs. Figure 2.1 visualizes the WOs during Tuesday nights. The green tracks are free from maintenance and freight traffic can be diverted via these routes. At the other tracks, blue, yellow and red, maintenance could be planned. At the red train tracks there are BTD due to the maintenance. At the blue tracks WOs can be planned, but at least two railway tracks stay available and at the yellow tracks WOs can be planned, but at least one track stays available.

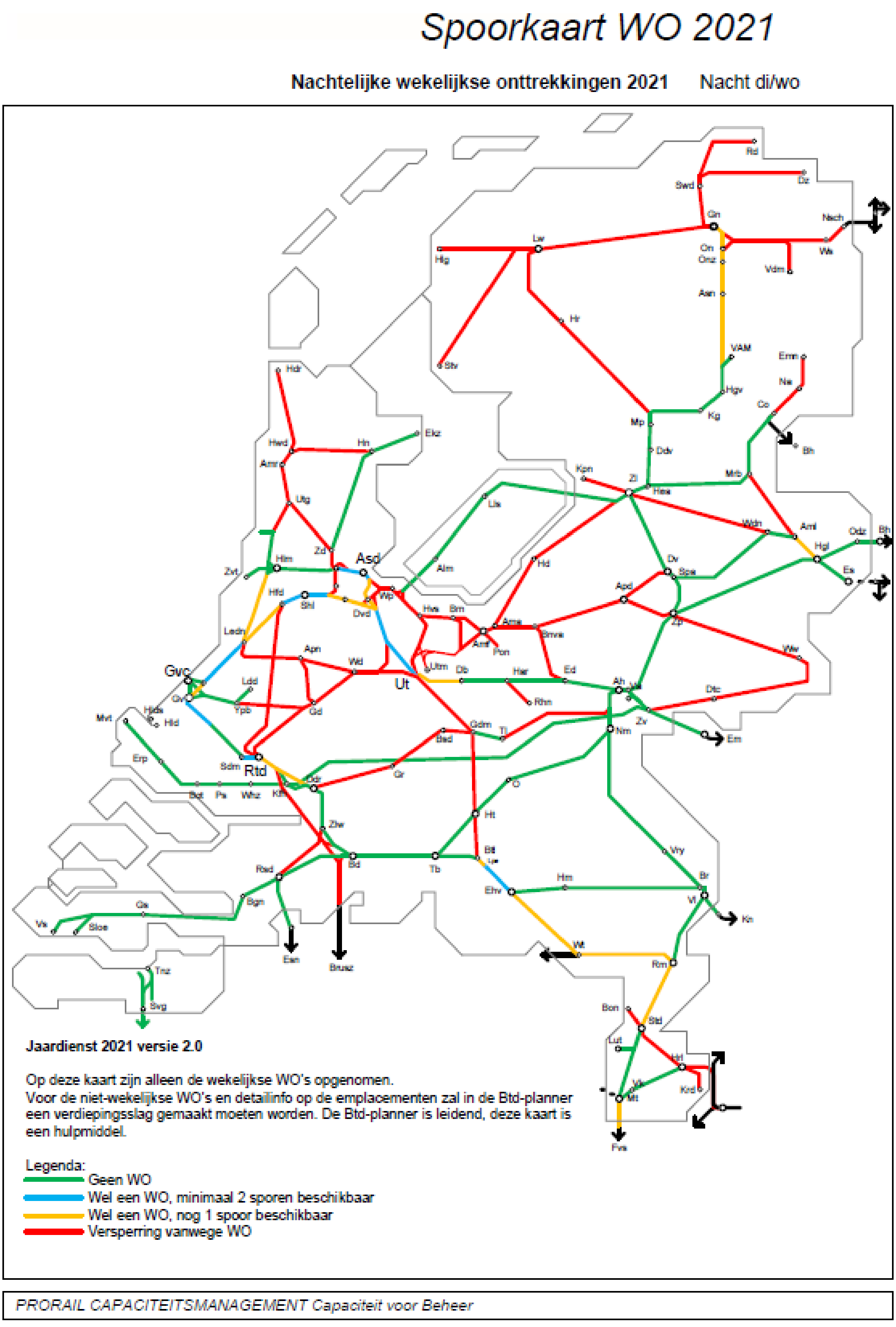
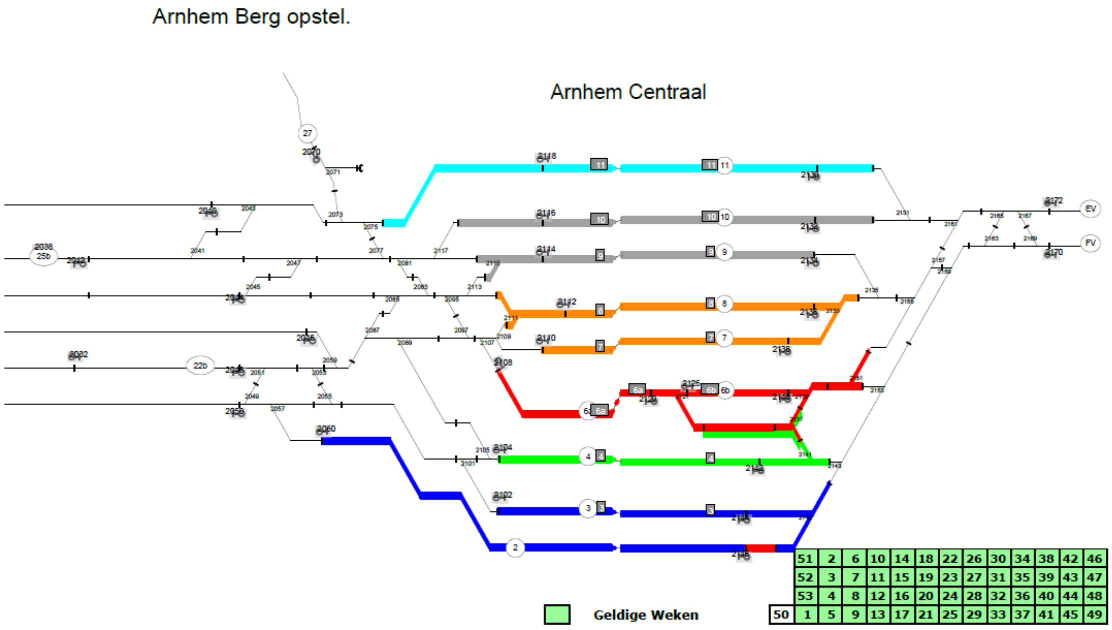


Figure 2.1 Example WO during Tuesday/Wednesday night. Source: (ProRail, 2021)

For every track section and emplacement, a drawing is made, together all these drawings create a WO map. Figure 2.2 visualizes the WO drawing of train station Arnhem Central. The lines in different colors represent the BTD for the WOs at different times. The WOs in this example are planned during Monday evening. This planning is used for small maintenance and cleaning of stations tracks.



Gebruikte IA laag van de IO(-B)/WO: Donna_78982_VER_1					
Nummer: NOR202-1849-00	Versie: 3 (2020-08-19 12:37)	Drgl-jaar: 2021	Aanvang: ma 20:22	Einde: ma 23:23	Duur: 3:01
Bijzonderheden: -					

Identificatie WO: WO-NOR202-1849-00-3

Legenda werkplekken in groep					
— B	Duur: 0:27	Tijdligging: ma 20:57 - ma 21:24	Spanningsloos: Nee	Buitendienst: Ja	Matopstelling: Nee
— C	Duur: 0:26	Tijdligging: ma 21:26 - ma 21:52	Spanningsloos: Nee	Buitendienst: Ja	Matopstelling: Nee
— D	Duur: 0:22	Tijdligging: ma 21:54 - ma 22:16	Spanningsloos: Nee	Buitendienst: Ja	Matopstelling: Nee
— E	Duur: 0:24	Tijdligging: ma 22:34 - ma 22:58	Spanningsloos: Nee	Buitendienst: Ja	Matopstelling: Nee
— F	Duur: 0:19	Tijdligging: ma 23:04 - ma 23:23	Spanningsloos: Nee	Buitendienst: Ja	Matopstelling: Nee

Identificatie WO: WO-NOR202-1849-00-3

Figure 2.2 WO map Arnhem Centraal. Source: (ProRail, 2021)

2.1.2 IO planning

IO is maintenance that does not fit into the WO schedule because it takes too long or needs more space on the railway track than a WO. Also, maintenance that takes place abroad but does influence the Dutch railways fall into the category IOs. For the IO planning, the RUs are also involved. BTD are mainly planned during the traffic-calmed periods. In the case that ProRail and the RUs do not agree about the planning of one IO or the planning of multiple IOs on different locations at the same time, ProRail makes final decision.

To make sure that train traffic still can be diverted, a corridor book is made. A corridor is an important connection between busy areas, over which goods or persons are transported (ProRail, 2017). In this corridorbook the designing, programming, coordinating and consequences of IOs are described (ProRail, 2021). The corridor book also includes overview maps of possible alternative routes during BTD.

When a train (planned) cannot run its normal route, for example due to work on the track, it may be decided to partially drive a different route. These different routes are called: diverting routes. Figure 2.3 Visualizes the overview map, where each number represents new maps for the diverting routes. For example, Figure 2.4 visualizes the diverting routes when there is a BTD at number 4. The number

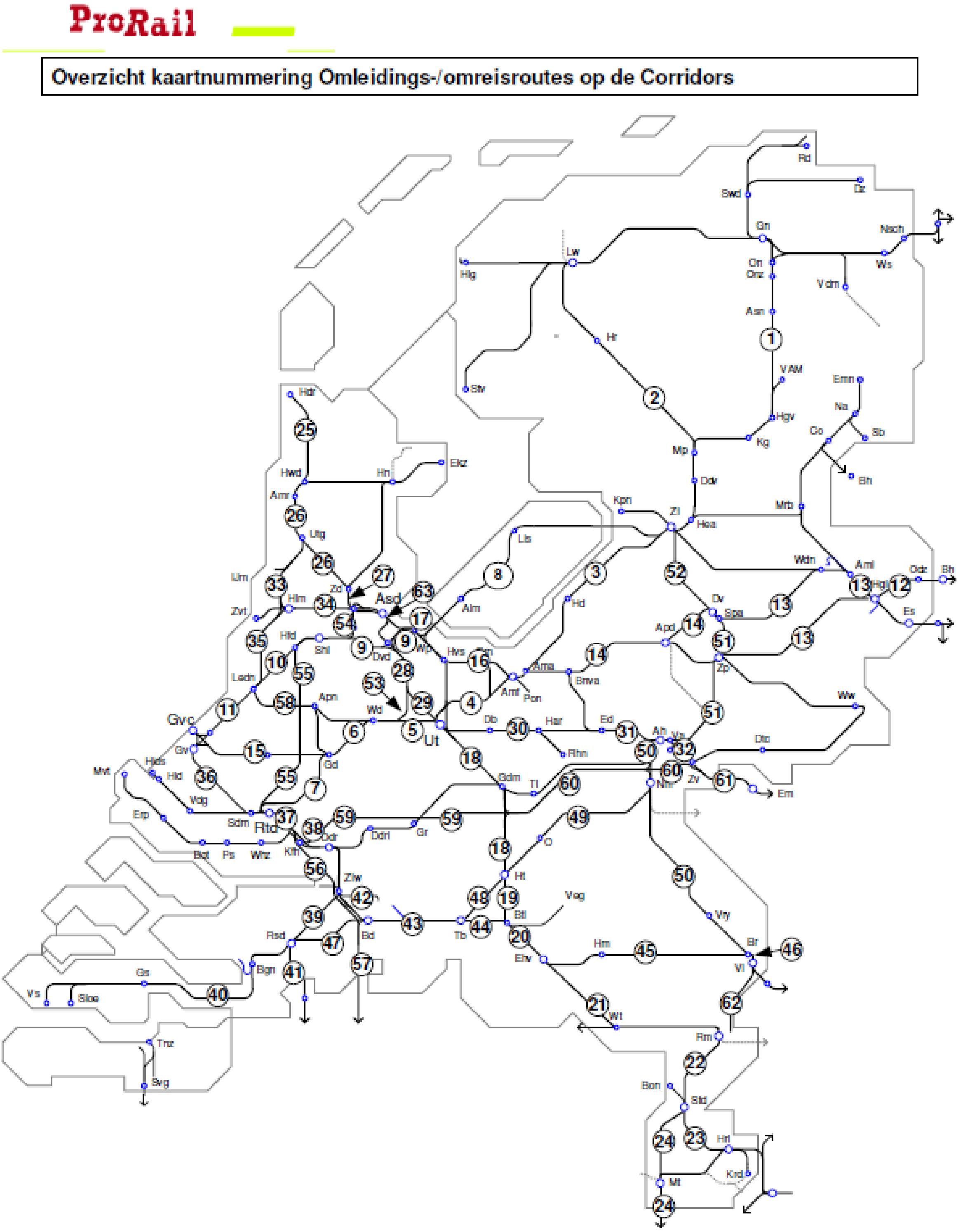


Figure 2.3 Overview map of possible diverting routes. Source: (ProRail, 2021)

"4G" at the top of the map, says this map is made for freight traffic ("Goederen"). If the number was "4R" the map would have been made for passenger traffic ("Reizigers"). The BTD takes place on the red line, the diverting routes are colored in green and the blue routes visualize the corridor.

For each IO is determined how much annoyance it causes and each IO is placed into a category of annoyance. There are two ways to categorize the annoyance. The first one is set up by "Landelijk Platform Overleg" (LPO), National Platform Consultation. The LPO uses these categories for programming the IOs in the national cohesion. According LPO, there are four categories of annoyance:

"Hindervrij" (V)/No annoyance: In this category, IO can be planned without causing annoyance or with only causing little annoyance of maximum three minutes delay for the train traffic.

"Hinderrijk" (R)/High annoyance: The IO causes a lot of annoyance because a lot of trains have to be canceled or diverted. In general, this annoyance lasts maximum one weekend or 52 hours. Freight traffic has to be rescheduled and leaves 20 minutes earlier or 30 minutes later.

"Uitzonderlijk hinderrijk" (U)/ Exceptional high annoyance: The IO causes a lot of annoyance for multiple days or longer than 52 hours. Therefore, a temporary change in the timetable is necessary. Many freight trains have to be diverted or canceled. For the passengers, busses are used.

"Hinderarm" (A): The IO does not fit in one of the other categories and/or causes a special category of annoyance. For example, no or limited availability of the capacity, accessibility of contractors or a large change in the timetable for a longer period. (ProRail, 2021)

The other way to categorize the annoyance is according to the Annex VII guideline. Annex VII, created by the European Union, aims to reduce diverting train routes and anticipate better on possessions by announcing capacity restrictions sooner. Also, they want to reduce the annoyance by better cooperation between infra managers during possessions.

According to the Annex VII categorization, the grouping is decisive for the moment of publication. The annoyance can be divided into the following categories: "Zeer Groot" (ZG)/Major, "Groot" (G)/high, "Middelgroot" (M)/medium-high, "Beperkt" (B)/limited and "Weinig" (W)/little. The corridor book also visualizes the translation of Annex VII annoyance categorizations to LPO categorization (Table 2.1) (ProRail, 2021).

Annoyance categorization Annex VII	***Translation 2020 to URAV***	***Duration (h) *****	***Consequences for train traffic ******			
			>50%	>30%	>10%	<=10%
Major consequences/ "Zeer Groot" (ZG)	Exceptional annoying/ "Uitzonderlijk hinderlijk" (U)	> 724	(a)	n/a	n/a	n/a
High consequences /" Groot" (G)	Exceptional annoying/ "Uitzonderlijk hinderlijk" (U)	> 172	(a)		n/a	n/a
Medium-high consequences I /" Middelgroot" (M I)	Exceptional annoying/ "Uitzonderlijk hinderlijk" (U)	> 52	(a)	n/a	n/a	n/a
Medium-high consequences II /" Middelgroot"(M II)	Annoying / "Hinderrijk (R)	<= 52	(a) *	n/a	n/a	n/a

Limited consequences /" Beperkt" (B)	Annoying / "Hinderrijk (R) or "Hinderarm" (A)	n/a	n/a	(b)		n/a
Little consequences /" Weinig" (W)	"Hinderarm" (A) or Annoying free "Hindervrij" (V)	n/a	n/a	n/a	n/a	

Table 2.1 Translation Annex VII annoyance categorization to LPO annoyance categorization. Source: (ProRail, 2021)

*	General guideline to determine the percentage: minimum 10 hours free in the night (14 hours inclusive night) by single track and IO >50%
**	Duration:
***	Percentage of train traffic that has to be diverted, canceled or replaced daily.
(a)	Automatic preselection in BTD-planner due to duration
(b)	Only when IO does not fit in HC:G

Furthermore, the corridor book also describes rules that have to be taken into account when the IOs are planned. Hereby, a distinction is made between general rules, rules for only passengers and rules for freight traffic.

General rules:

1. Determine the category of annoyance of IOs according to the LPO annoyance categorization.
2. When multiple IOs are merged or when one IO is divided into multiple IOs , annoyance of the total system has to be minimalized.
3. There should be at least 25 days between IOs of category R and U that cause annoyance at one track section or railway junction. Unless other agreements are made during the LPO.
4. IOs that last multiple days, have to be planned in passenger traffic-calmed periods.
5. Diverting routes must be free of BTD. Figure 2.4 visualizes an example of a diverting route for the track section of Ut-Amf (red line), that is BTD. When there are possessions between Ut-Amf, the green line becomes the diverting route (green line) and no IOs can be planned at this route.
6. When multiple IOs cannot take place at the same time, the LPO will revise all requests for capacity management, traffic and events. These requests will be rechecked on necessity, unavoidability and technical achievability. Furthermore, the clusters between the red nodes in Figure 2.5 are used more optimal. In the case that this does not give a solution, the IOs will be planned during workdays.
7. For single track IOs on international track sections: Zv-Em-Ob-Hgl-Odz-Bh, Vl-Kn, Rsd-Esn-Atw and Mt-Edn-Visé, the amount of capacity that stays available has to be determined.
8. Every year, exceptions are made for a few very large IOs. These IOs are added in the "Gebruikersoverleg (GO)" User's consultation. The condition for these exceptionally large IOs is that the alternative transport plan must be feasible.
9. For events that are held at the "Standard Event" locations, track sections have to be kept free (ProRail, 2021).

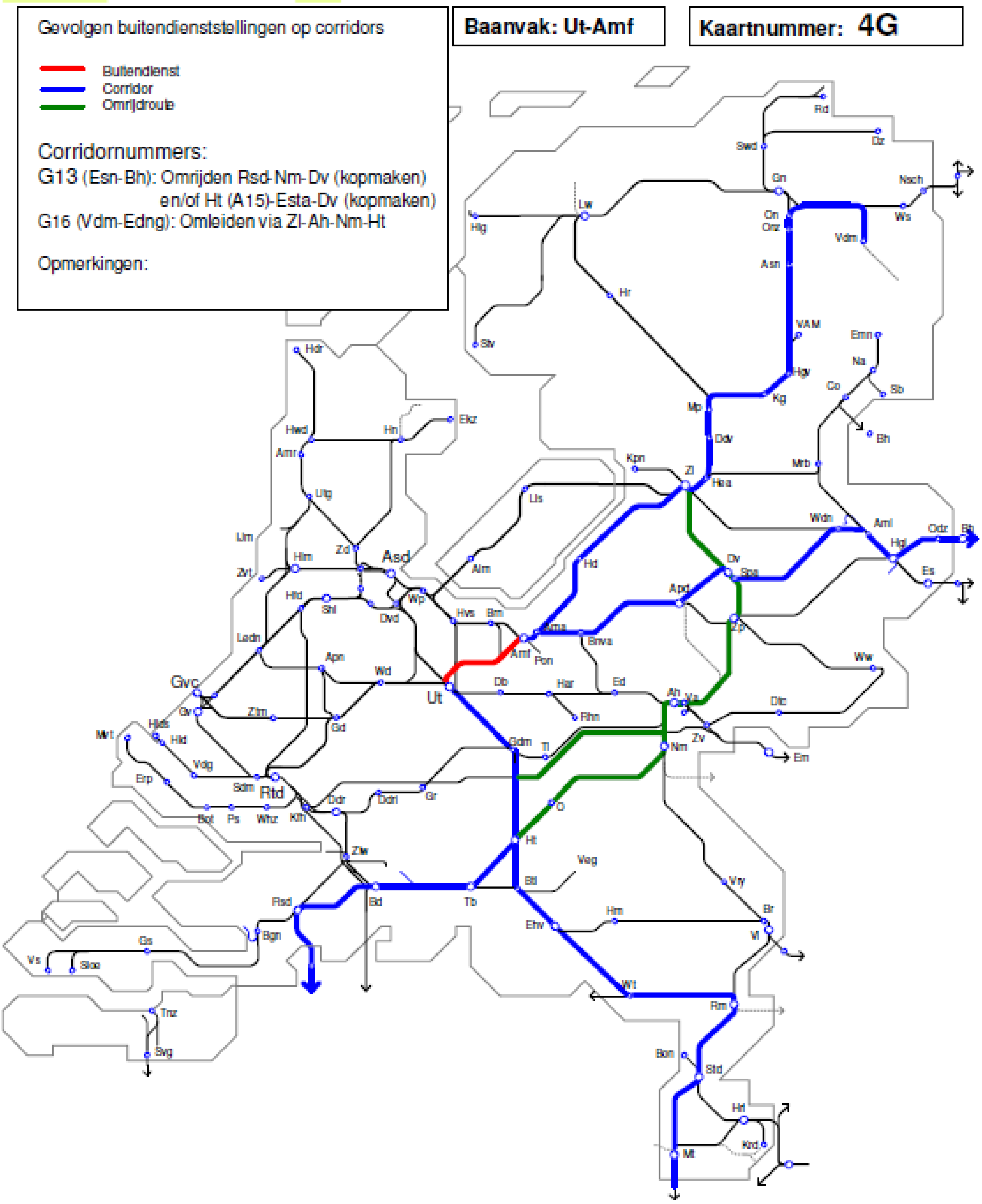


Figure 2.4 Example corridor, track section Ut-Amf. Source: (ProRail, 2021)

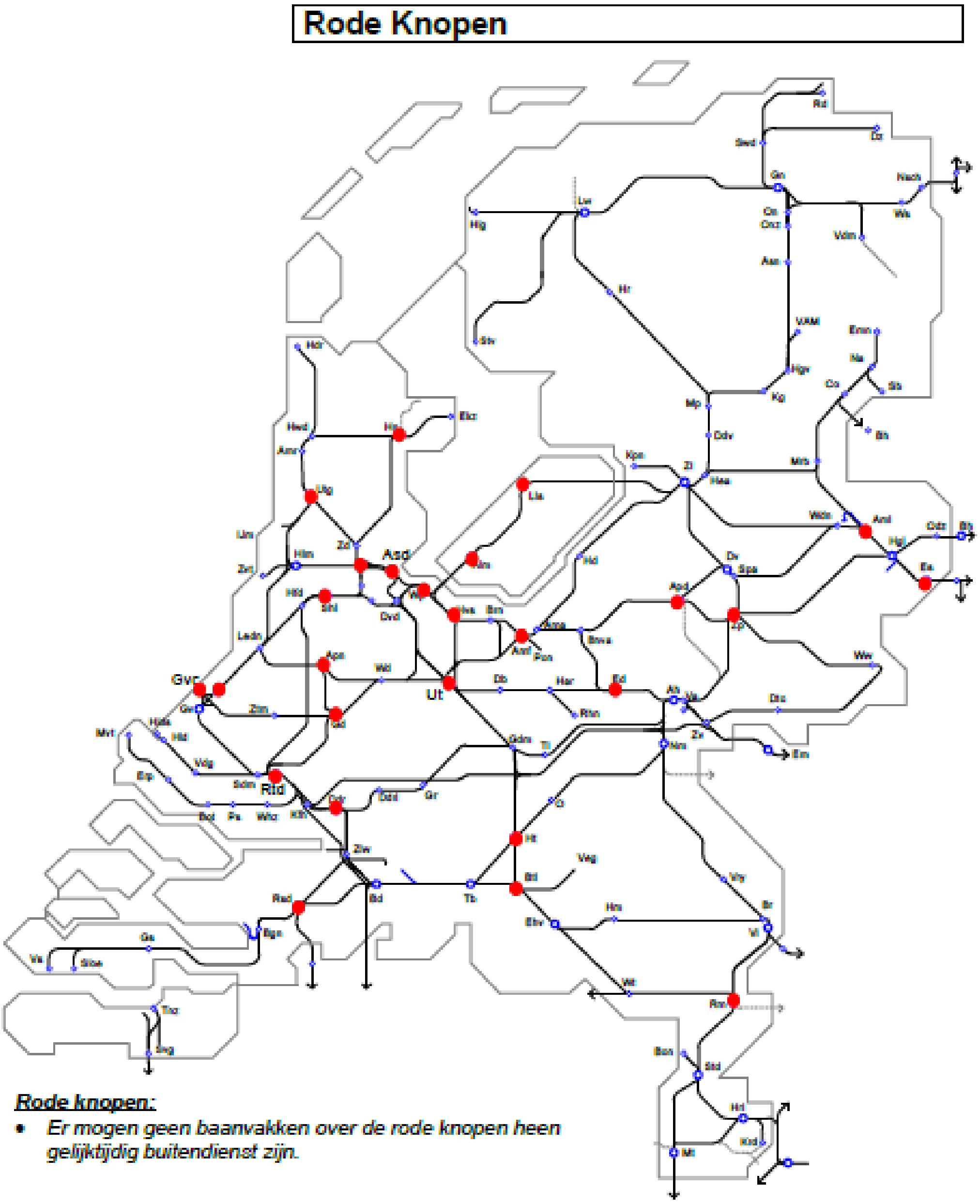


Figure 2.5 Nodes of the Dutch railway system. Source: (ProRail, 2021)

The contract with the RUs states when a BTD has to be published (Table 2.2). Therefore, the four categories of annoyance according to Annex VII and the duration of the BTD are taken into account. The publication of the BTD contains the duration, the track section, the planned days and the start and end time of the BTD.

Category	Capacity restrictions with	Duration of continuous capacity restrictions	Consequences for train traffic	Coordination with inframanagers
Z	Major consequences	> 30 days	> 50% of the daily expected traffic	18 months before start of the timetable
G	High consequences	> 7 days	> 30% of the daily expected traffic	13.5 months before start of the timetable
M	Medium-high consequences	≤ 7 days	> 50% of the daily expected traffic	13.5 months before start of the timetable

B	Limited consequences	Not determined	> 10% of the daily expected traffic	Not determined

Table 2.2 Capacity restrictions and time of publication BTD. Source: (ProRail, 2019)

2.1.3 Track switches

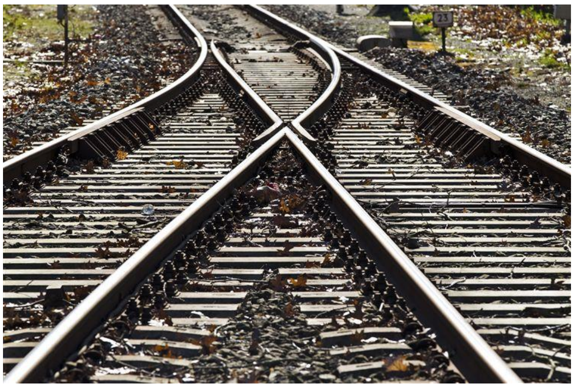


Figure 2.7 Example of a 40, 60, 80 and 130 km/h track switch. Source: Spoorpro.nl

Figure 2.6 Example of an English track switch. Source: ProRail

There are eight types of track switches, the most common are 40 km/h, 60 km/h, 80 km/h, 130 km/h, English track switch and high-speed switch. The track switch types: 40, 60, 80 and 130 km/h all look almost the same (see Figure 2.7). However, the longer the track switch, the higher the speed of the train can be. Therefore 130 km/h switches are a lot longer than the 40 km/h switches. The English track switches has a switch on both sides of their track (see Figure 2.6). Furthermore, the railway sleepers of the track switches exist of wood or concrete, where a wooden sleeper has a life cycle of 25 years and concrete sleeper has a life cycle of 40 years. In the past, only wooden sleepers were used. Nowadays mainly concrete sleepers are made.

To maintain the switches, contractors can check the performance of each switch everyone, two or four weeks during the WO. In addition, sensors are built in at every switch to measure the power consumption, vibration and heat to detect a failure in time. During WOs, the contractor can also perform small repairs on a switch. For example, lubricate, tighten parts, replace parts and measure the distance between rails.

Finally, to prevent rust, at least one train must pass the track switches every day. For some track switches that are not used every day, in most of the cases, one passenger train drives over the switch each day. As a result, the train is delayed by a few minutes, but this delay is made up within a half hour (Knijnenburg, 2021). Another solution is to have a contractor that remove the rust just before it is going to be used again, but at this moment this is only performed for specific track switches that are used rarely (for example the track switches at Amsterdam RAI) (Wittenberg, 2021).

Although preventive maintenance is performed, a track switch has an unpredicted failure every five years. When a switch is seldom used and generally only straight through traffic is passing by, the contractor can fix the switch in 1 position within a half hour. When a switch is used for multiple positions, the repair takes more than 2 hours. Which results in a total failure of 4 to 5 hours (Knijnenburg, 2021).

Maintenance costs

The costs of the track switches are visualized in Table 2.3, these numbers are obtained from the Asset Management Department. To remove switches, heavy machines are used which entails high costs. Since the track switch of 130 km/h is much longer than the track switches of 40 and 80 km/h and the English switch is more complex than the other switches, the costs vary per switch type. To prevent a switch from freezing in cold weather, each switch is equipped with a heater. The switch heating has a lifespan of 20 years (Knijnenburg, 2021). Table 2.4 visualizes the costs per km track section, these numbers are also obtained from the Asset Management Department. In recent years, almost no new track is installed, therefore the installation costs of a new track section are unknown.

Since ProRail does not have the exact numbers about the costs and the lifespan of the track switches and the track sections, the values given below are an estimation and could vary per situation. The lifespan of the switches and track sections depends on the number of trains and the weight of the trains that pass by. For example, parts that are located on the Betuweroute (many heavy freight trains are passing by) might have a lifespan on 20 years and the lifespan of parts that barely used might have a lifespan of 65 till 100 years. The costs of the track switches and track section could also vary, nowadays these costs are calculated by dividing the total maintenance costs over the number of track switches and track sections. Therefore, track sections and switches that are barely used might need less maintenance than parts that are located somewhere else (Knijnenburg, 2021).

	Track switch 40 km/h	Track switch 60 km/h	Track switch 80 km/h	Track switch 130 km/h	Track switch English
Lifespan (year)					
Installation new switch					
Replace with new switch					
Installation or replacement switch heating					
Remove switch					
Maintenance per year					

Table 2.3 Costs track switches and switch heating. Source: ProRail, Asset Management Department.

	Per km track section
Lifespan (year)	
Installation new track	
Replace with new track	
Remove track	
Maintenance per year	

Table 2.4 Costs per km track section. Source: ProRail, Asset Management Department.

2.2 Changes in the infrastructure

In this section first the categories of infrastructure development are briefly explained. After this, the initiation of the infrastructure projects is described (2.2.1). Finally, one type of development is further elaborated (Section 2.2.2).

Infrastructure development can be divided into two categories, namely, function maintenance projects “functie handhavingsprojecten” and function changing projects “functie wijzigingsprojecten”. Function maintenance projects keep the infrastructure up to standard, for example renewing of ballast, switches, signals or repair work. During the function changing projects, a part of the railway track is redesigned, this could mean that a particular switch or railway section will be removed (or added) (Wittenberg, 2021).

2.2.1 Initiation of projects

Changes in the infrastructure are initiated in two ways. Plans for changes in the infrastructure can be requested by such different parties as: (i) the Ministry of Infrastructure and Water Management, (ii) a province or (iii) a RU. An example is the current investment program of ProRail and the ministry which costs 4.5 billion (4.5 *10^9) euros. In this program, new product steps are created as certain train services will drive 15 minutes instead of 10 minutes. This does not fit in the current infrastructure and therefore changes have to be made (for example, extra track switches or longer platforms). At this moment, there are 15 of these projects (Hofstra, 2021).

In the last three years, the plan of changing the infrastructure can also be initiated by the infra development department themselves. When a product is at the end of its life-cycle, the infra development department checks if the product can stay the same or whether it needs to be adjusted. The department have functional maps of the Netherlands in which they visualize what parts of the railway has to be changed. This is also the case for the track switches. Therefore, every switch got the color black or blue. The color black means that this switch is functionally in order. The color blue means that this track switch needs more research and has to be removed, relocated or that the crossing angle in the switch needs to be changed. At this moment half of the switches is blue and need a change (Hofstra, 2021).

2.2.2 Function changing projects

Depending on the size and impact of the function changing project, the process is different. When it is a small project and the change has little consequences, only a message is sent to all parties with the notification that something will be adjusted. When it concerns a larger changing project, a System Engineering plan (SEP) is used. System Engineering focuses on defining the customer requirements and system validation. SEP takes both, company goals as technical needs into account. Figure 2.8 visualizes the process steps for the infrastructure development process (ProRail, 2015) .

During the elaboration of the concept, a Customer Requirement Specification (CRS) is created. The CRS records the requirements and wishes of the stakeholders, who are the RUs, administrators, contractors, municipalities and ProRail. Where requirements mean the description of the requested characteristic that the product or service to be delivered must meet. A wish is defined as the description of the requested characteristic that the product or service to be delivered should preferably meet. The input for CRS is collected at multiple conversations with the stakeholders. However, not all stakeholders attend these conversations. Some companies are too small to send a delegate to every meeting (Hofstra, 2021).

The CRS is the basis of the beginning of the design process. Finally, with help of the CRS, the system requirements are drawn up in the System Requirement Specifications (SRS) (ProRail, 2018). SRS contains the requirements of the functions that are needed in the product. In the SRS, all contradictions between different requirements have been removed. The length of this process differs, in some cases only one mail is sent to all stakeholders the other time several conservations are needed.

During the realization tests are executed to make sure the new plan fits in the infrastructure. Therefore, the Infra Development Department uses a standard methodology. Hereby, four aspects are taken into account:

1. Current timetable: Changes can not affect the current timetable. This is done by the infra development department themselves.
2. Future timetable: Changes can not affect the timetables in the future. This is done by the department of mobility development.
3. 24/7 set up: Every morning and evening trains need to shunt from their carriage siding. Also, freight terminals that are used once per hour or once per day must be included. This is also done by the infra development department.
4. Traffic adjustments: A manual is used for this, which states how the infrastructure should be designed during unexpected BTD and what the traffic adjustments are for the whole railway system (Hofstra, 2021).

During interviews, (freight and passenger) RUs, the department of capacity distribution and the department of Infrastructure Development are asked who are consulted for changes in the infrastructure. According to the RUs, they are consulted when there is a plan to change a part of the infrastructure. They are asked to come with arguments why the infrastructure should remain the same. For NS International and Arriva, the Infra Development Department is consulting other departments than the department that creates alternative routes. During the interview with Arriva,

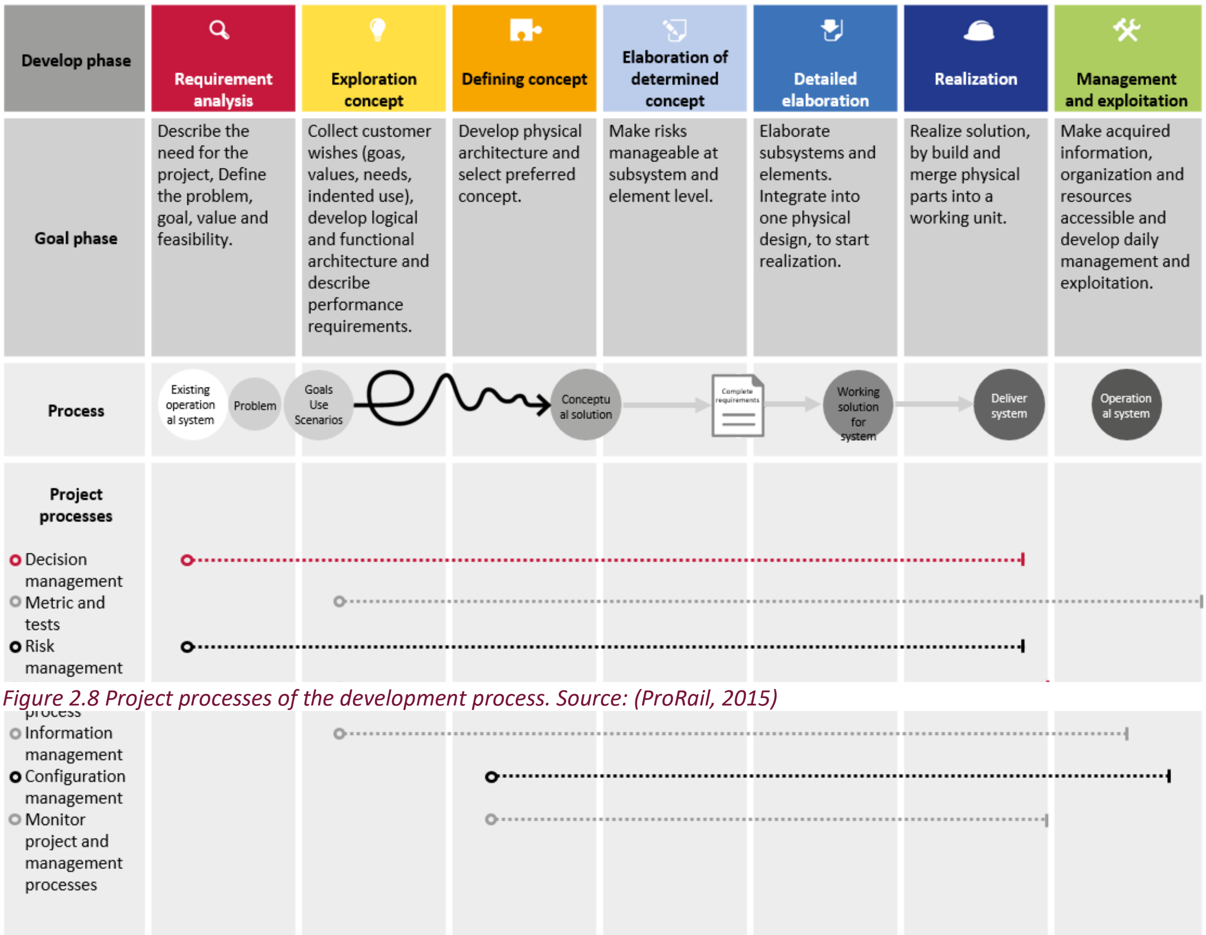


Figure 2.8 Project processes of the development process. Source: (ProRail, 2015)

two examples are mentioned, whereby the plan to change the infrastructure is canceled due to arguments of Arriva. The interviewee of DB Cargo complained that their opinion is asked but that it does not influence the decision of changing the infrastructure (NSR, 2021) (NS, 2021) (DB, 2021) (Arriva, 2021).

The Infrastructure Development Department also consults the department of capacity distribution (including the PreVAB), but their arguments are not decisive. According to the Department of Infrastructure Development, there are both economic and operational reasons for this. On average, a track switch has an (unexpected) malfunction once every two years. This means that the annual timetable could be disturbed by a track switch that is only used during some of the BTD. Furthermore, purchasing costs of a track switch are approximately €**X** and the switches have a maintenance cost of € **X** per year (Hofstra, 2021).

When the department of infra development decides to remove a track switch, they are allowed to add 10% of the purchasing costs plus the maintenance costs over twenty years to their own budget. In the case of a track switch: when they decide to remove a switch of € **X** that has a maintenance cost of € **X** per year, this will give the department of infra development an extra budget of € **X** . In practice, the infra development department negotiates with the stakeholders about which parts of the railway can be removed when they add another part to the railway. For example, when they are allowed to remove a track switch, the department will help the municipality with financing an underground railway crossing (Hofstra, 2021).

2.3 Capacity distribution of train traffic

The capacity distribution of the railway system can be divided into three phases (ProRail, 2019):

1. Preparation phase for annual timetable:

Every year, the department of capacity distribution of traffic "Capaciteitsverdeling Verkeer", creates the annual timetable for train traffic "Jaardienstverdeling verkeer". During this stage, stakeholders could come to an agreement with ProRail about the capacity applications which have to be submitted for the (both, passenger and freight) train paths for the annual timetable. At this stage, also the pre-arranged train paths (PAPs) for the international freight corridors are published.

The preparation phase for annual timetables exists of two steps, namely the MLT process (Mid-Long-Term) and the preparation annual timetable process.

The MLT process ends 24 months (X-24) before execution. The goal of this process is to make reliable agreements within the railway sector about the logistic product steps. All logistic product steps are combined, for two till seven years ahead. During this process, requests of the RUs are tested and bundled up to logistic product steps. ProRail checks if these logistic product steps fit into the railway infrastructure (energy supply, security, track stability and transfer capacity) and the surroundings (sound, level crossing safety and surrounding permits). Furthermore, it is determined which product steps require an adjustment in the infrastructure or surrounding.

During the preparation phase, which has to be finished in April (X-8) every year, outcomes of the MLT process are used as input. By the use of a simulation, this phase focuses on quality assessments. In the case that no agreement is reached about the annual timetable requests, this will be determined as "agree to disagree" (ProRail, 2019).

2. Annual timetable:

This phase has to be finished in August. After the RUs delivered their capacity requests in April, the process of capacity distribution starts. During this process, the applications for train paths and applications for WO's are processed into the timetable for a standard week. For freight traffic, a standard freight path is determined. Th7ese paths are used when prioritization has to be applied on the main railway infrastructure. Furthermore, ProRail uses realization numbers to predict the number of requests from freight traffic and private passenger traffic.

In addition to this, also deviations of the standard week as a result of IOs are included. Additional trains at events and incidental trains must be requested in the ad-hoc phase.

3. Ad-hoc phase:

This last phase concerns additions or changes to the annual timetable, based on the First-Come-First-Service principle. Ad-hoc applications could be submitted 4 months till 36 hours before the execution. Applications that fit in the timetable without conflicts are distributed by ProRail. The other applications that cannot be fitted without conflicts are only honored when RUs of already allocated capacity allow changes so that a new application can be fitted without conflict. ProRail can be asked to mediate in conflicts, but ProRail is not able to enforce changes for a new request (ProRail, 2019).

Work of the PreVAB team takes place during the ad-hoc phase. As described in section 1.1.2, the main goal of the PreVAB is to create diverting routes in time during BTD. Figure 2.9 visualizes the timeline of the PreVAB team. As visualized in the figure, PreVAB delivers an AUP, ("Alternatief Uur Patroon") Alternative Hour Pattern, to VAB in X-19. After this, VAB contacts the RUs in X-18 about the proposed alternative routes. In the case that the RUs do not agree with the adjusted routes, VAB contact PreVAB and then PreVAB adapt the alternative routes. When the RUs agree with the AUP, PreVAB delivers the alternative timetable to VAB in X-7. After this, VAB diverts trains via the alternative routes in X-5. (Wittenberg, 2021)

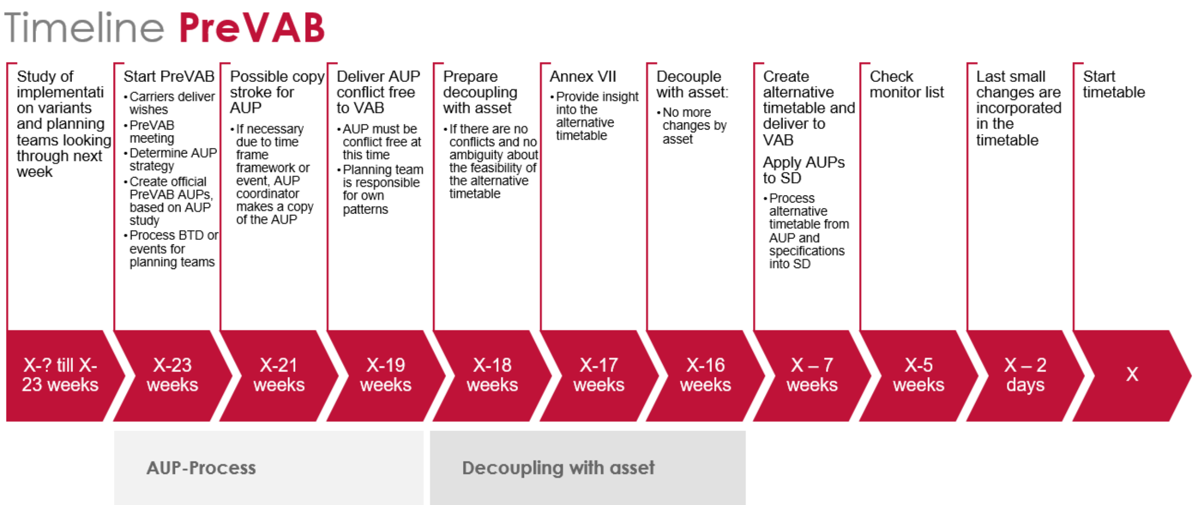


Figure 2.9 Timeline PreVAB

2.3.1 Planning process of a BTD

The planning of a BTD consists of four steps:

1. Formulate the principles for programming BTD: These principles are described in the corridor book. When a BTD will be planned at the same time of a WO, the WO will be cancelled. The corridor book describes the conditions under which different types of trains can be diverted due to a BTD on the normal route.
2. Announce the intended BTD: The BTD can be announced per project, per track section or for the entire railway system and the BTD is traceable to project level.
3. Consultation: During consultation of the proposed BTD, the entitled parties can request adjustments. Those involved can provide insight into their interests and can propose solutions. ProRail investigates whether and how the interest of the different parties can be met. This may be a reason for further consultation (ProRail, 2019). These consultations are called: RGO's (Regionaal GebiedsOverleg). Passenger and freight RUs are also present during these meetings. In the event that a BTD is planned in a period that also other BTD are planned and therefore the routes are not possible anymore, the BTD could be replaced to another week (RTB, 2021).
4. Determination of the BTD: After the consultation, the BTD is established.

2.3.2 Diverting process during BTD

This section first shortly, describes the diverting process during works on the railway track. After this the costs of diverting during BTD are further elaborated, hereby a distinction is made between function maintenance projects and function changing projects.

In general, the passenger and freight RUs receive the details about a BTD, 24 weeks in advance. Depending on the RU, the trains will be diverted, passengers themselves will be diverted or busses are used to divert the passengers. Arriva, a passenger RU who is mainly active in Limburg, uses busses in most of the cases. There are too few alternatives left to divert trains, because the railway tracks that are left are already occupied by other trains. Besides that, diverting trains in Limburg results in longer travel times for the passengers than use busses near the track of the BTD to transport the passengers (Arriva, 2021). NS "Reizigers" (NSR) or NS passenger, the largest passenger RU of the Netherlands, prefers to divert trains. But in most situations that is not possible, in that case the passengers themselves will be diverted via other train routes and busses are used between the stations where the BTD takes place (NSR, 2021).

However, in most of the cases the passengers are diverted instead of the trains. For the International trains of NS, only trains are diverted or the begin and end stations are changed. Most passengers that are going abroad have more luggage and therefore it is not desirable to divert the passengers (NS, 2021). Freight RUs only divert trains (DB, 2021). Together with the RUs, ProRail made agreements about the number of trains per RU that can enter an alternative route during BTD.

2.3.3 Costs of diverting

Works on the railway track can affect the capacity of the railway system and therefore the timetable of the train traffic. When this occurs, ProRail can provide financial compensation for the passenger and freight RUs. Yearly, ProRail pays approximately 20 million euros of compensation and bus costs (ProRail, 2021).

To decide if ProRail has to pay for the compensation, five aspects are taken into account. Namely:

1. Function changing project or function maintenance project. Which type of project is the possession?
2. Impact on the timetable. Do the RUs experience nuisance during works on the railway track?

3. Rush hours. When does the work on the railway track takes place?
4. Long- or short-term announcement. When were the possessions announced?
5. In time agreements with RUs. Are there agreements with the RUs about the BTD?

In this section, first a distinction is made between function changing projects and function maintenance projects. Rules for the function maintenance projects are divided into two parts; passenger RUs and freight RUs (ProRail, 2019).

Function changing projects

During function changing projects, there is **no** financial compensation for diverting train traffic. Unless the BTD take longer than 6 weeks (which is the duration of an average function changing project), the normal time table is negatively affected and can only be resolved by using diverting routes. In that case, the additional direct operating costs are paid by ProRail.

Furthermore, out-of-pocket costs can be compensated. But these costs are only reimbursed based on offers that are approved by ProRail in advance (see more information below under "Function maintenance projects, passenger RUs").

Function maintenance projects

For the compensation during function maintenance projects a distinction is made between passenger RUs and freight RUs (ProRail, 2019).

Passenger Railway Undertakings (RU)

For passenger RUs, **no** financial compensation is paid for BTD during the weekends, nights, between peak hours and passenger traffic-calmed periods or when the train traffic is not affected.

Financial compensation is paid for BTD during peak hours on working days. There is a reimbursement per canceled kilometer. The amount depends on the category in which the track section is classified (Appendix A.1). The reimbursement rate for train tracks is €11 (category 1) or €6 (category 2) per kilometer that is canceled. This reimbursement rate is per affected train. To calculate the number of affected trains, the average number of trains that were in the timetable one and two weeks before and one and two weeks after the BTD is used.

Passenger RUs can also be reimbursed for out-of-the-pocket costs, which are the costs for alternative transport. These costs can be reimbursed during function changing projects and function maintenance projects. Out-of-the-pocket costs for replacement of the normal passenger traffic during BTD can be divided into 5 categories (ProRail, 2021), namely:

1. Bus costs (hours and km)
2. Planning and preparation hours bus undertaking
3. Deployment of bus coordinators and traffic controllers from the bus undertaking
4. Resources necessary for traffic measures
5. Costs charged by other operators of passenger transport for the use of their services as part of the alternative transport

Freight Railway Undertakings (RU)

As a result of BTD, costs for the freight RUs increase. Since a train driver is only allowed to drive a train for a certain number of hours in a row, an extra diver is needed when the route becomes longer. Furthermore, an extra elocomotive (electric locomotive) or a diesel engine might be needed at the diverting route, which is more expensive than the elocomotive that is used at the normal route. Since locomotives are very expensive, the freight RU does not rent or buy more locomotives than necessary. In the event that an extra locomotive is necessary during a BTD, an additional locomotive has to be rented, which costs €50.000 per month (locomotives can only be rented for a month). To cover a part of these costs, ProRail has an agreement with the RUs about the compensation they receive for these costs (RTB, 2021).

For freight RUs, **no** financial compensation is paid for BTD during the weekends, nights, freight traffic-calmed periods, BTD less than 12 hours or when the train traffic is not affected.

Financial compensation is paid for BTD during working days or BTD longer than 12 hours. The compensation rate depends on the track section of the BTD and the number of affected trains. The compensation rates (per affected train) per track section are visualized in Appendix A.2. The number of affected trains depends on the average number of trains during the same period of the BTD (in terms of duration, day type and time of the day), that drove on the same track section one and two weeks before the BTD and one and two weeks after the BTD. In the event that the track was (partly) unblocked during the BTD, the number of freight trains that drove on the track section during the BTD are subtracted from the number of affects trains (ProRail, 2019).

Private passenger RUs can achieve an additional compensation for seasonal trains that cannot use the original route. Hereby, the reimbursement is €15 per additional train kilometer between the diverting route and the original route.

Furthermore, for ad-hoc BTD, an additional reimbursement rule can be used for direct operating costs. This can only be used in the event that disadvantage is encountered due to deviation of the previously allocated capacity. The compensation rate depends on whether the affected train will be canceled or whether the train has to be diverted. In the event that the affected train has to be diverted, the compensation depends on the weight of the train. The specific rules and compensation rates are described in appendix A.3.

Here is a calculation example of the direct operating costs: "*A freight train with capacity rights from the Maasvlakte West (via Moerdijkbrug) to Venlo will be canceled due to an BTD at the Moerdijkbrug that is planned two weeks ago. There is no alternative route (within 6 hours) available for this freight train. Therefore, a compensation rate of 195.5 km * €5.65/km = €1,105.27 will be paid."*

Combination of function changing and function maintenance projects

In the event that there is a combination of function changing and function maintenance projects, an average of costs between the two projects is calculated. Therefore, compensation will only be provided for the duration of the function changing project and only in the case that alternative transportation is necessary.

In the case that the duration of the combination of the projects is less than 10% of the other BTD, it will not be calculated according to the combination calculation (ProRail, 2019).

2.4 Stakeholders

In this section the stakeholders of ProRail are elaborated. In the annual report of 2019 ProRail divided the stakeholders into five categories (Table 2.5).

Category	Stakeholder	Dialogue
Government	Ministry of Infrastructure and Water Management (Grantor, grant provider, shareholder)	Management plans, semiannual and annual reports, discussions, meetings with shareholders
	Decentral authorities, security regions	Administrative consultations, discussions, customer arenas, steering groups, relationship days, reputation research
	Rijkswaterstaat	Joint projects, strategic alliance
Client	Clients (municipalities, provinces)	Relationship days, reputation research, satisfaction
	Railway partners	Tender, conferences, alliances, purchasing policy, innovation
Contractors	Contractors, suppliers, engineering firms	Discussions, relationship day
Customers	RUs	Capacity distribution, account management, spearheads, relationship days, satisfaction survey, collaboration, concession teams
	Decentral authorities	Discussions, relationship day
Public	Passengers, shippers, terminals, ports and consumer organizations	Satisfaction survey, spearheads, station management, relationship day
	Local residents	Environmental communication, questions and complaints
	Society	Environmental communication, campaigns and information, questions and complaints, satisfaction survey
	Media	News items prorail.nl, spokesperson
Employers	Employers	Satisfaction survey, performance management, panel, intranet, management cascade, new year's meeting, ProRail Festival
	Work council and trade unions	Consultation and discussion

Table 2.5 Stakeholders ProRail. Source: ProRail B.V. 2019

2.4.1 Satisfaction Railway Undertakings (RUs)

Every year a satisfaction survey is conducted among the RUs, railway partners, ministries, local residents, passengers and employees. For the satisfaction survey among the RUs two grades (subjective and objective) are given to ProRail. The subjective grade is given for the performance in general and the objective grade is given for the predefined performance of ProRail. The outcomes of the survey in 2019 are visualized in Table 2.6 (ProRail B.V., 2019).

Group	Year	Target value	Bottom value	KPI score	Subjective score	Objective score
Passenger RUs	2019	7.0	6.0	7.0	7.0	6.9
	2018	6.9	6.0	6.8	6.6	6.9
Freight RUs	2019	7.0	6.0	5.4	5.4	5.5
	2018	6.5	6.0	6.3	6.3	6.1

Table 2.6 Satisfaction survey RUs. Source: ProRail 2019

In general, the passenger RUs are satisfied about the expertise of the employers of ProRail. The department of Handling Security Incidents and the department of Relationship management and Account management got the highest scores with an average of 7.7 and 7.4 respectively.

As in previous years, the passenger RUs are the most critical about the processes of function maintenance (6.4) and function changing (6.0). Whereby, complex regulations and long lead times are mentioned as main causes. (ProRail B.V., 2019). In the future, passenger RUs want a better cooperation with ProRail to map out what is needed to guarantee good public transport in the Netherlands (ProRail B.V., 2019).

The freight RUs are not satisfied, in 2019 they gave ProRail a 5.4. In contrast with 2018, the largest freight RU did participate in the satisfaction survey in 2019. The survey showed that they are dissatisfied about the availability of the infrastructure. The process of function maintenance projects got a score of 4.3. As a result of overdue maintenance there were unplanned shutdowns regularly. In addition, there were also restrictions as a result of shortcomings about environmental permits.

In the survey, the freight RUs were positive about the departments of Account management, incident control and the traffic control. Furthermore, the freight RUs find that there is a clear improvement in the planning of shutdowns (ProRail B.V., 2019).

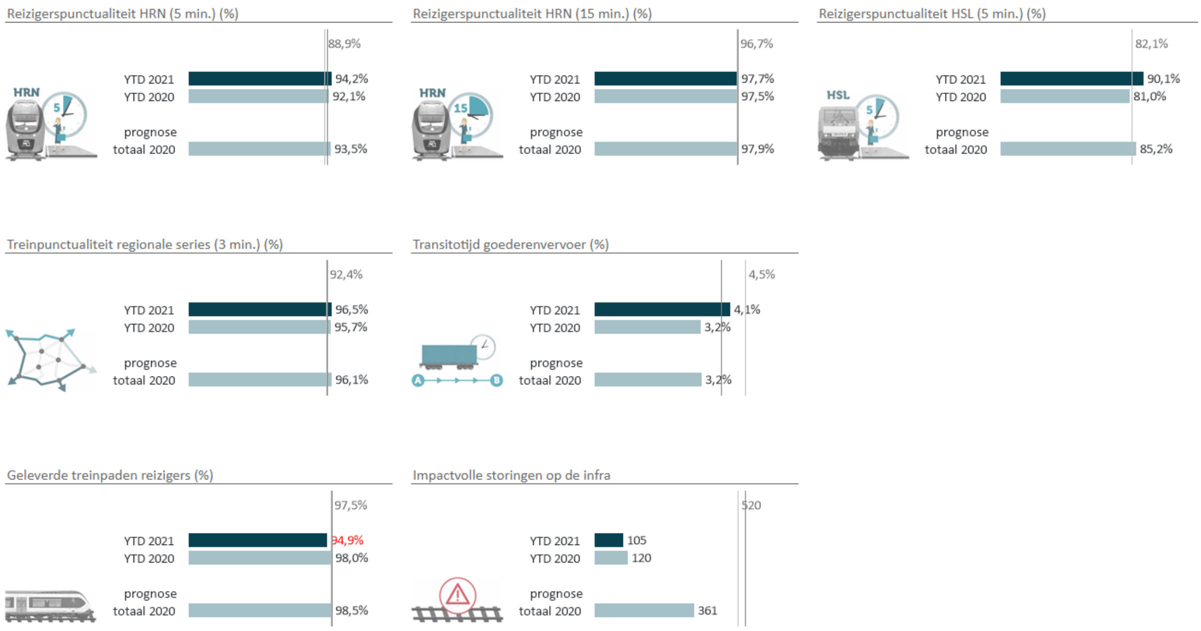
2.5 KPIs

KPIs ProRail wide

ProRail has seven prestation indicators that are measured, namely:

1. Passengers' punctuality HRN (Hoofd Railnet) Main Railway system (5 min.):
2. Passengers' punctuality HRN (15 min.):
3. Passengers' punctuality HSL (Hoge Snelheidslijn) High Speed Line (5 min.):
4. Train punctuality regional series (3 min.):
5. Transition time freight traffic %:
6. Delivered train path passengers:
7. Impactful disruptions on the infrastructure:

The PreVAB department does not use these KPIs of other KPIs. But the performances of the PreVAB do have influence on these KPIs. Since the number of trains that drive in time, the delivered train paths, transition time freight traffic are partly depended on the work of the PreVAB.



2.6 Conclusion

There are three phases in which the capacity is distributed, namely: (i) preparation phase for the annual timetable where stakeholders come to an agreement with ProRail about the capacity applications. (ii) annual timetable, where the applications are processed into the timetable for a standard week. (iii) ad-hoc phase, where additions or changes are made and processed to the annual timetable.

The maintenance planning can be divided into WOs (weekly withdrawals) and IOs (incidental withdrawals). Where WOs are the small repairs that can be executed during the night. For IOs, more time and workspace are needed. A corridor book is created to make sure that train traffic can be diverted. The compensation rate for diverting trains during BTD depends on the type of infrastructure project, when the BTD is scheduled (during day/night, weekday/weekend, rush hour, traffic-calmed period) RU (passenger or freight), the number of trains that are affected and when the RUs received a message about the planning of the BTD.

Infrastructure projects can be divided into two categories: function maintenance projects and function changing projects. Function maintenance projects keep the infrastructure up to standard by renewing and replacing spare parts. During function chancing projects, a part of the infrastructure is redesigned. Function changing projects could be initiated by various parties as the ministry or RUs. But also, the department of Infrastructure Development could decide to start a function changing project. When a product is at the end of its life-cycle and the department find out that the product is not used anymore it will be removed. Therefore, the department checks if the product is used in the annual timetable, future timetable, morning, and evening set up of trains or during unexpected traffic adjustments. Railway track that is only used during (planned) BTD, are not taken into account.

Since passenger RUs only divert international trains and in exceptional cases also domestic trains, the financial compensation that is paid for passenger traffic will remains, in most cases, the same after the infrastructure in changed. Therefore, these costs will not be further investigated. For the freight RUs, compensation is only paid for BTD during working days or BTD longer than 12 hours. This compensation rate depends on the track section of the BTD and the number of affected trains.

When looking at the KPIs that are described in Section 2.5, only the transition time and the impactful disruptions on the infrastructure can be taken into account. The other KPIs are only about the passenger traffic. A longer diverting route will increase the transition time of freight traffic. However, the transition time does not influence the compensation rate that ProRail pays to the freight RUs. Therefore, this KPI will not be included.

A satisfaction survey, that ProRail send to its RUs every year, showed that freight RUs are not satisfied. Freight RUs were unhappy about the unplanned shutdowns as a result of overdue maintenance.

3 Literature review

In this chapter describes the literature review. An answer will be given on the research questions: "*Which methods are described in available literature regarding cost-benefit analysis?"* and *"Which method is suitable for this research?"* Therefore, multiple methods are written down and compared. Finally, one method is chosen that fits the best in this research.

3.1 Indicators

Over the last decade, railway traffic is increased and due to increasing energy costs and demand to reduce emissions it is expected that railway traffic will increase further. For an increasing need of railway capacity, more efficient and effective operation and maintenance is necessary. To make sure that asset is used effectively, performance indicators are needed to measure and monitor the results of operation and maintenance activities (Stenström, Parida & Galar, 2021). Furthermore, the railway network must also be able to run the timetable. When setting up a timetable, possible delays, perturbations and variations in operation conditions must be taken into account, so that the trains can drive according to plan as best as possible (Goverde & Hansen, 2013).

3.1.1 Maintenance performance indicators (MPIs)

To evaluate the effectiveness of the maintenance that is carried out, maintenance performance indicators are used. MPIs can be related to costs and wastes, the reduction of downtime, productivity, quality, safety and the utilization of capacity. MPI is a product of different metrics that are used to measure the maintenance performance. The indicators have realistic targets to check the prognostic processes and to justify decisions.

The maintenance performance indicators can be used for customer satisfaction, health, safety and environmental ratings and financial and employee performances. Maintenance performance measurement (MPM) is important to know the value created by the maintenance process. MPM considers the requirements of stakeholders and the total maintenance effectiveness (Ahrén, 2008).

3.1.2 Timetable performance indicators

As described above, a railway timetable must withstand delays, perturbations and variations, in a way that the scheduled trains can drive according to the schedule as best as possible. Therefore, daily statistical variations and minor perturbations have to be taken into account during the design process. Most of the current timetables are deterministic, but the method and available tools are different for each country. To create a robust timetable that can withstand delays and perturbations, simulations of effects of delays are used. Depending on the country, microscopic and macroscopic tools are used. Microscopic tools compute timetables that are conflict-free on corridor level, while macroscopic tools focus on the network structure with good transfers between train paths (Goverde & Hansen, 2013). Microscopic tools are more precise, but they require a high amount of initial coding and calibration. Therefore, robustness indicators can be used as an alternative to the microscopic simulations (Jensen, Landex, & Nielsen, 2014).

Goverde and Hansen (2013) describe four main performance criteria for railway timetables, namely: infrastructure occupation, timetable feasibility, timetable stability and timetable robustness.

Infrastructure occupation

This indicator measures how much of the timetable is occupied by the infrastructure capacity. Infrastructure occupation quantifies the three main factors for the design of a timetable for a given infrastructure and time period: (i) the number of trains, (ii) average train speed and (iii) heterogeneity.

Basic definitions of capacity are the theoretical capacity of a track section and the effective capacity. In which the theoretical capacity is the maximum number of trains that can be operated in a given time period. Determined by infrastructure and rolling stock characteristic. The effective capacity is the maximum number of trains per time period that can be operated given the timetable pattern (Goverde & Hansen, 2013)

Timetable feasibility

Timetable feasibility is the ability of all trains to meet their scheduled train paths. The timetable is feasible when the scheduled train paths are conflict free, and the individual process are feasible within their scheduled process time. The process time (running time, dwell time and turn-around time) can be realized when the scheduled process time is longer than the minimum process time. The amount of scheduled train path conflicts is an example of a performance indicator for timetable feasibility, whereby the norm is zero conflicts (Goverde & Hansen, 2013).

Timetable stability

A timetable is stable when it has the ability to return trains to their scheduled train paths after the trains have delays. These delays could be initial and primary delays, in which initial delays are the delays when a train leaves its origin station too late or when it has a delay by entering the border. Primary delays occur when the train is delayed during its route (Goverde & Hansen, 2013).

Robustness

Robustness of the timetable makes sure that the timetable remains feasible when some trains deviate from the schedule. To make a timetable robust, infrastructure occupation computations are important for the design of feasible timetables (Goverde & Hansen, 2013).

Since railway infrastructure have long life-cycles, a long term sustainable strategy is needed. To optimize the performance of the railway system and to receive the Return On Investment (ROI) in time, technical and economical assessments are needed (Stenström, et al., 2012).

3.2 Cost analysis

This section first describes multiple methods of cost analysis for railway infrastructure projects. After this, one method is chosen which will be used for this research.

3.2.1 Challenges for infrastructure projects

Despite that hundreds of billions of dollars are spend on the development of the infrastructure, there is not many reliable knowledge about the performance of these projects in terms of actual benefits, costs and risks (Flyvbjerg, Skamris Holm, & Buhl, 2003). Flyvbjerg et al. (2003) researched 258 transport infrastructure projects in 20 countries and 45% of the railway projects exceeded the costs.

Therefore, in many countries, research has an important role in the decision-making of infrastructure investments. Research helps to estimate and evaluate the impacts of a new infrastructure project. In recent years, the process of decision-making is not only focused on the economic impacts, but it is also focused on the ecological and social impacts (Annema, Koopmans, & Van Wee, 2007).

Below different decision-making methods for (railway) infrastructure investments are described.

3.2.2 Cost Benefit Analysis (CBA)

The cost benefit analysis (CBA) is a tool for identifying the impacts of an investment decision by determining the costs and benefits (Siciliano, et al., 2016). CBA evaluates projects that are evolved from economic and customer constructs. In many western countries, CBA is one of the most widely accepted and applied methods for the evaluation of the transport infrastructure projects. There are several reasons for the popularity of CBA. To begin with, most of the costs and benefits are well known. Investment, maintenance and operation cost can be estimated with data of past projects. Usually, the most important benefits are the travel time savings for freight and passenger traffic (Priemus, Flyvbjerg, & van Wee, 2008). Furthermore, one of the advantages is that it includes a model of rationality, it creates, evaluates, and compares different alternatives and it monetarizes the costs and benefits (Jones, Moura, & Domingos, 2013).

Since the costs and benefits are divided over multiple years, inflation must be considered. Therefore, a discount rate is used to express the costs and benefits as net present values (NPV) (Van Wee, 2007).

Data of the investment, maintenance and operational costs can be collected from tenders and projects in the past. For the passenger traffic, travel times savings per trip can be compared with the current and the proposed infrastructure. Therefore, a distinction is made between business, commuting and other traffic. To express the travel times in monetary terms, Value of Time (VoT) is used. Hereby, freight traffic has a higher VoT than commuting travel and leisure travel has the lowest VoT (Van Wee, 2007)

CBA for the railway system

According to Van Wee (2007), CBA distinguish three categories of recommendations for the railway system. Firstly, a category for the general recommendations that is independent of the type of infrastructure. An example for this is the goal to improve the quality of the value of the discount rate. The second category is the comparison between different projects. For example, the differences in VoT between road and railway. The last category are the specific railway infrastructure projects. For example, the impact of internet on board of the train.

Weakness of CBA

CBA has been criticized for the fact that, in the end, the quality of the analysis depends on the assumptions and estimations that are made. A large error in the assumption or estimation can change the outcomes from positive to negative or the other way around (Jones, Moura, & Domingos, 2013).

Calculation methods

The residual value (RV) is the value of the infrastructure at the end of its lifetime or the value that is generated by asset during its lifetime. RV is the remaining value of the investment in the final year of the CBA. RV can be calculated in two ways; it can be calculated as the residual value of all assets and liabilities or it can be calculated as the residual market value of fixed capital at the end of its life-cycle (Jones, Moura, & Domingos, 2013).

3.2.3 Multi Criteria Decision Making (MCDM)

MCDM combines multiple criteria such as, mathematics, statistics, management and economics to decide which solution must be chosen. MCDM can be divided into two categories, Multi-Attribute Decision-Making (MADM) and Multi-Objective Decision-Making (MODM). Where MADM is used for discrete problems with a finite number of alternatives and MODM is used for continuous problems with an infinite set of alternatives (Yücel & Tasabat, 2019).

To define the MCDM methods, four aspects are considered. First the evaluation criteria and the alternatives are determined. Then a weight is assigned to each criterion and alternatives are evaluated with the criteria. Finally, the alternatives are sorted by their numerical value (Yücel & Tasabat, 2019).

Comparison CBA and MCA

Compared to MBA, CBA has a "neutral" character. MCA adds weights to the effects and uses weights per effect. However, CBA is not completely weight-free, for example the assumption that the price of a train ticket should be based on the preferences of the customer. There are multiple methods to determine the price of a train ticket (Vee Wee, 2007).

According to Yücel & Tasabat (2019) there are two methods to calculate the value of the criteria for railway system projects:

AHP

The first one is the analytical hierarchical process (AHP), which adds a preference or weight of importance to a criterion. AHP exists of three levels of hierarchy. The first level is about the main aim of the problem, the second level corresponds to the criteria and the third level corresponds to the alternatives. According to Kabir, Sadiq & Tesfamariam (2014), the AHP consists of four stages: (i) Defining the problem of decision making, (ii) creating pair-wise comparisons and computing the judgmental matrix, (iii) computing local weights and making the comparisons consistent and finally (iv) aggregation of the local weights.

Best Worst Method

In the Best Worst Method (BWM) exists of four steps: first, the best (the most important or most desirable) and the worst (the least important and east desirable) criteria are identified. Then pair-wise comparisons between each of these two criteria are created (Yücel & Tasabat, 2019). During the third step, to determine the weights of the criteria, a maximin problem is formulated and solved. During this step also the weights of the alternative criteria are obtained. In step four, the final scores of the alternatives is determined by aggregating the weights from different sets of criteria and alternatives. After calculating the final scores, the best alternative can be selected. To check if the comparisons are reliable, a consistency ratio is proposed. (Rezaei, 2015).

Compared to AHP, BWM requires fewer and also more consistent comparisons. Therefore, the total weights derived from BWM have a high reliability. Furthermore, BWM performs better on the minimum violation, conformity and total deviation (Rezaei, 2015).

3.2.4 Life-cycle costing (LCC)

Life-cycle costing (LCC) chooses the solution that results in the lowest total costs over the life-cycle of the railway system. Decisions about the design, construction, maintenance and operation of the railway system influence the costs and revenues during the rest of the life-cycle. Since the lifespan of the railway track is very long, discounting is used to include interest payments and incomes. According to Zoeteman (2001), there are three ways to do this. Namely, (i) Total present value (TPV), which is the sum of all discounted cash flows. A high TPV makes the investment less attractive. (ii) internal rate of return (IRR) that shows the profitability of an investment. (iii) Annual equivalent or annuity (ANN) which is the sum of interest and amortization that must be paid every year.

Furthermore, all costs and revenues must be considered and categorized. This can be done in three ways (Zoeteman, 2001):

1. Tangible and intangible costs: Tangible costs are “out-of-pocket”, such as construction and labor costs. Intangible costs are not directly paid but are the result of reduction in transport services, quality reduction and reduced safety.
2. Initial (capital) costs and running costs: The initial costs are made during the design process and the construction of the infrastructure. The running costs are made during the operational period.
3. Costs of ownership and cost of operation: Hereby, a distinction is made between the costs of the owner of the infrastructure (ProRail) and the costs of the operators (RUs) (Zoeteman, 2001).

When all costs are identified, the solution with the lowest life-cycle costs is chosen. Hereby, the solution must meet all service and technical standards.

For a railway system it is important that the data for estimating the maintenance need and failure rates are reliable. Therefore, assumptions must be made about the robustness of the infrastructure. According to Zoeteman (2001), a sensitivity analysis and an uncertainty analysis can be used for this.

Life-cycle costs of rail infrastructure

To estimate the life-cycle costs of a part of the infrastructure, factors that influence the transport service and the relations of the factors must be identified. Since, maintenance and failures are mainly caused by the degradation of the asset, a maintenance limit (or threshold) is determined to replace or repair a part.

3.3 Conclusion

In this thesis three methods that analyze the costs for railway infrastructure projects are described. The first one is the cost benefit analysis (CBA), which is a tool to identify the impacts of an investment decision by determining the costs and the benefits. CBA is one of the most widely applied methods for evaluation of transport infrastructure projects in which the costs can be estimated with data of the past. Secondly, the Multi Criteria Decision Making (MCDM) method combines criteria to decide which solution must be chosen. This method has four aspects; evaluation of criteria, assigning weight to each criterion and alternatives are evaluated with the criteria and finally the alternatives are sorted by their numerical value. Finally, the Life-cycle costing (LCC) chooses the solution with the lowest total costs over the life-cycle. Factors that influence the transport service and the relations of the factors must be identified to estimate these costs. Since, there is not much data available about past BTD and the life-cycle of the track sections and switches that are barely used is much higher much data need to be estimated and might be inaccurate. Therefore, the CBA method will be used for this research because with this method the pros and cons about the diverting routes and assets costs can be compared easily.

4 Case study: Emplacement Nijmegen

In this chapter the example of emplacement Nijmegen is further elaborated. In section 1.3, the function changing project of emplacement Nijmegen is briefly explained. In the future, a part of the tracks of emplacement Nijmegen (Figure 1.3) will be removed. Therefore, in Section 4.1 a short explanation is given about the motivation behind the project in Nijmegen. Section 4.2 describes the consequences of the plan at emplacement Nijmegen. Finally, Section 4.3 gives an overview of the costs that occur when the plan at emplacement Nijmegen in implemented.

For this case study, BTD that take place unexpectedly are not included. Since there is no historic data available about past unexpectedly BTD. Besides that, there are four track sections between Boxtel and Eindhoven and therefore the chance that all four sections are unexpectedly BTD is small. The track sections are visualized in Figure 4.1. Each line represents a track section. In some places tracks switches and railway tunnels are visualized that run over each other, but in the end, there are only four track sections between Boxtel and Eindhoven. Furthermore, depending on the duration of the BTD, affected freight trains must wait until the BTD is over or the trains could use different diverting routes than they use normally during an BTD.

Furthermore, only the freight RUs are taken into account since the diverting route through emplacement Nijmegen is not used by the passenger RU and therefore the changes at Nijmegen will not influence the diverting costs for the passenger RUs.

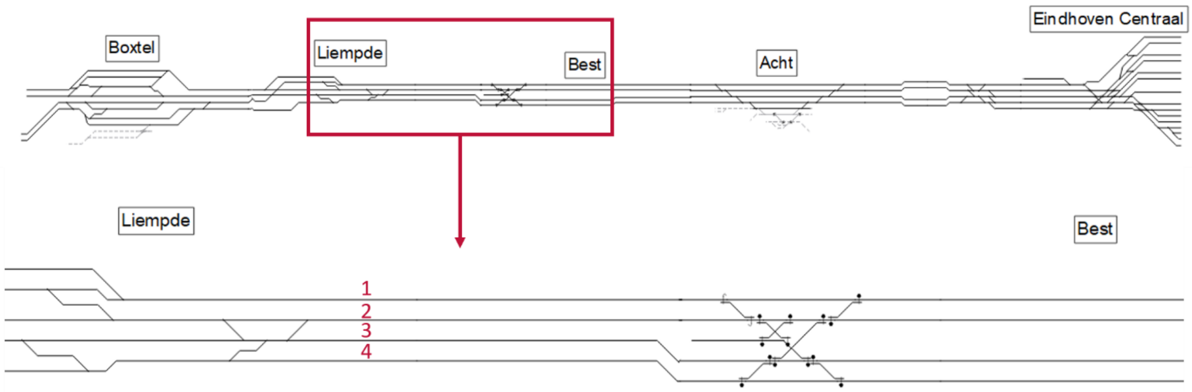


Figure 4.1 Railway track between Btl-Ehv. Source: Inframonitor

4.1 Function changing project

ProRail expects that in 2030, the number of passengers that are taking the train daily will grow by 30% and the number of tons transported by freight RUs on the railway will increase by 50% compared to today. To ensure that the railway network can cope with the increasing train traffic, more trains are used per hour. In December 2020 the number of direct passenger trains between Utrecht – Arnhem – Nijmegen increased from 2 to 4 per hour. ProRail predicts that station Nijmegen will be too small in the future. Therefore, the design of emplacement Nijmegen will be changed in several projects between 2024 and 2027. During these projects an extra platform island is added to the station on the place where the freight tracks are currently located. Therefore, the freight tracks have to be removed. Furthermore, also the passenger tunnels between the platform island will be widened (Ybema, 2021).

Figure 4.2 visualizes the current situation at emplacement Nijmegen. The current track switches of emplacement Nijmegen are visualized in **Fout! Verwijzingsbron niet gevonden.**. The light-yellow dots represent the 40 km/h switches that will be removed during the function changing project. The big dark yellow dot visualizes an English switch. The red dots are the 40 km/h switches that will remain and switches of 80 km/h are colored in gray. This means that twelve 40 km/h and one English switch will be removed. Figure 4.4 visualizes the situation after the function changing project is implemented.

Since all the space of the freight track sections is needed for the new passenger tracks, it is not possible to remove only a few of those 12 light-yellow tracks switches. These 12 track switches cannot be seen as 12 parallel systems. In this case the decision is remove all four freight track section (and therefore also all 12 track switches) and install passenger track sections or replace the four freight track sections with new four freight track sections. When less space was needed for the passenger track sections, it might be possible to remove for example only one track section (and two or three track switches).

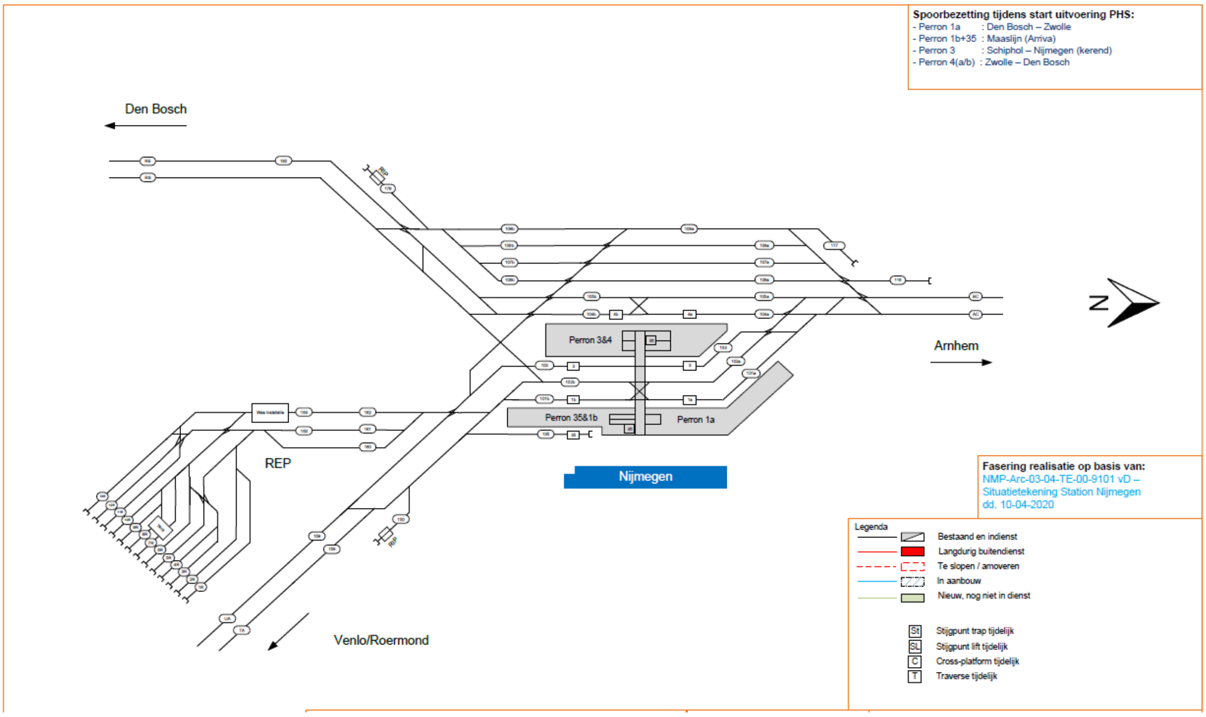


Figure 4.2 Emplacement Nijmegen before the function changing project. Source: (ProRail, 2020)

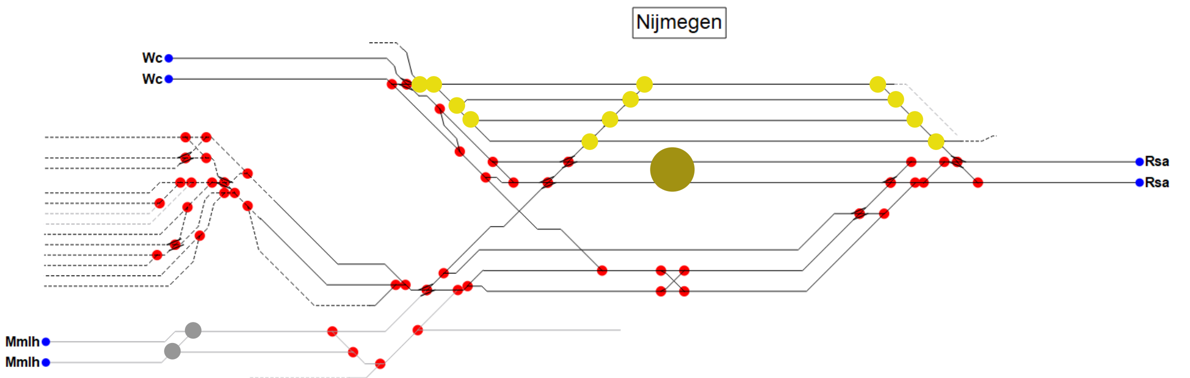


Figure 4.3 Current track switches at emplacement Nijmegen. Source: Inframonitor

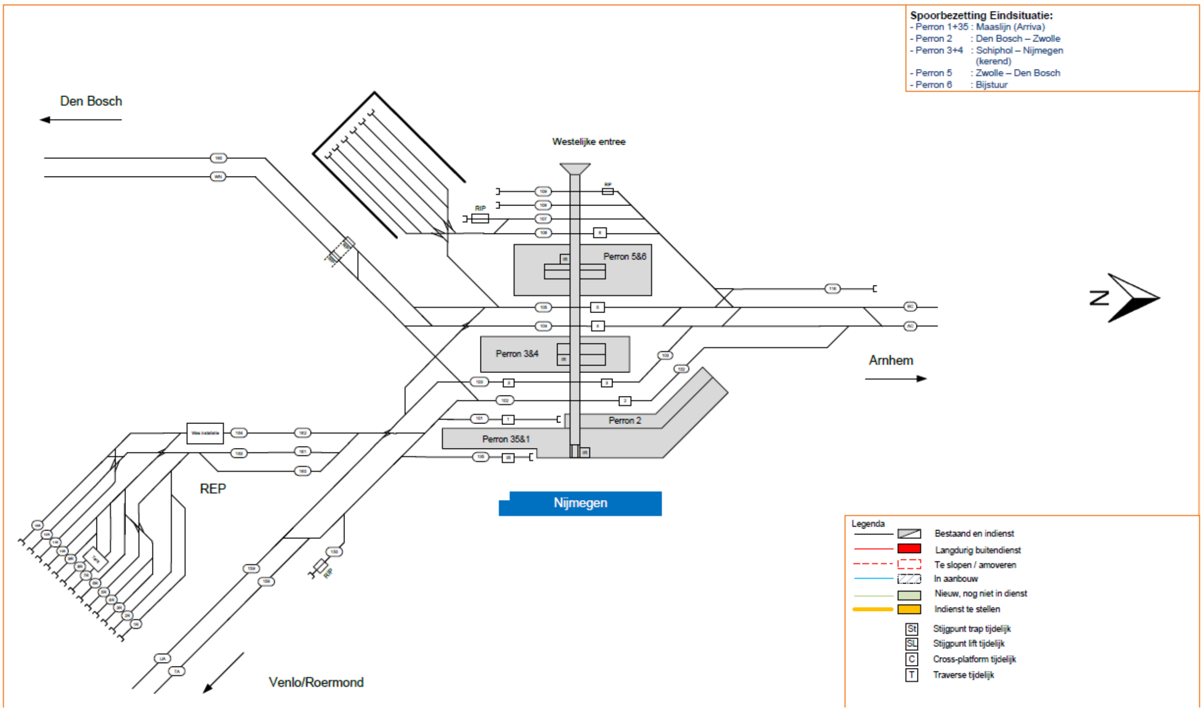


Figure 4.4 Emplacement Nijmegen after the function changing project. Source: (ProRail, 2020)

4.2 Diverting route

During a planned BTD between Eindhoven and Boxtel, all four track sections are closed for train traffic. Due to safety issues, the track sections next to the track section on which maintenance is performed, are closed. Besides that, it is more efficient to perform maintenance on all four of the train tracks at the same time. As described in Section 1.3, due to the function changing project at emplacement Nijmegen the diverting route during a BTD between Eindhoven and Boxtel will be changed. This means that if there is a BTD between Eindhoven and Boxtel in the future, the current diverting route cannot be used anymore (Figure 1.4). The new diverting route (321.9 km) is much longer than the current diverting route (177.5 km).

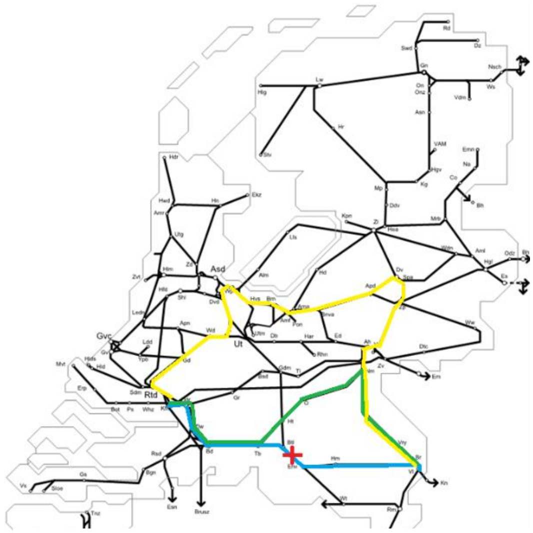


Figure 4.5 Diverting routes during BTD between Eindhoven and Boxtel

The red cross in Figure 4.5 represents the BTD, the regular route is colored in blue, the "old" diverting route is colored in green and the "new" diverting is colored in yellow.

Nevertheless, Figure 4.5 suggests that other routes also can be used as a diverting route, this is not the case. To reach Nijmegen via the Betuweroute a connecting arch is necessary, which is not put into service. Besides, this arch does not meet the requirements and therefore it is not possible to use this arch at this moment.

Another way to reach Nijmegen is to use the route: Kijfhoek-Betuweroute-Elst-Arnhem-Zutphen-Deventer goederen emplacement (kopmaken)-Arnhem-Nijmegen-Boxmeer-Venray-Venlo. However, this is not feasible in practice, because:

- During a BTD between Boxtel and Eindhoven, most of the freight traffic is diverted via Emmerich-Betuweroute. Therefore, other freight traffic that normally uses the route Emmerich-Betuweroute is diverted via Bad Bentheim-Deventer goederen-Arnhem-Betuweroute.
- Between Deventer and Arnhem, only one freight train per hour can pass by, because of the IJselbrug in Zutphen and the timetable of the regional RUs Arriva, Syntus and Abellio.
- The IC Berlijn that drives through Deventer, the commuter train of Abellio (between Düsseldorf and Arnhem) and the ICE that drives through Arnhem makes it impossible to increase the number of freight trains on this train track.

During an interview with RTB Cargo it emerged that they are not be able to run all their trains from the port of Rotterdam to the terminals in Venlo and Blerick. RTB Cargo is not able to use more trains and the travel time of the trains takes too much time to drive the number of trains of that day (RTB, 2021).

4.3 Diverting costs

Since the passenger RUs use buses between Boxtel and Eindhoven during a BTD instead diverting trains, their diverting costs will remain the same. Therefore, the diverting costs of the passenger RUs are not taken into account during this case study.

Unfortunately, ProRail does not record the data about the costs of past BTD. This makes it difficult to give an accurate insight in the diverting costs. Especially the directs costs, which could be a huge amount of the total diverting costs (in the event that the BTD is applicated 4 months till 36 hours before execution), are difficult to calculate. To calculate the direct costs the weight of the train is needed and the extra kilometers that the train has to drive due to the BTD are needed. Furthermore, no data is available about how many times a BTD is Ad-hoc. Nevertheless, a rough estimate can be made with the help of the data that is available:

For freight RUs, financial compensation is paid for BTD during working days or BTD longer than 12 hours. The compensation rate depends on the track section of the BTD and the number of affected trains (section 0). At this moment, the compensation rate for a BTD between Eindhoven and Boxtel is €770 per affected train (Appendix 8A.2). The compensation rate is determined based on the diverting route. Here the following cost components are included:

- Extra kilometers (€**X** per km)
- Extra change the direction of the train ("Kopmaken") (€**X** per "kopmaken")
- Non-commercial stops (€**X** per extra stop)
- Costs for reschedule the train in the timetable (€**X**)

It was examined which diversion routes are driven per BTD. Based on this information, one compensation rate has been determined per track section. Since, not all trains have the same end station, the diverting route differs per train. This means that some trains receive less compensation than the costs that are made. For example, if the trains have an average of 1x "kopmaken" on the diverting route and a certain train needs to "kopenmaken" twice at this diverting route, only one time "kopmaken" will be reimbursed (Brandt, 2021).

At this moment ProRail has not calculated yet what the compensation rate will be for the new diverting route (321,9 km) after the changes at Emplacement Nijmegen. However, for this research ProRail made an estimation that the diverting costs will increase with at least 300%.

To get an indication on the number of affected trains, first the train routes that change direction at emplacement Nijmegen have to be determined. These routes are:

1. Kfh-Ddr-Bd-Tb-Btl-Ehv-Br/Vl-Br will be diverted via Kfh-Ddr-Bd-Tb-Ht-Nm (change direction + loc switch)-Bmr-Vry-Br-Vl
    - This route is only used by freight traffic that drive to the terminals of Cabooter and ECT
    - Each day 5 trains use this route to the terminal of ECT
    - Each day 1 train use this route to the terminal of Cabooter
    - Each week 2 or 3 trains use this route on irregular days
2. Kfh-Ddr-Bd-Tb-Btl-Ehv-Wt-Std will be diverted via Kfh-Ddr-Bd-Tb-Ht-Nm (change direction + loc switch)-Bmr-Vr-Br-Vl-Std
    - Each weekday 2 trains use this route
3. Mdk-Bd-Tb-Btl-Ehv-Wt-Std will be diverted via via Kfh-Ddr-Bd-Tb-Ht-Nm (change direction + loc switch)-Bmr-Vr-Br-Vl-Std
    - Each week 3 or 4 trains use this rout during weekdays

This means that in total, approximately 10 trains per weekday will be affected when there is a BTD between Ehv-Btl.

Table 4.1 shows the dates of BTD between Ehv-Btl during the past four years. During these four years, there were four (week)days that a compensation is paid by ProRail.

Year	Week	Date
2017	31	Sat 05-08 till Sun 06-08
2017	34	Sat 26-08 till Sun 27-08
2019	19	Sat 11-05 till Sun 12-05
2019	42	**Thu 17-10 till Sun 20-10**
2020	15	**Sat 11-04 till Tue 14-04 05:00**
2020	31	Sun 02-08
2022	32,32	Fri 12-08 till Sun 21-08

Table 4.1 Btd between Ehv-Btl during the last four years.

4.4 Conclusion

There are four track sections between Boxtel and Eindhoven. Due to safety reasons, the track sections next to the section on which maintenance is performed, are closed. Therefore, all four of the tracks are blocked during possessions between Boxtel and Eindhoven. Trains that are affected must wait until the BTD is over, or they could use diverting routes.

Since the number of passengers that are using the train daily will increase by 30% within the next 10 years, more trains are needed per hour. ProRail predicts that station Nijmegen will be too small for the increasing numbers of passenger trains in the future. Therefore, the freight tracks and switches, which are currently located at station Nijmegen, will be replaced by an extra platform island and two more track sections of passenger trains. There are twelve 40 km/h switches and on English switch at the freight track. After the function chasing project in Nijmegen is executed, the diverting route through Nijmegen cannot be used anymore. The new diverting route (321.9 km) is much longer than the current diverting route (117.5 km).

Unfortunately, ProRail does not record the data about the number of trains that were affected during and BTD and the total compensation cost that is paid during a BTD. For the directs costs, that are paid during an Ad-hoc BTD, it is hard to make an estimation because the weight of the trains and the extra kilometers of the trains are not known. Besides that, the data about when a BTD is Ad-hoc is also not available.

At this moment, when the freight tracks at Nijmegen are still available, ProRail pays €770 per train that is affected due to a BTD between Eindhoven and Boxtel. When the freight tracks at Nijmegen are removed the compensation cost will increase with at least 300%. In total each weekday 10 trains are affected when there is a BTD between Eindhoven and Boxtel. Based on data of 2018 till 2021, each year there is only one weekday that there is a BTD between Eindhoven and Boxtel.

5 Model

In this chapter a model is proposed to determine whether the switch(es) on a certain location on the railway track should be replaced or removed. To make this decision, the costs of diverting and the asset costs are taken into account. In Section 5.1, the problem is introduced and the ILP model is explained. Section 5.2 gives proposed additions to the model, such as a more detailed calculation of the direct costs.

5.1 ILP model

Using the outcome of this model, a decision can be made about whether the track switches should be replaced or removed. For this model, the case study of emplacement Nijmegen was used as a starting point. In this model it is supposed that the track switch will reach the end of their life-cycle within five years. However, with a small adaption the model can also be used for within for example ten or two years. Furthermore, this is a single time model. In case that the track switches are replaced, the model can be used again after the track switches reaches the end of its life-cycle again. The outcome of this model is fully determined by the parameters values and the initial conditions, therefore the model is deterministic.

In the actual case, a decision has been taken: remove the switches. In this model the choice is still open. And therefore, a decision has to be made whether these switches will be replaced or removed and in which year this decision should be made. In the event that the switches will be replaced, the BTD costs will remain the same since the same diverting routes can be used. However, a one-off replacement cost for the track switch and the switch heater and a yearly maintenance cost must be paid. When the track switches will be removed, the BTD costs will increase since the diverting routes become longer and a removal cost (which is more than the replacement cost) must be paid per track switch. But there are no maintenance costs anymore. Therefore, to make a decision, the model calculates the minimal costs of diverting and the asset costs after replacing or removing the track switches. Since ProRail uses a 20-year cost calculation for a function changing project that concerns replacing or removing track switches, the total costs include the expected costs till 20 years after the decision. For a fair comparison of alternative decisions, the average costs per year are taken over the period from the current year until 20 years after the decision year.

Since the costs of passenger traffic will not change after the track switches are replaced or removed, only freight traffic is taken into account.

5.1.1 Assumptions

To make this model work, the following assumptions are made:

- Since all switches are installed at the same time, it is assumed that all switches have the same age. Besides that, when it is possible to remove only a number of track switches, the younger track switches can be used during diverting and therefore the cost of diverting will be different. Depending on the situation, all trains or a part of the trains could use the younger track switches, which leads to a lower diverting cost.
- All switch heaters have the same current age, since all the switches and therefore also the switch heaters are installed at the same time.
- There is no data available about unpredicted failures on the track sections between Eindhoven and Boxtel. Therefore, the unpredicted failures are not taken into account and is it assumed that when an unpredicted failure occurs, at least one of the track sections is still working.

- The replacement costs of track switches are entirety depreciable within 20 years. Because ProRail uses a 20 year cost calculation for their function changing projects, which includes all expected costs till 20 years after the project executed.

5.1.2 Set

During the next five decision years $n \in N$, a decision $j \in J$ has to be made about the track switches. The model includes five types of switches $s \in S$, where the costs vary per type. Furthermore, the model contains the expected BTD $b \in B$ for the next 25 years $t \in T$ (max 5 decision years and 20 year cost calculation).

BTD	*B = {1,2,…}*
Switch types	*S = {40,60,80,130,English}*
Decision	*J = {1,2,3} (see **Fout! Verwijzingsbron niet gevonden.**)*
DecisionYear	*N={1,2,3,4,5}*
Year	*T = {1,2,…,25} (Needed for max 5 decision years and for a 20 year cost calculation)*

J	Where
1	This year no decision is made yet
2	Switch is replaced this year
3	Switch is removed this year

Table 5.1 Decision (J)

Indices

BTD	$b \in B$
Switch type	$s \in S$
Decision	$j \in J$
DecisionYear	$n \in N$
Year	$t \in T$

5.1.3 Decision variable

The model determines which decision will be made and during which year this decision will be made:

$$R_{jn} = \begin{cases} 1, & if\ decision\ j\ is\ made\ during\ year\ n \\ & 0, otherwise \end{cases}$$

5.1.4 Input parameters

Number of switches *NumberSwitches*

Age of switch — *SwitchAge*

Age of heater — *HeaterAge*

Expected Lifespan of switch type *s* (Table 5.2) — $LifespanSwitch_s$

Expected Lifespan of switch heater (Table 5.2) — *LifespanHeater*

Maintenance cost of switch type *s* in year *t* (Table 5.2) — $MaintenanceCost_{st}$

Replace costs of switch type *s* in year *t* (Table 5.2) — $ReplaceCost_{st}$

Remove costs of switch type *s* in year *t* (Table 5.2) — $RemoveCost_{st}$

Replace costs of switch heater of switch type *s* in year *t* (Table 5.2) — $ReplaceHeaterCost_{st}$

Number of affected trains during BTD *b* — $AffectedTrains_b$

The reimbursement per BTD depends on the number of affected trains. To calculate the number of affected trains, the average number of trains that were in the timetable one and two weeks before and one and two weeks after the BTD is used.

Compensation rate for BTD *b* in decision *j* in year *t* — $CompensationRate_{bjt}$

The compensation rate depends on the track section where the BTD takes place, the diverting route (and therefore it also depends on the decision) and the year in which the BTD takes place. The compensation rates, with the current diverting routes (switches are still on the track), per track section in year 2021 are visualized in table Table A.1 in Section 8A.2. The compensation rates, when the switches will be removed and larger diverting route is needed, are not calculated yet (See Section 4.3 for an explanation of the different cost components).

Direct costs of BTD b in decision *j* in year *t* — $DirectCost_{bjt}$

The direct costs are described in Section 4.3. These costs depend on the weight of the train and the extra kilometers of the diverting route. Direct costs are only paid when a BTD is ad-hoc, which means that the BTD is applicated 4 months till 36 hours before the execution.

Train km of an affected train during decision *j* during an ad-hoc BTD — $TrainKm_j$

Inflation rate — *InflationRate*

Increasing (freight) traffic rate — *TrafficRate*

The $LifespanSwitch_s$, *LifespanHeater*, $MaintenanceCost_{st}$, $ReplaceCost_{st}$, $RemoveCost_{st}$ and $ReplaceHeaterCost_{st}$ depend on the switch type and can be found in Table 5.2, this table is also visualized in Section 2.1.3.

	Track switch 40 km/h	Track switch 60 km/h	Track switch 80 km/h	Track switch 130 km/h	Track switch English
Lifespan (year)					
Lifespan heater (year)					

Installation new switch	
Replace with new switch	
Installation or replacement switch heating	
Remove switch	
Maintenance per year	

Table 5.2 Costs track switches and switch heating. Source: ProRail, Asset Management Department.

Since the compensation rate has a different increase than the inflation rate, there is a separate parameter for this:

Increasing compensation rate *IncreasingCompensationRate*

With data of the past, it can be estimated how often there is an unexpected possession at the place of the BTD and how many trains are affected by this possession. Therefore, the following parameter is added:

Number of yearly affected trains due to unplanned possessions *Unplanned*

Since there will only be a compensation for BTD that take place during weekdays (and when there is no traffic-calmed period), per BTD it has to be determined whether a compensation will be paid:

$$C_b = \begin{cases} 1, & if\ compensation\ is\ paid\ for\ BTD\ b \\ 0, & otherwise \end{cases}$$

In the case that the BTD is ad-hoc, also direct costs have to be paid to the freight Rus. Ad-hoc BTD are BTD that are applicated 4 months till 36 hours before the execution (See Section 2.3):

$$A_b = \begin{cases} 1, if\ BTD\ b\ is\ ad-hoc \\ 0, otherwise \end{cases}$$

To determine the compensation rate per BTD, it has to be determined in which year the BTD takes place:

$$B_{bt} = \begin{cases} 1, if\ BTD\ b\ takes\ place\ during\ year\ t \\ 0, otherwise \end{cases}$$

5.1.5 Auxiliary variables

BTDcost, Assetcost

Each track switch has a heater to prevent the switch from freezing. The heaters have a lifespan of 20 years, after those 20 years the heater has to be replaced by a new one. For this model, there are two situations when the switch heaters have to be replaced. 1) Since each heater has a lifespan of 20 years and this model is a 20 years cost calculation, the heater has to be replaced in the case that the switch is also going to be replaced. Furthermore, 2) in the event the heater will reach the end of its life-cycle before the decision of replacing or removing of the switch is made, the heater also needs to be replaced. This variable is partly dependent of the decision variable.

$$H_t = \begin{cases} 1, if\ heater\ reaches\ the\ end\ of\ its\ life-cycle\ during\ the\ decision\ years\ and\ needs\ to\ be\ replaced \\ 0, otherwise \end{cases}$$

5.1.6 Objective

The goal of the objective function is to minimize the costs. The function consists of two parts, namely the BTD costs and the asset costs.

Min BTDcost + Assetcost

s.t.

This model has a time horizon of maximum 25 years, therefore an (constant) inflation rate should be taken into account. According to Buzacott (1975), the following formula can be used on each parameter to assume there is a constant inflation rate. Where b_0 is the cost at time zero:

$$b(t) = b_0 * e^{InflationRate*t}$$

Therefore:

$$DirectCost_{bjt} = DirectCost_{bj} \cdot e^{rt}$$

$$ReplaceCost_{st} = ReplaceCost_s \cdot e^{rt}$$

$$RemoveCost_{st} = RemoveCost_s \cdot e^{rt}$$

$$MaintenanceCost_{st} = MaintenanceCost_s \cdot e^{rt}$$

$$ReplaceHeaterCost_{st} = ReplaceHeaterCost_s \cdot e^{rt}$$

The same formula is used for the compensation rate, but then with the increasing compensation rate instead of the inflation rate:

$$CompensationRate_{bjt} = CompensationRate_{bj} \cdot e^{IncreasingCompensationRate*t}$$

The formula for the increasing traffic rate:

$$AffectedTrains_{bt} = AffectedTrains_b \cdot e^{TrafficRate*t}$$

BTDcost

This are the costs that have to be paid to the freight RUs during BTD. All the costs are looped over the BTD (b). This cost includes the affected trains, the compensation rate and the direct costs in case that the BTD is ad-hoc. All these costs depend on the BTD. The compensation rate also depends on the length of the diverting route during the BTD. In the event that the track switches are removed, the diverting route will increase and therefore also the compensation rate will become higher.

The formula of the BTD consist of two parts: the costs before a decision is made (j=1) and when a decision is made (j=2,3). When there is no decision made during n=1 till n=4, the decision should be made at n=5, therefore $R_{15} = 0$. During the years that $R_{1n} = 1$ the compensation rate and the direct costs are from the short diverting route. In the case that the switches are removed, the compensation rate and the direct costs will increase after and during the year of the decision.

$$BTDcost = \sum_{n=1}^{4}\sum_{b}\sum_{t=1}^{n-1}((AffectedTrains_{bt} \cdot (CompensationRate_{b1t} \cdot C_b + DirectCost_{b1t} \cdot A_b \cdot TrainKm_1) \cdot B_{bt} \cdot R_{1n})) + \sum_{n}\sum_{b}\sum_{t=n}^{n+20}\sum_{j=2}^{3}((AffectedTrains_{bt} \cdot (CompensationRate_{bjt} \cdot C_b + DirectCost_{bjt} \cdot A_b \cdot TrainKm_j)) \cdot B_{bt} \cdot R_{jn})$$

Assetcost

This cost consists of the maintenance cost per year, the replace and remove costs and the costs for replacing the heater. In the event that the switches will be replaced, maintenance costs have to be paid for the next 20 years. When $\sum_n R_{2n}$= 1, the maintenance costs are calculated, when $\sum_n R_{2n}$= 0 the maintenance costs are not taken into account. As states above, there are two situations when the heaters have to be replaced. When $R_{2n} = 1$, the heater should be replaced within these 20 years of cost calculation. When the heater reaches the end of its life-cycle before a decision is made, it has to be replaced (H=1).

During the years that the switches are on the railway, maintenance costs have to be paid. When $R_{2n} = 1$, there will be maintenance costs for the next 20 years. In the event that the switches will be replaced, the next 20 years also maintenance costs have to be paid. In case that $R_{2n} = 1$ there is a replace cost per switch and in case that $R_{3n} = 1$ there is a remove cost per switch.

$$Assetcost_s = \sum_{t=n}^{n+20}(MaintenanceCost_{st} \cdot NumberSwitches \cdot \sum_{n} R_{2n}) + \sum_{t}(ReplaceHeaterCost_{st} \cdot NumberSwitches \cdot H_t) + \sum_{n}(\sum_{j=1}^{2}(MaintenanceCost_{st} \cdot NumberSwitches \cdot R_{jn}) + (ReplaceCost_{st} \cdot NumberSwitches \cdot R_{2n}) + (RemoveCost_{st} \cdot NumberSwitches \cdot R_{3n}) + (ReplaceHeaterCost_{st} \cdot NumberSwitches \cdot R_{2n}))$$

5.1.7 Constraints

Since this is a single time model, the decision about removing or replacing the switches, has to be made only once:

$$\sum_n R_{2n} + R_{3n} = 1$$

If there is no decision made yet, R_{1n} = 1 and after the decision is made, j=1 cannot be chosen:

$$R_{1n} + \sum_{k=1}^{n} (R_{2k} + R_{3k}) \ = 1 \ \forall n$$

If the heater reached the end of its life-cycle (20 year old), it need to be replaced AND if the switch will be replaced, the heater also has to be replaced (20 years cost calculation). See Section 5.1.5 for an explanation about variable H_t:

$$\sum_t (1 - H_t)(\sum_n R_{1n} + HeaterAge) \leq LifespanHeater$$

Other constraints:

R_{jn} = {0,1} $\forall j, n$

$BTDcost, Assetcost, H_t \ \geq 0$

5.2 Proposed addition

In this section, an addition to the model in Section 5.1 is proposed. At this moment, no data is available on direct costs of BTD in the past. Therefore, the model in Section 5.1 only contains a rough estimation of the directed costs. In the future this addition can be added to the model to get a more accurate indication of the direct costs. An example of the direct costs is described in Section 2.3.3. These direct costs are only paid when a BTD is ad-hoc, which means that the BTD is applicated 4 months till 36 hours before execution.

Additional set and index:

Affected train	A = {1,2,…}
Affected train	$a \ \in A$

Additional input parameters:

Additional direct costs for changed capacity (per train km) in weight class of affected train *a*	$WeigthCost_a$
Additional direct cost for changed capacity per (diverted) train km	*ChangedCapacityCost*
Cost for canceled capacity per train km	*CanceledCapacityCost*
Train km of affected train *a* during decision *j* during an Ad-hoc BTD	$TrainKm_{aj}$

Since the train km and the weight class differ per affected trains, a new binary input parameter is needed:

$$Z_{ab} = \begin{cases} 1, & if\ train\ a\ is\ affected\ during\ BTD\ b \\ & 0, otherwise \end{cases}$$

Z_{ab} calculates the number of affected trains in BTD *b.* Therefore, the parameter $AffectedTrains_s$ will be deleted:

~~Number of affected trains during BTD *b* — *AffectedTrains*$_b$~~

In the case that the BTD is ad-hoc and affected train *a* will be diverted:

$$ChangedCapacity_a = \begin{cases} 1, if\ affected\ train\ a\ will\ be\ diverted \\ \quad 0, otherwise \end{cases}$$

In the case that the BTD is ad-hoc and affected train *a* will be canceled:

$$CanceledCapacity_a = \begin{cases} 1, if\ affected\ train\ a\ will\ be\ canceled \\ \quad 0, otherwise \end{cases}$$

Changes in the objective:

The formula of the BTDcost will change to:

$$\begin{aligned} BTDcost\ = & \sum_{n=1}^{4} \sum_{a} \sum_{b} \sum_{t=1}^{n-1} ((Z_{ab} \cdot CompensationRate_{b1t} \cdot\ C_b + DirectCost_{b1t} \cdot A_b \\ & + DirectCost_{b1t}) \cdot B_{bt} \cdot R_{1n}) \\ & + \sum_{n} \sum_{a} \sum_{b} \sum_{t=n}^{n+20} \sum_{j=2}^{3} ((Z_{ab} \cdot CompensationRate_{bjt} \cdot C_b + DirectCost_{bjt} \cdot A_b \\ & + DirectCost_{b1t}) \cdot B_{bt} \cdot R_{jn}) \end{aligned}$$

Where the direct costs are:

$$\begin{aligned} DirectCost_{bjt} = & \sum_{a} Z_{ab} \cdot\ TrainKm_{aj} \cdot (ChangedCapacity_a \cdot (WeightCost_{at} \\ & + ChangedCapacityCost_t) + CanceledCapacity_a \cdot CanceledCapacityCost_t) \end{aligned}$$

The formula of the asset cost will remain the same since this cost does not depend on the direct cost.

Additional constraints:

In case of an Ad-hoc BTD, the capacity will be changed or canceled:

$$ChangedCapacity_{at} + CanceledCapacity_{at}\ \leq 1, \qquad \forall a, \forall t$$

6 Results of the model

In this chapter the results of the ILP are described. Section 0 gives an overview of the start values for the input parameters of the ILP model. After this, several possible situations and their outcomes are described in Section **Fout! Verwijzingsbron niet gevonden.**.

6.1 Input of ILP model

To calculate the outcomes of the ILP model, the excel solver is used. The excel file consists of three sheets, “Fixed costs”, “Parameters” and “Outcome”. For this ILP model the costs that are described in Section 2.3.3 are used and visualized in the “Fixed costs” sheet (Appendix B.1).

The second excel sheet (see Appendix B.2) visualizes the parameters that are described in Section 5.1.4. For this model the example of emplacement Nijmegen is used as input, but the values of these parameters can be changed to another situation. The values of the parameters according to the example at emplacement Nijmegen are:

- Number of switches: 12. The example of emplacement Nijmegen contains 12 switches.
- Switch type: 80 km/h. The example of emplacement Nijmegen mainly contains switches of type “80 km/h”.
- Number of BTD where compensation needs to be paid per year: 1 (Section 4.3)
- The compensation costs will increase with approximately 300% when the freight tracks switches
  a station Nijmegen cannot be used anymore (Section 4.3)
- Affected trains: on average 10 trains will be affected when there is a BTD between Eindhoven and Boxtel. Therefore, a random number is drawn between 8 and 12 trains per BTD (Section 4.3)
- Due to work on the railway system ProRail expects to have a BTD (between Boxtel-Eindhoven) with a consecutive period of 16 days somewhere between 2023 and 2026. Therefore, the number of affected trains in year 2023 and 2024 will be multiplied by 2 and 10 respectively.

For the other parameters, some assumptions are made since not all the data is available:

- Switch age: 35. In this ILP model, the track switch will reach the end of their life-cycle within five years. Since most of the switch types have a life-cycle of 40, the current switch age is 35 years.
- Heater age: 10
- Inflation rate: 1,2%
- Increasing traffic rate: 3%
- Increasing compensation cost: 3,5%. The compensation costs depend on the costs that the freight RUs have to make during an BTD. The amount of the compensation cost is re-established every year. In 2020 and 2021, the compensation cost between Boxtel-Eindhoven was €770. In 2022, this cost will be €840.
- Direct costs: The direct costs are not taken into account because there are many parameters of which no data is available yet.

The outcomes of the model are visualized in the third sheet (see Appendix B.3 for an overview of this sheet). The excel solver calculates the best solution in this sheet, by minimizing the total costs (objective) over the next 20 years. Furthermore, a solution can also be obtained manually by using the DIY-tool. Every possible solution can be entered here, after which the model calculates the costs. In this way it is also possible to check whether the excel solver provides the best solution. In 8Appendix D a user manual is written.

6.2 Sensitivity analysis

For this thesis seven situations are proposed, in each situation some of the parameters are changed. First the model is used for the situation of emplacement Nijmegen. After this, several input parameters are changed.

1. Situation emplacement Nijmegen
2. Change in switch type
3. Change in number of track switches
4. Change in heater age
5. Change in increasing compensation rate
6. Change in increasing traffic rate
7. Change in compensation rate
8. Ad-hoc BTD

6.2.1 Situation emplacement Nijmegen

The input values of the start situation are visualized in Figure 6.1. The motivation behind these values is described in Section 6.1. Figure 6.2 gives an overview of the outcome of the excel solver.

Figure 6.1 Input values of the start situation

Figure 6.2 Outcome of start situation

According to the solver, the track switches should be removed during the first year (R_{31}). The maintenance and replace costs will be €0 since the track switches will be removed immediately. The remove costs are 12*€X = €12X. Since the switches will be removed during the first year, the compensation costs are 3*€770 = €2,310 (plus inflation during the 20 years) per affected train. This gives a total BTD cost of €X.

To check if the solver gave the best solution, the DIY-tool is used. Every possible solution is calculated. The results are visualized in Table 6.1. The results show that removing the track switches somewhere in the next five years is cheaper than replace the switches. Furthermore, due to the increasing inflation rate, increasing traffic rate and increasing compensation costs, removing or replacing the switches in the first year is the most beneficial.

Solution	Objective of 20 years
R_{21}	

R_{22}	
R_{23}	
R_{24}	
R_{25}	
R_{31}	
R_{32}	
R_{33}	
R_{34}	
R_{35}	

Table 6.1 Outcomes of DIY-tool in start situation.

6.2.2 Change in switch type

For the next experiment the types of the track switches are changed. The results are visualized in Table 6.2. For each switch type, the solver finds the best solution when the switches are removed in year 1. The asset costs (=maintenance cost + remove and replace cost) are much higher than the costs for the BTD. Furthermore, since the switch types does not influence the costs of the BTD, this cost is the same for all types.

Switch type	Solution by solver	Asset cost	BTD cost	Objective	Objective of 20 years
40	R_{31}				
60	R_{31}				
80	R_{31}				
130	R_{31}				
English	R_{31}				

Table 6.2 Outcome of change in switch type.

6.2.3 Change in the number of track switches

For the event that the number of switches is changed, the objective of 20 years is calculated for 1 till 20 track switches. In practice, the number of track switches cannot be below 4. Since there are at least 4 switches needed to change the direction of the train ("kopmaken") at Nijmegen. The outcomes are visualized in Appendix C.1Table C.. But for other situations where, the train does not need to change of direction, less switches are needed. Therefore, it is calculated (with the data of emplacement Nijmegen) what the decision would be with another number of track switches.

When the number of track switches increases, it becomes more likely that R31 becomes a better solution. This is because, the diverting costs will remain the same, but the asset costs will increase when there are more track switches.

In Figure 6.3 the objective function is plotted against the number of track switches. This figure shows that when only 1 till 5 track switches were located at emplacement Nijmegen, it would be cheaper to replace the track switches in year 1. For 6 track switches the best solution is to remove the track switches at year 3. In that case, the switches are still available during the 16 extra days of BTD between Boxtel and Eindhoven (see 4.3), but after that the switches will be removed. When there are more than 6 track switches, it is cheaper to remove them in the first decision year. While the asset costs rise in a straight line, the cost of BTD are increasing from € X to € X after the switches are removed.

Figure 6.3 The costs of removing (R31 and R33) and replacing (R21) track switches is plotted against the number of track switches. If there are only 1 till 5 track switches, replacing in year one gives the lowest objective function. When looking at 6 track switches, they should be removed in year three and when the case has 7 track switches of more, it is more beneficial to remove all the switches in year 1.

6.2.4 Change in heater age

In the start situation the heaters of the track switches are 10 years old, which means that the heaters will only be replaced when the track switches will be replaced. Heaters have a life-cycle of 20 years, since the new track switches will be on the railway for at least 20 years, the heater have to be replaced somewhere within those 20 years. In the event that the heater is 17 years old and the track switches will be replaced in year 3, the heater has to be replaced two times. However, due to the inflation rate it is never profitable to replace the switches in year two till five. Therefore, the solver will not give other solutions when the age of the heater will be adjusted.

6.2.5 Change in increasing compensation rate

Since a change in the increasing compensation rate influences the costs of BTD, this is further elaborated. Hereby, the rate is changed to a value between 0.0% and 10.0%. The results are visualized in Appendix C.2.

Despite the fact that the costs of BTD will rise when the increasing compensation rate is higher, the costs of the BTD are still much lower than the asset costs. Therefore, it is more likely that R31 the best solution. Figure 6.4 visualizes the objective function per increasing compensation rate when the switches are removed or replaced in year one. However, this graph shows that the objective function increases more when the track switches are removed, the objective function when the switches will be replaced is still much higher. Therefore, a change in the increasing compensation rate will not influence the solution.

Figure 6.4 The objective function for 20 years for the decisions R21 and R31 per increasing compensation rate. For every compensation rate between 0.0% and 10.0% the decision of removing the track switches in year one results in a lower objective function than replacing the track switches in year one.

6.2.6 Change in increasing traffic rate

A change in the increasing traffic rate influences the number of affected trains per BTD and therefore also the compensation costs and the costs of the BTD. Therefore, when the traffic rate increase, it becomes more likely that the objective function for R31 will increase more than the objective function for R21.

The objective function (over 20 years) is calculated for a traffic rate that varies between 0.00% and 10.00% percent. The results can be found in Appendix C.3. As visualized in Figure 6.5, the switches only need to be replaced when the increasing traffic rate is 10.00% or higher. However, it is not realistic that the number of affected trains increase with 10% per year for the next 20 years.

Figure 6.5 The objective function for 20 years for the decisions R21 and R31 per increasing traffic rate. For every traffic rate between 0.0% and 9.5% the decision of removing the track switches in year one results in a lower objective function than replacing the track switches in year one. For a traffic rate that is 10.0% or higher, replacing in year one will lead to a lower objective function.

6.2.7 Change in compensation rate

According to the department that calculates the compensation rate for freight traffic, the compensation costs will increase with 300% after the switches will be removed at emplacement Nijmegen. When the compensation rate (j=3, remove switches) changes after the switches are removed, the BTD costs will also change. In Appendix C.4, the objective functions with different values of compensation rate (j=3) are visualized.

Since the compensation rate of j=2 will not change, but the compensation rate of j=3 does. The objective function or R31 (and R33) will become higher than the objective function of R21 at some point. In Figure 6.6, the objective function is plotted against the different compensation rates of j=3.When the compensation rate of j=3 is max 4.5 times higher than the compensation rate of j=2 (replace switches), the best solution is to remove the switches in the first year. When the compensation rate of j=3 is 5 times higher than the compensation rate of j=2, the best solution is to remove the switches in year three. If the compensation rate of j=3 is more than 5.5 times higher than the rate of j=2, it is more profitable to replace the switches in year one.

Figure 6.6 The objective function for 20 years for the decisions R21 and R31 per compensation rate. For every compensation rate between 100% and 450% the decision of removing the track switches in year one results in the lowest objective function. When the compensation rate is 500%, removing in year three gives the lowest objective function. For a compensation rate that is 550% or higher, replacing in year one will lead to a lower objective function.

6.2.8 Ad-hoc BTD

In the event that the trains need to be diverted, the direct costs depend on the number of trains, the weight classes of the trains and the extra km that the train has to drive. When there is no diverting route and the trains are canceled, the direct costs only depend on the number of trains and the number of kilometers of the original route (see Appendix 8A.3). Since there is no data about past BTD that were ad-hoc (BTDs that were applicated 4 months till 36 hours before execution) and the trains (and their weight class) that were affected. Only cancelled trains are taken into account, which means the direct costs are €5.65 per original train km. For the case of emplacement Nijmegen, the original route is 144.8 km. To calculate the direct costs, the number of affected trains is multiplied by 5.65 and 144.8. To decide whether a BTD is ad-hoc, a random number between 1 and 10 is generated per BTD. When this number is higher than a certain value (this value can be entered in the "Parameters" sheet), the BTD will be marked as ad-hoc. In the "Parameters" sheet, new random numbers can be generated by pressing on the "Generate random ad-hoc"-button. Since the numbers are randomly generated, the button will be used three times per certain value that is higher than the random number. The outcomes are visualized in Appendix 8C.5. Although, the BTD costs increases when the BTD are ad-hoc, it is still cheaper to remove the track switches instead of replacing them.

6.3 Conclusion

For the situation at emplacement Nijmegen, there are 12 track switches of type 80 km/h that have to be removed or replaced within 5 years. Each year there is one weekday on which there is a BTD between Eindhoven and Boxtel and in that day, 10 trains are affected. With an inflation rate of 1.2%, increasing traffic rate of 3.0%, compensation rate of 300% and an increasing compensation cost of 3,5%, the excel solver decided to remove the track switches in year 1.

After changing the switch types, the number of track switches, the heater age, the increasing compensation rate, the increasing traffic rate, the compensation rate and ad-hoc BTD, to see how these parameters influences the results of the model. Changes in the switch type, heater age and increasing compensation rate did no gave a different result.

When the number of track switches is below 5, it is cheaper to replace the switches in the first year and when there are 6 switches it is cheaper to remove them in year three. When there are 7 switches or more R31 becomes the best solution. However, in the case of emplacement Nijmegen, at least four switches are needed to change the direction of the train ("kopmaken"). When looking at the increasing traffic rate, only a yearly increasement of 10% will change the decision from removing the switches in the first year to replace the switches in the first year.

The compensation rate when the switches are removed also has an influence on the solution, when the compensation rate increases with 500%, the best solution is to remove the track switches in year three. When the compensation rate increases with 550% or more, it is cheaper to replace the switches in year one.

7 Conclusion and recommendations

First an answer is given on the main research question in the conclusion (Section 7.1). The limitations and recommendations are described in Section 7.2.

7.1 Conclusion

At this moment, there are two different visions regarding the design of the infrastructure. The Infrastructure Development Department wants to reduce the maintenance costs and therefore a robust infrastructure that is focused on undisturbed situations. This results in removing parts of the infrastructure that are not used during the annual timetable, common traffic adjustments or during the 24/7 timetable set up. On the other hand, the PreVAB wants to continue as much train traffic as possible, during possessions. Therefore, alternative routes and other track switches are necessary during BTD. Since the costs of the alternative routes are not known yet, they are not taken into account when the infrastructure is changed.

Therefore, the main research question of this thesis is:

What are the impacts of removal and replacement decisions of existing track switches on costs of train diversion routes during possessions and how can these decisions be made properly?

The problem of finding new diverting routes after these track switches are removed, does not occur at the passenger traffic. The Infrastructure Development Department checks if the track switches are used in the current timetable, future timetable, during the 24/7 set up or often used during traffic adjustments. During BTD, passengers themselves are diverted instead of the trains. Therefore, passenger RUs does not make use of track switches that are barely used.

Freight RUs on the other hand, need to divert trains. The Infrastructure Development Department consults freight RUs and the Department of Capacity Distribution (including the PreVAB), but their arguments are not decisive. According to the Department of Infrastructure Development, there are both economic and operational reasons for this. On average, a track switch has an (unexpected) malfunction once every two years. This means that the annual timetable could be disturbed by a track switch that is only used during some of the BTD. A side note here is that switches that are only used in one position, which is the case with these switches. Can temporarily be locked in one position, therefore the train traffic is delayed for one hour max.

For every function changing project, a 20-year cost calculation is made. Herby, the remove and replacement costs, the yearly maintenance costs and the inflation costs are taken into account. The costs of BTD are not considered because it is expected that these costs are insignificant.

Freight RUs do not receive a financial compensation for BTD during the weekends, nights, freight traffic-calmed periods, BTD less than 12 hours or when the train traffic is not affected. Financial compensation is only paid for BTD during working days or BTD longer than 12 hours. This compensation rate depends on the track section of the BTD and the number of affected trains.

To receive more insight into the costs, a case study at emplacement Nijmegen is executed. ProRail predicts that station Nijmegen will be too small for the increasing numbers of passenger trains in the future. Therefore, the freight tracks and switches, which are currently located at station Nijmegen, will be replaced by an extra platform island and two more track sections of passenger trains. There are twelve 40 km/h switches at this freight track. After the function chasing project in Nijmegen is executed, the diverting route through Nijmegen cannot be used anymore. The new diverting route (321.9 km) is much longer than the current diverting route (117.5 km).

Unfortunately, ProRail does not record the data about the number of trains that were affected during and BTD and the total compensation cost that is paid during a BTD. For the directs costs, that are paid during an Ad-hoc BTD, it is hard to make an estimation because the weight of the trains and the extra kilometers of the trains are not known. Besides that, the data about when a BTD is Ad-hoc is also not available. Therefore, these numbers are estimated:

At this moment, when the freight tracks at Nijmegen are still available, ProRail pays €770 per train that is affected due to a BTD between Eindhoven and Boxtel. When the freight tracks at Nijmegen are removed the compensation cost will increase with at least 300%. In total each weekday 10 trains are affected when there is a BTD between Eindhoven and Boxtel. Based on data of 2018 till 2021, each year there is only one weekday that there is a BTD between Eindhoven and Boxtel.

With an LP model, a 20 year cost calculation is made and the decision is made whether the track switches at emplacement Nijmegen should be replaced or removed. In this LP model includes the asset costs (maintenance costs + replace and repair costs), BTD costs, inflation rate, increasing traffic rate, increasing compensation rate (after switches are removed) and an increasing compensation cost rate. With the current (estimated data), the model decided to remove the switches in year 1. This decision gives an objective function of € X. In the event that the switches will be replaced in year 1, the objective function is € X.

The situation at Nijmegen is used as input parameters, a sensitivity analysis is carried out by changing the input parameters. The model did not gave a different decision after changes in the switch type, heater age and increasing compensation rate.

When the number of track switches is below 5, it is cheaper to replace the switches in the first year and when there are 6 switches it is cheaper to remove them in year three. However, in the case of emplacement Nijmegen, at least four switches are needed to change the direction of the train ("kopmaken"). When looking at the increasing traffic rate, only a yearly increasement of 10% will change the decision from removing the switches in the first year to replace the switches in the first year. The compensation rate when the switches are removed have a higher influence, when the compensation rate will increase with 550%, it is cheaper to replace the switches.

7.2 Limitations and recommendations

- There is no data available about past BTD. The number of affected trains, whether a BTD is Ad-hoc and in that case the weight class of the train is not recorded. Ad-hoc BTD have a much higher compensation cost than the other BTD (especially the ad-hoc BTD where trains are still diverted), which could change the decisions of the model. This problem can be solved easily. By creating an file in which record: 1) the track section where the BTD takes place, 2) the number of days that a BTD of more than 12 hours that takes place during weekdays, 3) whether the BTD is ad-hoc or not, 4) the number of affected trains, 5) in the event that the BTD is ad-hoc; the weight class of the train and the extra km that occur after diverting the train

- The maintenance costs are not accurate. At this moment, ProRail divides the total amount of maintenance through the number of track switches. Then they divide these costs proportionally per switch type. Besides that, all switches of the same type have the same life-cycle according at this moment. In practice, switches that are used more often and/or switches on which heavy freight trains are passing by have a lower life-cycle than switches that are barely used. In the case of emplacement Nijmegen, the track switches might have a longer life-cycle and give less maintenance than the average. To improve the maintenance costs, the switches can be divided into three groups according to the usage of the switch: high usage, moderate usage and low usage. Based on the number of trains and the weight of the trains, switches can be added to one of these three groups. After this, the maintenance costs can be divided proportionally among the three groups.

- At this moment the compensation cost after removing track switches is estimated to be at least 300% more expensive than replacing the track switches. In order to receive a more accurate compensation cost, data about the extra kilometers after diverting, extra times that the train needs to change the direction of the train, the number of non-commercial stops and the costs for reschedule the train should be recorded. Then the compensation rate can be calculated by the average cost of all the freight trains that are affected by the BTD.

- Only the case study of emplacement Nijmegen is used to set up the model. In order to make the generic model more accurate, more case studies have to be executed.

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Appendix A Costs of diverting

A.1 Costs of diverting: passenger traffic

As described in Section 2.3.3, for passenger trains that are canceled as result of a BTD during a function maintenance project, the train track is divided into two categories (1 and 2) (ProRail, 2019). Hereby a reimbursement will be paid per canceled km. In Figure A.8.1 all track sections of category 1 are colored in red.

Track sections of category 1:

- Den Helder – Alkmaar – Amsterdam Centraal – Eindhoven – Maastricht / Heerlen
- Woerden – Leiden – Haarlem – Amsterdam Centraal
- Rotterdam Centraal / Den Haag Centraal – Utrecht Centraal – Zwolle – Groningen / Leeuwarden
- Amsterdam Centraal – Amersfoort – Deventer – Enschede / Oldenzaal grens
- Amsterdam Centraal – Schiphol Airport – Den Haag HS – Rotterdam Centraal – Roosendaal – Vlissingen / Roosendaal grens
- Schiphol Airport – Duivendrecht – Lelystad – Zwolle
- Hilversum – Utrecht Centraal – Arnhem – Zevenaar grens/ Nijmegen
- Zwolle – Arnhem – ’s Hertogenbosch
- Roosendaal / Lage Zwaluwe – Breda – Tilburg – Boxtel / ’s-Hertogenbosch
- Eindhoven - Venlo

All track sections that are left, are classified in category 2.

Figure A.8.1 Track sections of category 2 visualized.

A.2 Costs of diverting: freight traffic

The compensation rates of the most frequently used freight routes are visualized in the table below. In case that the BTD takes place on multiple track sections and therefore the usual diverting routes cannot be used, a specific compensation rate is determined on a tailor-made basis.

Track section	Compensation rate
Amersfoort – Deventer	€550
Amersfoort – Zwolle	€330
Amersfoort – Duivendrecht Aansluiting	€770
Amersfoort – Utrecht	€550
Almelo – Mariënberg	€110
Alphen a/d Rijn – Gouda	€330
Amsterdam Centraal – Breukelen	€550
Breda – Roosendaal	€550
Breda – Tilburg	€550
Breukelen – Utrecht	€110
Boxtel – Eindhoven	€770
Boxtel – Vught Aansluiting	€330
Beverwijk – Haarlem	€770
Eindhoven – Roermond	€330
Eindhoven – Venlo grens	€770
Gouda – Harmelen Aansluiting	€330
Herfte Aansluiting – Mariënberg	€990
Haarlem – Amsterdam Sloterdijk	€770
Harmelen Aansluiting - Breukelen	€770
Harmelen Aansluiting – Utrecht	€110
's-Hertogenbosch – Lunetten	€550
Kijfhoek – Lage Zwaluwe	€550
Kijfhoek – Meteren Aansluiting	€550
Leeuwarden – Meppel	€550
Meppel – Onnen	€550
Meteren Aansluiting – Zevenaar Oost	€550
Roermond – Sittard	€1210
Roermond – Venlo	€990
Gouda – Rotterdam Zuid	€330
Deventer – Oldenzaal grens	€770
Sittard – Eijsden grens	€550
Tilburg – Boxtel	€550
Tilburg – Vught aansluiting	€330
Utrecht – Zevenaar Oost	€110
Lage Zwaluwe – Breda	€330
Lage Zwaluwe – Roosendaal	€1210

Table A.1 Compensation rates per affected train per track section. Source: ProRail, 2019

A.3 Additional reimbursement due to disadvantage of ad-hoc capacity

The following rates (Table A.1 and Table A.3) apply as reimbursement of the disadvantage for the freight RUs that is experienced by deviation from previously allocated capacity in that case of not in the annual timetable divided (maintenance) work (ProRail, 2019).

Reimbursement for changed capacity per extra (diverted) km with respect to the original divided km	Rate (per train km)
Additional reimbursement for train path service (depending on weight)	See Table A.4
Additional costs locomotives	€2.57
Additional costs energy	€1.93
Extra costs machinists	€0.99

Table A.2 Additional reimbursement due to disadvantage of ad-hoc capacity. Source: ProRail, 2019

Reimbursement for canceled capacity per extra (diverted) km without alternative (km of the original route)	Rate (per train km)
Total	€5.65

Table A.3 Additional reimbursement due to canceled capacity. Source: ProRail, 2019

Weight class of the train	Rate (per train km)
Up to and including 120,000 kg	€0.7872
From 121,000 kg up to and including 160,000 kg	€0.9840
From 161,000 kg up to and including 320,000 kg	€1.2516
From 321,000 kg up to and including 600,000 kg	€1.7397
From 601,000 kg up to and including 1,600,000 kg	€2.7397
From 1,600,000 kg up to and including 3,000,000 kg	€3.3612
From 3,001,000 kg	€3.6446

Table A.4 Tariff for the use of train paths. Source: ProRail, 2019

There are specific conditions that must be met in order to be eligible for this additional reimbursement (ProRail, 2019):

- Only distribution allowances that are affected by ad-hoc BTD and lead to diverting or cancelling a train, qualify for reimbursement of direct operating costs.
- If deviation from the previously allocated capacity leads to diverting or cancelling of a train.
- A train is considered as canceled when, within six hours of the last divided capacity, there is no alternative path available via the mixed network or the Betuweroute. The train has not run because of the BTD. In those cases, the kilometers on the original path count as the additional reimbursement as calculated in Table A.3.
- The reimbursement only includes direct operating costs.
- The reimbursement only applies if the RU agrees with the planning of the BTD and the deviations from the previously allocated capacity.
- Individual locomotives are excluded from the cancellation rules, but are not excluded from the reimbursement rule.
- Only allocated capacity rights that are known before the new distribution of capacity and that are affected by the new distribution, are eligible for this reimbursement rule.
- Compensation for the disadvantages as a result of a train rerouting will not be reimbursed, if reimbursement is paid for the cancellation of the same train.

Appendix B ILP model

B.1 Sheet: Fixed costs

Figure B.1 Fixed costs sheet.

B.2 Sheet: Parameters

Figure B.2 Sheet Parameters.

B.3 Sheet: Outcome

Figure B.3 Outcome sheet excel solver.

Appendix C Results

C.1 Change in the number of track switches

Switch type	Solution by solver	Asset cost	BTD cost	Objective	Objective of 20 years
1	R_{21}				
2	R_{21}				
3	R_{21}				
4	R_{21}				
5	R_{21}				
6	$\mathbf{R_{33}}$				
7	R_{31}				
8	R_{31}				
9	R_{31}				
10	R_{31}				
11	R_{31}				
12	R_{31}				
13	R_{31}				
14	R_{31}				
15	R_{31}				
16	R_{31}				
17	R_{31}				
18	R_{31}				
19	R_{31}				
20	R_{31}				

Table C.1 Outcome of change in number of switches

C.2 Change in increasing compensation rate

Increasing compensation rate	Solution by solver	Asset cost	BTD cost	Objective	Objective of 20 years
0,0%	R_{31}				
0,5%	R_{31}				
1,0%	R_{31}				
1,5%	R_{31}				
2,0%	R_{31}				
2,5%	R_{31}				
3,0%	R_{31}				
3,5%	R_{31}				
4,0%	R_{31}				
4,5%	R_{31}				
5,0%	R_{31}				
5,5%	R_{31}				
6,0%	R_{31}				
6,5%	R_{31}				
7,0%	R_{31}				
7,5%	R_{31}				
8,0%	R_{31}				
8,5%	R_{31}				
9,0%	R_{31}				
9,5%	R_{31}				
10,0%	R_{31}				

Table C.2 Outcome of changes in the increasing compensation rate.

C.3 Change in increasing traffic rate

Increasing compensation rate	Solution by solver	Asset cost	BTD cost	Objective	Objective of 20 years
0,0%	R_{31}				
0,5%	R_{31}				
1,0%	R_{31}				
1,5%	R_{31}				
2,0%	R_{31}				
2,5%	R_{31}				
3,0%	R_{31}				
3,5%	R_{31}				
4,0%	R_{31}				
4,5%	R_{31}				
5,0%	R_{31}				
5,5%	R_{31}				
6,0%	R_{31}				
6,5%	R_{31}				
7,0%	R_{31}				
7,5%	R_{31}				
8,0%	R_{31}				
8,5%	R_{31}				
9,0%	R_{31}				
9,5%	R_{31}				
10,0%	R_{21}				

Table C.3 Outcome of changes in the increasing traffic rate.

C.4 Change in compensation rate

Increasing compensation rate	Solution by solver	Asset cost	BTD cost	Objective	Objective of 20 years
100%	R_{31}				
150%	R_{31}				
200%	R_{31}				
250%	R_{31}				
300%	R_{31}				
350%	R_{31}				
400%	R_{31}				
450%	R_{31}				
500%	R_{33}				
550%	R_{21}				
600%	R_{21}				
650%	R_{21}				
700%	R_{21}				
750%	R_{21}				
800%	R_{21}				
850%	R_{21}				
900%	R_{21}				
950%	R_{21}				
1000%	R_{21}				

Table C.4 Outcome of change in compensation rate.

C.5 Ad-hoc BTD

Ad-hoc if random number >	Solution by solver	Asset cost	BTD cost	Objective	Objective of 20 years
1	R_{31}				
1	R_{31}				
1	R_{31}				
2	R_{31}				
2	R_{31}				
2	R_{31}				
3	R_{31}				
3	R_{31}				
3	R_{31}				
4	R_{31}				
4	R_{31}				
4	R_{31}				
5	R_{31}				
5	R_{31}				
5	R_{31}				
6	R_{31}				
6	R_{31}				
6	R_{31}				
7	R_{31}				
7	R_{31}				
7	R_{31}				
8	R_{31}				
8	R_{31}				
8	R_{31}				
9	R_{31}				
9	R_{31}				
9	R_{31}				

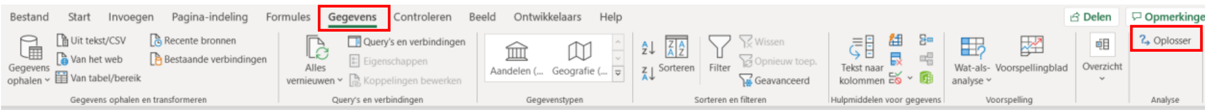
Table C.5. Outcome of ad-hoc BTD.

Appendix D User manual

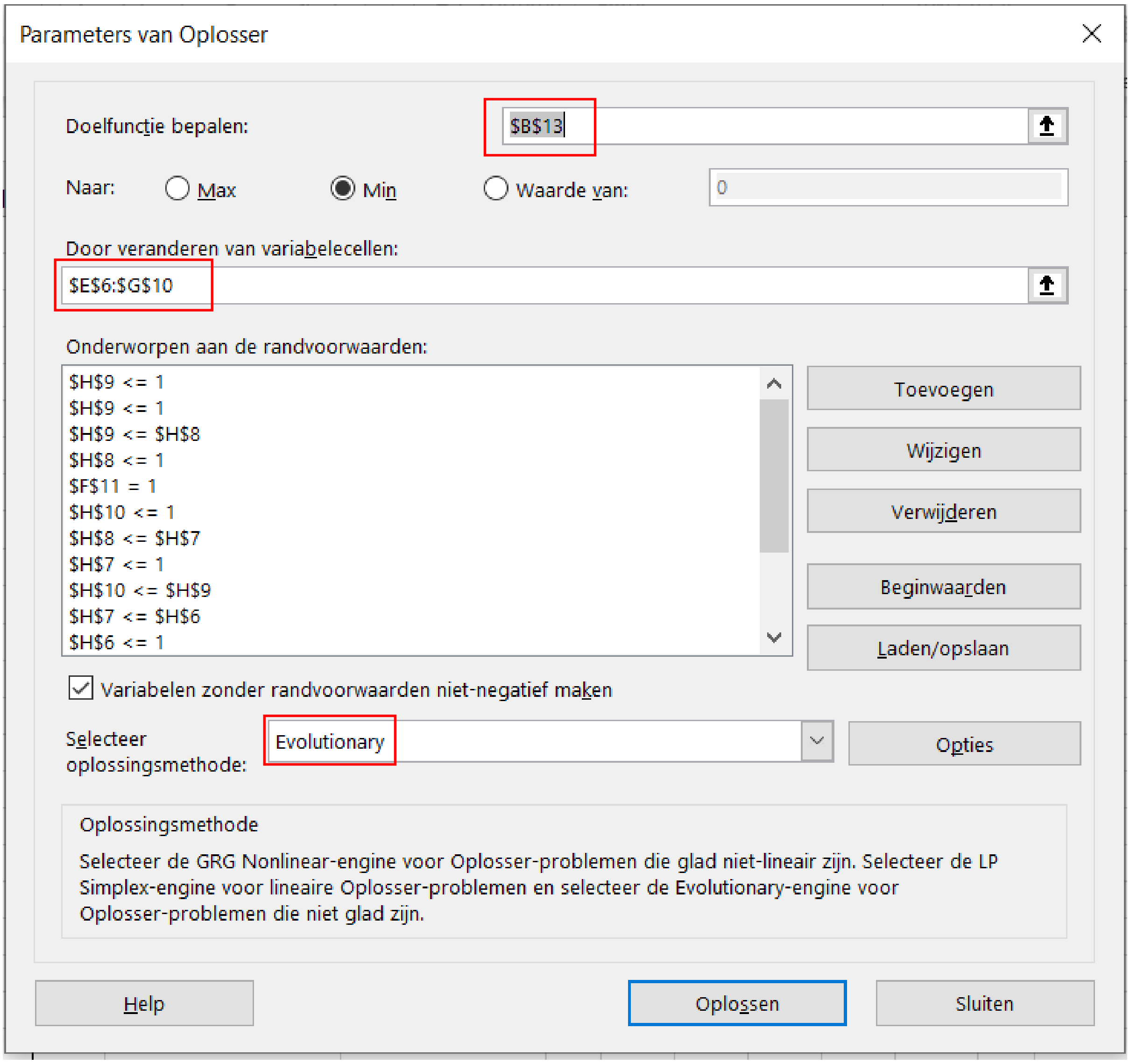
In this chapter a user manual is written. To begin with, only cells that are colored in grey can be adapted. Under the “Parameters” sheets the data about the BTD and switches can be entered (see Appendix B.2). In the same sheet also the inflation rate, increasing traffic rate, compensation rate and increasing compensation cost can be filled in. The next sheet “Outcome” calculates the objective. The outcomes can be calculated by the excel solver and by a Do-It-Yourself option.

To use the excel solver the following steps must be followed:

1) Go to “Data” → “Solver”



2) Make sure that the solution method “Evolutionary” is used, the goal function is cell “B13” and the variable cells are “E6:G10”



3) Then press the “solve” button. After a few minutes the solver will give the optimal solution.

To use the DIY method the gray cells in Figure D. can be changed to every possible solution. Reminder: only one solution can be made, so only one cell can be filled with the number 1. Furthermore, due to reaching the end of life-cycle in the fifth year it is not possible to have R_{15} =1.

Figure D.1 DIY method