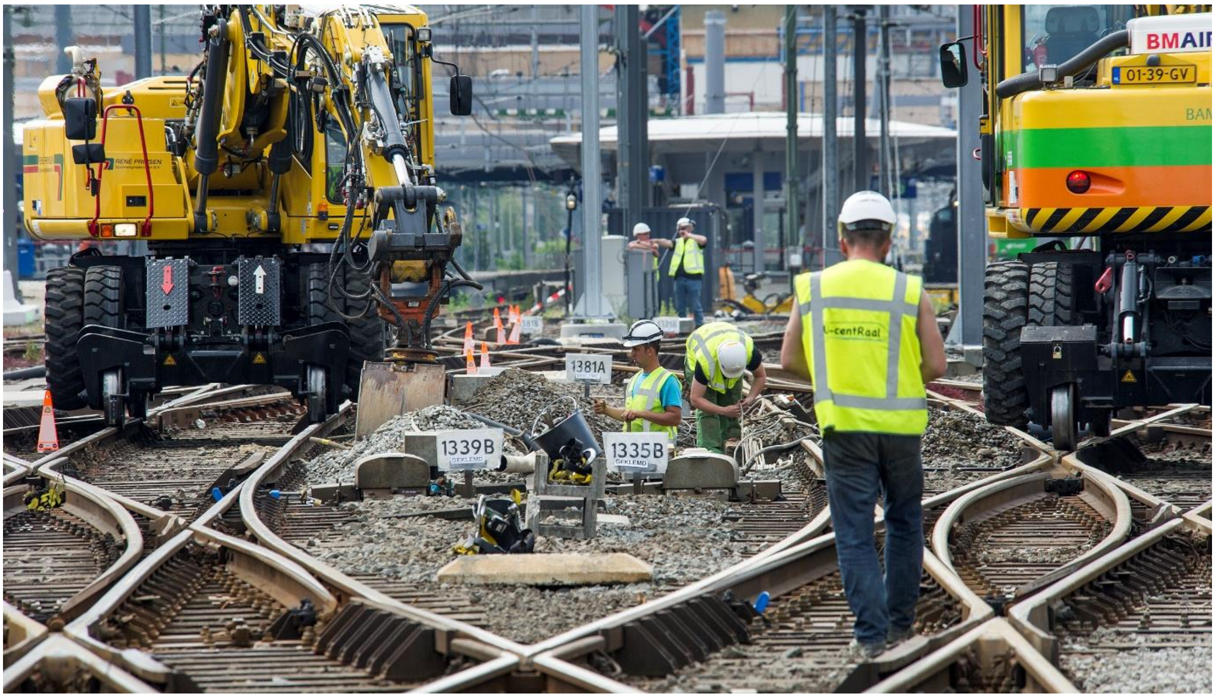
Improving the Planning of Train Infrastructure Maintenance



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Sietske & Duuk
Bedankt.

Improving the Planning of Train Infrastructure Maintenance

CREATING INSIGHT IN THE EXPERIENCED NUISANCE AND FINANCIAL IMPACT OF TRACK POSSESSIONS BY OPTIMIZING THE MAINTENANCE PLANNING

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Management Summary

The *motivation* for our work is the challenge ProRail is having with their maintenance planning process. The *main problem* is that standard practice at Prorail is to not plan more than 4 years ahead. This leads to a lack of overview for tactical decisions and unused opportunities to reduce nuisance. Nuisance will be based on the expected number of passengers during track work multiplied by the amount of experienced nuisance. The experienced nuisance is based on the expected extra time people travel by bus or train, when there is track work. When track work is done, a part of rail infrastructure is reserved for that purpose. This is called a possession. Possessions signify which tracks are out of service, at what date and for what duration. By moving possessions from various years to the same year possessions could be clustered together, and as such reduce the amount of nuisance. Moving possessions will induce some cost, for example for extra maintenance or the early write-off of assets. We use a fictive cost model, to proof the benefits of our planning process. Our main goal is to create a method which determines which possessions, from a period of five years, should be performed together. This method should be able to optimize the balance between induced experienced nuisance for passengers and financial impact (and steer tactical decision making on track work planning). The possessions that are considered are those longer than four hours and which can be planned two years ahead. Furthermore, we will look at combining possessions that are on unique parts of tracks that can be completely replaced by busses or a detour. For our *approach* we created an integer linear model, which is solved using CPLEX and a compound heuristic. The compound heuristic consists of a greedy construction heuristic and two local search steps: Steepest Hill Climbing and Simulated Annealing. Our *findings* are that CPLEX could be used in the Netherlands, where there are not more than 22 possessions. When there are 22 possessions the computation time of CPLEX is 2,2 hours. Using the compound heuristic, were able to reduce the computation time by 90%. This was done with an average gap of 0,09% for the CPLEX configuration. To *conclude,* this research gives ProRail understanding how to cluster possessions on the middle-long-term, which will lead to more control over the amount of nuisance and the financial impact. Our *recommendations* are that ProRail should initiate a cultural change, reducing the focus on available data and promoting the prediction of future track work requirements. Work more towards planning instead of solely on scheduling.

Content

Glossary

Bussable part of track	A *bussable part of track* is the combined amount of track that can still be replaced by busses or a detour, as defined by NS. The Netherlands is divided into 96 unique *bussable part of track*s, without any overlap. Each bussable part of track consist of multiple uninterrupted *track segments*. All the bussable part of tracks can be found in Appendix Bussable part of tracks F.
Clustering	By clustering two or more *possessions*, we assume that they will be performed at the same time. Multiple *possessions* in one cluster on the same *bussable part of track* lead to a reduction in *nuisance*.
Combining	See *clustering*.
ETM	Measurement for experienced amount of extra travel time for a train passenger due to a *possession* at ProRail "Dutch: Ervaren reizigers minuten".
Nuisance	The amount of experienced nuisance a *possession* gives on a *bussable part of track*. In our research nuisance will be measured using *ETM* multiplied with the expected number of passengers during a *possession* on that *bussable part of track*.
Pm	The measurement for *nuisance* is in pm (passenger * minutes). Which tells how many passengers, experience how many minutes of *nuisance*.
Possession	Moments that are used for track works are called *possessions*. A *possession* could contain various type of track works at the same time. One or more *track segments* could be occupied during a *possession*.
Track segment	A track segment is used to refer to all parts of the rail infrastructure between two consecutive stations. If there is track work on a station in general that means two consecutive *track segments* are used in the *possession*. So, in size: Dutch railway infrastructure -> bussable part of track -> track segment -> components (e.g. rail track, catenary, signs)

1. Introduction

In this thesis we will suggest a method for improving the train maintenance planning process at ProRail. We will first introduce ProRail and explain the current maintenance planning. This will lead to the formulation of our research questions. Finally, we will give an overview of the structure of the rest of the thesis.

1.1 ProRail

1.1.1 Description of ProRail

The mission of ProRail is to enable pleasant travel and sustainable transport, and to connect people, cities and companies, now and in the future. ProRail is responsible for the Dutch rail infrastructure: construction, maintenance, management and safety. They control all train traffic and build and manage all stations and tracks. To give an impression of the complexity of this objective, the Dutch rail infrastructure contains 7.219 km of track, 404 stations, 56 bridges, 15 tunnels, 12.092 signals, 7006 switches and 2368 railroad crossings. On average, there are 1,1 million passengers per day and 3,3 million freight transport trains per year (ProRail, 2016).

ProRail has the following functions:

a) Deliver train paths (construction and maintenance)
b) Capacity management (management)
c) Controlling of rail traffic (safety)

a) To deliver *train paths*, the required infrastructure to go from A to B, ProRail is responsible for the construction and maintenance of the infrastructure. The clients of ProRail are the railway undertakings: passenger transporters, freight transporters and maintenance control companies. To deliver these train path, the infrastructure is maintained, renewed and modified. All the work on the infrastructure is outsourced by so-called “performance-oriented maintenance contracts", where the four biggest maintenance contractors are: Asset Rail, Strukton, VolkerRail and BAM. In these contracts a precise description is given of what is expected with respect to quality. Contractors are responsible to achieve this quality. ProRail does not tell the contractors how to carry out the maintenance, but evaluates the quality by using several modern measuring instruments, and by monitoring and analysing the disturbances (Improverail, 2002; Budai-Balke, 2009). Figure 1 gives an overview of the relation between ProRail and its Clients.

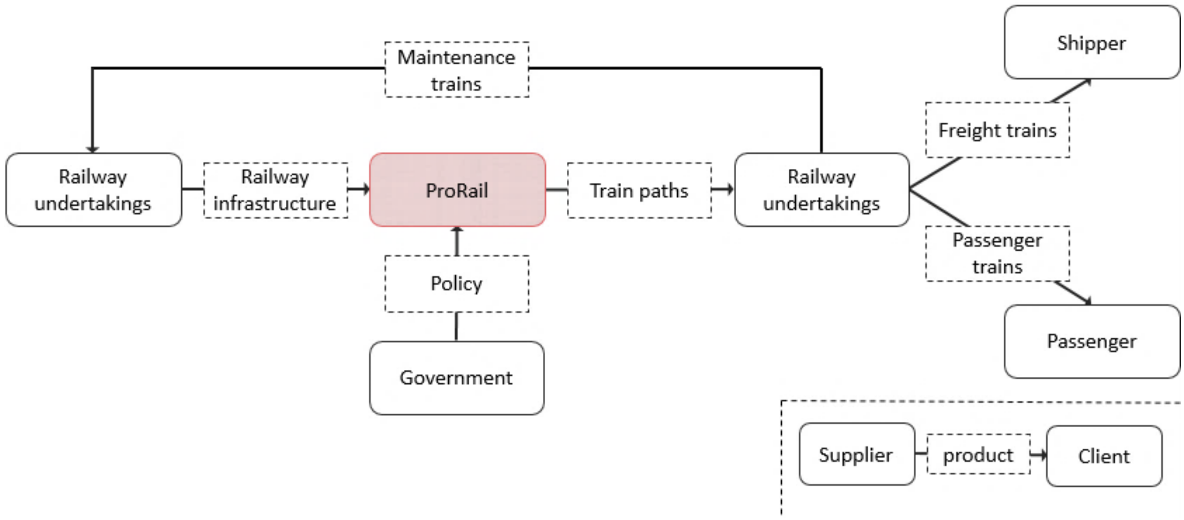

Figure 1 flow diagram of products, client and supplier. (Jonge, 2018)

b) Capacity management is the task of determining when, what infrastructure is used for which function. The function could for example be: transporting passengers or maintaining the infrastructure. This is difficult, because there is a constant conflict between improving the infrastructure and using the infrastructure.

c) Controlling of rail traffic, ProRail is controlling all passenger and freight trains. There are thirteen traffic control centres throughout the Netherlands. They make sure that all trains leave and arrive on time. Furthermore, they are the centre of management during calamities and try to reduce the amount of conflicts that arise.

The goal of this thesis is to improve the availability of train paths. The department *Possessions* (In Dutch: *Buitendienststellingen)* is the client of this research. How this department is positioned within ProRail is shown in Figure 2. The department *Possessions* plans possessions; a possession is a moment that is used for work on the infrastructure.
A possession contains one or more (different type of) track works at the same time. One or more *track segments* could be occupied during a possession. A track segment is used to refer to all parts of the rail infrastructure between two consecutive stations. The track works could be on the same track segment. So, it is what track segments cannot be driven during which period, so to rail path is not delivered.

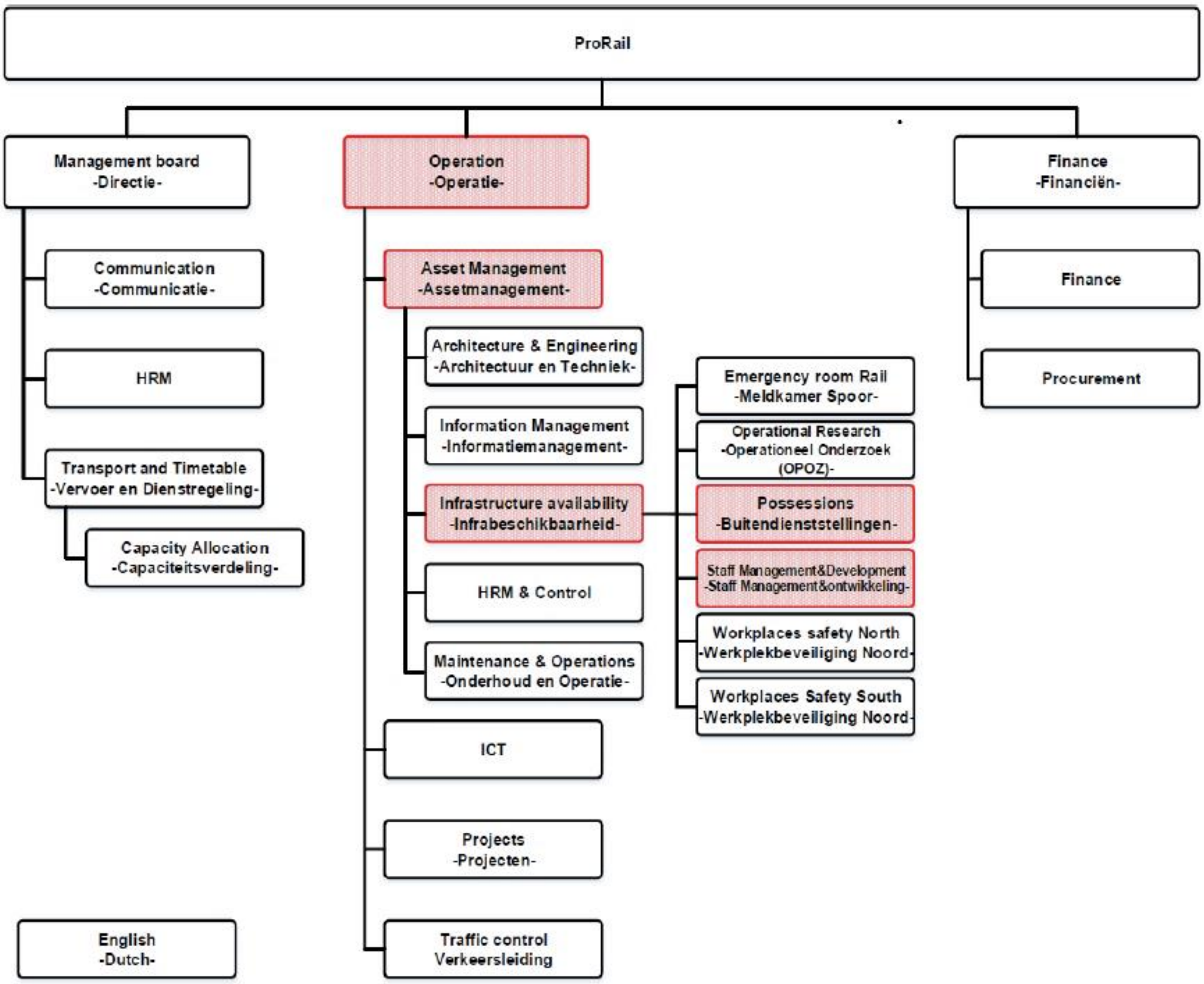

Figure 2 Organogram of ProRail (Jonge, 2018)

1.1.2 Current planning process at ProRail

The planning of possessions involves various departments of ProRail, both regional and national. The process involves more than 200 people, and many decisions. Among others: "what assets need maintenance?", "what type of renewal should ProRail do?", "when do they need maintenance?", "can we cluster them with other possessions?" and "is there enough work capacity on the market to do all the possessions?". All these different aspects make the planning of work on the infrastructure a very complex process. We will first explain the various type of work on the infrastructure, following on this we will explain how the various type of work are planned, and which departments are involved.

Work on the infrastructure, track works, can be categorized into two major classes: (i) *maintenance* and (ii) *renewal*. Within maintenance the two categories are: *preventive* and *corrective maintenance*. An overview of all the type of track works can be seen in Figure 3.

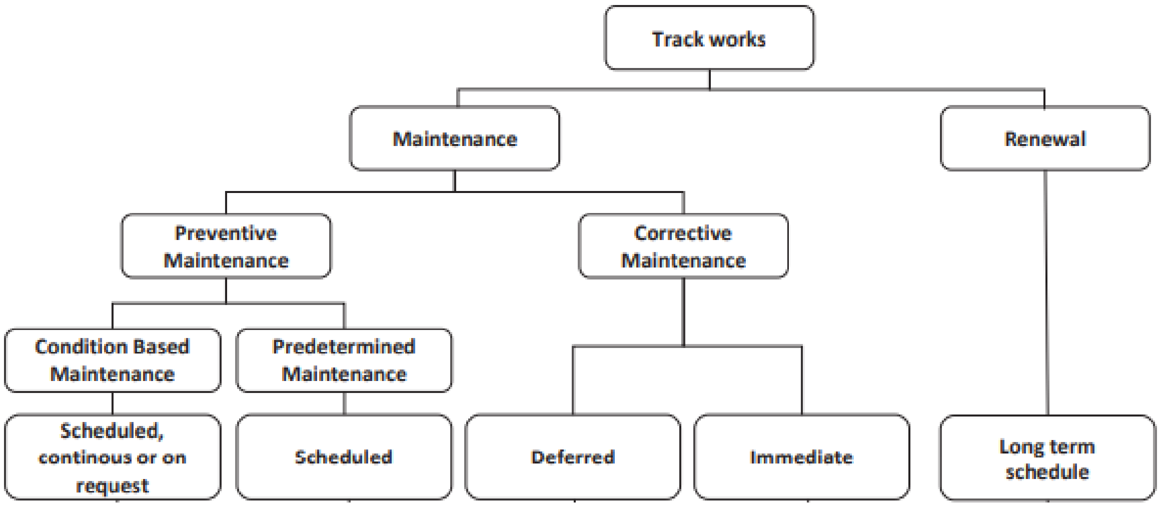

Figure 3: Possession requirement for maintenance and renewal of railway infrastructure adapted from (Paragreen, 2010) taken from (Famurewa, 2015)

a) Maintenance

Preventive maintenance itself can be categorized into two classes: *Predetermined maintenance* and *Condition-Based Maintenance* (CBM). *CBM* is being performed given a certain input reaching a threshold. The type of input could be sensor data or any other direct monitoring method. Given a certain condition, the maintainer will plan a maintenance possession. At ProRail for example, monitoring could be: measuring the thickness of the overhead line. The corresponding condition is then: if the line is thinner than one-centimetre, initiate action. The corresponding action is: replace the overhead line. We will also include age-based maintenance. At ProRail, if an asset is a certain number of years away from the theoretical replacement age, the asset will be inspected. If the condition of the asset is not up to standards it needs to be replaced, otherwise a new age will be determined. A classical assumption in CBM modelling is that the system failure can be explained by a deterioration process (Ahmad & Kamaruddin, 2012; Deloux, Castanier, & Bérenguer, 2009). *Predetermined maintenance* is also known as systematic preventive/time-based maintenance (TBM). TBM schedules are typically determined based on a probabilistic model of system failure. TBM policies are developed based on historical failure data (Alaswad & Xiang, 2017)

Corrective maintenance, is a reactive approach to maintenance because the action is triggered by an unscheduled event. This type of maintenance has a high priority because failure is most common cause for those maintenances. Therefore, this maintenance must be done urgently, therefore the scheduling and planning of this type of maintenance is difficult to do in advance.

b) Renewal

At ProRail, renewal is divided in *change of function* and *local projects*. *Change of function* includes possessions that involve a change in the current rail infrastructure network. For example, if the railway undertakers (passenger transporters, freight transporters) would like to drive more trains on a route, this could imply an extra railroad switch should be placed. Placing this switch is a change of function. *Local projects* are infrastructure projects initiated in the Netherlands by local governments who would like to alter the surroundings of the rail. For example: removing a crossing, placing a tunnel or placing a sound wall.

Each possession result in delay experienced by travellers. Nuisance is the amount of deviation in travel time compared to the normal train service times the number of expected passengers. At ProRail, the amount of deviation in travel time is measured in extra amount of experienced travel time (ETM). ProRail, Locov[1] and NS together created estimations for extra travel time for each part of track in the Netherlands if it would be out of service. ETM is based on how many minutes of extra travel time a passenger experiences whether he/she needs to take busses or a detour. Furthermore, within ProRail there are different categories for the duration of a possession. An overview of the different categories can be seen in Table 1. The separation at 52 hours comes from the amount of work that can be performed in a weekend as defined by ProRail. It starts on Saturday at 1:00 and ends on Monday at 5:00.

Table 1 Nuisance categories from ProRail

Category	Requirements	# Possessions in 2018	Avg. execution time (Hours)
U	Possession time ≥ 52hr	409	379
R	Possession time > 4hr < 52hr	2686	22
A	Possession time ≤ 4hr	505	3,7
V	Possession without nuisance	X	X

[1] Locov is a collaboration of consumer organizations where they represent the interests of the train passenger.

1.1.3 Planning of various type of maintenance

The track works planning process for rail infrastructure can be described in eight steps: 1) Budget determination, 2) Long-term quality prediction, 3) Project identification and definition, 4) Project prioritization and selection, 5) Possession allocation and timetabling of track possession, 6) Project combination, 7) Short-term maintenance and project scheduling, 8) Work evaluation and feedback loop (Budai-Balke, 2009). In this thesis the focus will be on step 3 up to step 6, these steps are structured at ProRail as show in Figure 4

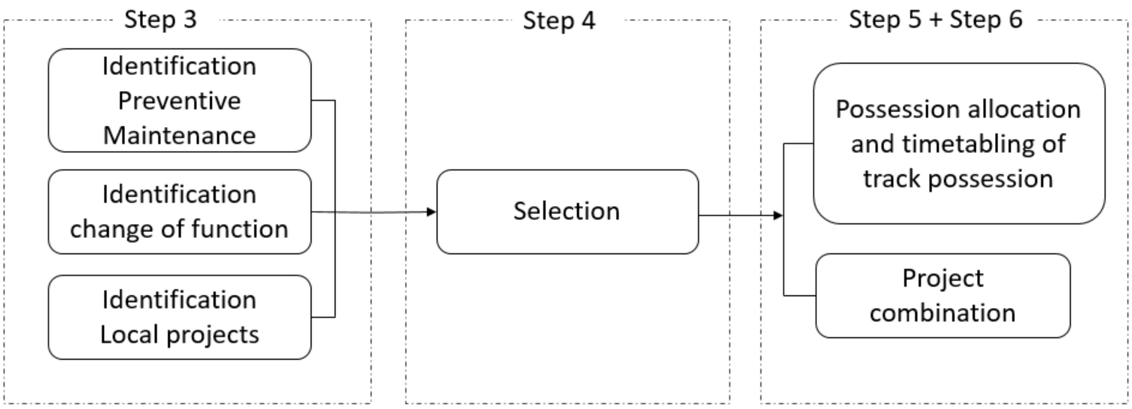

Figure 4: Three steps to describe the current track planning process at ProRail. With the steps above associated with the steps identified, for describing the planning process, by (Budai-Balke, 2009)

At ProRail, possessions smaller than 4 hours are planned in a different way compared to the category type R and U possessions. There is a separate schedule in which type A possessions are planned. This type of possessions are mainly below four hours. There are fixed routine nights in which these possessions can be performed, as such it does not give a lot of nuisance for passengers.

Preventive maintenance is planned based on regionally identified work. Further explanation about the identification can be found in Appendix C. Different maintenance activities are clustered into a maintenance project, which creates the advantage of one setup time and could also induce economic scale advantage. Now, maintenance is identified three years ahead, for each year separately. During the identification of preventive maintenance, the people in the region also determine the preferred year of execution. *Changes of function* are planned by ProRail, based on the requests of railway undertakers. The amount of years before the change of function should be performed can vary between two and six years. *Local projects* are planned by ProRail based on the requests of local governments. They imply a year for when they would like the activity to be performed (deadline). Because the local governments gather their own budget, the local projects have a higher priority.

Step 4, estimations are made whether all track works, of a year, could be performed in one year. The workability is tested mainly on the amount of work, amount of personnel for executing work and budget constraints.

Step 5+6, track work gets a possession with a date of execution. Furthermore, they look at which possessions can be performed together, to reduce the amount of possessions in a year. This step happens on trial and error, combinations are created based on instinct. Combinations must be checked by rail system engineers. Rail system engineers are responsible for designing the track works, so they can determine whether work can be performed together. Step 5 and 6 are performed two years before the execution of track work. Each year is planned individually.

Track works possessions planning usually involves recurrent interaction between different departments. For example, after step 4, track work possessions regularly return to step 3. Eight departments are involved in ProRail's track work planning process. For each department, a detailed description of their focus, responsibilities, and influence on the planning process is included in Appendix C.

The current track works process is mainly focussed on short-term planning (three years ahead), while middle-to-long term planning (7 years ahead) is undervalued. This is also recorded in literature, where they performed a study across railway infrastructure managers in Europe. They confirm that long possession windows for maintenance are planned 18—24 months in advance (Paragreen, 2010). ProRail's focus lies with routine decisions and short-term track work planning. Furthermore, instead of having a proactive planning process for track works they have a re-active planning process. The planning of track works is highly depending on the needs, instead of looking ahead what could be a smart planning.

1.2 Problem definition

In the current situation, *maintenance* is planned based on the work that is regionally identified. *Renewal* is planned by ProRail based on the requests of railway undertakers and local governments. Lack of communication and overview often leads to *possessions* being planned in the same area multiple times in a five-year window. *Possessions* the same area could be better combined to create less *possession* over five years. Resolving this lack of planning, which is the primary aim of this thesis, can as such dramatically improve ProRail's *possessions* planning process. Furthermore, it improves ProRail's decision-making capability by giving insight into the total amount of nuisance and financial consequence for a planning further in the future. Finally, it will help to control the balance between *cost* and *nuisance*, by actively steering on these two factors.

1.2.1 Scope

The focus of our research is part of step 5 and 6 from Figure 4, possession allocation and timetabling of track possession and possession combination. We will only look possession category U and R (possessions larger than 4 hours), which can be planned at least two years in advance. So far, we specifically discussed track works, but we consider any possession that takes more than 4 hours and that can be planned at least 2 years in advance. The impact, of leaving out category A possessions is very low. This can be seen by the fact that category U and R caused 99%[2] of the possession time in 2018.

We will look at *clustering* possessions, on a *bussable part of track*, to minimize the amount of possessions necessary. A reduction in the amount of possessions directly reduces *nuisance experienced* by travellers, but it might increase the *cost* of the track work possessions in the possession. We will now explain the following concepts: *Clustering*, *bussable part of track*, *which possessions can be clustered*, *nuisance impact* and *impact on cost.*
Clustering will be done by combining possessions, on the same *bussable part of track,* that should take place simultaneously. A *bussable part of track* is the combined amount of track that can still be replaced by busses or a detour as defined by NS. The Netherlands is divided into 96 unique bussable part of track, without any overlap between different bussable part of tracks. So, each part of track is part of a unique bussable part of track. Den Haag HS and Rotterdam Central is an example of a bussable part of track, see Figure 5. So, the track between Den Haag HS and Delft is only part of the bussable part of track Den Haag HS and Rotterdam Central. All the bussable part of track can be found in Appendix F "Bussable part of tracks".

Which possessions can be clustered is not part of this research. We assume it is known which possessions can be performed simultaneously. Now at ProRail, it takes a lot of time to determine for possessions whether they can be performed simultaneously. This is especially valid for possession on the same *track segment*[3], the rail infrastructure between two consecutive stations, because track work could need the same part of the rail. For example, sleepers are under the track while the power cable of the train is above the track, they both use the track for maintenance. Sometimes, it is still possible to cluster this type of track work, but it needs careful scheduling in the execution timing and placing of work. Therefore, it is difficult to generalize the clustering of track works on the same track segment. Clustering possessions that are not on the same track segment do not have this problem, and so yield a higher chance of possessions being performed simultaneously. For example, in Figure 5, the possessions of 2022 and 2023 are both on track segment 6, as such yield a lower chance of being able to be performed simultaneously. For this thesis we will create the list, which possessions can be combined, by looking which possessions are not performed on the same track segment but still on the same bussable part of track. This type of clustering is almost[4] always allowed.

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[2] $0{,}99 = \frac{(409*379)+(2696*22)}{(409*379)+(2696*22)+(505*3{,}7)}$ (see Table 1)
[3] If a possessions takes place on a station that means two different track segments are possessed. The numbers 1 to 6 in the leftmost image of Figure 5 represent different track segments.
[4] Almost, because there is some track work that needs connectebillity by rail. As such, they cannot be enclosed by other possessions. In practice this list could be altered based on the projects that couldn't be combined.

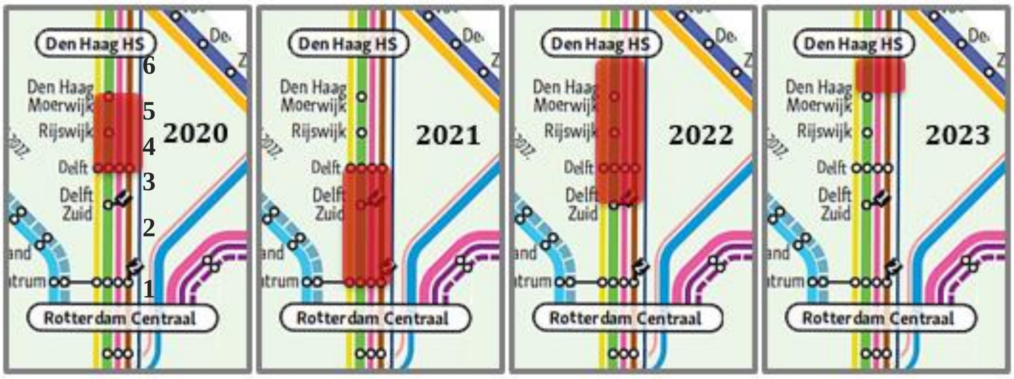

Figure 5 Example of the planning of four possessions over four years, between Den Haag HS and Rotterdam Central. Highlighted in red is one possession, of a year. In the leftmost image the numbers, right of the track, one to six represent different track segments, for example Den Haag HS- Moerwijk is 6.

The effectivity of the possession planning is measured in the amount of nuisance and financial cost. In rail infrastructure management, there is a continuous tension between the financial impact of track works and the nuisance as experienced by travellers. For ProRail to be able to adequately assess this tension and optimise its decisions surrounding possession planning, it is important to have a clear picture of estimated nuisance and the financial costs a possession planning gives.

Nuisance impact is measured by looking at the number of passengers that would normally travel on this bussable part track during a possession, multiplied by the estimated amount of extra experienced amount of experienced travel time. This will be further explained in Section 3.1.3. The bussable parts of tracks can be optimised independently of each other, when combining possessions. Furthermore, taking out a larger part of the bussable part of track once is better compared to taking out two smaller part of tracks twice. This assumption comes from the number of travellers that travel between the smaller stations. For our example the number of passengers between Den Haag Moerwijk, Rijswijk, Delft, Delft Zuid, Schiedam is relatively small, compared to the passengers between Den Haag HS and Rotterdam. This can be seen in Table 2, where the variation between different stations is low compared to the average amount of travellers. We assume that if there is a possession on a bussable part of track, that the whole bussable part of track will be out of service.

Table 2 Average number of travellers between two locations.

Location 1	Location 2	Avg. passengers peak[5]	Avg. passengers off peak
Den Haag HS	Den Haag Moerwijk	36.381	43.560
Rijswijk	Den Haag Moerwijk	36.837	44.140
Rijswijk	Delft	36.899	44.224
Delft	Delft Zuid	35.651	42.506
Schiedam Centrum	Delft Zuid	35.615	42.480
Schiedam Centrum	Rotterdam Central	35.900	42.934

[5] Average has been taken over all days in 2017. Peak hours are on Monday till Friday between 6:30-9:00 and 16:00-18:30.

*Financial impact, s*hifting possessions over years has a certain amount of financial impact. By shortening the life of an asset, you will have some financial impact. By postponing maintenance possessions, you can also have some increase in cost, because you might need to do extra maintenance to keep the asset running. Handling the financial impact of possessions by shifting them over time compared to an expected year will be part of this research. Now it is not clear at ProRail how cost will change by shifting possessions to another year. Therefore, fictive numbers are used to both model a steady increase in cost per year and a financial penalty for performing possessions after a preferred year.

We assume that preferred year, financial impact for different years, track segment and nuisance estimation of possessions are known. Therefore, we assume the total work to consist of a given amount of known possessions. Furthermore, to narrow down the scope of this research, we will focus on passengers and not on cargo.

To select the right week in a year to perform the possessions, the national coherency is also relevant. The national coherency, are rules for which bussable part of track can have a possession at the same time. This selection step would be the next step in the planning process, and is suggested as valuable future research. Summarizing we will I) cluster possession on a bussable part of track and II) suggest a year the clusters could be performed.

1.3 Research Questions

Main question

How to minimize the nuisance and financial impact for train travellers by determining which possessions should take place simultaneously in a two to seven year period?

1.3.1 sub questions

In line with the research objective and goals, the following research sub questions are stated:

Q1 - What is written in literature concerning possession planning on the medium-to-long term?

- What are characteristics of a possession planning?

Q2 - How to formulate a mathematical formulation to describe the possession planning?

- What are good planning process performance measurements?
- What KPI's are related to planning?

Q3 – What method should be used to determine the allocation of possessions over years?

- What methods are available to solve this mathematical formulation?
- Which methods are suitable for the situation at ProRail?

Q4 – What is the performance of the method to combine possession of multiple years?

- What is the impact on nuisance and financial cost?
- What parameters have a strong influence on the method to create the planning compared to other parameters?
- How does the method react to different circumstances[6]?
- Is the algorithm valid to use in the situation of ProRail?

Q5 - What are recommendations for ProRail?

- What steps should be taken to implement this algorithm and by who?
- What will happen to the performance of planning of ProRail if they would implement this algorithm?
- What other recommendations are noted for ProRail during this research?
- What is the biggest risk for implementing these recommendations and how can this risk be managed?

[6] Circumstances can be defined as different situation, for example the number of projects, the spread of the projects, the durations of the projects etc.

1.4 Overview of the thesis

In this thesis the sub questions will serve as handles to answer the main question. The sub questions are also leading for the creation of chapters. This chapter, Chapter 1, functioned as an introduction and to explain the research questions.

Chapter two

What is written in the literature concerning a maintenance possession planning on the medium long term? We will start by making a literature architecture plan. This plan will contain the important key words, questions that will be used in the different search engines[7]. The architecture plan will be used so the results, that will follow from a query, will be focussed on our research questions. Using this method, we found a review on rail track maintenance planning. This review is used as a basis to create our own review on the work relevant.

Chapter three

How to formulate a mathematical formulation to describe the maintenance planning problem? Based on literature and the needs from ProRail we will formulate a model which can help to describe the problem. First, we will put the problem description down in words, after that we will give a mathematical description of the model.

Chapter four

What method should be used to determine the allocation of possessions over years? Literature will be used to determine what are suitable heuristics to solve the mathematical model created in Chapter three.

Chapter five

What is the performance of the algorithm? Different heuristics will be tested and compared with an exact solution. Furthermore, a case will be used to see what the heuristics could in a real-life situation.

Conclusion and recommendations

What are recommendations for ProRail? The experience gained by walking at ProRail for more than six months will be used to write the conclusion and recommendations.

[7] Web of science, Scopus, Google Scholar. Databases: ScienceDirect, JStor, MathSciNet and Emerald

2. Literature review

Planning of rail infrastructure maintenance has already been researched for some decades. Over these decades, different approaches, models and method have been created in relation to planning of rail maintenance. In this part, we will first discuss different researches that have been executed, including why and how this work is relevant for our research. This will form the theoretical basis on which we base our mathematical model.

2.1 Review

For an overview of all the research that has been conducted until 2014 regarding rail maintenance, the work of (Lidén, 2015) is suggested. Lidén (2015) did an extensive literature review to map all research performed on the different maintenance planning facets. The focus is put on the coordination of train traffic and maintenance projects. Explanation about actual maintenance work itself and the degradation of assets are not included. It is very useful for orientation in the broad world of maintenance scheduling and planning, more than 75 different researches are considered.

For us the interesting works from Lidén (2015) are on possession scheduling, in order to minimize possession time and maintenance cost: (Budai, Huisman, & Dekker, 2006), (Budai-Balke, 2009), (Pouryousef, Teixeira, Sussman, & Link, 2010) and (Jenema, 2011). Furthermore, we will gain insight into model features by studying the following more recent works: (Caetano & Teixeira, 2016) and (Pargar, 2015; Pargar, Kauppila, & Kujala, 2017).

The framework of this research is the work of (Budai-Balke, 2009; Budai et al., 2006), in which different heuristics and an exact method are compared to solve the *preventive maintenance scheduling problem* (PMSP). The following items are the main features of the model:

- Preventive maintenance is planned in deterministic time slots (weeks) in a two-year period. The preventive maintenance they plan consist out of routine projects and undefined projects. Some routine works and projects may be combined to reduce the possession cost, but others may exclude each other. A list of projects that need to be performed in the planning period, duration and the earliest and latest possible starting times for each project are assumed known. Figure 7 is an example of a possible planning solution generated by (Budai et al., 2006))
- The objective is to minimize track possession costs and the maintenance costs.

$$\text{Overall cost } = possession\ cost + maintenance\ cost + penalty\ cost \quad (2.1)$$

The *possession cost* is only dependent on the time slot t. It is assumed that each activity gives the same amount of nuisance. *Maintenance cost* are the cost for executing a possession. Usually, *maintenance costs* are due to manhours, materials, loss of production, environmental damages or safety consequences (Budai-Balke, 2009). The Maintenance cost are assumed the same for each time slot within the planning horizon. The *maintenance costs* of each routine work and project and the costs of having a track possession in the planning period are assumed known. The *penalty cost*, are cost for executing routine maintenance before maintenance was necessary.

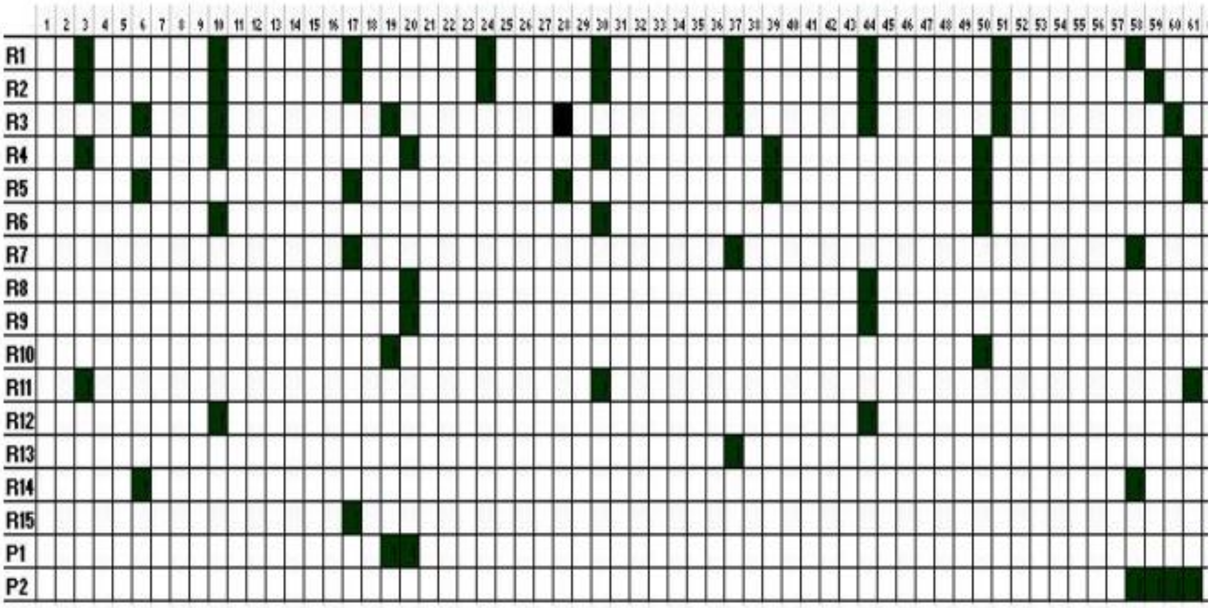

Figure 7 example of a maintenance schedule for 61 weeks containing 15 routine works (R1-R15 on Y-as) and 2 projects (P1 and P2 on Y-as) (Budai et al., 2006)

To escape local optimum, local search methods can be used. Within Memetic Algorithm and Iterative Heuristics, they looked at two local search methods: Simulated Annealing (SA) and Tabu-search. From these two Budai-Balke (2009) concluded that SA tended to give the best results in general. Out of 80 test instances, 49 times, SA gave a lower objective value than Tabu-search (TS). This leads to the conclusion that we will also use SA, as stochastic local search method.

Pouryousef et al. (2010) has created an extension to the model of (Budai-Balke, 2009). The following shortcoming in the model of Budai-Balke et al. is noted: the model is not sensitive to the simultaneous planning of several segments. Therefore, it might cause some mismatching between different segments for one maintenance action. An upgraded model of PMSP is created, called Multi-segment PMSP model. This model is solved using LINDO. An alteration is created by consideration varied maintenance actions and relevant cost through every segment dependently.

Jenema (2011) also looked at the minimization of track possession costs and the maintenance costs. She has created an alteration to the PSMP, which is solved using branch-and-bound and the Gurobi solver. She used the segment system of (Pouryousef et al., 2010), but created an alteration on the possession sizes. These are the special features of her research:

- A distinction is made between possession cost at night than during day.
- The size of the possessions is depending on the maintenance activities that are planned in the possession. The different sizes of possession are predetermined.
- Furthermore, a top 10 maintenance activities are determined that are influencing the possession planning in such a way that the top 10 could solely determine the possession planning. This list is determined by an analysis on a benchmark on realization data and discussion with experts. This list consists of routine maintenance activities, which can be performed between a minimum possession duration of 0,5 and 6 hours.

After the review of Lidén (2015) there are two more recent literature studies carried out, which we will discuss. The work of (Caetano & Teixeira, 2016) and (Pargar, 2015; Pargar et al., 2017)

Caetano & Teixeira (2016) have created a model to determine for each time slot whether renewal of ballast, rail and sleepers in different track sections of a bussable part of track will take place. As operational constraint of the model, it is assumed that the track component in each of the track segments is only renewed once during the planning time window. Furthermore, the model also incorporates the decision to reuse railway track components from other tracks in renewal operations, to discount the maintenance cost. Finally, they also determine the number of maintenance activities for each track component $k \in K$ during time slot $t \in T$ in each track segment $n \in N$ of the bussable part of track. Same as in (Jenema, 2011) their model can select different possession types to perform the renewal operation. There nuisance cost is differently compared to the other researches, because the possession cost is not only dependent on possession time. With complete abstraction of the rail tracks they used the following calculation for nuisance:

$$Nuisance = \psi_{d,n,b} * ETM * VoT_d \quad (2.\ 2)$$

VoT_d = value of time (€) for each type of passenger with trip purpose $d \in D$, D is the total number of trip purposes in which the value of time can vary.
$\psi_{d,n,b}$ = average number of passengers with trip purpose $d \in D$ in track segment $n \in N$ on bussable part of track $b \in B$ during track possession;
ETM = expected increase in travel time for one passenger when other public transportation modes (e.g., bus) are used to replace train on segment $n \in N$.

ProRail has developed a measurement methodology together with Locov and NS called extra amount of experienced travel time (ETM) to express experienced nuisance in minutes. This is different from the ETM of (Caetano & Teixeira, 2016), because it does not look at real increase travel times but at experience increase in travel time. An assumption of the model of ProRail is that all tracks are blocked by a maintenance possession. Furthermore, bus to bus transits are ignored. The formula created to calculate the ETM value of one passenger is:

$$ETM = (TT + 1{,}3 * BT + 2 * XWT + 34\, XOTT + 43\, XOBT) \quad (2.3)$$

TT = average extra train time (min.) compared to the normal trip of one passenger multiplied with percentage of people expected to take detour by train
BT = bus time (min.) multiplied with percentage of people expected to take the bus
XWT = average extra amount of waiting time (min.) on bus or train.
$XOTT$ = average extra amount of transits train to train.
$XOBT$ = average extra amount of transits bus to train or train to bus.

The numbers 1,3; 2; 34 and 43 are based on research conducted by Schakenbos, Paix, Nijenstein, & Geurs (2016), they represented the experience time passengers experienced for the different variables. For example, one transit from train to train (XOTT), is equally experienced like traveling 34 minutes by train. For example, on a bussable part of track with three adjacent stations A, B and C. And there is a possession between A and B. The track is replaced by busses, the bus time is 15 minutes, and there is an average extra waiting time at station B between the bus and the train of 5 minutes. This leads to: $ETM = 72{,}5 = \big(0 + (1{,}3 * 15) + (2 * 5) + (34 * 0) + (43 * 1)\big)$

Compared to equation 2.2, ProRail doesn't include the VoT of different type of passengers. So, there is no difference in weight for a person who is traveling for work or leisure. This leads to the following equation for nuisance:

$$nuisance = \psi_{n,b} * ETM \quad (2.4)$$

$\psi_{n,b}$ = average number of passengers on segment n, on bussable part of track $b \in B$ during the track possession.

In more recent work Pargar also worked on improving the PSMP model, by trying to find the right moment to renew a component instead of doing more preventive maintenance. The same structure of using different segments, like in (Pouryousef et al., 2010), is used. But there is also a reduction if work is planned in sequential track segments. A CPLEX solver is used to solve the model. He concludes that his model is too complex to use for large-sized real-life cases.

- Objective function: minimizes the sum of possession cost, maintenance cost of performing maintenance or renewal and the cost of renting and installing the machines to perform renewal and maintenance.
- Decide for each time slot for each component of each part of track one of the following actions: do nothing, do maintenance or do renewal.
- There is a reduction, of installing cost, if maintenance is carried out on sequential track segments in the same time slot.

2.2 Conclusion

We have identified different methods used for optimisation of a maintenance planning. What we have learned is that both exact methods as well as heuristics have been used in the past by researchers. In practice the problem could become too large to use an exact approach. Therefore, a heuristic need to be created to find a solution. So far there is no research specifically on heuristics for the middle-to-long term rail infrastructure possession planning. Short term scheduling methods could be used, but need alterations due to the nature of the type of track work. As a framework we will use the work of (Budai-Balke, 2009; Budai et al., 2006). Our problem description is in many ways comparable to *preventive maintenance scheduling problem* (PMSP). We are also planning a given amount of work in each amount of deterministic time slots under certain constraints. Our solution has the same format as presented in their work, see Figure 7. Furthermore, we will use the alteration of Pouryousef et al. (2010) to simultaneous plan several segments. And same as Jenema (2011), different size possessions are accepted. Possession can have different properties compared to each other. But, there are four points that need alteration in our model compared to PMSP things that we will do different in our model are:

- *i) The type of maintenance*
- *ii) The Objective function*
- *iii) Variable weight between cost and nuisance*
- *iv) Longer time window*

In the next chapter, we will further explain these concepts and how this thesis will contribute to this gap in literature. Finally based on results from Budai-Balke et al. (2009) Simulated Annealing heuristic (SA) will be tested as one of the solution methods to create a planning. All the solution methods will be explained in Chapter 4 after the full model is explained in Chapter 3.

3. Problem modelling

This chapter consists of three parts. In the first part we will create a descriptive part explaining our model. Secondly, we illustrate our model by giving an example of its workings. In the third part of this chapter we will define the mathematical model. The mathematical model will include an objective function, parameter description and the constraints to which the model is subjected.

3.1 Model description

As explained in the conclusion of Chapter 2, there are some differences compared to the work on which we based our model (Budai-Balke, 2009; Budai et al., 2006). We will now create a descriptive part how our model will look like.

3.1.1 Assumptions

The following assumptions underpin the model developed in this chapter.
It is assumed that for each possession the following items are known:

- The cost for performing the possession in each year.
- The deadline, before which year the possession needs to be performed.
- The possessions that cannot be performed together on a bussable part of track.

Furthermore:

- There is no limit to the amount of possessions that can be planned in a year.
- All Possessions are independent.
- The amount of experience nuisance can be based on an estimation for each bussable part of track, on the extra amount of travel time and number of passengers.
- Opening the bussable part of track partly is negligible in relation to the amount nuisance reduction this will induce.

3.1.2 Type of maintenance

Our focus is on possessions larger than 4 hours, this can be different types of track works. The possessions are planned separately for each bussable part of track in the Netherlands. This is different compared to all the literate that is reviewed, which focusses mainly on routine maintenance. As explained in the section 1.2.1 *Scope,* on page 12, we are not looking at routine maintenance shorter than 4 hours. As such, we will not include any constraints on repeating possessions. We assume the possessions are independent of each other, and are only executed once in the time window. Therefore, we will not look at the sequence of possessions. There are possessions that can be performed simultaneously, we assume these are known. For our results we will create a list which possessions cannot be combined based on the track segment(s)[8] needed of each possessions. If possessions are on the same track segment we assume they cannot be combined.

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[8] If possessions are on a station, as such two squentual track segements are possessed.

3.1.3 Objective

Given a set of known possessions on one bussable part of track, which consist of multiple segments of track. The objective is to minimize the summed weighted nuisance and track work cost of the whole time window. We will now explain what measurement we will use for track work cost and nuisance.

Different from (Budai-Balke, 2009; Budai et al., 2006), but similar to (Pouryousef et al., 2010) and (Jenema, 2011), track work cost depend not only on the possession but also on the time slot in which the possession takes place. Now, there is no clear model at ProRail how the cost will change by shifting of possessions to another year. The main goal of this cost is to show that in the model it is possible to take different financial cost into account for different possessions over different years. To realize a model that is practical for ProRail, the following options should be included:

- *i) Different cost for different possessions*
- *ii) Change of cost over years*
- *iii) Penalty cost*

i) There are many different types of track works, so the cost for performing a possession can vary for different possessions. *ii)* In practice, cost can change over years by postponing/advancing of possessions. *iii)* Penalty cost are also introduced, to model the more binary type of cost. By postponing the execution of a possession, ProRail might want to do to extra maintenance or it will induce extra risk. This extra maintenance or risk could be starting from a certain year and not a steady increase over years that is included in type ii). Any other type of penalty cost or financial could be easily implemented in our maintenance cost parameter, because this is a parameter. This financial cost model is just a proof of concept. The topic of creating a financial cost model could be further researched, to create a model that is closer to the practice at ProRail.

The nuisance for a possession, will be based on the research of ProRail and Caetano and Teixeira (2016). Based on Caetano and Teixeira (2016), a difference between the average people travelling during work days and weekend days a separation will be used to calculate the average number of passengers during a possession on a bussable part of track.

$$\Psi_{d,b} = P_{work} * D_{work} + P_{weekend} * D_{weekend} \quad (3.1)$$

P_w: Estimated number of passengers per hour on a bussable part of track during w ∈ {work day, weekend day}.

D_w: Number of hours the possession takes during w ∈ {work day, weekend day}.

A formula is created to measure the amount of experienced nuisance of passengers:

$$Nuisance = \psi_b * (XR_b * (U_{bus} * 0{,}3 + 1)) \quad (3.2)$$

$\psi_{d,b}$: average number of passengers during a possession on bussable part of track b $\in$ B; B all the bussable part of tracks in the Netherlands.

XR_b[8]: Estimated amount of extra time (min.) compared to the normal trip of one passenger. Simplified version of ETM.

U_{bus}[9]: Estimated percentage of passengers that travels with the bus.

This formula does not take the extra waiting time and extra transits into account. We think this is justified because in comparing a longer or shorter possession on the same part of track, you should have the same amount of transits and waiting time (when looking at a traveller who is travelling the complete bussable part). ETM is replaced by: $XR_b * (U_{bus} * 0{,}3 + 1)$. This contains an estimation, by ProRail, of the extra train time and extra bus time (XR_b) multiplied by the expected percentage travellers to travel by bus (U_{bus}) multiplied by the factor that 0,3+1 (this is the extra weight for traveling by bus compared to train). So, if everyone would travel with the bus, $U_{bus} = 1$. This would lead to nuisance $= \psi_{d,b} * 1{,}3 * XR_b$, such that all the extra time ((XR_b) is extra travel time by bus. Finally, we assume that if there is a possession on a bussable part of track, the whole bussable part of track will be out of service.

3.1.4 Variable weight between cost and nuisance

In the literature reviewed so far nuisance cost and track work cost where compared without looking at the balance between the two factors. With one exception, in the work of (Caetano & Teixeira, 2016) where VoT is used from the work of (Wardman, 2004) Value of Time, is a measure of how much time of a passenger is worth. A downside of VoT is that a planning cannot be steered towards more/less nuisance/cost. In our model, we will use a factor K, to compare nuisance with cost. So ProRail could use factor K to create different solution scenarios depending on whether cost or nuisance is more important. This leads to the objective value:

$$Objective\ value = cost * K + nuisance \quad (3.3)$$

3.1.5 Longer time window

The time window of our model is 5 years, as requested by ProRail. In practice not, all weeks of this time window are used to plan possessions. The number of time slots should be as low as possible, to reduce the computation time. To reduce the number of time slots in which a possession can be planned we use clusters.

A cluster represents a list which can be filled with possessions, the possessions that are on this list will be performed at the same time. If a possession is planned in a cluster, you know in which year it will be executed but not in which week. There can be multiple clusters in a

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[9] XR_b and U_{bus} are determined by ProRail for each bussable part of track, and are simplified factors for ETM eq. (2. 4)

year. For the model, there are always equal number of clusters in each year, this makes it easier to create a solution method. It is possible in a year. Within a year, it is indifferent in which cluster a possession is planned for nuisance and cost. The number of clusters in a year is a predetermined number. But the number of clusters in a year can vary depending on the number of clusters necessary to find the optimum. A rule of thumb is presented in Chapter 5. If there is at least one empty cluster in each year, you can say for certain that you have enough clusters to find the optimum, when using an exact method. Increasing the number of clusters will also increase the solution space, as such it will take longer to find a solution for the heuristic. Therefore, a balance exists between computation time and good results.

3.2 Example of the model

An example will be used to show:

i. How the list of possessions that cannot be clustered will be generated;
ii. The amount of nuisance that is induced by individual possessions;
iii. The amount of nuisance reduction that is induced by clustering possessions.

In this example three fictional possessions A, B and C on the bussable part of track between Den Haag HS and Rotterdam CS are used (Figure 8).

(A) *(B)* *(C)*

Figure 8 bussable part of track between Rotterdam Central and Den Haag HS, with three possessions A, B and C. The red part indicates on which track segments a possession will take place. (A) possession between Delft and Schiedam Centrum, (B) possession between Den Haag HS and Den Haag Moerwijk, (C) possession between Den Haag HS and Schiedam Centrum.

The parameters for calculating the amount of nuisance for this bussable part of track can be seen Table 3, and the parameters for the possessions, A, B and C, in Table 4. Now, possessions are planned as much as possible in the weekend at ProRail, so we assume that if a possession is shorter or equal than 52 it will be fully performed in the weekend. It is possible to include different number of expected passengers for each year, for this example the amount of nuisance is kept steady over different years.

Table 3 estimated parameters for the bussable part of track between Den Haag HS and Rotterdam Central.

Variables	Values
XR	30 min.
U_{bus}	25 %
P_{work}	$4,1 \ * 10^3 \left(\frac{Passengers}{Hours}\right)$
$P_{weekend}$	$2,2 \ * 10^3 \left(\frac{Passengers}{Hours}\right)$

Table 4 nuisance and cost parameters for three fictional possessions A, B and C, displayed in Figure 8.

Possession	Track segments	D_{work} (hours)	$D_{weekend}$ (hours)	preferred execution year	Deadline	Cost [10] (euro)
A	2,3	0	52	2021	2023	$5,00 \times 10^4$
B	6	0	18	2023	2025	$2,00 \times 10^6$
C	2,3,4,5,6	0	52	2025	2027	$2,00 \times 10^6$

The list of non-combinable possessions in this thesis is generated based on the non-overlapping track segments of the possessions. Possession A and B have no overlapping track segments, as such we assume they can be clustered. Cluster A-C and B-C do have overlapping track segment; therefore, the list of non-combinable possessions consist of {A-C; B-C}.
Now we will show how the amount of nuisance for each possession can be calculated. Using equation 3.2[11], the amount of nuisance can be calculated for different planning solutions.

$$Nuisance(A \ or \ C) = \ 3,7 \ * 10^7 \ (\text{passengers} \ * \ \text{minutes}) \\ = (0 + 52 * 2,2 \ * 10^3) * \big(30 * (0,25 * 0,3 + \ 1)\big)$$

$$Nuisance(B) = 2,0 \ * 10^6 \ (\text{passengers} \ * \ \text{minutes}) \\ = (0 + 18 * 2,2 \ * 10^3) * \big(30 * (0,25 * 0,3 + \ 1)\big)$$

[10] Cost for performing the possession in the prefered performance year.

[11] $Eq. 3.2$: $Nuisance = \psi_{d,b} * (XR_b * (U_{bus} * 0,3 + \ 1))$

The combination A and B in the same cluster is not on the list of non-combinable possessions so it is possible to cluster possession A and B. This cluster will lead to the following amount of nuisance:

$$nuisance = 3{,}7 * 10^7 \text{ (passengers } * \text{ minutes)}$$
$$= (0 + 52 * 2{,}2 * 10^3) * \left(30 * (0{,}25 * 0{,}3 + 1)\right)$$

The amount of nuisance reduction created by clustering possessions A and B is the complete amount of nuisance that would be induced by solely possession B. Because the whole bussable part is out of service during a possession, $Nuisance(A \cap B) = Nuisance(C)$. It does not matter for nuisance that $(A \cap B) \neq C$, even though $A \cap B$ does not include the track segment between Den Haag Moerwijk and Delft. As such, if possession A, B and C would have the same duration they would give the same amount of nuisance.

So far, in this example, we have calculated the amount of nuisance of each possession and the possible cluster. Finally, we will use this example to show how cost calculation will work. Steady increase of cost for advancing/postponing compared to the preferred year could for example be 3% over the cost of performing the possession (see Table 4) and a static penalty cost of € $1{,}00 \times 10^6$. In Table 5 we have calculated the cost for performing the three possessions A, B and C in different years, to show the steady increase and penalty works. Looking at possession A, the cost in 2021 are retrieved from Table 4 for performing the possession in the preferred year. Each year there is an increase of 3%, in 2024 and 2025 possession A is out of deadline (see Table 4) so a single penalty of € $1{,}00 \times 10^6$ is required.

Table 5 Amount of cost for possessions A, B and C. In bold, the cost for performing the possession in the preferred year, using the parameters of Table 4.

Possession	2021	2022	2023	2024	2025
A	**€ $5{,}00 \times 10^4$**	€ $5{,}15 \times 10^4$	€ $5{,}30 \times 10^4$	€ $1{,}05 \times 10^6$	€ $1{,}05 \times 10^6$
B	€ $2{,}12 \times 10^6$	€ $2{,}06 \times 10^6$	**€ $2{,}00 \times 10^6$**	€ $2{,}06 \times 10^6$	€ $2{,}12 \times 10^6$
C	€ $2{,}25 \times 10^6$	€ $2{,}19 \times 10^6$	€ $2{,}12 \times 10^6$	€ $2{,}06 \times 10^6$	**€ $2{,}00 \times 10^6$**

In Table 6, we have calculated the total amount of nuisance and cost based on Table 5 for the scenario where we cluster A+B and the scenario were A and B are not clustered. There is a difference between these scenarios of: $nuisance\ (pm) = -0{,}2 \times 10^6$ and for $cost(euro) = 0{,}3 \times 10^4$.

Table 6 two scenarios, were the cost are minimized based on Table 5, for the example: clustering A+B and not clustering A and B

Possession	Clustering A+B			Not clustering A + B		
	Execution year	Nuisance (pm)	Cost minimized	Execution year	Nuisance (pm)	Cost minimized
A				2021	$3{,}7 \times 10^7$	€ $2{,}00 \times 10^6$
B				2023	$2{,}0 \times 10^6$	€ $5{,}00 \times 10^4$
C	2025	$3{,}7 \times 10^7$	€ $2{,}00 \times 10^6$	2025	$3{,}7 \times 10^7$	€ $2{,}00 \times 10^6$
A+B	2023	$3{,}7 \times 10^7$	€ $2{,}05 \times 10^6$			
Total		$7{,}4 \times 10^7$	€ $405{,}03 \times 10^4$		$7{,}6 \times 10^7$	€ $405{,}00 \times 10^4$

Different scenarios can be generated based on factor K. Using equation (3. 3) this leads to:

$$objective\ difference = -0{,}2 \times 10^6 + K * 0{,}3 \times 10^4 \qquad (3.4)$$

So, for $K = \frac{2}{3} \times 10^2$, the objective difference between clustering and not clustering would be 0. For $K < \frac{2}{3} \times 10^2$ there is less weight on cost (so more on nuisance), as such leads to preference to cluster. For $K > \frac{2}{3} \times 10^2$, there is more weight on cost (so less on nuisance) which as such leads to a preference of the model not to cluster.

In this example the optimum solution could be achieved using one cluster per year. If we would like to perform possessions A, B and C in the same year, multiple clusters are necessary in one year to achieve the minimum solution. Because there can be multiple clusters in one year the generated solution is not unique. For example, if the number of clusters in a year is two, cluster 1 and cluster 2 are of the first year. As such, cluster 1 and cluster 2 have the same nuisance and cost parameter. So, if possession A and B are in cluster 1 and possession C in cluster 2 this would result in the same objective value as putting possession C in cluster 1 and possession A and B in cluster 2. This explains how there can be different optimal solutions.

The amount of nuisance reduction can change depending on the clustering of possessions compared to doing possession individual. To reduce the number of decision variable in the model, we decided to calculate the amount of reduction in the following matter: by combining two possessions, there is a reduction of the smallest amount of nuisance of the two individual possessions. The amount of reduction will be calculated based on combinations in a cluster by taking the minimum value of the amount of nuisance of the two possessions.

1. Check if possession m and n are in set *non-Comb.* which contains all the possession combinations that are not allowed to be performed together, or m is equal to n
2. If so, $nd_t^{m,n} = 0$
3. If not, $nd_t^{m,n} = min(n_t^m, n_t^n)$

To reduce the number of model variables we will not look correctly at the nuisance reduction. Because of this, there will be an overestimation of nuisance reduction than is valid. If more than two possessions are clustered. There is a reduction in decision variables, because we don't look whether three (or more) possessions are combined in a cluster. This will help in the speed of solving the model using CPLEX. An example is used to show how the reduction is modelled: if there are three possessions, A, B and C in a cluster and the amount of nuisance of these possessions is n(A), n(B), n(C). The total amount of nuisance calculated by the model will be n(A)+n(B)+n(C)-min(n(A), n(B)) -min(n(A), n(C)) -min(n(B), n(C)). As such, there is one reduction term too much. The correct calculation would be: max(n(A), n(B), n(C)). In the results we will make an analysis of the effect of this overestimation.

3.3 Mathematical Formulation

Sets:

P	contains a list with all the possessions that are on a bussable part of track.
T	list containing the clusters in which a possession can be placed.
N	the number of clusters in one year.
non-Comb.	{(m, n) | possession m is not combinable with n, ∀m, n ∈ P}.

Decision variable:

x_t^p	1 if possession $p \in P$ is performed in cluster t ∈ T, 0 if it is not performed in cluster t ∈ T. {0, 1}
$r_t^{m,n}$	gives a value 1 if possession m ∈ P and n ∈ P are in the same cluster t ∈ T. {0,1}

Parameters:

K	factor for to have a balance between finance and nuisance. Can be different for each bussable part of track. (Euros per pm[12])
n_t^p	the amount of nuisance (pm) if possession $p \in P$ is performed in cluster t ∈ T.
$nd_t^{m,n}$	the amount of nuisance reduction (pm) possessions m and $n \in P$ give in cluster t ∈ T, because possession m and n are combined.
cp_t^p	cost in euros for performing possession p ∈ P in cluster t ∈ T.
M	is a large number compared to x_t^p, $M \geq 2$.

[12] Pm = passengers * minutes

Objective function

$$min \sum_{t \in T} \sum_{p \in P} \left(x_t^p * (n_t^p + K * cp_t^p) - \left(\sum_{\substack{m \in P \\ m \neq p}} r_t^{p,m} * nd_t^{p,m} \right) \right) \quad (3.\ 5)$$

Subject to

$$\sum_{t \in T} x_t^p = 1 \quad \forall p \quad (3.\ 6)$$

$$x_t^m + x_t^n \leq 1 \; \forall t, (m\text{-}n) \in \text{non-}Comb. \quad (3.\ 7)$$

$$x_t^m + x_t^n - 1 \leq M * r_t^{m,n} \qquad \forall m, n, t \quad (3.\ 8)$$

$$2 - (x_t^m + x_t^n) \leq M * (1 - r_t^{m,n}) \; \forall m, n, t \quad (3.\ 9)$$

$$r_t^{m,n}, x_t^p = \{0,1\} \; \forall m, n, t, p \quad (3.\ 10)$$

The objective function

The objective function consists of two parts. In the first part, it is stated whether a possession is performed in a cluster. If so, how much nuisance and cost this will induce. The second part is a reduction of nuisance if two possessions are in the same cluster. $nd_t^{p,m}$ is the amount of reduction if possession a and m are in the same cluster t indicated by decision variable $P_t^{p,m}$. The amount of nuisance and cost are summed for each possession for each cluster, were this objective value is calculated for one bussable part of track.

Constraints:

Constraint (3. 6) ensures that every possession is performed once in the time horizon.

Constraint (3. 7) ensures that the combination of two possessions that are on the list non-Comb cannot be clustered.

Constraints (3. 8) and (3. 9) are responsible for the reduction of ETM if possessions are combined. When both possession m and n are in period t, then $r_t^{m,n}$ will become 1. This will give a reduction of $nd_t^{m,n}$ in the objective function.

Constraint (3. 10) makes the decision variables binary. A possession can either be, or not be assigned to a cluster.

Furthermore, it could be easily implemented that possession p is restricted of being performed in year t by adding the constraint $x_t^p = 0$. We assume that it is possible to perform a possession in any year at some cost, so we aren't using this constraint in our model. For example, for planning a possession after the deadline will induce a penalty cost could be included in parameter cp_t^p.

3.4 Conclusion

In this chapter we created two descriptions of the model, a description in words and a mathematical formulation. Furthermore, we have given an example of the model, using three fictive possessions on the bussable part of track between Den Haag HS and Rotterdam CS. Compared to the *preventive maintenance scheduling problem* (PMSP) (Budai-Balke 2006), (Budai-Balke, 2009) there are four points that we altered in our model:

1. *The type of maintenance*

We will plan a set of known *possessions* longer than 4 hours on a *bussable part of track*.

2. *Variable weight between cost and nuisance*

Factor K can be used to influence the relation between experienced nuisance and financial cost. Therefore, it is possible for ProRail to create scenarios for the possession planning.

3. *The Objective function*

We minimize the objective function which is: over all possessions and clusters the summed amount of *nuisance* and *factor K* times the *cost of* a possession for performing the possession in cluster t.

4. *Longer time window*

We are working on a 5-year time window. Each year will have a predetermined number of *clusters* in which possessions can be performed, this will reduce the problem size compared to planning in every week.

In the Chapter 4 we will explain which methods will be tested, as possible solution methods for ProRail, to solve the model described in this chapter.

4. The solution method

There are 96 unique bussable parts of track in the Netherlands. For each *bussable part of track* we need to determine which *possessions* to combine into *clusters*. To determine the optimal solution of small instances, solving methods such as branch and bound, dynamic programming (dip) and solving a Mixed Integer Linear Problem (MILP) with CPLEX can be used. The *IBP IBM ILOG CPLEX Optimizer* is used to solve the mathematical model described in Chapter 3 in *MATLAB*. Because the model is too large, for bussable part of tracks with lots of possessions, a *heuristic* can be used to find a solution. The question remains whether this solution is good enough. Our heuristics consist of a *construction* and an *improvement step*. In Section 4.1 we will explain what *construction heuristics* we will use and why. In Section 4.2 we will explain what *improvement heuristic* we will use. The goal of this chapter is to show the different possibilities for the construction and improvement step. Furthermore, explain how the heuristics work that are used. Finally, explain which component of the heuristic are investigated using numerical result in the next chapter.

4.1 Constructive heuristic

In the *constructive heuristic* an initial solution will be generated. In general, the constructive heuristic can be described as:

Define the possessions that aren't assigned to a cluster yet;

1. Use a selection method to select a possession from step 1;
2. Assign the possession to a cluster;
3. Repeat step 1-3 until all possessions are assigned to a cluster.

The possession can be selected and assigned deterministic or probabilistic, these are two different type of construction heuristics. Considering the consistency of deterministic heuristics, we will use a greedy approach as a candidate construction heuristic. We leave out probabilistic construction methods, because we will already be using a probabilistic improvement heuristic. A downside of greedy construction methods is that they are not designed to escape local optimum. The global optimum is always a local optimum. As such, there is a chance that the local optimum found by the greedy approach is the global optimum. An example is shown in Figure 9, where in the red area (a smaller solution space), L would be the local optimum (minimisation). In Figure 9, G is the global optimum. A greedy method could get stuck in the local minimum L, while there is are better solution G.

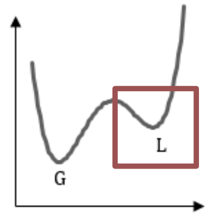

Figure 9 Example solution space showing local optimum (L) and global optimum (G), objective finding the minimum.

Greedy approach is a deterministic approach in which at every step, one possession is added to a cluster in the order of a priority list. The priority list consists of every possession sorted following a priority rule. Possessions are assigned to the cluster that gives the lowest objective value. Three parameters which have a high influence on the objective function are selected for the priority rule:

i) *Duration* (decr.)
ii) *Cost* (decr.)
iii) *Combinations possible* (incr.)

Same as (Budai-Balke, 2009) possessions will be sorted from *largest duration* to smallest duration, because longer possessions will induce more nuisance. Also by combining possession with a longer duration a higher reduction of nuisance could be achieved. There is a higher reduction of nuisance in combining two large possessions, compared to combining a smaller possession to a large possession or compared to combining two small possessions. Furthermore, cost also has a direct influence on the objective function. The *cost* is determined by the year in which possessions are executed. So, to perform costlier possessions not in the preferred year is more expensive compared to less expensive possessions. Finally, amount of c*ombinations possible* also has an indirect impact on the objective function. The amount of combinations possible, can be determined by counting the amount of times the possession occurs on the list non-Comb. which is assumed known. The last possessions that will be clustered in the construction heuristic, will have less possibilities to be placed in clusters. When there are less possibilities to place a possession with another possession, there is a lower chance that it can still be clustered. If possessions cannot be clustered this could lead to a lower reduction of nuisance. Beforehand, it is difficult to say which prioritising will give the lowest objective value therefore we will test different orders with the three parameters described above.

To conclude, the deterministic construction method we will be testing is:

1. Sort all the possessions in the order of Table 7, were priority 2 and 3 are tie breakers.
2. Pick the highest possession in the sorted list that hasn't been planned.
3. Place the possession in a cluster that will give the lowest objective value that is feasible.
    a. If there are equal objective values for different clusters, place the possession in the first possible cluster.
4. Repeat step 2 and 3 until all possessions are planned.

Table 7 Sorting priorities for the deterministic construction approaches.

	Priority 1	Priority 2	Priority 3
Approach 1	Nuisance	Possession cost	# of combinations possible
Approach 2	Nuisance	# of combinations possible	Possession cost
Approach 3	Possession cost	Nuisance	# of combinations possible
Approach 4	Possession cost	# of combinations possible	nuisance
Approach 5	# of combinations possible	Nuisance	Possession cost
Approach 6	# of combinations possible	Possession cost	Nuisance

4.2 Improvement heuristic

Improvement heuristic are used to improve an initial solution which is generated with a constructive heuristic, which are keen to get stuck in local optimum. Examples of improvement algorithms are steepest hill climbing (SHC), *r*-opt, Or-opt, Simulated Annealing (SA), Tabu-search (TS), Genetic Algorithm (GA), Memetic Algorithm (MA), Iterative Heuristics (IH). We would like to test both the results of a deterministic and stochastic improvement heuristic, to determine what type is probably most effective. Considering the results of Budai-Balke et al. (2006), as explained in chapter 3, we will use SA as stochastic improvement heuristic. GA, MA and IH are left out due to the larger computation time compared to SA. Note, we don't think these are not useful for this problem, and could be considered in future research. Same as Budai-Balke et al. (2006), Steepest hill climbing (SHC) will be used as deterministic improvement heuristic.

In this section we will first explain how SHC and SA work. Secondly, we will explain what neighbourhoods are considered in this research.

4.2.1 Steepest Hill Climbing (SHC) and Simulated Annealing (SA)

i) Steepest hill climbing:

Looking at all the neighbours in a neighbourhood, and select the neighbour that will give the lowest objective function. Repeat this step until no neighbours give a lower objective function.

1. Start with an initial solution.
2. Construct a neighbourhood, using one of the methods explained in Section 4.2.2.
3. Select the neighbour that gives the lowest objective value.
4. Repeat step 2-3 until the objective values stops decreasing.

ii) SA

The S*imulated Annealing* algorithm is based on the amount of movement particles have when cooling down. With high temperature, there is fast movement and with lower temperature, there is slower movement. In simulate annealing, the temperature is slowly lowered. The temperature indicates the percentage that a bad neighbour solution is accepted. In the beginning, when the temperature is high, (almost) all neighbour solutions are accepted. When reaching lower temperatures, (almost) only better solutions are accepted. This is designed to help escape local optimum.

1. Start with an initial solution.
2. Construct a neighbour solution, using one of the methods explained in Section 4.2.2
3. Compute the difference in objective value between the current solution and the constructed neighbour solution.
    a. If the neighbour solution is better than the current solution, then the neighbour is accepted as the new current solution.

b. Otherwise, the neighbour solution is accepted with a probability equal to $e^{-\Delta/T}$, where Δ is the difference in costs and T is the temperature.

4. Decrease the current temperature by the cooling rate α. Thus, $T_{new} = T_{current} - \alpha$.
5. Repeat step 2-5 until the current temperature T is higher than the limit temperature.

4.2.2 Neighbourhoods

Selecting the right neighbourhood method is important for the solution generated. Because there is not yet a lot of research to the topic of neighbour creation for the *preventive maintenance scheduling problem* (PSMP), we will use related problems. As identified by (Budai-Balke, 2009), the model presented in Chapter 3 seems to be related to the machine scheduling problem and the multi-job scheduling problem. Both these types of problems have been researched more extensively. The similarity among these three problems is that there are jobs/possessions, with given durations, which should be scheduled in a certain time slot. The objective of these problems is different namely, finding a schedule such that the jobs/possessions are finished as soon as possible. Here we schedule the possessions together such that the total cost or/and nuisance is as low as possible. But because they are using the same structure for their solution output, an order in which jobs/possessions are performed, similar type of neighbour structures could also be effective for our solution method.

Jin et. al. (2009) studied the problem of scheduling jobs, with the objective to minimize the maximum lateness on a single machine with setups reduction by clustering jobs. They explain how the traditional move-based neighbourhood is inefficient to search neighbours. The traditional move-based neighbourhood select one possession and place it in a new cluster (different methods for selecting and placing are possible). Such a neighbourhood is inefficient, since there are a lot of non-improving neighbours in it. More greedy approach insures less non-improving neighbours. Based on this we have found three interesting neighbourhood methods with a more greedy approach in literature, furthermore a new method is created:

i) Chained swapping (Meng, 2010)
ii) Iterative Greedy (IG) (Ruiz, 2008)
iii) Cluster-based IG (Jin et. al., 2009)
iv) Highest reward

i) Chained swapping

Meng (2010) Studied a more elaborate form of swapping, called chain swapping. Swap operator: two possessions are selected and swapped from the cluster they are currently in. They suggest the following neighbourhood:

1. Select the initial cluster. (All clusters are selected once to create the whole neighbourhood)
2. Check for all possessions from that cluster with all other possessions which swap will give the lowest objective value.

3. The cluster that is selected to swap with, will be the new initial cluster.
4. Repeat step 2 and 3 until no more swaps are possible that improvement the objective value.

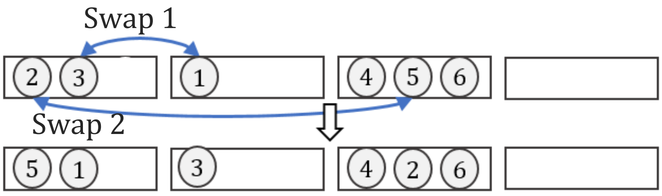

Figure 10 Chained swapping, were the rounds are possessions and the blocks are clusters, such that there are 6 possessions and 4 clusters.

The size of the neighbourhood is depending on the number of clusters. Because in step 1 each cluster can give a different neighbour.

ii) Iterative Greedy (IG)

The destruction and construction phases are two central procedures of the IG heuristic. The destruction phase consists of extracting N possessions from the planning. Each of these N possessions will be clustered again. The construction phase re-inserts the chosen possessions in the cluster that minimises the objective function. (Ruiz, 2008)

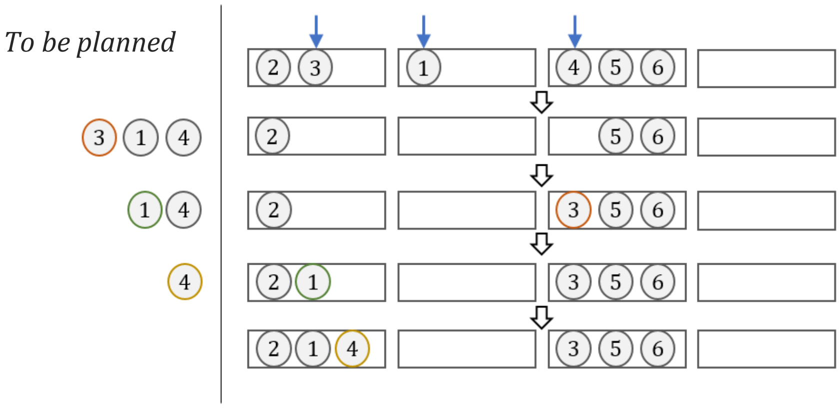

Figure 11 Iterative Greedy, the rounds indicate possessions, the blocks indicate clusters, the blue arrows select the possessions that are destructed.

The size of the neighbourhood is dependent on number of possessions N. A complete neighbourhood consist of each combination of possessions destructed a constructed. Where the number of possessions in the combination is N. The larger N is, the longer the computation time will be. Different values of N will be tested in Chapter 5.

iii) Cluster-based IG

Jin (2009) proposed a neighbourhood structure were in the destruction phase, all the possessions of a clusters need to be re-planned. In the construction phase place all the destructed possessions in the best possible cluster, based on minimum objective value. The cluster-based neighbour generation procedure looks as follow:

1. Select N clusters, and destruct them. Place all the possession from those clusters in a list, to be planned possessions. The first destructed cluster will be put on the top of the list. (Each combination of N clusters is selected from all the clusters to create the neighbourhood)
2. Select the first possession, from the list of destructed possessions, place that possession in the cluster which gives the lowest obj. val.
3. Repeat step 2 until all possessions are assigned to a cluster.

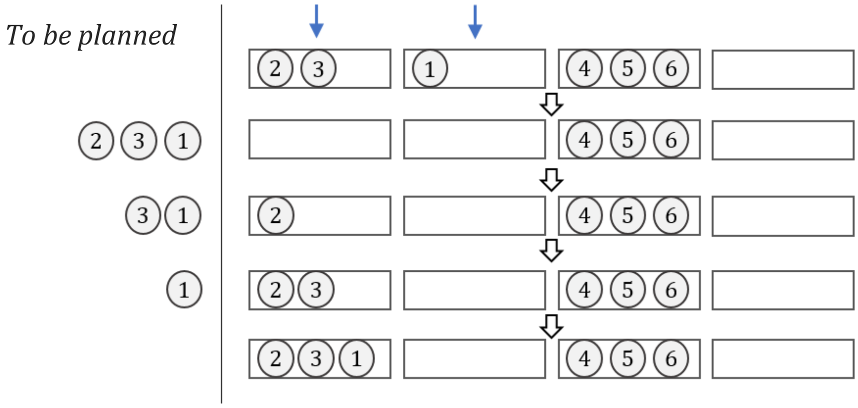

Figure 12 Cluster-based IG, the rounds indicate possessions, the blocks indicate clusters, the blue arrows select the clusters for which the possessions are destructed.

The size of the neighbourhood is dependent on number of clusters N. A complete neighbourhood consist of each combination of clusters destructed a constructed. Where the number of clusters in the combination is N. Again, the larger N is, the longer the computation time will be.

iv) Highest reward first

Finally, we suggest a type of neighbourhood that we could not find in literature, which is based on the amount of reduction in the objective value. Possession which induce a high change in objective value are an opportunity to improve the solution. Multiple possessions are removed to destruct multiple clusters in the same step to create the possibility for new clusters. It looks as follows:

1. By removing each possession and putting them back, check what the change in objective function is.
2. Remove the N possessions that give the most change in objective function, when they are removed.
3. Put them back in the same order, highest change in objective function first.
4. Place the possessions in the cluster that gives the lowest objective function.

So far, it is not yet clear which neighbourhood structure will give the lowest objective values, that is why we will show the results in the next chapter for all neighbourhood structures.

4.3 Conclusion

We have identified different techniques used for optimisation of a maintenance planning. Both exact methods as well as heuristics have been used in the past by researchers. In practice the problem could become too large to use an exact approach. Therefore, a heuristic need to be created to find a solution. We will use CPLEX, a *constructions heuristic* and two different improvement heuristics.

The *construction heuristics* we will use is a greedy approach, in this approach the possessions will be sorted on the cost (decreasing), the amount of nuisance (decreasing) and the number of cluster combinations (increasing) each possession will give. Based on this sorted list the possessions will be assigned to clusters such that the objective value is minimized. In the next Chapter we will discuss, based on the results, which order for these three factors is most effective.

After considering solely the construction heuristic, we will see how the improvement heuristics can further improve the constructed solution. First, we will use *Steepest Hill Climbing (SHC),* which is a deterministic local search heuristic. SHC will be used in combination with the four neighbourhood structures to see which neighbourhood structure is most effective. The neighbourhood structures are: Chained swapping, Iterative Greedy (IG), Cluster-based IG and Highest reward first. Secondly, Simulated Annealing (*SA)* a stochastic local search heuristic is used to further improve the solution created by SHC. SA can help escape local optimum to further improve the possession planning. In SA, also Chained swapping, IG and Cluster-based IG are considered. In chapter 5 we will conclude whether it is efficient just to use CPLEX or a Construction heuristic, or whether ProRail should also use improvement heuristics. If so, which improvement method should they use.

5. Computational study

In this chapter we present the results of solving the 5-year maintenance planning problem using both a CPLEX solver and heuristics. We will try to find the best solution method for different situations. In the first section of this chapter we will start by explaining the experimental design, which will set the situations. We would like to know how "good" the heuristics are. Good can be measured in different ways, we will do an empirical analysis where we will compare the objective value achieved with the construction and improvement heuristic with the objective value of the CPLEX solver.

In section 5.2 we will start by creating an initial solution using a construction heuristic were possessions are sorted using six different approaches. In section 5.3 we will first see whether Steepest Hill Climbing (SHC) could further improve this solution, were we will test the four different neighbourhood structures. Secondly, we will test whether SA could further improve the solution generated by the construction heuristics + SHC. As such, the best solution could be a compound heuristic, consisting of multiple heuristic, see Figure 13. Finally, we will run a case for the bussable part of track between Den Haag HS and Rotterdam CS, for the possessions between 2013-2017.

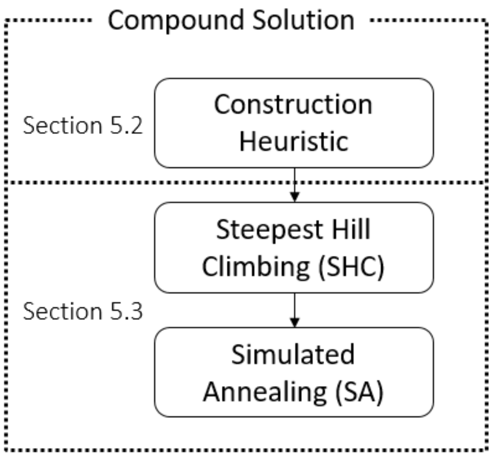

Figure 13 Schematic showing how the different heuristic fit create a compound solution and in which section in this chapter each solution is presented.

Short recap of the model, we assume that the bussable part of track is completely possessed if there is a possession. Our objective is to minimize the nuisance plus the cost times factor K. Factor K, is used to create different solutions depending on how high the priority on cost or nuisance is. In the created scenarios the amount of nuisance does not change during the 5-year period, but the heuristic is capable of handling changing nuisance over time. Finally, if two possessions are combined, the resulting nuisance reduction is taken as the smallest amount of nuisance of the two possessions. A more thorough description can be read in Section 3.1.

5.1 Experimental design

In this chapter we would like to show two points:

I. Show which heuristic is most suitable to create a possession planning.
II. Show how the solution is dependent on factor K.

To show these points, we will alter the following input parameters: K and the number of possessions that should be planned. Furthermore, we will use different setting for SA to achieve the best results, therefore we will alter the amount of iterations and the cooling down coefficient.

5.1.1 Number of possessions

Different conditions are used to show which (compound) heuristic is the most suitable. To see how the results vary with the number of possessions we have created four scenarios based on the possessions in the past at ProRail. The average amount of possessions on a bussable part of track in a period of five year is 10 and the maximum numbers of possessions to cluster is 40. In Figure 14 the bussable part of tracks are counted based on the amount of possessions that are on bussable part of tracks from 2013-2017.

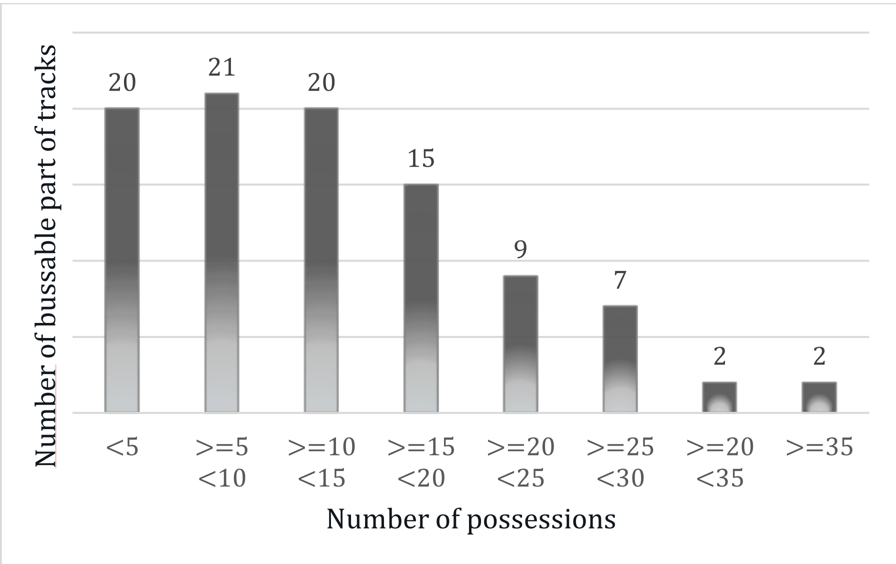

Figure 14 The distribution of number of possessions on the bussable part of tracks in the Netherlands

Based on the number of possessions there are on a bussable part of track in the Netherlands, see Figure 14, we chose to use 5, 10 and 40 possessions for scenario 1,2 and 4 respectively. Between Den Haag HS and Rotterdam central of 2013-2017 there were 22 possessions, this will be used for the third scenario. The possession duration, location, segments and cost are randomly changed for the four scenarios compared to possessions between Den Haag HS and Rotterdam Central. The four scenarios can be seen in Appendix G.

5.1.2 Cost model

For this research, we will use fictive number based on the cost of possessions performed at ProRail in the past. We choose to work with three different scales possession cost, to show the effect cost size can have on the planning. The cost of a possessions we will use are $5{,}00 \times 10^4$, $5{,}00 \times 10^5$ and $2{,}00 \times 10^6$ euro. For this chapter the steady cost change over the five-year period will be modelled by a fictive 3% and a fictive cost penalty of €10,00E+09.

5.1.3 K value

To show how the K value can create different planning outcome scenarios by altering the balance between nuisance and cost, four situations will be considered. First K_1 will put the focus on nuisance. K_2 and K_3 will put the focus between cost and nuisance. And the fourth K_4 value to put the focus on cost. The K values are calculated using the maximum and minimum values for cost *(PC)* and nuisance *(N)* of the possessions on the bussable part of track between Den Haag HS and Utrecht CS. The following K values are used:

1. The amount of nuisance of each individual possession on a bussable part of track (N) is higher than the cost of each individual possession (PC) times K.

$$K_1 = 0{,}65 = \frac{Min(N)}{Max(PC)} = \frac{1{,}3E + 06}{2E + 06}$$

2. The nuisance value of the possession with the highest amount of nuisance is not higher than the cost value of the possession with the highest cost variable times K, but higher than the cost value of the possession with the lowest cost variable.

$$K_2 = 9{,}5 = \frac{Max(N)}{Max(PC)} = \frac{1{,}97E + 07}{2E + 06}$$

3. The nuisance value of the possession with the lowest amount of nuisance is not higher than the cost value of the possession with the highest cost variable times K, but higher than the possession with the lowest cost variable times K.

$$K_3 = 26 = \frac{Min(N)}{Min(PC)} = \frac{1{,}3E + 06}{5E + 04}$$

4. The highest nuisance variable is not higher than the lowest cost variable.

$$K_4 = 380 = \frac{Max(N)}{Min(PC)} = \frac{1{,}97E + 06}{5E + 04}$$

So, outcome scenarios are created with four K values: 0,65; 9,5; 26 and 380.

5.1.4 Number of clusters

The reduce the computation time, the number of clusters should be kept to a minimum. To show for our scenarios how many clusters are needed, (approximated) deterministic approach 1[13] is used to determine when the objective value is no longer reduced by increasing the number of clusters.

Table 8 Objective values for different number of cluster per year for the four scenarios. Settings [Deterministic approach sorting in order nuisance, cost, # of combinations possible; K=0,65)

# of clusters	Scenario 1	Scenario2	Scenario3	Scenario 4
1	2,97E+07	2,00E+20		
2	2,97E+07	3,95E+07		
3	2,97E+07	3,95E+07	6,54E+09	
4			4,32E+07	6,60E+09
5			4,32E+07	9,69E+07
6				9,69E+07

From Table 8 we can learn that number of clusters per year needed for scenario 1, 2, 3 and 4 are 1, 2, 4, 5 respectively. This can be explained by the numbers of possession that aren't allowed to be clustered, which is determined by the number of possessions that are on the same segment. For scenario 1, 2, 3 and 4 the number of possessions on the same segment are 3, 7, 11, 20 respectively. Because we are working with 5 years, and equal number of clusters per year, there are at least 5 clusters. We suggest a rule of thumb (eq. 5.1), using the number of possession the least combinable possession cannot be combined with, in this research the maximum number of possession on one segment. Add two to this number (to avoid border cases, see scenario 4 were the number is 20 but the number of clusters required is 5) and divide this by 5 to find the number of clusters per year.

$$Number\ of\ clusters\ per\ year = \frac{\max(\#\ nonCombinable\ possession) + 2}{5} \qquad (5.1)$$

[13] Approach 1 sorts the possession in the order of nuisance, possession cost and then on #of combinations possible

5.1.5 Size of N, for IG and Batch-based IG

Scenario 3 is used to determine the influence of different size of N which is used for neighbourhood structure IG and Batch-based IG. Construction approach 1 in combination with SHC is used. From Table 9 we can see that the computation time increases drastically, but the objective value does not further increase. Based on these results an N value of 3 will be used throughout these results. In future research more scenarios could be used to determine the influence of N on the results.

Table 9 the objective value and computation for different N values, using scenario 3, approach 1 + SHC, K = 0,65.

N	Batch based-IG		IG	
	Objective value (pm)	Computation time	Objective value (pm)	Computation time
3	4,49E+07	534 sec	4,33E+07	100 sec
4	4,49E+07	1.385 sec	4,33E+07	441 sec
5	4,49E+07	3.871 sec	4,33E+07	1.614 sec

All the input parameters and experience possibilities are summarized in Table 10

Table 10 Input parameter setting of test instances and SA heuristic.

Parameter	Values
Number of possessions	$\lvert P \rvert = [5;\ 10;\ 22;\ 40]$
Number of segments	6
Possession cost (Euro)	cp_t^a = [50k; 500k; 2000k]
Penalty cost	€10 billion
Steady cost increase	3% per year
Possession nuisance (pm)	$n_t^a = [1{,}2 \times 10^6; 1{,}4 \times 10^6; 3{,}6 \times 10^6; 3{,}7 \times 10^6; 6,9 \times 10^6; 1{,}9 \times 10^7]$
Number of years	5 years
Factor K	K = [0,65 9,5 26 380]
Cooling down coefficient	$\alpha = [0{,}1;\ 0{,}01]$
Number of iterations	NI = [500; 1.000]
All the tests are executed on an Intel Core I5-5200U 2.20GHZ 8GB RAM.	

5.2 Performance of the construction heuristic

The results are generated for the greedy heuristic, which is explained in section 4.2.1. The objective values of the six priority rules are compared among each other, to see whether one approach is working better for a certain amount of possessions and for certain K values. Table 11 shows the objective values for the solutions generated with the six approaches, the values in bold represent the lowest objective value for each scenario and K value. There is no clear best heuristics for all scenarios, for all K values. All the orders of priority of the construction approaches can be found in Table 12, which, for readability, is a repeating of Table 7 of page 34. Approach 1 gives the best results for scenario 2 and 4 for all K values.

Approach 2 gives the best result for scenario 1 for all K values. Approach 5 gives the best result value for scenario 3, for K = 0,65; 9,5; 26. But approach 3 and 4 give the best result for scenario 3 and K = 380. For K = 0,65; 9,5; 26, approach 1 or approach 5 show the best results depending on the scenarios. For K = 380 approach 1 or approach 3 show the best results again depending on the scenarios. From this we can conclude that there is no correlation between the increasing in number of possessions and the approach which shows the best results.

Table 11 Objective value (passengers * minutes) of the six construction heuristics, tested with four different scenarios, for different K values. In bold are the lowest objective values of the different approaches, for each value of K and each scenario.

	Scenario 1			
K	0,65	9,5	26	380
Approach 1	2,98E+07	7,61E+07	1,62E+08	**1,97E+09**
Approach 2	**2,98E+07**	**7,58E+07**	**1,62E+08**	**1,97E+09**
Approach 3	2,98E+07	7,61E+07	1,62E+08	**1,97E+09**
Approach 4	2,98E+07	7,61E+07	1,62E+08	**1,97E+09**
Approach 5	2,98E+07	**7,58E+07**	**1,62E+08**	1,97E+09
Approach 6	**2,98E+07**	**7,58E+07**	**1,62E+08**	1,97E+09
	Scenario 2			
Approach 1	**3,95E+07**	**9,04E+07**	**1,85E+08**	**2,22E+09**
Approach 2	3,95E+07	9,07E+07	1,86E+08	2,23E+09
Approach 3	5,49E+07	1,06E+08	2,02E+08	**2,22E+09**
Approach 4	5,49E+07	1,06E+08	2,02E+08	2,24E+09
Approach 5	4,32E+07	9,44E+07	1,90E+08	2,24E+09
Approach 6	4,32E+07	9,44E+07	1,90E+08	2,24E+09
	Scenario 3			
Approach 1	4,32E+07	1,83E+08	4,44E+08	5,93E+09
Approach 2	4,31E+07	1,82E+08	4,40E+08	5,93E+09
Approach 3	4,49E+07	1,84E+08	4,42E+08	**5,93E+09**
Approach 4	4,49E+07	1,84E+08	4,42E+08	**5,93E+09**
Approach 5	**4,31E+07**	**1,81E+08**	**4,39E+08**	5,93E+09
Approach 6	4,47E+07	1,82E+08	4,39E+08	5,93E+09
	Scenario 4			
Approach 1	**9,69E+07**	**3,60E+08**	8,51E+08	**1,12E+10**
Approach 2	9,81E+07	3,61E+08	**8,50E+08**	1,13E+10
Approach 3	1,15E+08	3,79E+08	8,70E+08	1,12E+10
Approach 4	1,12E+08	3,77E+08	8,68E+08	1,12E+10
Approach 5	1,27E+08	3,88E+08	8,75E+08	1,13E+10
Approach 6	1,12E+08	3,75E+08	8,63E+08	1,13E+10

Table 12 repetition of Table 7 *"Sorting priorities for the deterministic construction approaches."*

	Priority 1	Priority 2	Priority 3
Approach 1	Nuisance	Possession cost	# of combinations possible
Approach 2	Nuisance	# of combinations possible	Possession cost
Approach 3	Possession cost	Nuisance	# of combinations possible
Approach 4	Possession cost	# of combinations possible	nuisance
Approach 5	# of combinations possible	Nuisance	Possession cost
Approach 6	# of combinations possible	Possession cost	Nuisance

To see how good the construction heuristic is working we will compare the lowest objective values of the construction heuristic with the solution values of the exact solution generated with CPLEX. For scenario 4, with 40 possessions, CPLEX is not able to find a solution independent of the number of clusters. The objective value of the exact solutions, generated by CPLEX, are given in Appendix I. CPLEX could solve the problem within 5 second for scenarios with equal or less than 10 possessions, see Table 13. Therefore, the majority of the bussable part of tracks in the Netherlands could be solved exact using CPLEX, see Figure 14.

Table 13 computation time of the CPLEX model

K	Scenario 1	Scenario 2	Scenario 3
# possessions	5	10	22
0,65	<1 sec	<1 sec	5.434 sec (1.5 h)
9,5	<1 sec	1,44 sec	9.521 sec (2.6 h)
26	<1 sec	2,56 sec	14.046 sec (3.9 h)
380	<1 sec	3,44 sec	2.096 sec (0.6 h)

The gap between CPLEX and Construction is calculated using eq. (5. 2).

$$Z_{Gap} = \frac{Z_{Solution} - Z_{Objective\ value\ CPLEX}}{Z_{Objective\ value\ CPLEX}} \quad (5.\ 2)$$

In Table 14 we can see that construction approach 1 is already capable of finding the exact solution for scenario 2. Furthermore, there is still a larger gap for scenario 3. Finally, the low gap for high K can be explained by the fact that for high K it is easier to achieve the minimum objective value. The objective value is almost completely dependent on cost, where cost is depending on the shifting of possessions to other years then preferred. So, by placing each possession in the preferred year, the minimum cost is reached and combinations are less important.

Table 14 Difference between lowest objective value of the solution found with construction heuristics (Best cons.) and CPLEX

Scenario	Best cons.	K = 0,65	Best cons.	K = 9,5	Best cons.	K = 26	Best cons.	K = 380
1	2,5,6	0,07%	2,5,6	0,38 %	2,5,6	0,49 %	1,2,3,4	0,00 %
2	1	0,00 %	1	0,00 %	1	0,00 %	1,2	0,00 %
3	5	0,16 %	5	0,55 %	5	0,55 %	6	0,01 %

5.3 Performance of the two local search heuristics

In section 5.3.1. we will first explain which neighbourhood method from the heuristic Steepest Hill Climbing (SHC) is the best. Then we will see how much SHC is able to improve the construction heuristic. Finally, we will also look at the gap between the objective values of the exact solutions found by CPLEX, for scenario 1,2 and 3. In section 5.3.2 we will look whether Simulated Annealing (SA) could further improve the solution created with the best possible combination of construction heuristic + SHC.

5.3.1 Deterministic improvement heuristic

In Table 15 we can see that Cluster-based IG and IG are on average the best approaches. All the computational results for all construction heuristics combined with all SHC neighbourhood methods can be seen in Appendix I. However, in Table 15, we can also see how inefficient these neighbours are, by comparing the amount of computation time they need compared to chained swapping and the highest reward first neighbours.

Table 15 Normalised average of the different neighbourhood methods of the improvement heuristic steepest hill climbing.

Neighbourhood method	Normalised average objective value [14]	computation time			
		Scen. 1	Scen. 2	Scen. 3	Scen. 4
Chained swapping	0,021	< 1 sec	< 1 sec	12 sec	47 sec
Cluster-based IG	0,005	< 1 sec	7 sec	100 sec	5.672 sec (1,3 h)
Iterative Greedy (IG)	0,015	< 1 sec	33 sec	534 sec	4.860 sec (1,6 h)
Highest reward first	0,022	< 1 sec	< 1 sec	< 1 sec	7 sec

The improvement compared to the construction heuristic will be calculated using eq. 5.3.

$$Z_{\text{Improvement}} = \frac{Z_{\text{construction}} - Z_{\text{compound improvement}}}{Z_{\text{construction}}} \qquad (5.3)$$

The best compound heuristic, for low K factors (0,65; 9,5; 26) and all scenarios, is *construction heuristic approach 6* in combination with SHC with neighbourhood *cluster-based IG*. The best improvement heuristic, for a K factor 380 and all scenarios, is the combination, *construction heuristic approach 3* and SHC with neighbourhood *cluster-based IG*. For scenario 1 and 2 no improvement is achieved compared to the best construction heuristic for each K value, Table 16. But for the scenarios 3 and 4, with larger number of possessions (22; 40) an improvement is achieved compared to the best solution found with solely the construction heuristics.

[14] We take the normalized value by dividing each objective value of each method, by the minimum objective value of all methods of that K value of that scenario. So if a method gives the minimum objective value for a scenario and for a K, it will have a normalized value of 0. The average is taken over all K and all scenario's

Table 16 $Z_{\text{Improvement}}$ of construction 3/ 6 + improvement heuristic IG (6 for K = 0,65; 9,5; 26, 3 for K =380) compared to the minimum objective values obtained with solely the construction heurists 3/6.

K	0,65	9,5	26	380
Scenario 1	0,00%	0,00%	0,00%	0,00%
Scenario 2	0,00%	0,00%	0,00%	0,00%
Scenario 3	0,08%	0,29%	0,53%	0,01%
Scenario 4	0,25%	0,97%	1,03%	0,09%

5.3.2 Simulated Annealing

So far, the construction + deterministic improvement heuristics are not able to solve the problem as good as CPLEX. The stochastic improvement heuristic SA is used to see whether it could further reduce the objective value. IG is selected as the neighbourhood structure, based on the results for scenario 3 which are presented in Appendix J. From the computation times of CPLEX, Table 13, we can conclude that CPLEX could be used for scenarios with 10 possessions or smaller. Because CPLEX can solve smaller problem instances, the focus of our results for SA are on scenario 3 and 4. In Table 17 we can see that SA is able to further improve the solution for scenario 3 and scenario 4.

We will compare the results of SA with the solution found, using *construction heuristic approach 1* in combination with SHC with neighbourhood *cluster-based IG* for all K. The amount of improvement is calculated using eq. 5.4. In Table 17 we can see that SA is able to further improve the solution found by the compound heuristic, greedy approach 1 and SHC-batch based IG. However, there is a big difference between scenario 3 and 4. Were for low K and scenario 4, SA is not able to further improve the solution. From this we can conclude that the heuristic is sensitive for the conditions of the bussable part of track.

$$Z_{improvement\_SA} = \frac{(Z_{Construction(1)+SHC-batch\ based\ IG}) - Z_{SA}}{(Z_{Construction(1)+SHC-batch\ based\ IG})} \qquad (5.\ 4)$$

Table 17 $Z_{improvement\_SA}$ using construction 1 + SHC with neighbourhood batch based IG + SA compared to the objective values obtained with the construction 1 + improvement heuristic with neighbourhood batch based IG. [SA settings: it. = 500; cooling down = 0,1, Neighbour = IG]

K	0,65	9,5	26	380
$Z_{improvement\_SA}$ -Scenario 3	0,14%	0,31%	0,57%	0,01%
$Z_{improvement\_SA}$ -Scenario 4	0,00%	0,00%	0,19%	0,03%

Using improvement equation 5.2, we can see, in Table 18, how far we are from the exact solution for scenario 3 and how much we gained in computation time. The amount of distance from the exact solution is less than 0,3% for each K, which is roughly equal to € 100K a nuisance for 20.000 passengers of 5 minutes.

Table 18 Difference between lowest objective value of the solution found with SA and CPLEX. [SA settings: it. = 500; cooling down = 0,1]

Scenario 3	K = 0,65	K = 9,5	K = 26	K = 380
$Z_{improvement\_SA}$	0,02%	0,24%	0,08%	0,00%
Computation reduction	94%	95%	96%	76%

5.4 Case: Den Haag HS – Rotterdam Central (2013-2017)

Between Den Haag HS and Rotterdam Central there were 22 possessions between 2013 and 2017. These possessions, Table 19, will be used to show four points.

5.4.1 Explain the effect of over estimating higher order nuisance reduction terms in the objective function.

5.4.2 Improvement compared to the current possession planning process at ProRail.

5.4.3 Show the effect on cost and nuisance using different K.

5.4.4 See whether the solution generated with SA is robust

Table 19 Possession between Den Haag HS and Rotterdam Central between 2013 and 2017. (Segments corresponding to the leftmost image of Figure 5 of page 14)

Possession	Preferred year	Segments occupied	Nuisance (pm)	Cost
1	2013	4	3708770	€ 610.000
2	2013	2 3	1997030	€ 40.000
3	2013	4 5 6	3708770	€ 800.000
4	2013	1	3708770	€ 626.000
5	2014	2 3	3637447	€ 185.000
6	2014	2 3 4	3637447	€ 256.000
7	2014	2 3 4	3637447	€ 300.000
8	2014	4 5 6	1711740	€ 23.000
9	2014	2 3 4 5 6	3637447	€ 86.000
10	2015	2 3 4	3637447	€ 50.000
11	2015	4 5 6	3637447	€ 67.000
12	2015	4 5 6	3637447	€ 67.000
13	2015	2 3 4	3637447	€ 5.000
14	2015	1 2	3708770	€ 250.000
15	2016	3 4 5 6	6878262	€ 213.000
16	2016	3 4 5 6	3708770	€ 120.000
17	2016	1 2	3708770	€ 700.000
18	2016	3 4 5 6	6878262	€ 900.000
19	2017	1 2	19027983	€ 1.200.000
20	2017	3 4 5 6	3708770	€ 63.000
21	2017	4 5 6	19027983	€ 800.000
22	2017	3	3708770	€ 56.000

5.4.1 Effect of over estimating higher order nuisance reduction terms

As explained in section 3.2, there is an over estimation of nuisance reduction of the ILP presented in Chapter 3. This is done to reduce the amount of decision variables which reduces the computation time. We can however determine the true amount of nuisance and cost if it is known which possessions are in which cluster. For each cluster the nuisance can be determined by looking which possession has the highest nuisance, this is also the total nuisance for the whole cluster. Table 20 shows the difference between the objective value used and the true objective value of the same value. Higher order cluster, are clusters which contain more possessions. Because the nuisance reduction is over estimated for higher order clusters therefore the model favours the decision: moving a possession from one year without a combination to a year with a combination even though this might induce a higher cost. This can be compensated by choosing a higher K, which would increase the value of the cost parameter.

Table 20 Difference between objective function used in the model and the true objective function. Based on the possessions of Table 19, using construction heuristic 6 + SHC cluster-based IG + SA. Settings [it. = 500; alpha = 0,1; clusters/year = 4; N=5]

Factor K	0,65	9,5	26	380
Total objective (with over estimation) (pm)	72.276.772	138.032.714	260.504.862	2.888.087.562
True cost	€ 7.430.050	€ 7.430.050	€ 7.422.550	€ 7.422.550
True nuisance (pm)	74.793.456	74.793.456	74.864.779	74.864.779
True objective (pm)	79.622.989	145.378.931	267.851.079	2.895.433.779

5.4.2 K factor to create scenarios

We will now further explore what the influence of K is on nuisance and cost. The nuisance will decrease with a higher K value, but that the cost will increase, see Figure 15. Figure 15, shows exactly the behaviour as expected, from this we can conclude it would be possible for ProRail to actively use their possession planning to influence the balance between nuisance and cost. In this case there is a difference of € 7.500,00 and 71.323 (pm) between the two possible situations.

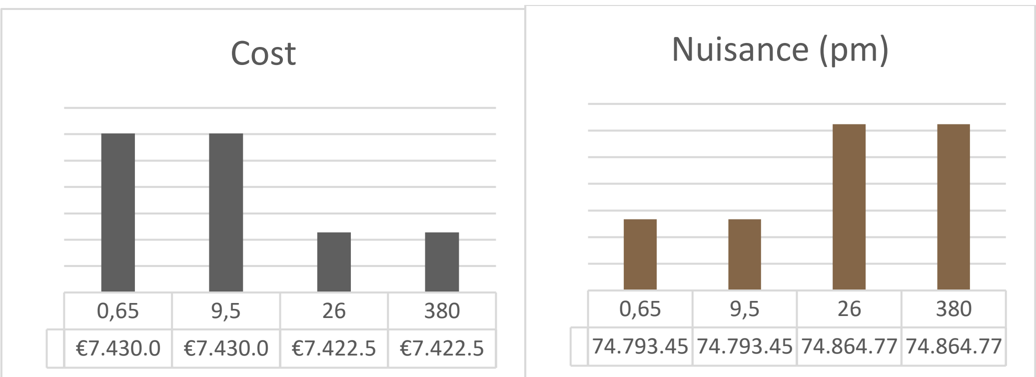

Figure 15 nuisance (pm) and cost (euro) for K values [0,65; 9,5; 26; 380]. [SA parameter settings: number of iterations = 500; alpha = 0,1; neighbourhood: chain with N= 5; number of cluster per year = 4]

5.4.3 Improvement compared to the current planning process used at ProRail

Using the current approach of ProRail only possessions of the same preferred year are cluster, this is the reference point. In our model this is the same as choosing a very high K, but this could also be achieved using the following steps:

1. Start with zero clusters.
2. For each preferred year
    a. Put the longest possession, that is not in a cluster, in a new cluster.
    b. Put the other possessions (with the same preferred year) in order of duration in the same cluster, if the possessions are combinable.
    c. If there are not more possessions that could fit in this cluster, go back to step a. If all the possessions of a preferred year are in a cluster, go the next preferred year.

For this case, Table 21 shows which possessions would end up in which cluster, for the reference point. In total there is a nuisance of 74.864.779 (passenger*minutes) and a cost of M€ 7,42. Because no possession is shifted over years, we know that there is no increase in cost compared to the minimum. So, M€ 7,42 is the minimum amount of cost that could be achieved for the possessions of this case. Table 22 shows an alternative possession planning using a low K value, therefore putting the emphasis on nuisance reduction. In this case a nuisance reduction of 71.323 (pm) could be achieved against a cost of € 16.650,00. In this case there where a lot of possessions on the same segments (15/22), therefore the list of which possessions can be combined is small. As already mentioned, the heuristic is sensitive for the conditions of the bussable part of track. In this case there are only seven possession that could for a combination with the other 15 possessions, this limits the amount of options. From this we can learn that our compound heuristic works best in a situation where there are a lot of combination possible. An example can be seen by looking at Figure 16, were we have displayed the true cost and true nuisance for scenario 3. In scenario 3 the amount of maximum number of possessions on the same track segment is ten. Here we also see that K has a bigger impact on the output of the heuristic, and there are more different outcomes compared to Figure 15.

Table 21 Clusters of possessions, were possessions are only clustered when they have the same preferred year.

Year	Cluster	Possessions	Nuisance (pm)	Cost
2013	1	1,2	3.708.770	€ 650.000,00
2013	2	3,4	3.708.770	€ 1.426.000,00
2014	3	5,6	3.637.447	€ 441.000,00
2014	4	7	3.637.447	€ 300.000,00
2014	5	8	1.711.740	€ 23.000,00
2014	6	9	3.637.447	€ 86.000,00
2014	7	10	3.637.447	€ 50.000,00
2015	8	11,14	3.708.770	€ 317.000,00
2015	9	12	3.637.447	€ 67.000,00
2015	10	13	3.637.447	€ 5.000,00
2015	11	15,17	6.878.262	€ 913.000,00
2016	12	16	3.708.770	€ 120.000,00
2016	13	18	6.878.262	€ 900.000,00
2017	14	19,21,22	19.027.983	€ 2.056.000,00
2017	15	20	3.708.770	€ 63.000,00
	Total		74.864.779	€ 7.417.000,00

Table 22 Possession planning, were possessions are planned using construction heuristic 6 + SHC cluster-based IG + SA. [SA parameter settings: number of iterations = 500; alpha = 0,1; neighbourhood: chain with N= 5; number of cluster per year = 4; K = 0,65]

Year	Cluster Per year	Possessions	Nuisance (pm)	Cost
2013	1	-	0	€ -
2013	2	1, 2	3.708.770	€ 650.000,00
2013	3	-	0	€ -
2013	4	3, 4, 5	3.708.770	€ 1.616.550,00
2014	1	8	1.711.740	€ 23.000,00
2014	2	9	3.637.447	€ 86.000,00
2014	3	6	3.637.447	€ 256.000,00
2014	4	7	3.637.447	€ 300.000,00
2015	1	14, 16	3.708.770	€ 381.100,00
2015	2	12	3.637.447	€ 67.000,00
2015	3	10	3.637.447	€ 50.000,00
2015	4	11	3.637.447	€ 67.000,00
2016	1	15, 17	6.878.262	€ 913.000,00
2016	2	13	3.637.447	€ 5.000,00
2016	3	18	6.878.262	€ 900.000,00
2016	4	-	0	€ -
2017	1	19, 21, 22	19.027.983	€ 2.056.000,00
2017	2	20	3.708.770	€ 63.000,00
2017	3	-	0	€ -
2017	4	-	0	€ -
	Total		74.793.456	€ 7.433.650,00

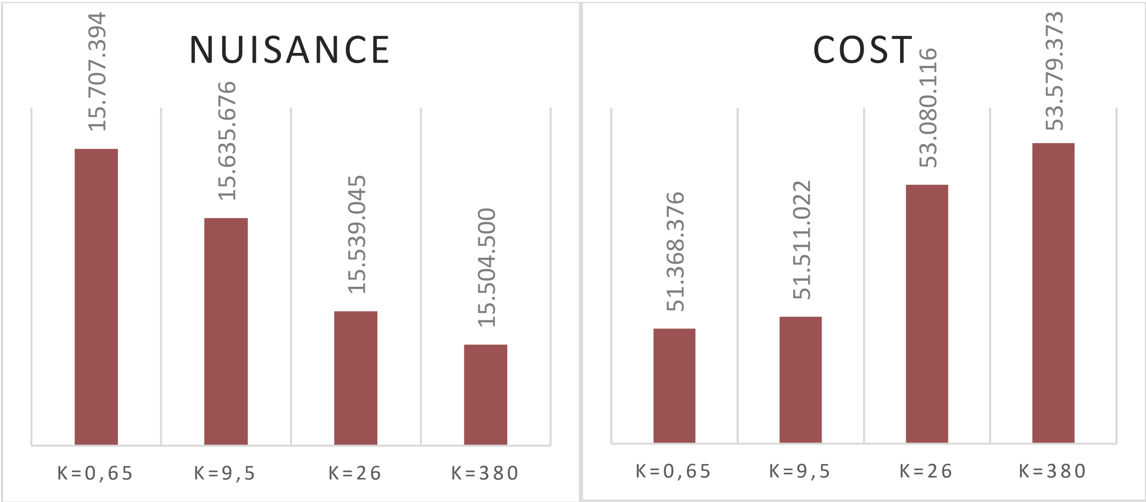

Figure 16 nuisance (pass. * min.) and cost (euro) for K values [0,65; 9,5; 26; 380]. [SA parameter settings: number of iterations = 500, cooling down coefficient 0,1 scenario 3, Neighbourhood = Chain with n= 5]

5.4.4 Robustness

To see how robust SA in combination with Construction 6 + Improvement SHC-Cluster-based IG is run 10 times with the same parameters. The settings are: number of iterations = 500, cooling down coefficient 0,1, K =0,65 and 4 clusters per year. In 10 runs the heuristic can give the same result each run, see Table 23.

Table 23 The objective value of 10 runs of construction 6 + SHC- cluster based IG + SA. [Settings: number of iterations = 500, cooling down coefficient 0,1, K =0,65, number of clusters per year = 4].

Run	Objective value (pm)
1	72.276.772
2	72.276.772
3	72.276.772
4	72.276.772
5	72.276.772
6	72.276.772
7	72.276.772
8	72.276.772
9	72.276.772
10	72.276.772

5.5 Conclusion

To test the heuristics four scenarios are created based on the possessions on the bussable part of track between Den Haag HS and Rotterdam CS between 2012-2017. The different scenarios contain 5, 10, 22 and 40 possessions. Furthermore, we have looked at various values for K = 0,65;9,5; 26; 380.

CPLEX can solve to problem within 5 seconds for the scenarios with 5 and 10 possessions. For 22 possessions needs on average 2,2 hours to solve the problem, and for 40 possessions to problem becomes too big to solve. The best combination of heuristics is using the construction heuristic and two local search heuristics. A greedy heuristic to construct an initial solution prioritizing the possessions on cost, using nuisance and number of combinations possible as tie breakers. Steepest Hill Climbing with neighbourhood structure batch-based IG followed by Simulated Annealing (SA). Simulated Annealing (SA) can reduce the computation time by 90% for scenario 3, with and average gap from CPLEX of 0,09%. Therefore, we conclude that the best method for solving the possession planning is:

- Using CPLEX for smaller problem instances (at least smaller than 22 possessions)
    - Future research is suggested to find the optimal conditions whether to use the compound heuristic or CPLEX.
- In other situations, use the combination of construction approach 1[15] + SHC-cluster based IG + SA-IG

Case: Den Haag HS – Rotterdam Central (2013-2017)
For the case we divided the objective function into two parts: nuisance and cost, to see the effect of K on the planning. From this we learned that it is possible to use K for creating different scenarios for the same scenario as expected. But the heuristic is sensitive to the conditions of the bussable part of track. The heurist works better in a situation where there is a lot combination between possessions possible. However, when working in such a situation the heuristic can create a wide variate of scenarios. These scenarios could help ProRail in actively steering on cost and nuisance.

[15] Construction heuristic 1 uses sorting order, cost, amount of nuisance, combinations possible.

6. Conclusion & Recommendations

6.1 Conclusion

The problem that we identified at ProRail is a lack of overview, which often leads to possessions being planned on the same bussable part of track multiple times in a five-year window.

- Create a model of the possession planning problem.

We have translated the possession planning problem into a mathematical description. For this description possessions are being planned based on cost and nuisance. Here we assumed it is known for each year what the cost and amount of nuisance is for each possession. Furthermore, we assume that it is known which combinations of possessions are possible.
By solving this model, a solution is generated, which implies which possessions must be performed simultaneously in the same year.

- Create a heuristic to solve this model.

For smaller problem instances (<10 possessions) CPLEX is able to solve the problem within five seconds. However, for 22 possessions the average computation increases to an average of 2,2 hours. Different constructions and local search heuristics are tested on four scenarios. From this we concluded that the best results for all K occur when using a compound of the greedy construction heuristic sorting on possession cost, amount of nuisance, and number of combinations possible; in combination with Steepest Hill Climbing with neighbour method cluster based Iterative Greedy (IG) and Simulated Annealing with neighbour method IG. The compound heuristic is able to reduce the computation time by 90% for scenario 3, with and average gap from CPLEX of 0,09%.

- We created a step in a planning system that could actively steer on the balance between nuisance and cost.

Using factor K, our heuristic can help with achieving control over the balance between cost and nuisance, and steer in tactical decision making on the possession planning. A case of the possessions from 2013-2017 between Den Haag HS and Rotterdam Central is used. Using this case, we were able to show how different values for K lead to different outcome scenarios. In scenario 3 a nuisance reduction of 1,3% could be achieved against a cost increase of 4%. Using this over the whole of Netherlands could have big impact on the nuisance reduction of track works.

6.2 Recommendations

6.2.1 Recommendations for ProRail

There are two steps that should be taken at ProRail before they can achieve the results from this research, get the data in order and change the planning process.

I. *Structure data*

The input data is not yet in order at ProRail. The input data is: what possession do you want to perform in the time window, what is the duration of these possession, what is the nuisance this possession will cause in each year, what possession could be combined, what are the cost for performing the possessions in each year and what is the deadline of each possession. Without this information it is difficult to optimize the planning of possessions. Creating the data necessary could be difficult. To work with a time window of five years, seven years ahead, information needs to be predicted. Predicting things can be difficult.

II. *Work proactive towards planning, throughout the whole planning chain, instead short-term reactive planning*

The planning process of possessions need to change. Planning and scheduling is something different and should be treated that way. One of the problems is that planning is not yet incorporated in the culture of ProRail. Implementing this new planning process can be difficult, because of the difference in the nature of planning and scheduling. The nature of scheduling is a lot more certain compared to planning. Planning comes with accepting risk and allowing changes in the plan to occur. It might be that a lot of the people currently working at ProRail find it difficult to change from a more operational approach to a more tactical approach. Were possessions should be planned with a lot of uncertainty about financial cost, execution date, duration. This cultural change can be managed by implementing in small steps, so people have time to adept. Use pilots, to provide insight in the advantages. Create involvement, so people feel responsible for the success. And finally, make it a shared problem of the whole planning chain, so the whole organisation is working together.

6.2.2 Recommendations for further research

During our research we have crossed many interesting topics which could be used for further research. We will give three recommendations which are most valuable to both literature and ProRail in general:

I. *Improve the measurement of nuisance.*

In our thesis we have created a measurement of nuisance based on the number of passengers that travel on average on that bussable part of track times the duration times the estimated extra experiences travel time. Were we assumed that there is not a lot of difference between taking out one part of the bussable part of track and taking out the whole bussable part of track. We believe that the definition of nuisance could be further optimised, by researching the following two points:

- How can freight trains be included?
- How should we handle partly blocking possessions?

II. *Improve the expected value of financial impact for performing track work in different years.*

In our thesis we have constructed a model the mimic the behaviour of postponing/advancing possessions to other years. Fictive values are used for the behaviour of steady increase over years and a penalty cost. It would be highly beneficial for the control on financial impact of the possession planning, if it would be further specified what the financial impact is of each possession over different year. Furthermore, we have assumed that there is no financial benefit in combining possessions. We believe that the further improvement of the expected value of financial impact for performing track work in different years could help in the optimising of the possession planning, by researching the following two points:

- What is the financial impact of advancing or postponing track work?
- What is the financial advantage of combining two possessions?

II. *More extensive testing on real life cases*

In our theses we used four scenarios and one real life case to test the heuristic created. All these situations are based on the same bussable part of track. In this bussable part of track there are no side-branches. Furthermore, the number of segments remained steady throughout these researches. We believe that testing more extensive testing on real life cases could further proof the validity, this could be achieved by researching the following point:

- How can different, more complex, bussable part of tracks be optimised?

To complete this thesis a question to think about: "What is the value of time, compared to the amount of happiness in life?"

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8. Appendices

A. Clients

The following passenger transporters are responsible for passenger transport:

- Abellio Rail NRW
- Arriva
- Connexxion
- DB Regio
- Exploitatie Museumstoomtram (Private transport)
- Keolis
- NS International
- NS Reizigers
- Syntus
- Veolia
- Veluwse Stoomtrein Maatschappij (Private)
- ZLSM-Bedrijf (Private transport)

The following freight transporters are responsible for operating freight trains:

- Bentheimer Eisenbahn
- B Logistics
- Captrain Netherlands
- Crossrail Benelux
- DB Cargo Nederland
- Duisport Raul
- ERS Railways
- KombiRail Europe
- LOCON Benelux
- LTE Netherlands
- PKP Cargo
- RTS Rail Transport Service
- RailTraxx
- Rheincargo
- Rotterdam Rail Feeding
- RTB Cargo Netherlands
- SBB Cargo Deutschland
- Shunter Tractie
- Train Services
- TX Logistik

B. PGO-Contracts

The following contractors are responsible for operating maintenance and control trains

- BAM Infra Rail
- Eurailscout Inspections & Analysis
- NedTrain
- Ricardo Rail
- Spitzke Spoorbouw
- Strukton Rail Equipment
- Voestalpine Railpro
- Volker Rail Nederland
- Asset Rail

ProRail is not do doing the maintenance as a company. ProRail uses PGO contracts to buy out the maintenance. These contracts last five years, and during these five years the contractors are responsible for maintaining the track. Between two contracts, ProRail is responsible. In this contract ProRail and the contractors agree on a certain state the network has to be when het contract ends. The contractors decide for themselves how they carry out

the maintenance. The contracts go through a public tender. Because the assets have an theoretical life of multiple decades, it is almost always the case that ProRail is responsible for the replacing the assets. But it can happen that an assets breaks during a contract, than the contractor is responsible.
The Netherlands is divided in PGO regions, the division can be seen in Figure 17 PGO-regions [http://www.spoordata.nl/sites/default/files/2017-10-26%20PGO-gebiedenkaart.pdf].

Table 24 List of all the PGO regions and in which region they are located. (RZ = Randstad Zuid, RN= Randstad Noord, Z = Zuid, NO= Noord Oost see Figure 18)

Contract area	PGO region	Region
Leiden	Rijn en Gouwe	RZ
Den Haag	Den Haag	RZ
Rotterdam	Rotterdam	RZ
Europoort	OPC: 4-Europoort	RZ
Dordrecht	OPC: 5-Dordrecht	RZ
Heerhugowaard	Hollands Noorderkwartier	RN
Alkmaar	Hollands Noorderkwartier	RN
Haarlem	OPC: 8-Haarlem	RN
Amsterdam	Amsterdam	RN
Duivendrecht	OPC: 10-Duivendrecht	RN
Weesp	OPC: 11-Weesp	RN
Amersfoort	Eemland	RN
Utrecht	OPC: 13-Utrecht	RN
Woerden	OPC: 14-Woerden	RN
Driebergen	OPC: 15-Driebergen	RN
Maarn	Eemland	RN
Goes	Zeeland	Z
Roosendaal	Zeeland	Z
Breda	OPC: 20-Breda	Z
Den Bosch	Betuwe	Z
Geldermalsen	Betuwe	Z
Boxtel	OPC: 23-Boxtel	Z
Eindhoven	De Peel	Z
Roermond	OPC: 25-Roermond	Z
Maastricht	OPC: 26-Maastricht	Z
Venlo	De Peel	Z

Maas en Waal	Gelre	NO
Gelderse Vallei	Veluwe	NO
Achterhoek	Gelre	NO
IJsselstreek	Veluwe	NO
Twente	Twente	NO
Gelderland	Veluwe	NO
Overijssel	Drenthe	NO
Drenthe	Drenthe	NO
Friesland	Wadden	NO
Groningen	Wadden	NO
HSL	OPC: 70-HSL	RZ
A15trace	OPC: 71-A15trace	RZ
Rijn en Gouwe	Rijn en Gouwe	RZ

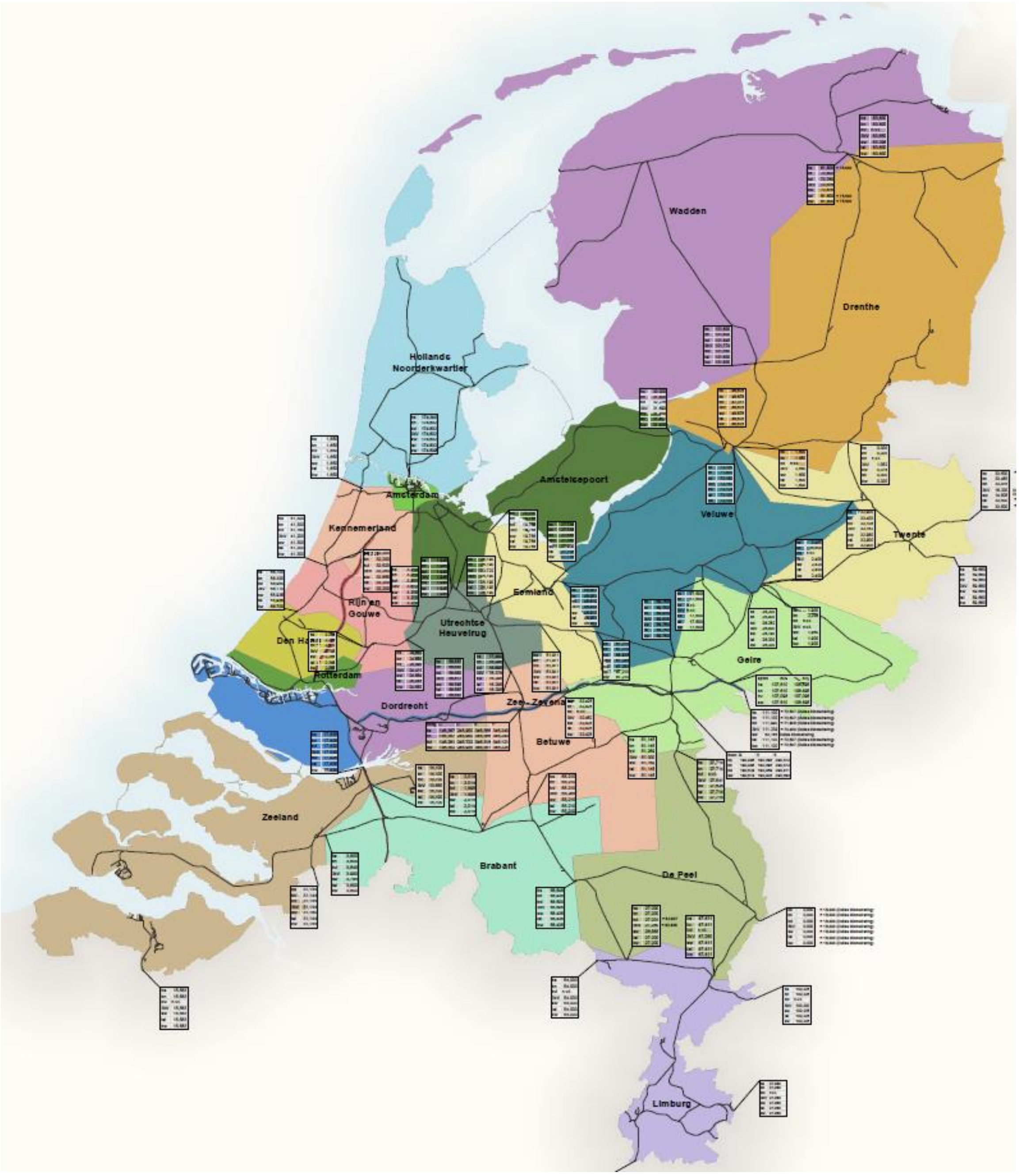

Figure 17 PGO-regions [http://www.spoordata.nl/sites/default/files/2017-10-26%20PGO-gebiedenkaart.pdf]

C. Involved parties

In this part, we will explain what all the parties involve do, to get a better understanding of how the current process maintenance planning works. Asset specialist, railway undertakers and local governments are the first in the chain of identifying maintenance work. Maintenance work is defined as all the renewal work of assets, change of function projects and local projects in this research. These terms are further defined in the problem description and will be included in the full thesis in Chapter 1.

The *asset specialist*, is the specialist of a certain type of asset e.g. energy supply installations, switches, crossings etc. The asset specialist is divided into four regions and assets. So, each region as at least one asset specialist for every type of asset. The division of regions can be seen in Figure 18. The asset specialist uses a system to keep track of the status of assets. The status, says something about its life time, the chance of a failure and the impact of the failure. The status is determined by the asset specialist. Currently, at ProRail, there is a difference between the theoretical life and the practical life. The theoretical lifetime of an asset is determined nationally. Because the final lifetime is dependent on a lot of external factors like the number of trains run pass the asset the type of ground, the number of maintenance etc. the final lifetime is not determined nationally. More about the deterioration process can be found in Chapter 3. To keep track of possible risk full events, priority scores are given consisting of the following points: reputation, security, costs, availability of rail, durability, compliance and customer satisfaction. Risk is indicated by a five-step scale: none, small, limited, considerable, great, very large. At approximately 80% of the theoretical life time the asset specialist will do a visual check of the assets. Based on the above information the final due date will be determined by the asset specialist. The final due date is the year before the asset must be replaced. From this list, they will make a production plan with all the work that must be done during a year. This list is used to cluster different maintenance projects.

Main focus: Have the assets running.

Figure 18 Netherlands divided into four regions for asset management, yellow Randstad North, pink North-East, light-blue Randstad South, green South

The *local governments*, can use their funds to improve the infrastructure locally. The most common projects of local governments are replacement of crossings for tunnels and creating sound walls. These possessions are performed when there is enough funding. These possessions are initiated to improve the overall standard of living of the residents of that area. For example, if there are a lot of trains on a corridor this could lead to a lot of waiting time for cars at a crossing, the local government could decide to replace the crossing by a tunnel.

Main focus: Reducing the nuisance, sound and waiting time of traffic. Improving the standard of living of residents.

The *transport companies* are responsible for giving strategy what they would like to achieve with the train service. An example could be running six train per hour on a corridor instead of four trains. This process is not standardized, so there is no time planning when the request come in. From this strategy ProRail will determine the makeability by looking at the capacity of the current infrastructure. If this is not possible, but the strategy still should be implemented, ProRail will determine which change of function should be performed to make this possible.

Main focus: Increase the number of traveling options by train, increase the amount of trains on corridors and reduce the waiting time for travellers.

Regional plan coordinators are responsible for collecting the work of all the different asset specialist and see whether clustering is possible. In each region, as defined in Figure 18, four plan coordinators are active. Each region is also divided into four regions, each having their own plan coordinator. The Plan coordinator clusters work and is the communicating link between different asset specialists and the communication between a region and both the bedrijfsbureau and the central plan coordinator.

Main focus: Making sure the work from the region is clustered in a way that gives it a high probability that it will be accepted by the bedrijfsbureau projects.

Bedrijfsbureau projects and *central plan coordinators* should determine whether projects are makeable. They should check whether a project is feasible to be performed. They check the following constraints on single project level: permits, marketability, socially accepted. But they also check the following constraints of the workability of the complete workload: budget, critical workforce capacity, work time. Together with the regional plan coordinators they will resize, combine and shift projects to the next years. After the projects are labelled feasible, projects are assigned to a project manager.

Main focus: Making sure that all the work is makeable.

The *project manager* is responsible that the project is performed. The project manager makes the request for a possession, a possession is a capacity request. A request consists of a concept track and concept duration. The exact location, time category (night, weekday, weekend) and duration are agreed on in a regional consultation (RGO) with the railway undertakers.

Main focus: Getting a possession

Possession planners are responsible for fitting every possession request in a year. A request is made in the form of a drawing, called a FOT, with information about the duration. An example of a FOT nearby station Enschede Kennispark can be seen in Figure 19. During the national platform consultation (LPO) the date for every possession is agreed on with the railway undertakers. The possession planners use the corridor book to minimize the nuisance for the railway undertakers. The *corridor book* is designed for helping with scheduling of the possessions. Furthermore, it gives guidelines how to handle conflict between ProRail and railway undertakers. The corridor book gives insight which sections of a corridor should be available when other sections are used for work. The book contains both rules for cargo and passengers.

Main focus: Making sure all the possessions fit in one year

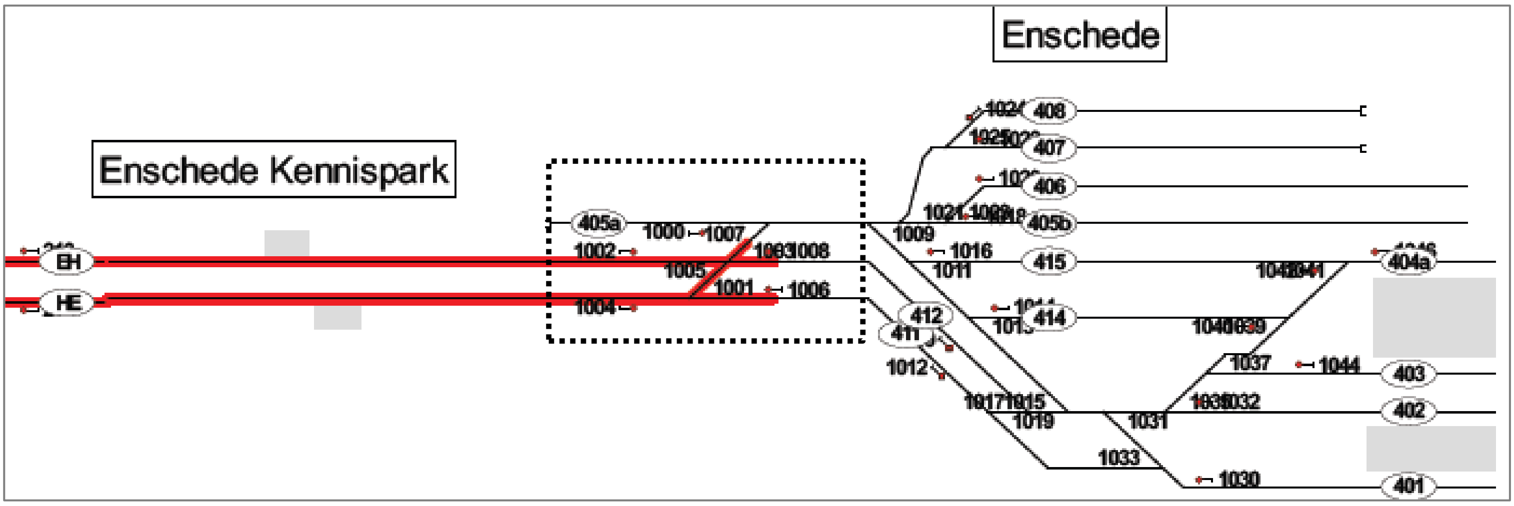

Figure 19 FOT of an infra possession of tracks BH and HE. The possessions are coloured red, meaning no trains can drive up to the switch (seen in the black dashed square). The shunting yard of Enschede is available to operate trains, however, regular trains cannot be driven from and towards Hengelo from Enschede (ProRail, ProVIO: Visulalisatie RADAR en KADER Databases. In ProRail (Ed.). Utrecht: ProVIO., 2016).

The *capacity allocation department* is responsible for allocating the capacity of the rail infrastructure. Capacity can be defined as track per time. So, if you have certain capacity, you know what part of the track is for who for how long. Capacity allocation dep. is an independent party of ProRail at ProRail. As such, they look neutral to the capacity allocation dilemmas. The capacity allocation dep. is chair in RGO and LPO consultations. Figure 20 shows the planning for both the possession planners and the capacity allocation department. It can be seen how the process starts roughly 1.5 year in advance. To create a fair capacity allocation, they try to let ProRail and the railway undertakers discuss and agree on the allocation themselves. If that does not work, the capacity allocation department looks at the highest needs. Different examples of needs are a big event (i.e. festival) or an asset in bad condition. So, if the consultations get stuck the capacity allocation dep. will make the end decision who gets the capacity. They are responsible to deliver the end schedule, of every capacity request.

Main focus: Making a fair capacity allocation.

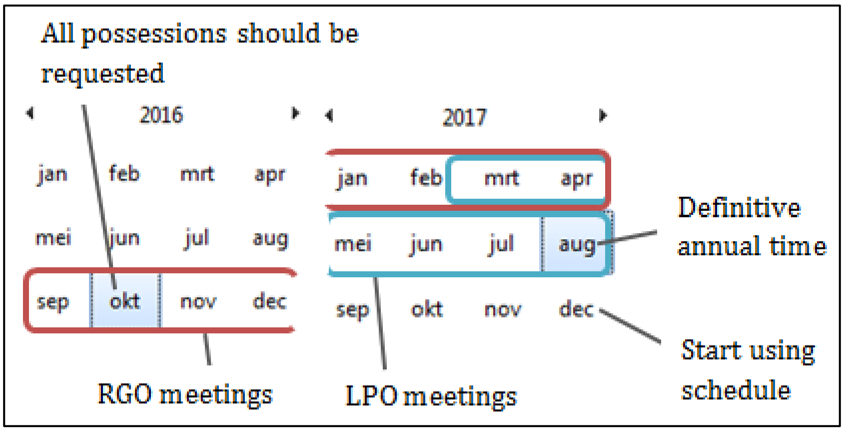

Figure 20 Possession request planning for the possession schedule of 2018

D. Budget exploitation

Budget Exploitatie exclusief BTW (x mln euro)	2016	2017
Exploitatiebijdrage Rijksoverheid	781	808
Amortisatie investeringsbijdragen	-	-
Gebruiksvergoeding	339	330
Bijdragen	**1.119**	**1.139**
Opbrengst uren eigen productie	80	78
Overige bedrijfsopbrengsten	30	40
Diverse bedrijfsopbrengsten	**110**	**117**
BEDRIJFSOPBRENGSTEN	**1.230**	**1.256**
Grootschalig onderhoud	129	120
Kleinschalig onderhoud	286	310
Onderhoud transfer	76	78
Beheer en calamiteiten	174	183
Verkenning en innovatie	13	15
Uitbesteed werk	**678**	**706**
Lonen en overige bedrijfslasten	409	408
Afschrijvingskosten	129	129
Financiële baten en lasten	14	14
BEDRIJFSLASTEN PRORAIL	**1.230**	**1.256**
BEDRIJFSRESULTAAT	**0**	**0**

Budget Investeringen exclusief BTW (x mln euro)	2016	2017
Bovenbouwvernieuwingsprojecten	86	140
Overige vervangingsprojecten	170	214
Vervangingsinvesteringen	**255**	**354**
Uitbreidingsprojecten (MIRT)	652	464
Geoormerkte programma's	-	-
Ministerie IenM	**907**	**818**
Projecten provincies en gemeenten	285	240
Projecten FENS	2	-
Derden	**287**	**240**
BRUTO INVESTERINGEN	**1.194**	**1.058**

Figure 21 budget exploitation of 2016 and 2017 [https://prestaties.prorail.nl/FbContent.ashx/pub_1000/Downloads/beheerplan-2017.pdf]

E. Number of travellers between intercity stations

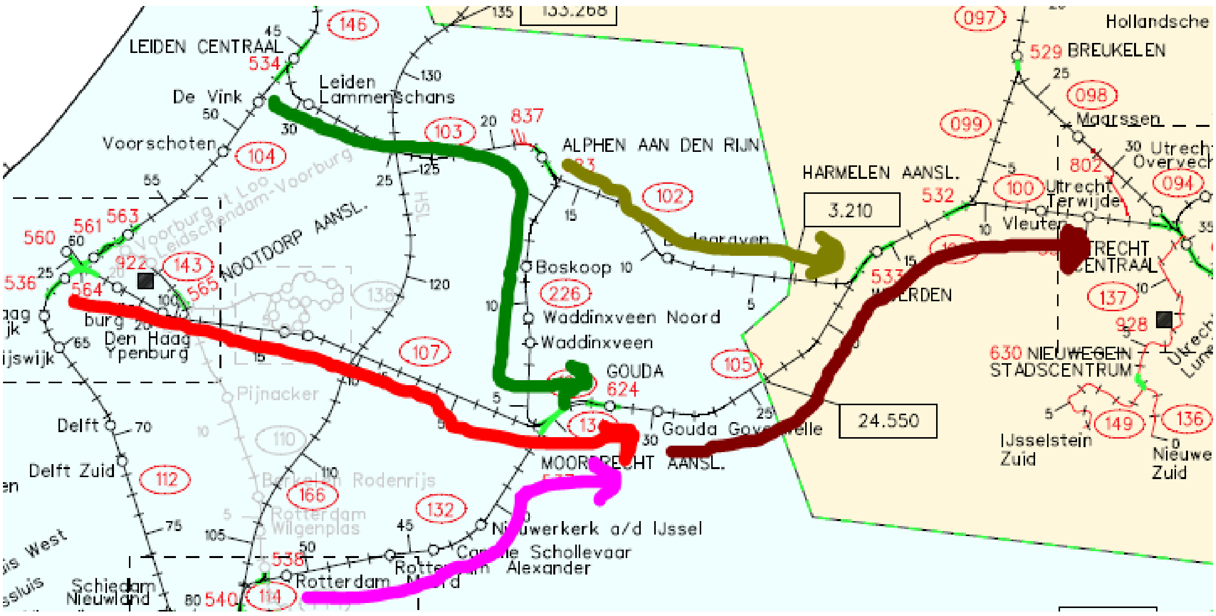

Figure 22 Showing the traveller streams to Utrecht that traveller through Woerden, on average per day in 2017

Geocode	From	To	Number of travellers
560	Den Haag CS	Voorburg	68.656
107	Voorburg	Den Haag Ypenburg	69.376
107	Den Haag Ypenburg	Nootdorp Oost	70.268
107	Zoetermeer	Nootdorp Oost	70.268
107	Zoetermeer Oost	Zoetermeer	71.020
105	Gouda	Bleiswijk-Zoetermeer	70.914
105	Gouda	Gouda Goverwelle	145.988
105	Woerden	Gouda Goverwelle	143.666
100	Woerden	Vleuten West	160.844
100	Vleuten	Utrecht Terwijde	168.768
100	Utrecht Leidsche Rijn	Utrecht Terwijde	173.972
100	Utrecht Leidsche Rijn	Utrecht Majella	176.494
531	Utrecht CS	Utrecht Majella	176.494
	Input from Rotterdam, Leiden		0
537	Gouda	Moordrecht	84.582
132	Nieuwerkerk a/d IJssel	Moordrecht	84.582
099	Woerden	Breukelen	10.964
102	Bodegraven	Woerden	21.718
226	Gouda Westergouwe	Waddinxveen Zuid	7.630

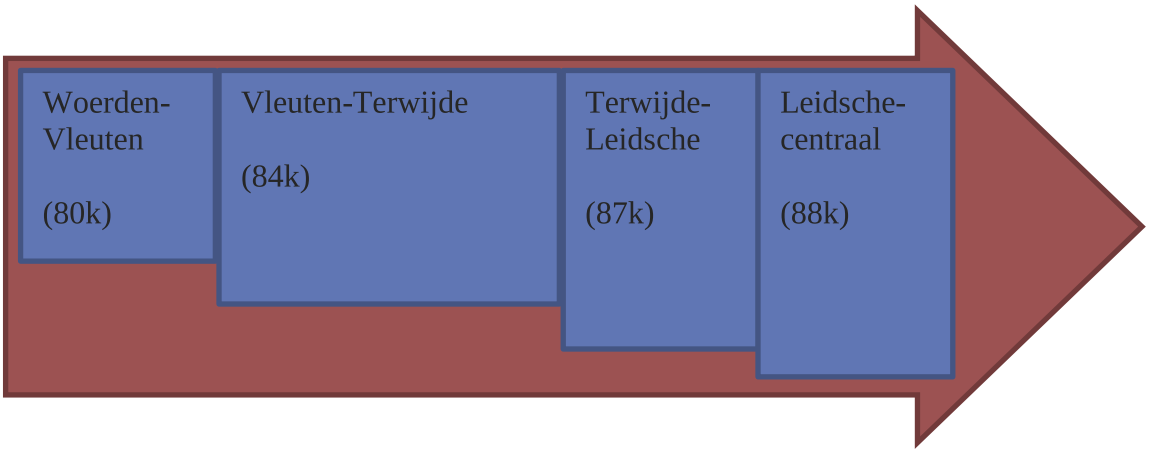

Figure 23 Showing the number of all travellers to Gouda

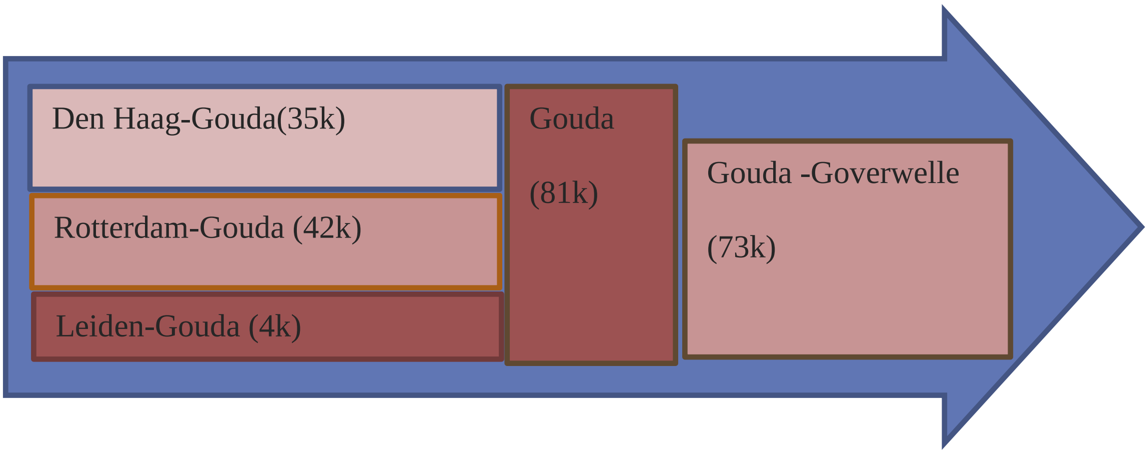

Figure 24 Showing the number of travellers from Woerden to Utrecht

F. Bussable part of tracks

Table 25 All the different track sections identified by NS as parts of the network that can be replaced by bus or detour. Abbreviations can be found on: https://nl.wikipedia.org/wiki/Lijst_van_huidige_en_voormalige_spoorwegstations_in_Nederland

Gn-Asn	Amr-Hwd	Apn-Gd	Zwd-Rsd	Nm-Ah
Asn-Mp	Hwd-Hdr	Wd-Ut Spr	Bgn-Gs	Ut-Db Spr
Gn-Mp	Amr-Hdr	Wd-Ut IC	Gs-Vs	Ut-Db IC
Lw-Hr	Hwd-Hn	Wd-Bkl	Rsd-Bgn	Db-Ed
Hr-Mp	Hlm-Utg	Ut-Asb Spr	Rsd-Vs	Db-Rhn
Lw-Mp	Asd-Ass	Ut-Asb IC	Zlw-Bd	Ed-Ah
Mp-Zl	Ass-Hlm	Asb-Asd	Bd-Rsd	Ut-Ah/Nm
Zl-Dv	Hlm-Zvt	Asd-Ut Spr	Bd-Tb	Ht-Btl
Dv-Zp	Hlm-Ledn	Asd-Ut IC	Tb-Ht	Btl-Ehv
Zp-Ah	Ass-Shl	Ut-Amf Spr	Tb-Btl	Ht-Ehv
Zl-Wdn	Shl-Ledn	Ut-Amf IC	Tb-Ehv	Ehv-Vl
Dv-Wdn	Ledn-Laa	Ut-Hvs	Ut-Gdm Spr	Ehv-Wt
Dv-Aml	Gv-Laa	Dld-Brn	Ut-Gdm IC	Wt-Rm
Wdn-Aml	Ledn-Gv	Gvc-Gv	Gdm-Ht	Ehv-Rm
Aml-Hgl	Gvc-Laa	Gv-Rtd	Ut-Ht	Rm-Std
Hgl-Es	Ledn-Apn	Gvc-Gd	Gdm-Tl	Std-Hrl
Aml-Hgl-Es	Apn-Wd	Rtd-Gd	Ht-O	Std-Mt
Zl-Amf	Wd-Ledn	Gd-Wd	O-Nm	Rm-Mt/Hrl
Apd-Amf	Lls-Alm	Rtd-Ddr	Ht-Nm	HSL-Zuid
Dv-Apd	Alm-Wp	Ddr-Zlw	Amf-Hvs	HSL-Noord
Amf-Dv	Almo-Wp	Zlw-Rsd	Hvs-Wp	Ass-Zd
Zl-Kpn	Zd-Utg	Rtd-Zwd	Amf-Wp	Zd-Pmd
Zl-Lls	Utg-Amr	Dvd-Shl	Wp-Asd	Pmd-Hn
Zl-Almo	Zd-Amr	Wp-Shl	Wp-Dvd	Hn-Ekz
				Zd-Hn-Ekz

G. Parameters of bussable part of track Den Haag HS-Rotterdam CS

Table 26 Nuisance (passengers * minutes) for project 1-22, for year 2013-2018, of bussable part of track Den Haag HS - Rotterdam CS

Projects	2013	2014	2015	2016	2017
1	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06
2	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06
3	2,0E+06	2,0E+06	2,0E+06	2,0E+06	2,0E+06
4	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06
5	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06
6	3,6E+06	3,6E+06	3,6E+06	3,6E+06	3,6E+06
7	3,6E+06	3,6E+06	3,6E+06	3,6E+06	3,6E+06
8	3,6E+06	3,6E+06	3,6E+06	3,6E+06	3,6E+06
9	1,4E+06	1,4E+06	1,4E+06	1,4E+06	1,4E+06
10	3,6E+06	3,6E+06	3,6E+06	3,6E+06	3,6E+06
11	1,3E+06	1,3E+06	1,3E+06	1,3E+06	1,3E+06
12	3,6E+06	3,6E+06	3,6E+06	3,6E+06	3,6E+06
13	3,6E+06	3,6E+06	3,6E+06	3,6E+06	3,6E+06
14	3,6E+06	3,6E+06	3,6E+06	3,6E+06	3,6E+06
15	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06
16	6,9E+06	6,9E+06	6,9E+06	6,9E+06	6,9E+06
17	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06
18	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06
19	1,9E+07	1,9E+07	1,9E+07	1,9E+07	1,9E+07
20	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06
21	1,9E+07	1,9E+07	1,9E+07	1,9E+07	1,9E+07
22	3,7E+06	3,7E+06	3,7E+06	3,7E+06	3,7E+06

Table 27 nuisance reduction in (pm) for possession 1-10 of bussable part of track Den Haag HS - Rotterdam CS

Projects	1	2	3	4	5	6	7	8	9	10
1	0	3,7E+06	2,0E+06	3,7E+06	3,7E+06	-1,0E+20	-1,0E+20	-1,0E+20	1,4E+06	-1,0E+20
2	0	0	-1,0E+20	-1,0E+20	3,7E+06	3,6E+06	-1,0E+20	3,6E+06	-1,0E+20	3,6E+06
3	0	0	0	-1,0E+20	2,0E+06	2,0E+06	-1,0E+20	2,0E+06	-1,0E+20	2,0E+06
4	0	0	0	0	3,7E+06	3,6E+06	-1,0E+20	3,6E+06	-1,0E+20	3,6E+06
5	0	0	0	0	0	3,6E+06	3,6E+06	3,6E+06	1,4E+06	3,6E+06
6	0	0	0	0	0	0	-1,0E+20	-1,0E+20	1,4E+06	-1,0E+20
7	0	0	0	0	0	0	0	-1,0E+20	-1,0E+20	-1,0E+20
8	0	0	0	0	0	0	0	0	1,4E+06	-1,0E+20
9	0	0	0	0	0	0	0	0	0	1,4E+06
10	0	0	0	0	0	0	0	0	0	0

Table 28 Financial cost for possession 1-22, for year 2013-2018, of bussable part of track Den Haag HS - Rotterdam CS

Projects	2013	2014	2015	2016	2017
1	5,0E+04	5,2E+04	5,3E+04	1,0E+10	1,0E+10
2	2,0E+06	2,1E+06	2,1E+06	1,0E+10	1,0E+10
3	5,0E+05	5,2E+05	5,3E+05	1,0E+10	1,0E+10
4	5,0E+05	5,2E+05	5,3E+05	1,0E+10	1,0E+10
5	5,2E+04	5,0E+04	5,2E+04	5,3E+04	1,0E+10
6	2,1E+06	2,0E+06	2,1E+06	2,1E+06	1,0E+10
7	5,2E+05	5,0E+05	5,2E+05	5,3E+05	1,0E+10
8	5,2E+04	5,0E+04	5,2E+04	5,3E+04	1,0E+10
9	5,2E+05	5,0E+05	5,2E+05	5,3E+05	1,0E+10
10	2,1E+06	2,1E+06	2,0E+06	2,1E+06	2,1E+06
11	2,1E+06	2,1E+06	2,0E+06	2,1E+06	2,1E+06
12	5,3E+05	5,2E+05	5,0E+05	5,2E+05	5,3E+05
13	5,3E+04	5,2E+04	5,0E+04	5,2E+04	5,3E+04
14	5,3E+04	5,2E+04	5,0E+04	5,2E+04	5,3E+04
15	5,5E+04	5,3E+04	5,2E+04	5,0E+04	5,2E+04
16	2,2E+06	2,1E+06	2,1E+06	2,0E+06	2,1E+06
17	5,5E+04	5,3E+04	5,2E+04	5,0E+04	5,2E+04
18	2,2E+06	2,1E+06	2,1E+06	2,0E+06	2,1E+06
19	5,6E+04	5,5E+04	5,3E+04	5,2E+04	5,0E+04
20	5,6E+04	5,5E+04	5,3E+04	5,2E+04	5,0E+04
21	5,6E+05	5,5E+05	5,3E+05	5,2E+05	5,0E+05
22	5,6E+04	5,5E+04	5,3E+04	5,2E+04	5,0E+04

H. Possessions scenarios

Scenario 1 ↓

Possession	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	ETM	Duration	Start Date	Costs
1	0	1	1	0	0	0	19027983	168	2013	2000000
2	0	0	1	0	0	0	3708770	52	2014	500000
3	0	0	1	0	0	0	19027983	168	2015	500000
4	0	0	0	1	1	1	3708770	52	2015	50000
5	1	0	0	0	0	0	3708770	52	2017	50000

Scenario 2 ↓

Possession	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	ETM	Duration	Start Date	Costs
1	0	0	1	1	0	0	19027983	168	2013	50000
2	0	0	0	1	0	0	3708770	52	2013	50000
3	0	0	1	1	0	0	1997030	28	2013	50000
4	0	0	0	1	1	1	3708770	52	2014	500000
5	1	0	0	0	0	0	19027983	168	2015	500000
6	0	1	0	0	0	0	3637447	51	2015	50000
7	0	0	0	1	1	1	3637447	51	2016	2000000
8	0	1	1	1	0	0	3637447	51	2017	50000
9	0	0	0	1	1	1	3637447	51	2017	2000000
10	0	1	1	0	0	0	3637447	51	2017	500000

Scenario 3 ↓

Possession	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	ETM	Duration	Start Date	Costs
1	0	1	1	0	0	0	3708770	52	2013	50000
2	0	0	0	1	0	0	3708770	52	2013	2000000
3	0	0	0	1	0	0	1997030	28	2013	500000
4	0	0	0	1	1	1	3708770	52	2013	500000
5	1	0	0	0	0	0	3708770	52	2014	50000
6	0	1	1	0	0	0	3637447	51	2014	2000000
7	0	1	1	1	1	1	3637447	51	2014	500000
8	0	1	1	0	0	0	3637447	51	2014	50000
9	0	0	0	1	1	1	1426450	20	2014	500000
10	0	1	1	0	0	0	3637447	51	2015	2000000
11	0	1	1	0	0	0	1283805	18	2015	2000000
12	0	0	0	1	1	0	3637447	51	2015	500000
13	0	0	0	1	1	0	3637447	51	2015	50000
14	0	1	1	0	0	0	3637447	51	2015	50000
15	1	0	0	0	0	0	3708770	52	2016	50000
16	0	0	0	1	1	0	6878262	76	2016	2000000
17	0	0	0	1	1	1	3708770	52	2016	50000
18	1	1	0	0	0	0	3708770	52	2016	2000000
19	1	0	0	0	0	0	19027983	168	2017	50000
20	0	0	0	1	0	0	3708770	52	2017	50000
21	0	0	0	0	1	1	19027983	168	2017	500000
22	0	1	1	0	0	0	3708770	52	2017	50000

Scenario 4 ↓

Possession	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	ETM	Duration	Start Date	Costs
1	0	0	1	1	0	0	3708770	52	2013	2000000
2	0	0	0	1	0	0	3708770	52	2013	50000
3	1	1	1	0	0	0	3637447	51	2013	50000
4	0	0	0	1	1	1	19027983	168	2013	500000
5	1	0	0	0	0	0	3708770	52	2013	2000000
6	0	1	0	0	0	0	3708770	52	2013	500000
7	0	0	0	1	1	1	3708770	52	2013	50000
8	0	1	1	0	0	0	1283805	18	2013	500000
9	0	0	0	1	1	1	3708770	52	2013	500000
10	0	1	1	0	0	0	3708770	52	2013	500000
11	0	0	1	1	0	0	3708770	52	2013	2000000
12	0	0	0	1	0	0	3708770	52	2013	50000
13	0	1	1	0	0	0	19027983	168	2014	2000000
14	0	0	0	1	1	1	3708770	52	2014	50000
15	1	0	0	0	0	0	3708770	52	2014	50000
16	0	1	0	0	0	0	3708770	52	2014	2000000
17	0	0	0	1	1	1	1283805	18	2014	500000
18	0	1	1	1	0	0	3708770	52	2014	50000
19	0	0	0	1	1	1	3708770	52	2014	50000
20	0	1	1	0	0	0	1283805	18	2014	2000000
21	1	1	0	0	0	0	3708770	52	2014	2000000
22	0	0	0	0	1	1	3708770	52	2014	500000
23	0	0	1	1	0	0	3708770	52	2014	500000
24	0	0	0	1	0	0	3708770	52	2014	50000
25	1	1	1	0	0	0	3637447	51	2015	500000
26	0	0	0	1	1	1	19027983	168	2015	50000
27	1	0	0	0	0	0	3708770	52	2015	50000
28	0	1	0	0	0	0	3708770	52	2015	50000
29	0	0	0	1	1	1	3708770	52	2015	50000
30	0	1	1	0	0	0	1283805	18	2015	2000000
31	0	0	0	1	1	1	3708770	52	2015	2000000
32	0	1	1	0	0	0	3708770	52	2015	50000
33	1	1	1	1	1	1	3708770	52	2015	500000
34	0	0	0	1	0	0	3708770	52	2015	500000
35	1	1	0	0	0	0	19027983	168	2015	2000000
36	0	0	0	1	1	1	3708770	52	2016	50000
37	1	0	0	0	0	0	3708770	52	2016	2000000
38	0	1	0	0	0	0	3708770	52	2016	50000
39	0	0	0	0	1	1	1283805	18	2016	500000
40	0	1	1	1	1	0	3708770	52	2016	500000

I. Objective solutions

Scenario 1

K	0,65	9,5	26	380
		CPLEX		
	29.700.000	**75.500.000**	**160.800.000**	**1.970.672.183**
		Construction		
1	29.775.757	76.089.258	162.436.464	1.970.672.183
2	29.755.370	75.791.300	161.621.000	1.970.672.183
3	29.775.757	76.089.258	162.436.464	1.970.672.183
4	29.775.757	76.089.258	162.436.464	1.970.672.183
5	29.755.370	75.791.300	161.621.000	1.973.739.630
6	29.755.370	75.791.300	161.621.000	1.973.739.630
		Improvement		
Chained swapping	29.775.757	76.089.258	162.436.464	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.775.757	76.089.258	162.436.464	1.970.672.183
	29.775.757	76.089.258	162.436.464	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.973.739.630
	29.755.370	75.791.300	161.621.000	1.973.739.630
Cluster based IG	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
IG	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
Highest reward first	29.775.757	76.089.258	162.436.464	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.970.672.183
	29.775.757	76.089.258	162.436.464	1.970.672.183
	29.775.757	76.089.258	162.436.464	1.970.672.183
	29.755.370	75.791.300	161.621.000	1.973.739.630
	29.755.370	75.791.300	161.621.000	1.973.739.630
Minimum	**29.755.370**	**75.791.300**	**161.621.000**	**1.970.672.183**

Scenario 2

K	0,65	9,5	26	380
		CPLEX		
	39.500.000	**90.400.000**	**185.400.000**	**2.221.900.000**
		Construction		
	39.528.249	90.442.698	185.367.940	2.221.945.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	54.938.549	106.122.081	201.549.006	2.221.945.870
	54.938.549	106.122.081	201.549.006	2.242.113.853
	43.185.460	94.368.992	189.795.917	2.237.137.217
	43.185.460	94.368.992	189.795.917	2.237.137.217
		Improvement		
Chained swapping	39.528.249	90.442.698	185.367.940	2.221.945.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	54.938.549	106.122.081	201.549.006	2.221.945.870
	54.938.549	106.122.081	201.549.006	2.227.914.997
	43.185.460	94.368.992	189.795.917	2.237.137.217
	43.185.460	94.368.992	189.795.917	2.237.137.217
Cluster based IG	39.528.249	90.442.698	185.367.940	2.221.945.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	39.549.017	90.746.223	186.198.640	2.221.945.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
IG	39.528.249	90.442.698	185.367.940	2.221.945.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	39.549.017	90.746.223	186.198.640	2.221.945.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
Highest reward first	39.528.249	90.442.698	185.367.940	2.221.945.870
	39.549.017	90.746.223	186.198.640	2.234.086.870
	43.185.460	94.368.992	189.795.917	2.221.945.870
	43.185.460	94.368.992	189.795.917	2.238.294.317
	43.185.460	94.368.992	189.795.917	2.237.137.217
	43.185.460	94.368.992	189.795.917	2.237.137.217
Minimum	**39.528.249**	**90.442.698**	**185.367.940**	**2.221.945.870**

Scenario 3

K	0,65	9,5	26	380
		CPLEX		
	42.984.499	**180.345.349**	**436.441.849**	**5.926.032.300**
		Construction		
	43.170.139	183.058.549	443.591.254	5.927.633.854
	43.090.969	181.901.449	440.424.454	5.928.117.751
	44.932.796	183.572.286	442.052.689	5.927.458.169
	44.936.784	183.630.568	442.212.199	5.927.458.169
	43.051.774	181.328.599	438.856.654	5.928.171.974
	44.655.200	182.428.371	439.293.606	5.926.816.846
		Improvement		
Chained swapping	43.051.774	181.328.599	438.856.654	5.926.459.654
	43.051.774	181.328.599	438.856.654	5.928.100.651
	43.117.703	181.931.869	440.412.272	5.927.386.846
	43.157.610	182.061.474	440.643.105	5.927.386.846
	43.051.774	181.328.599	438.856.654	5.928.171.974
	43.034.253	181.072.527	438.432.019	5.926.816.846
Cluster based IG	43.094.928	181.959.304	439.125.869	5.927.206.500
	43.015.758	180.802.204	436.522.189	5.927.458.169
	44.932.796	183.572.286	442.052.689	5.927.458.169
	44.936.784	183.630.568	442.212.199	5.927.458.169
	43.022.524	180.901.099	436.792.849	5.926.816.846
	43.051.803	181.329.027	439.293.606	5.926.816.846
IG	43.170.139	183.058.549	442.697.449	5.927.206.500
	43.090.969	181.901.449	439.530.649	5.928.117.751
	44.932.796	183.572.286	442.052.689	5.927.458.169
	44.936.784	183.630.568	442.212.199	5.927.458.169
	43.051.774	181.328.599	437.962.849	5.927.458.169
	44.655.200	182.428.371	439.293.606	5.926.816.846
Highest reward first	43.170.139	183.058.549	443.591.254	5.927.633.854
	43.090.969	181.901.449	439.744.846	5.928.117.751
	44.932.796	183.572.286	442.052.689	5.927.458.169
	44.936.784	183.630.568	442.212.199	5.927.458.169
	43.051.774	181.328.599	438.856.654	5.928.171.974
	44.655.200	182.428.371	439.293.606	5.926.816.846
	43.015.758	**180.802.204**	**436.522.189**	**5.926.459.654**

Scenario 4

K	0,65	9,5	26	380
	CPLEX			
	-	-	-	-
	Construction			
	6.596.572.966	95.355.324.302	260.837.742.045	3.811.077.000.000
	13.097.492.639	190.351.286.169	520.824.460.546	7.610.903.000.000
	6.614.618.154	95.378.438.937	260.869.195.160	3.811.227.000.000
	6.612.266.783	95.376.118.498	260.866.932.388	3.811.226.000.000
	6.627.373.178	95.388.327.287	260.874.851.897	3.811.267.000.000
	13.112.178.635	190.374.830.174	520.862.998.484	3.811.262.000.000
	Improvement			
Chained swapping	96.842.590	359.264.959	848.527.001	11.228.265.916
	98.097.799	360.130.811	848.666.936	11.246.723.899
	96.887.212	359.917.124	849.198.841	11.243.442.484
	96.891.112	359.974.124	849.354.841	11.242.319.584
	112.028.423	372.634.772	858.511.014	11.239.025.129
	96.831.251	359.099.231	846.591.431	11.239.025.129
Cluster based IG	96.666.895	356.697.109	841.499.201	11.223.019.931
	96.774.019	358.328.249	845.924.375	11.230.894.944
	96.833.532	359.132.567	844.636.205	11.234.603.714
	96.736.023	357.707.434	844.288.065	11.234.603.714
	111.987.473	372.036.272	856.873.014	11.245.091.257
	96.735.994	357.707.006	843.472.601	11.245.074.157
IG	96.725.395	357.552.109	843.839.201	11.229.687.146
	98.136.994	360.703.661	850.234.736	11.257.248.565
	112.113.745	373.881.780	861.923.878	11.240.890.814
	112.117.996	373.943.910	862.093.918	11.239.750.814
	127.384.881	388.498.335	875.320.027	11.246.231.257
	112.182.863	374.891.972	863.207.784	11.246.231.257
Highest reward first	96.904.733	360.173.197	851.012.705	11.233.395.916
	98.136.994	360.703.661	850.234.736	11.260.886.012
	112.380.194	362.953.047	868.292.024	11.244.599.584
	112.296.358	362.408.670	866.147.422	11.243.459.584
	127.384.881	388.498.335	875.043.832	11.253.204.342
	112.182.863	374.891.972	863.207.784	11.253.204.342
Minimum	**96.672.800**	**356.783.500**	**844.882.841**	**11.227.150.000**

J. Neighbour comparison for SA

Table 29 Objective value, comparison between different neighbours [SA parameter settings: number of iterations = 500, cooling down coefficient 0,1, K =[0,65; 9,5; 26; 380], scenario 3]. Using the following setting for the neighbour structures [Shift number of possessions = 2, Chain number of chains = 6, IG number of possessions = 6, number of clusters = 4]. Improving construction solution 1.

Neighbour method	**500 iterations**			
	K = 0,65	K = 9,5	K = 26	K = 380
Shift	43.310.622	183.240.000	441.143.235	5.927.458.169
Chain	43.147.324	182.454.850	439.255.241	5.927.458.169
IG	**43.030.412**	**180.930.964**	**437.998.708**	**5.926.032.300**
Cluster based IG	43.310.622	181.429.052	439.466.235	5.927.458.169
CPLEX	42.984.499	180.345.349	436.441.849	5.926.032.300