

ProRail

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Delft Institute of Applied Mathematics**

**An optimization model for a Train-Free-Period
planning for ProRail based on the maintenance needs
of the Dutch railway infrastructure**

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An optimization model for a Train-Free-Period planning for ProRail based on the maintenance needs of the Dutch railway infrastructure

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Preface

The master thesis that is staring you in the face is the result of nine months research at ProRail, alternated with some (musical) tours. This research is my graduation project, so it is the very last assignment I had to do to graduate as (applied) mathematician at the Delft University of Technology. I chose to do my graduation project within a company, to get experience in the business sector, but also to have the possibility to apply my mathematical skills in practice. The complexity of the Dutch railway infrastructure seemed an appropriate subject to me, so my choice fell on ProRail, the Dutch railway network manager.

During this project, I got familiar with the company ProRail, especially with the department Infrabeschikbaarheidsplanning (Availability Infrastructure Planning). The capacity for maintenance steadily decreases, so this department is (together with other departments) thinking of a new interpretation to performing and scheduling maintenance. Therefore, I developed an optimization model to determine an (approximately) optimal TVP planning, in terms of capacity and costs. This model makes only use of the 10 most determinative maintenance activities, which I determined by expert judgement. The thesis reports on the company, what is done before on this subject, the Top 10, the developed model, the results of the model, and finally gives conclusions and recommendations.

Now this project is almost finished, I am looking back on nine instructive months. Besides the musical skills I developed in the Dutch Student Orchestra, I learned about the difficulties of filtering an assignment in such a complex (railway) world, about respecting the scope of the project, about doing a project of this size and last but not least about writing a master thesis in the English language.

This thesis would not have been written without support from my daily supervisors Prof.dr.ir. K.I. Aardal and Ir. C. Grootenboer. Within the man's worlds such as ProRail and the Delft University of Technology, we were a female team determined to deliver good products: our model and this thesis. Karen, many thanks to your confidence in me since the Bachelor graduation project and for the accurate comments on my texts, even in your holiday in Norway. Caroline, thanks for all the support you gave during the project, even when I was less motivated you were able to motivate me again. Also thanks for the useful comments on the texts, I wish you luck in your new job.

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Also many thanks to Dr.ir. R.J. Fokkink and Prof.dr. C. Witteveen for being part of my graduation committee. Greg Glockner, thanks for helping me with the solver Gurobi.

Finally I have to thank all my family and friends, without them, my student days would be more boring, since I would have miss a lot of relaxation like parties, dinners and other activities. Special thanks to my parents, who made it possible to study and always stood behind me. Papa, thanks for reading the entire thesis and giving useful comments. Last but definitely not least, I want to thank my lovely friend Edo very very much. He has been interested in my project from the beginning to the end, he was always willing to talk about it. Moreover, he helped me a lot with technical computer problems, with the English language and with reading each page of the thesis more than one time. During busy periods, he gave me all the time I needed and took care of dinner. Edo, thanks a lot for all your support in every possible way. I am looking forward to give you all the time and attention back during our 7 week's road trip in the USA.

Rianda Jenema
11 September 2011, Monnickendam

Abstract

The future Dutch railway infrastructure capacity will become more and more scarce due to increased transport, increasing safety requirements and an increasing number of projects. This is why ProRail, the Dutch railway network manager, concluded that the current maintenance schedule is not future-proof and started the program Maintenance Model 2020 (OHM2020) to give a new interpretation to performing and scheduling maintenance.

The current maintenance schedule is based on the longest lasting systematic maintenance activity and on traffic wishes: maintenance is scheduled such that the disturbance to the traffic will be minimized (so the maintenance will mainly be performed during the night). Under OHM2020, the question is whether a maintenance schedule based on the essential maintenance necessities of the infra objects will be better (in terms of capacity and costs) than the current maintenance schedule.

To execute maintenance and projects, the train table needs *train-free periods*: TVPs. The main problem investigated in this research is to find a TVP planning, based on the maintenance necessities of the infra objects, including the possibility to integrate the planning of projects to investigate the influence of integrating the scheduling of projects into the scheduling of systematic maintenance (this is an actual discussion). Therefore, mathematics will be applied to optimize the TVP planning in terms of capacity. The maintenance necessities will only be based on the "Top 10" of most *determinative* maintenance activities (maintenance activities that influence the TVP planning the most), which will be determined first by expert judgement.

First, we get familiar with the company ProRail and the railway branch. ProRail manages and maintains the Dutch railway infrastructure system and ensures that the railway system is reliable and safe and that it is available for use by different carriers. It monitors the condition of the tracks, builds new railways and allocates the capacity of the railways between the stakeholders. ProRail cooperates with the government, carriers and other stakeholders of the railways and is the contracting authority for (specialized) companies that, among others, perform maintenance and constructing of infrastructure.

ProRail has a conservation system to live up to the ambition: require an availability of the railway infrastructure as high as possible, while the life cycle costs decrease with 20 percent. The maintenance activities belonging to the conservation system can be divided into preventive and corrective maintenance activities, this research focuses on preventive maintenance. Life Cycle Management is used in preparing the maintenance plans. For the execution of the maintenance activities and projects, ProRail contracts rail contractors and other specialized companies. A transition is going on from the (old) contract type based on specified maintenance activities (Output Process Contracts) to the (new) contract type based on required quality levels (Performance Based Maintenance).

The research is done within the department Availability Infrastructure Planning, that ensures that the maintenance at, and the expansion of, the railway infrastructure can be performed safely and that the concerning infrastructure is available for that maintenance. The maintenance takes place in a maintenance schedule (or: TVP planning). Nowadays, every piece of railway area has scheduled once in every two weeks 2.5 hours TVP and once in every four weeks 5.5 hours TVP, regardless whether the area is a busy one or not. OHM2020 examines, among others, whether the TVP planning could be based more on the mainte-

nance necessities and more dynamic.

The infra objects that are part of the Top 10, are described: level crossings (an area where one or more tracks cross a path), catenary (the total of bearing constructions, wires and accessories serving to supply energy for the electric traction), railway tracks and switches (the infra objects that realize the physical branching in the railway network).

Besides getting familiar with the company, there is some literature study done to find out what has previously been done on the subject of this thesis. Our developed model has the most similarities with the model described in the thesis of Budai-Balke [3]. The article of Higgins et al. [8] has another similarity with our model. Badr et al. [2] gave some insights about inter-dependency constraints. ProRail also did some research before. One of these researches developed a maintenance schedule quantifying tool [29] that checks whether the maintenance necessities fit the maintenance schedule. Another research determined norms how many TVP-hours are needed per year for every kind of infra object [28]. Finally, the used software (MATLAB [13] and The Gurobi Optimizer [7]) is described.

The first concept of the *Top 10 maintenance activities that are influencing the TVP planning in such a way that the TOP 10 could determine the TVP planning* is determined by an analysis on a benchmark on realization data. After discussing the first concept with experts (contractor and contract manager) the final Top 10 is set up. We do not claim that this Top 10 is definitive, but we believe that it approximates the reality, so we used it in the rest of the research.

The model that will find a TVP planning based on this Top 10, is an optimization model. So it formulates an objective function and constraints (restrictions) and finds the combination of decision variables that satisfy the constraints and minimizes the objective function. The objective of the model is to make a TVP planning such that the capacity for maintenance will be minimized. This is realized by minimizing the costs: possession costs, maintenance costs and project costs. A distinction is made in time: possession costs are cheaper during the night than during the day, while maintenance activities during the night are more expensive than during the day. Constraints used in the model concern TVP lengths, coupled switches, intervals between two successive maintenance activities, combination possibilities, maximum number of executable maintenance activities at the same time, extra possession costs when the total railway yard is obstructed, projects and day/night/weekend-requirements.

Besides the Top 10, the model will base the TVP planning on the concerning infra objects of the corresponding area, a list of possible time moments, a list of possible TVP lengths and (optionally) a list of projects, which are all described (including their sources). Of course, the mathematical description also is described and explained comprehensively.

We prove that the developed model is of the complexity class \mathcal{NP} -hard, so it is not likely that there exists an algorithm that solves the problem in polynomial time. So other techniques are necessary: the branch-and-bound method and the way the solver Gurobi is used are described in the report.

To test the model, 24 scenarios are set up, with distinctions in work zones (smaller and larger), ranges in randomness of previous executions of maintenance (random scenario and 'worst case scenario'), TVP lengths (current maintenance schedule versus an advice as result of another research) and projects (including and excluding).

The results show that larger work zones are more approximating the reality and that integrating the scheduling of the projects into the scheduling of the systematic maintenance is worthwhile. Other remarkable facts are that almost every maintenance activity is scheduled at night, that the most of the work is scheduled in the first quarter and that adding the option of TVPs of just 2 hours are worthwhile. However, the efficiency of 7 hours versus 2 hours (due to personnel costs) is not taken into account in this model. Moreover, the model also does not schedule serial, so two not-combinable maintenance activities with a length of 2 hours could not be scheduled in the same night in this model, while in practice this is possible in 4 hours. These and other recommendations for further research are made at the end

of the report.

Concluding, the model that makes a TVP planning based on the determined Top 10, considers a lot of factors, and already gives some insights. For example, integrating the scheduling of projects into the scheduling of maintenance seems to be valuable. From discussions about the results, we have noticed that the expectations of the possibilities of the model are high. However, for further implementation, the model still needs some improvements, such as improving the input data, adding serial scheduling and efficiency constraints.

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Glossary

\forall for all: $\forall a$ means for all elements a .

\in in: $a \in A$ means element a in set A .

\cap intersection: $A = B \cap C$ means that set A contains all the elements that are both in set B and set C , A is the intersection of B and C .

\cup union: $A = B \cup C$ means that set A contains all the elements of set B and set C , A is the union of B and C .

carrier a railway company whose (main) activity is supply to railway transport services for goods (freight) or passengers and that has traction to provide the services, as well as every other company that uses or is intended to use the railway and also has traction, examples are NSR, Railion, Eurailscout and VolkerRail (*vervoerder*).

catenary equipment the total of bearing constructions, wires and accessories serving to supply energy for the electric traction (*bovenleiding*).

catenary sector a sector in the catenary that is acting as one part: the current can be switched off per sector (*bovenleidingsgroep*).

catenary system the construction for the transfer of electrical power of one or more power points along the railway track to the current receiver of a train (*bovenleidingsysteem*).

contact wire a part of the catenary equipment which makes contact with the current takers (*rijdraad* (*bovenleiding*)).

corridor a route section that is reserved specifically for separate handlings of a traffic flow. The separate exploitation also indicates that for “material” and “personnel” no crosslinks exist with other traffic flows (*corridor*).

cross-over a facility to switch tracks on an open track by means of (at least two sets of) switches, see Figure 1 (*kruising*).

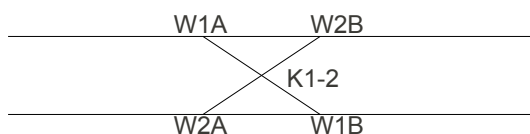


Figure 1: Cross-over (K) between two sets of switches (W)

infra the railway infrastructure that is property of ProRail, including buildings and areas.

infra object a physical element or construction that is determinative for the design of the railway infrastructure or the operation of it; according to the objects structure [15] it is a separately identifiable physical structure or a component of it (*infraobject*).

interruption a not (properly) working functionality of the railway infrastructure, a disturbance of the operation of the railway infrastructure (*storing*).

level crossing an area where one or more tracks cross a path (other traffic road) in the same plane (Asset Management (AM) considers a level crossing as an infra object) (*overweg, spoorwegovergang*).

maintenance operation a bundle of maintenance activities (*onderhoudsbeurt*).

maintenance schedule a schedule of Train Free Periods (TVPs) per tracing, intended for maintenance (*onderhoudsrooster*).

open track an area that connects two train-path points, there are no turning possibilities on an open track, it has one or more tracks (*vrije baan*).

out of order an area is out of order when an infra possession (see below) concerns that area, whereby the responsibility lies with the leader of the work place safety (*buiten dienst*).

possession an area that is temporarily not available for trains (*(infra-) onttrekking*).

rail-grinding train train which grinds the railway tracks (*slijptrein*).

route section a succession of connected train-path points and open tracks, starting and ending at a train-path point (*baanvak*).

signaling collective noun for all infra objects and maintenance activities related to signs (*seinwezen*).

sleeper a part of the substructure on which the rails will be mounted, the sleeper ensures that the rails keep the correct wideness and that the load of the train is transferred uniformly to the ballast bed, see Figure 2 (*dwarsligger*).



Figure 2: Timber sleeper (left) and concrete sleepers (right)

switch an infra object that realizes the physical branching in the railway network (*wissel*).

switch mechanism a part of the operating mechanism of a switch, which provides the reciprocations of the switch tongues (*wisselsteller*).

systematic maintenance includes the proactive maintenance activities, replacements of components, property management, functionality inspections and service, these activities are necessary to maintain the safe functioning of the railway infrastructure (*klein onderhoud*).

tamper a machine that corrects longitudinal profile, cross level and alignment of track; a number of sleepers at a time are lifted to the correct level by filling up the ballast bed. (*stopmachine*).

tracing a geographically restricted area from km to km and indicated with a geocode number (*tracé*).

traction the force exerted of the propulsion of a rail vehicle (*tractie*).

traffic control the organisation of people and systems with the following tasks:

- ensuring railway safety
- releasing routes to users of the infrastructure
- in case of a deviation between the requested and available routes, revision of the process plan and the provision of information on the changes made
- taking appropriate measures in case of a disaster and reporting the occurrence thereof

(*verkeersleiding*).

traffic control center center where the traffic is controlled by traffic controllers, also see traffic control (*verkeersleidingpost*).

traffic controller an employee of ProRail who is responsible for the train traffic (*treindienstleider*).

train-path point a primary area that forms a consecutive restricted part of the railway network and that fulfills a function in the scheduling of the train time table (*dienstregelpunt*).

work place safety instruction a description of the measures on behalf of work place safety at work activities on the railway infrastructure (*werkplekbeveiligingsinstructie*).

Acronyms

AM Asset Management.

BVW Route Section Value (*BaanVakWaarde*).

CV Capacity Allocation (*CapaciteitsVerdeling*).

FT Function Test (*FunctieTest*).

GAO Operating Time Based Maintenance (*GebruiksduurAfhankelijk Onderhoud*).

IBP Availability Infrastructure Planning (*InfraBeschikbaarheidsPlanning*).

IO Infra Operation (*Infra Operatie*).

IP Integer Programming.

KPI Key Performance Indicator.

LCM Life Cycle Management.

LP Linear Programming.

LT Long Term (*Lange Termijn*).

MILP Mixed Integer Linear Programming.

MIQP Mixed Integer Quadratic Programming.

NO North East (*Noord Oost*).

NSR NS Passengers (*NS Reizigers*).

OHM2020 Maintenance Model 2020 (*OnderHoudsModel 2020*).

OHR Maintenance Schedule (*OnderHoudsRooster*).

OPC Output Process Contracts (*OutputProcesContracten*).

OS sub-station (*OnderStation*).

PGO Performance Based Maintenance (*PrestatieGerichtOnderhoud*).

PHS Program High Frequency Railway (*Programma HoogFrequent Spoor*).

PMSP Preventive Maintenance Scheduling Problem.

QP Quadratic Programming.

RAMSHE Reliability, Availability, Maintainability, Safety, Health and Environment.

RCB Rail Case Base.

RCF Rolling Contact Fatigue.

RN Randstad North (*Randstad Noord*).

RZ Randstad South (*Randstad Zuid*).

SAO Interruption Based Maintenance (*StoringsAfhankelijk Onderhoud*).

TAO Condition Based Maintenance (*ToestandsAfhankelijk Onderhoud*).

TU Delft Delft University of Technology (*Technische Universiteit Delft*).

TVP Train Free Period (*TreinVrije Periode*).

VenD Traffic and Timetable (*Vervoer en Dienstregeling*).

WBI Work Place Safety Instruction (*WerkplekBeveiligingsInstructie*).

Z South (*Zuid*).

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Chapter 1

Introduction

The future Dutch railway infrastructure capacity will become more and more scarce due to increased transport (trains will run with a higher frequency), increasing safety requirements and an increasing number of projects (both require extra capacity). This is why ProRail, the Dutch railway network manager, concluded that the current maintenance schedule is not future-proof and started the program Maintenance Model 2020 (OHM2020) to give a new interpretation to performing and scheduling maintenance. The current Maintenance Schedule (*OnderHoudsRooster*) (OHR) is based on the longest lasting maintenance activity at an infra element and on the train traffic schedule. There is no distinction in location and maintenance needs: whatever the place, the number of train activities per day and the conditions of the infra objects are, the area gets the same time for executing the maintenance activities. Moreover, the maintenance schedule is mainly based on traffic wishes: maintenance is scheduled such that the disturbance to the traffic will be minimized.

Under OHM2020, the question is whether a maintenance schedule based on the essential maintenance necessities of the infra objects will be better (in terms of capacity and costs) than the current maintenance schedule. The infra objects have their own certain maintenance needs, which result in required maintenance activities that have to be scheduled. Would a maintenance schedule based on specific maintenance needs lead to lower costs and use of capacity than the current maintenance schedule?

Systematic maintenance requires train-free periods in the train table: TVPs. Until now maintenance and projects are planned independently of each other. ProRail wants to integrate the separate planning processes into one process and one planning/schedule. Therefore, from now on, the term TVP planning is used instead of OHR (maintenance schedule).

The main problem investigated in this research is to find such a TVP planning, based on the maintenance necessities of the infra objects. Therefore, mathematics will be used to optimize the TVP planning in terms of capacity. The maintenance necessities will only be based on the ten *most schedule-determining* maintenance activities.

The research will provide answers to two questions: 1. *Which 10 systematic maintenance activities are determining the TVP planning the most? And why?* Or in other words, which 10 maintenance activities influence the TVP planning in such a way that this Top 10 could determine the TVP planning? This question will be investigated by analyzing data of executed systematic maintenance and by interviewing different experts/stakeholders. The second research question is: 2. *What is an (approximately) optimal TVP planning for a specific route section/railway yard based on the maintenance needs of the infra objects, using the Top 10 from question 1?* This question will be more mathematical: an optimization model will be used to formulate the problem and find or approximate an optimal TVP planning.

First of all, Chapter 2 makes the reader familiar with the company ProRail and the railway sector. Chapter 3 reports on the literature study on the research subject. Then Chapter 4 describes the tracking of the Top 10, after which Chapter 5 will describe the designed model. Chapter 6 will report on the testing of the model and discuss the results. Finally, Chapter 7 and 8 will discuss some conclusions and provide some recommendations for further research respectively.

Chapter 2

ProRail

This thesis reports on my graduation project for my study Applied Mathematics at Delft University of Technology (*Technische Universiteit Delft*) (TU Delft). I chose to do this project at ProRail to apply the knowledge I acquired during the study in practice. ProRail is the Dutch railway network infrastructure manager, so it is necessary to get familiar with the company and the railway branch. The railway branch has a lot of jargon, so the reader of this thesis also has to get familiar with the rail terminology.

While introducing the company, the most important rail terms will come along. Besides that, from page 15 a list with terminology and a list with acronyms is given. The glossary lists the used terms followed by a short description and in *italics* the Dutch translation of the term. The definitions are based on the Dutch terminology list with rail terms [16], on the (English) glossary appendix of the Network Statement 2010 [14] and on the Dutch definitions document [24]. The list of acronyms lists the abbreviations followed by the definitions. Mostly, the acronyms are based on the Dutch definition, in that case the definition of the acronym is given in both English and Dutch.

First, the main tasks and facts of the company are described in Section 2.1. Next, Section 2.2 describes the conservation management system of ProRail, which is followed by Section 2.3 about Life Cycle Management. ProRail is changing its type of maintenance contracts, both the old and the new type of contract are explained in Section 2.4. The department I am working for is introduced in section 2.5. One of the tasks of this department, that also is an important part of this research, is drawing up the maintenance schedule, which is explained in Section 2.6. Then some relevant current projects are described in Section 2.7. Finally, the most important infra objects are introduced in Section 2.8.

2.1 Company

ProRail manages and maintains the Dutch railway infrastructure system. ProRail ensures that the railway system is reliable and safe and that it is available for use by carriers. The system consists of about 7,000 kilometers of railway tracks. Almost forty carriers and other stakeholders use this railway. The carriers transport more than a million passengers and 100,000 ton goods per day over the railways [18].

The railway network managed by ProRail is portrayed at route section level in the network overview map in Figure 2.1 [14].

ProRail monitors the condition of the tracks, builds new railways and allocates the capacity of the railways between the stakeholders: carriers (passengers and goods like NS Passengers (*NS Reizigers*) (NSR) and Railion) and ProRail itself and contractors (like VolkerRail) for maintaining the railway infrastructure. From thirteen traffic control centers in the Netherlands and a nationwide control center in Utrecht, ProRail regulates the train traffic and the information for passengers and carriers¹. At the stations, ProRail possesses the transfer areas for travelers like the station halls, the platforms and the tunnels.

¹During this research, the information tasks are transferred to the carrier NSR.



Note: In junctions not all connections are shown

Figure 2.1: General overview map of network configuration

An optimization model for a TVP planning for ProRail based on maintenance needs of the infrastructure
Rianda Jenema - TU Delft

ProRail cooperates with the government, carriers and other stakeholders of the railways and is the contracting authority for (specialized) companies that, among other things, perform maintenance and new building of infrastructure.

Capacity on the railway infrastructure is scarce and it is becoming more and more scarce, due to steadily increasing traffic. Hence, maintenance necessities are also increasing, but the capacity to execute maintenance decreases. Besides that, different users have different preferences and requirements on the capacity; travelers do not accept hindrance during the day because of the maintenance, while the goods carriers will use the railway infrastructure at night for running their heavy trains. The contractors also have their preferences, working during the day for instance is preferred to working during the night. Moreover, the residents in neighbouring areas prefer day work because of their night rest. Ultimately the choice is often to perform the maintenance during the night, because then less trains are running, and so the capacity for train movements will be higher [18].

2.2 Conservation management

ProRail wants to arrange the railway infrastructure maintenance to limit the nuisance for the train traffic (or: ProRail wants the availability of the railway infrastructure as high as possible) and the environment while decreasing the life cycle costs with 20 percent. To live up to this ambition, ProRail has a conservation system: a coherent system of processes, rules and activities that conserve the railway infrastructure practically optimal. With this, ProRail ensures that the installations, which are part of the railway system, like switches and level crossings, keep working [18].

Conservation management means:

managing the conservation of the infrastructure, pointed at the control and the improvement of the relation between the performance of the infrastructure (both railway infrastructure and station infrastructure) and the costs of the conservation of the infrastructure over the whole life cycle.

The performance of an installation is represented by the parameters Reliability, Availability, Maintainability, Safety, Health and Environment (RAMSHE) [17].

The maintenance activities belonging to the conservation concept can be divided into preventive and corrective maintenance activities. *Preventive maintenance* is maintenance to prevent interruptions to the train movements. This form of maintenance can be categorized into three maintenance approaches:

1. Maintenance after a certain operating time (Operating Time Based Maintenance (*Gebruiksduur-Afhankelijk Onderhoud*) (GAO)), including periodic revision and parts replacement. The maintenance takes place at a fixed interval, this can be a fixed period or an operating time.
2. Maintenance based upon a certain condition (Condition Based Maintenance (*ToestandsAfhankelijk Onderhoud*) (TAO)), this is based on a periodic inspection to determine the condition of a certain part and replacement of parts when the limit value is reached. The inspections take place at a fixed interval (term or operating time), but when the replacement will take place is not known in advance.
3. Function test after a certain operating time (Function Test (*FunctieTest*) (FT)), including a test to determine whether the concerning (sub)system/part still functions.

Corrective maintenance is maintenance after an interruption occurred: Interruption Based Maintenance (*StoringsAfhankelijk Onderhoud*) (SAO). This includes repairs, restorations and replacements of a defected part [21].

Periodical inspections and measurements are necessary to monitor the condition of the infra objects. To maintain the condition, cleaning and preventive replacements of parts are necessary. If parts fail due to wear or other causes, it may lead to interruptions which cause nuisance for carriers, passengers or the

environment.

Deciding which of the maintenance approaches will be used for the different infra objects influences some RAMSHE factors. Choosing for GAO with a short cycle causes a high reliability and safety, but a low availability, and high maintenance costs. Choosing for SAO causes some risks, because you do not know what the interruption is beforehand, how serious the interruption is, when the interruption is (during the busiest moment of the day?), and how long it takes for the work men arrive on the right place to fix the problem. So the GAO approach could be cheap when the object does not fail for many years, but when it does fails, solving the interruption can be expensive. ProRail documented their choices in the conservation documents, for example the conservation document railway tracks [22] and the conservation document switches [21].

Because capacity of the railway infrastructure is scarce, ProRail wants to minimize its use of capacity for maintenance purposes. That is why the maintenance activities are bundled in maintenance operations. In one maintenance 'bundle' preventive maintenance is planned, next to capacity for maintenance of which the necessity is discovered during an inspection or during the performance of the other activities. So the exact content of a maintenance activity is difficult to plan ahead [18].

2.3 Life Cycle Management

The maintenance claims a part of the railway infrastructure capacity, but it also costs money. The higher the performance requirements are, the more maintenance is needed, and the higher the costs will be. And the higher the availability requirements are, the higher the reliability has to be. ProRail has the task of establishing the maintenance in such a way that the desired performance is reached at the lowest possible cost, moreover without affecting the safety.

Carriers determine (to some extent) which degree of reliability and availability of the infrastructure they want without affecting the safety. For example, when the carriers want a high reliability of the infrastructure, then the availability will decrease so that ProRail have more time to ensure that reliability without affecting the safety. And vice versa. However, it has consequences for the price; with intensive usage of the railway infrastructure more inspections and maintenance activities are needed, and when a higher reliability is preferred, the parts have to be replaced earlier.

ProRail establishes the relationship between the performance of the infrastructure and the costs in *conservation concepts*, these are general (per type of object). Besides that, there are long term plans for maintenance and replacements, these are more specific (per location and individual objects). These plans give insight into the future replacement necessities and the related costs.

ProRail uses Life Cycle Management (LCM) in preparing the maintenance plans. This is a method to optimize the costs during the life cycle of (installations of) the railway system. With LCM it is possible to weigh the desired variants and get insight into the related costs. Also the nuisance for the train traffic during building and using the concerning object is weighed in LCM [18].

To make these LCM considerations, ProRail developed an LCM-tool. This tool calculates costs over the total life cycle of the scenarios and shows which scenario will be cheaper on the long term.

2.4 Type of contracts

ProRail defines the targets (such as the Key Performance Indicator (KPI) Availability) together with the government and the carriers, and ProRail translates these wishes and requirements into maintenance activities and projects. For the execution of the maintenance activities and projects, ProRail contracts rail contractors and other specialized companies.

Previously, the contracts specified exactly how the contractors had to perform the (systematic) maintenance activities [18]. Every maintenance activity had a norm unit (including a code, description and frequency) which is related to a price, so the contractor got paid for all the maintenance activities which he executed (as agreed beforehand). So all maintenance activities and their frequencies were prescribed. These type of contracts are called Output Process Contracts (*OutputProcesContracten*) (OPC). The Dutch railway network counted 38 OPC contract areas, which were divided over three contractors.

Nowadays, the contracting of the systematic maintenance is developing into Performance Based Maintenance (*PrestatieGerichtOnderhoud*) (PGO). In this new contract form, objective and measurable performances that should be achieved, are defined [17]. So the quality level is prescribed by ProRail, the contractor determines the type of maintenance activity and their frequencies by himself. Besides, the PGO type of contract will stimulate the competition in the market, because every contractor can offer a proposal for being the contractor of the PGO contract area. The development started with defining the generic conservation norms (safety and limit values) which the contractors have to perform. The contractors got paid for the performances they deliver, so it is their own challenge to reach the required performance as cheaply as possible. Meanwhile there are 5 ([23], 9 June 2011) contract areas contracted based on the PGO-contracts. In a time span of about 2 years, all regions in the Netherlands will have these new PGO-contracts.

Because the PGO contracts are relatively new, there is not much data available. That is why I used the data of contract areas which still have the OPC contracts to find a Top 10 of maintenance activities. Maybe it is possible to find such a Top 10 based on the new type of contract in the future, but because of the nature of this type of contract it would be even more complicated than finding the Top 10 based on the old type of contract. The fact that in the old type of contract maintenance activities have to be executed with a certain frequency compared to the more voluntary approach for the contractors in the new type of contract, underlies that thought.

2.5 IBP - Availability Infrastructure Planning

Availability Infrastructure Planning (*InfraBeschikbaarheidsPlanning*) (IBP) is the operational branch of Planvorming (English: planning) that ensures that the maintenance at, and the expansion of, the rail infrastructure can be performed safely and that the concerning infrastructure is available for that maintenance. There are Train Free Period (*TreinVrije Periode*)s (TVPs) needed to make the work at the railways possible, the TVPs are requested among others by the railway contractors. IBP optimizes and groups the submitted requests, handles the requests in close consultation with Traffic and Timetable (*Vervoer en Dienstregeling*) (VenD) and publishes the Work Place Safety Instruction (*WerkplekBeveiligingsInstructie*) (WBI) which the maintenance contractors have to follow. Besides the systematic maintenance (KO), also the incidental possessions (GIO and KIO) are scheduled by IBP.

The maintenance takes place within a maintenance schedule, which each year is drawn up by IBP, see Section 2.6. In preparing the maintenance schedule, IBP takes into account the interests of the railway contractors and companies. Also, the use of rail-grinding trains, video inspection trains (VST) and mobile work places (MWP) are included in the annual planning by IBP.

IBP is working on further optimization of the planning of maintenance, and the development of supporting information systems like Optimizer of Rail Capacity (ORCA). To have alternatives for the current maintenance model, IBP started a program "Maintenance Model 2020" (OHM2020), in which a solution is searched for the restrictions in time and place of the availability of the railway infrastructure for performing maintenance given the steady increase in the utilization [23]. These increasing developments are

- increasing traffic demand (High Frequency Program to be implemented in 2020)
- increasing amount of maintenance activities
- increasing complexity of safety measures resulting in more out of service hours

The new planning will be based upon another frequency of service hours with an adjusted time slot. At the same time it will optimize the service hours needed for projects and systematic maintenance. Major benefits will be an increase of capacity available for traffic and a decrease in cost.

The place of IBP in the organization is shown in the organizational structure of ProRail in Figure 2.2.

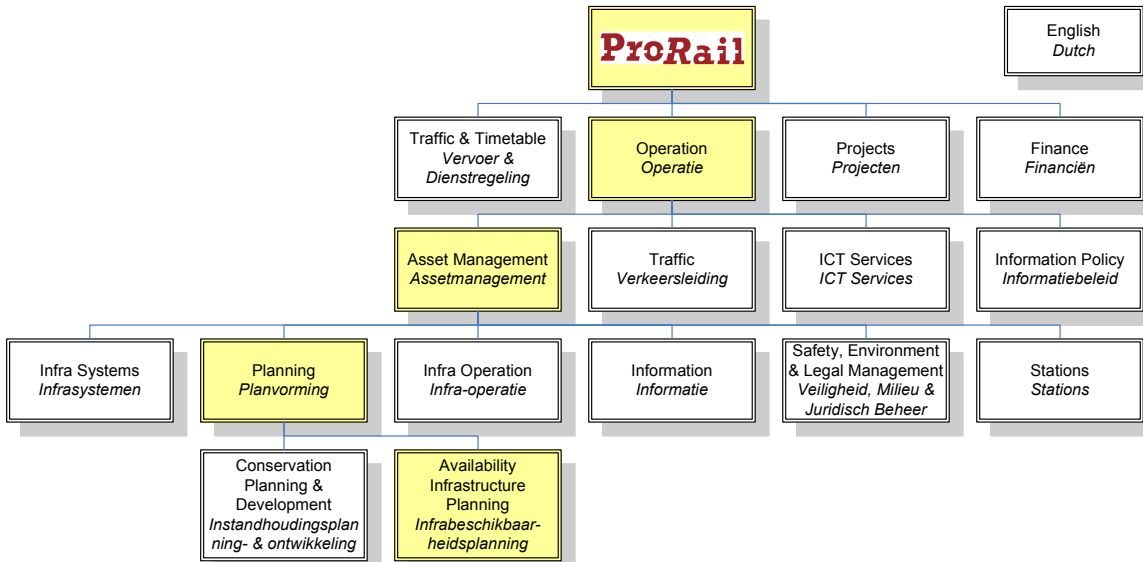


Figure 2.2: Organizational structure of ProRail

The role of IBP is shown schematically in Figure 2.3. The Long Term (*Lange Termijn*) (LT) plans of Asset Management yields management activities like systematic maintenance for Infra Operation (*Infra Operatie*) (IO) and the contractors, and projects or other plans made by ProRail. IBP collects the request of these parties and coordinates this to a maintenance schedule. Besides the asset management requirements, transport also has requirements on the capacity. The sub-department Capacity Allocation (*CapaciteitsVerdeling*) (CV) of the department VenD has an annual cycle during which it allocates the capacity between ProRail, the carriers and the other stakeholders, in consultation with IBP. The blue horizontal arrow represents this capacity allocation. See also Section 2.6 for more explanation on the capacity allocation.

The IBP central office plans the annual maintenance schedule that is then transferred to the four regions² of IBP: North East (*Noord Oost*) (NO), Randstad North (*Randstad Noord*) (RN), Randstad South (*Randstad Zuid*) (RZ), South (*Zuid*) (Z). The regions take over the short term planning and test and complete the work place safety instructions, which are set up by the contractors, to execute the OHR, set up and test the WBIs and control the execution of the OHR. Traffic control ensures that the concerning railway tracks are free for maintenance, the contractors execute the maintenance activities.

The feedback on the realization of the maintenance schedule is evaluated by IBP, which could lead to improvements for the LT plans of AM. This will complete the process management circle (plan-do-check-act).

Moreover, IBP also gives advice concerning safety and availability to the departments Projects, AM and VL. These advices come from both IBP central and the regions. Finally, IBP runs a number of innovative programs on availability, information, TVP processes and management information like dashboards and Key Performance Indicators.

²See Appendix A for the region division

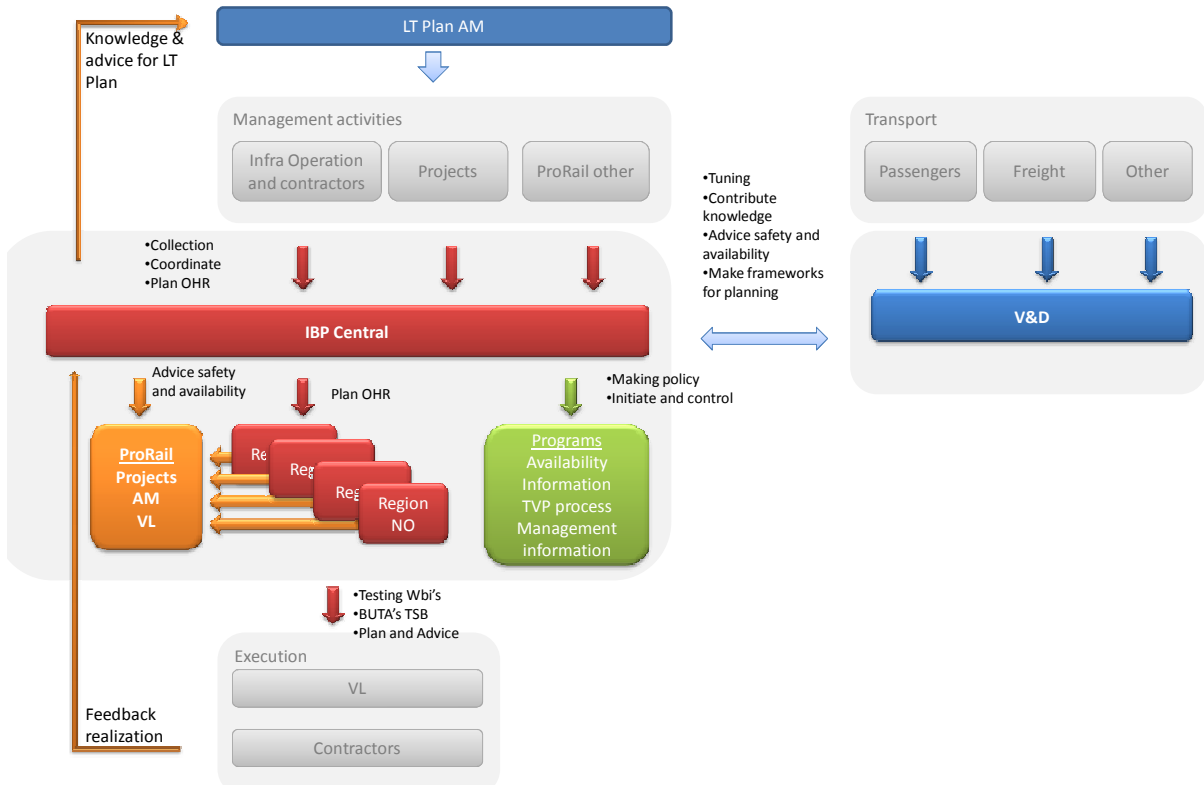


Figure 2.3: Schematic overview of the role of IBP in ProRail

2.6 Maintenance schedule

When maintenance takes place at the railway infrastructure, ProRail possesses the work zone. The zone is then “out of order”, i.e. it has a TVP. This part of the railway is assigned to the maintenance contractors and as long as it has a TVP, no train can come in the zone (like the definition of TVP says). The planning of the periodic maintenance operations is in line with the scheduling patterns of the carriers [18].

The periodic maintenance is fixed in the maintenance schedule (OHR: OnderHoudsRooster). The OHR is determined every year. In the OHR, every railway area gets a TVP of 5.5 hours once every four weeks, and once every two weeks a TVP of 2.5 hours [27]. This kind of maintenance schedule is used since 2004-2005. Notice that every railway area could use these 5.5+2.5+2.5 hours for maintenance every month, whatever the place, the number of train activities per day and the conditions of the infra objects are. For instance, an area with one track and one train per hour, without switches, in the North of the country, and an area in the busiest region of the country with twenty trains per hour, with switches that are sensitive for technical malfunctioning will get the same maintenance schedule (OHR). However, the first region will get less maintenance than the second region, because of the necessities of the infra objects. In other words, the OHR only gives the time slots which are allocated for maintenance and makes no distinctions in location specific maintenance necessities, but the different regions use these OHR on different ways. See Figure 2.4 for an illustration that explains this phenomenon.

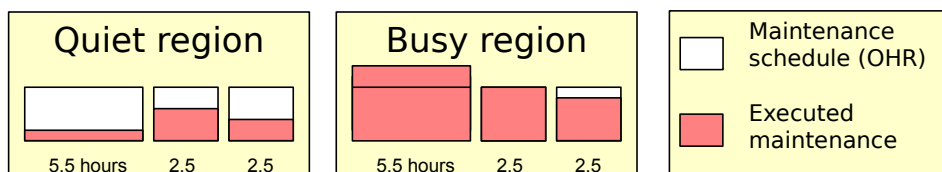


Figure 2.4: Illustration of the difference in maintenance executions on same maintenance schedules

The OHR consists of a schematic map of the railway network of a region. Figure 2.5 shows a part of the OHR of 2011 of region RN, for the night between Saturday and Sunday in the A-weeks³. Appendix B gives a total OHR of 2011 of region RN for the night between Monday and Tuesday in the B-weeks. The coloured areas are TVP in the time slots given in the frames. Note that the blue area in the upper left corner has a single track TVP from 01.50 to 02.50 and a double track TVP from 2.50 to 7.50. This picture shows only 'long' TVPs, the figure in the appendix also shows TVPs of approximately 2.5 hours.

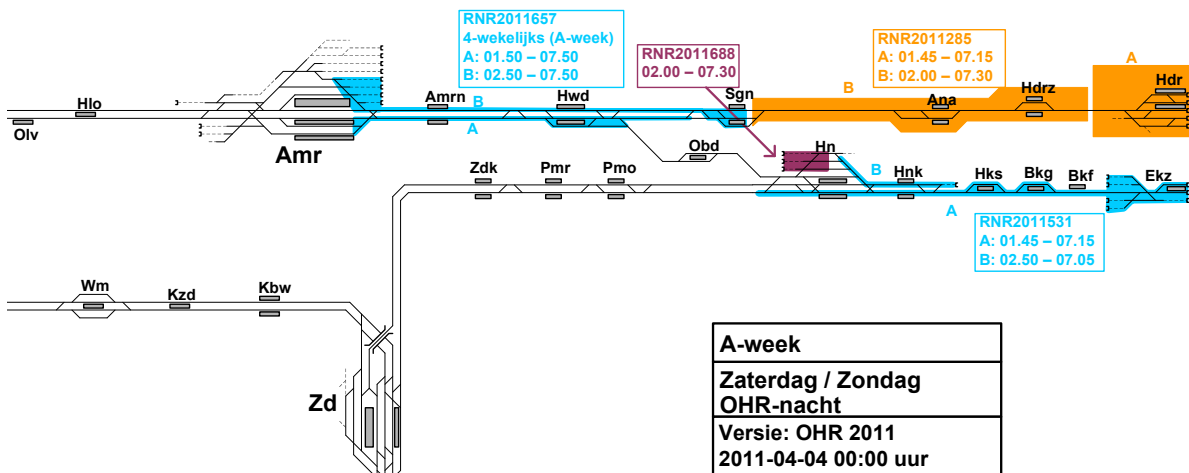


Figure 2.5: Part of OHR 2011 region RN Saturday/Sunday night week A

Although the OHR has the frequency of once in every two weeks and once in every four weeks, in practice the maintenance schedule will be applied every day: ProRail asks in the capacity allocation process once in the two weeks 2.5 hours and once in the four weeks 5.5 hours capacity for maintenance, but the carriers do not want to make exceptions every two weeks (because of clarity reasons for the passengers), so they do not schedule on that moment for every week or even for every day. So this capacity allocation is very inefficient, because ProRail gets a lot more than asked, but cannot use all obtained time.

There are three basic reasons behind the rule of 5.5 hours every four weeks. These are related to the maintenance activities to perform, the critical capacity and the cost efficiency [27]:

- *Type of maintenance activities*: the total package of maintenance activities (a maintenance operation) that possibly have to be performed, needs circa 5 hours. So a TVP of 5.5 hours is (technically) necessary to finish the maintenance activities without requesting extra WBIs.
- *Critical capacity*: technically high-educated people are working on the railway infrastructure. For certain crucial disciplines (signaling mechanics, welders) there is a shortage of employees/experts. TVPs of an insufficient size result in the non-optimal usage of this critical capacity (the working team get paid per eight hours, so the more the length of the shift deviates from eight hours, the less optimal it will be).
- *Cost efficiency*: reducing or breaking up TVPs causes unproductive periods between the TVPs, which are undesirable from a cost efficiency perspective. Also, some tools and machinery used at the maintenance activities are so costly that a long TVP-time is necessary. Think of railway and switch tampers and recovery of the catenary equipment. The rent of big material is per use, so renting once for 5 hours will be much cheaper than twice renting for 2.5 hours.

All the stakeholders wanting to use the railway infrastructure (carriers, ProRail Asset Management etc.) make agreements on the capacity allocation before the 2nd Monday in April each year for the following year. During that phase (before the actual capacity allocation), all parties have the same rights. The

³The OHR has a four weekly pattern, the four weeks are indicated with the letters A, B, C and D.

department Capacity Allocation of ProRail is the responsible party to ensure the capacity allocation. Then in the beginning of June, the first draft of the annual timetable will be derived. On the 4th Friday in August the annual timetable is final. After August, the ad-hoc phase will start. That means that every extra or changing request will be handled separately, but when the request is impossible, the applicant will not obtain what he asked. Half December, the new annual timetable will start. The process of capacity allocation is shown in Figure C.1 in Appendix C.

2.7 Current relevant ProRail projects

The railway capacity available for maintenance will decrease, because of increasing traffic, safety requirements and the number of projects. Moreover, the maintenance necessities also increase due to increasing traffic and safety requirements. Therefore, there are several projects that deal with how the future maintenance can be performed best. The program Maintenance Model 2020 (Subsection 2.7.1) deals directly with that problem. DynamITe (Subsection 2.7.2) is part of that program and investigates a more dynamic approach to railway maintenance. The projects 24/Safety (Subsection 2.7.3) and The Program High Frequency Railway (Subsection 2.7.4), which is creating a train schedule with a higher frequency (6 trains every hour between certain pairs of cities), are some of the causes of the decreasing capacity available for maintenance.

2.7.1 Maintenance Model 2020

IBP draws up an annual plan for the maintenance to be carried out, both systematic and project based. For the systematic maintenance, a maintenance schedule is determined. The capacity on the railways is becoming scarcer because of increasing security requirements, increased transport and proliferation of projects. For example, for security reasons, the time between the last train before the TVP and the moment when the first man may come into the work zone could increase, so the net work time will decrease, i.e. the capacity for maintenance decreases. Moreover, both the rail sector and its contractors have to remain vital: the contractors need day work to satisfy the employees. This puts demands on the amount of day work and the work distribution spread over the year. The current maintenance schedule no longer meets the capacity requirements at various points. A system transition is necessary. The project Maintenance Model 2020 (*OnderhoudsModel 2020*) (OHM2020) provides this system transition.

In the coming years, the system transition will consist of sub-steps. Each step contains a substantiation (what are the benefits in terms of availability, safety, manufacturability and costs) and a process based foundation (which process changes in the organization are required to implement the step).

Mindsets in the OHM2020 are among others [10]:

- developing current innovations like the mobile work place (MWP), video inspection train (VST) and grinding trains,
- examining significant rest capacity in the current OHR,
- examining a more dynamic maintenance schedule (the new possession concept DynamITe, see Subsection 2.7.2),
- examining a more central and coupled information,
- examining innovations on traffic,
- examining innovations on contractors,
- examining infra that needs less or none maintenance.

2.7.2 DynamITe

There are many aspects that influence the maintenance and the schedule. One of the components that OHM2020 focuses on, is the new possession concept DynamITe: a dynamical maintenance schedule. In cooperation with the department V&D, IBP will investigate new possession concepts on the aspects availability, safety, manufacturability and costs. ProRail prefers the model changing to a more dynamic model, namely with the possibility to claim parts of the maintenance schedule in a more dynamic way: on a shorter-term and only when necessary. A necessary condition is availability of information (by IT-systems) in the whole chain (from carrier to contractor). Moreover, the dynamical maintenance schedule will be based on the actual maintenance necessities, like our research.

DynamITe is [10]

- investigating the different possession concepts in cooperation with an organization consultancy bureau.
- determining the extent of the maintenance to be performed in the coming years (taking into account the increasing traffic, infra and quality requirements), looking at contractors, maintenance concepts of AM (Asset Management) and the impact on the contracting (see Section 2.4).
- drawing conclusions and choosing a detailed possession concept.
- developing the concept in terms of time, extent of maintenance, contracts, internal and external processes etc.
- preparing a pilot DynamITe (2012).

2.7.3 24/Safety

ProRail aims at zero accidents, therefore ProRail introduced the idea 24/Safety (Figure 2.6). 24/Safety means that one should do everything practically possible to prevent incidents, and that safety continues 24 hours a day, seven days a week. ProRail tries to do as much as possible to prevent deaths and injuries on and around the railways.



Figure 2.6: Logo of 24/Safety

ProRail speaks about three domains of safety: travel safely (over the railways), work safely (at the railways) and live safely (around the railways). Work safely is relevant for our project: *work safely* means that nobody working for, at or around the railways should be at risk. Track workers stand with confidence in a piece of railway track which is out of order (TVP) and the risks of the work are controlled. This is done together: as client and as contractor; as railway manager and as carriers [1].

These increasing safety requirements are influencing the TVP planning: when a work zone is out of order for maintenance, the leader of the work place safety has the responsibility to make the work place safe. The higher the safety requirements, the more time this takes. For example (again), safety requirements could lead to increasing time between the last train and the first man into the work zone. So, if the length of the TVP for a given zone cannot increase, then the net working time will have to decrease. In other words, the increasing safety requirements make more and more demands on the capacity.

2.7.4 Program High Frequency Railway

Both the passenger and freight rail are expected to grow rapidly in the coming years. The Program High Frequency Railway (*Programma HoogFrequent Spoor*) (PHS) stands for increasing traffic capacity, such that more passenger trains can run on the busiest routes in the country. Meanwhile, PHS aims at managing the growing freight.

PHS is required for a good accessibility of the main cities of the Netherlands (“de Randstad”), an essential condition for the development of the country. To keep the economical centers of the Netherlands accessible, the capacity of the railway infrastructure has to increase. High Frequency railway traffic should make using the train more attractive for current car drivers. That is why PHS is seen as a weapon in the struggle against the traffic congestion. The current PHS-plans have a broad support within the sector, but also within the regional governments and civil society.

Within PHS it is examined what should be done to run with a high frequency on three corridors, and how the goods traffic can be managed over the rail network. Therefore it is first examined what the optimal routes for goods traffic are [23].

Meanwhile, ProRail decided to implement the High Frequency Railway in the near future, so PHS is a fact. When the train traffic will take place with a higher frequency, then the railway infrastructure will need more maintenance, but meanwhile there is less capacity left over for maintenance. So it is clear that PHS influences the maintenance model.

2.8 Infra objects

Infra is the railway infrastructure that is property of ProRail, including buildings and areas. This railway infrastructure contains a lot of infra objects: the Business Information Document Objects Structure and Basic List Objects [15] that lists all infra objects, contains 37 pages, structured from total catenary equipment until a screw as part of that equipment.

Railway vehicles are bore by wheels of steel on rails of steel (steel on steel). The conduction of the vehicles takes place in the flanges of the wheels, see Figure 2.7.

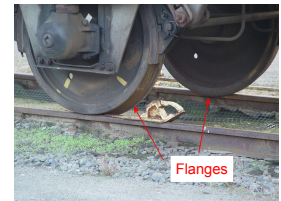


Figure 2.7: Flanges of the wheels of the train

The energy comes from the vehicle (Diesel) or from the catenary equipment. Branching is possible by switches. These are the basic principles of the railways. The building of the railways consists of substructure (foundation or structures (bridges and tunnels)), superstructure (ballast bed, sleepers and rails) and catenary, as shown in Figure 2.8.

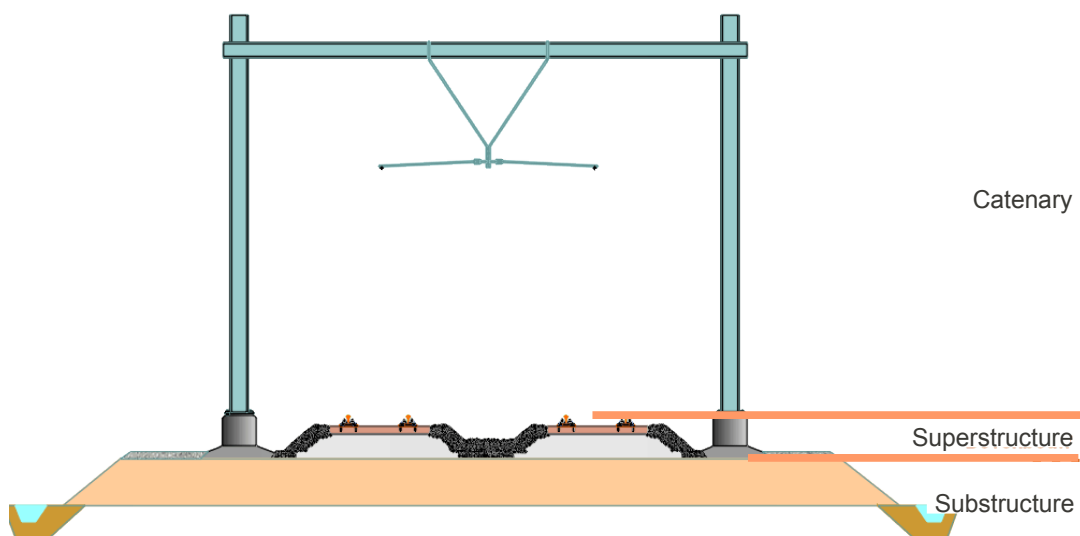


Figure 2.8: Building of the railways

The subsections describe more detailed the infra objects which are important for this research⁴: level crossings (Subsection 2.8.1), catenary (Subsection 2.8.2), railway tracks (Subsection 2.8.3) and switches (Subsection 2.8.4).

2.8.1 Level crossings

A level crossing is an area where one or more tracks cross a path (other traffic road) in the same plane (the same 'height'), provided with St Andrew's crosses (Andreaskruizen) or fences, see Figure 2.9.



Figure 2.9: Protected level crossing

There are protected and unprotected level crossings. Protected means that there is a warning system that starts when a train is arriving. Protected level crossings have barriers, fences or even men with flags. Unprotected level crossings have only St Andrew's crosses, scaring fences and speed signs, see Figure 2.10.



Figure 2.10: Unprotected level crossing

Level crossings do not need much maintenance, but when they do need maintenance, it will be complicated. For instance, the maintenance operation revision of the level crossing needs to lift the entire floor of the level crossing. The floors of the level crossings are per track, so a level crossing that crosses two railway tracks, will have two floors. The revision of the level crossing can be executed separately for each level crossing floor. When the time of the TVP is finished, the contractor cannot stop the operation immediately, the operation has to be finished completely. This often leads to overrunning the TVP time.

⁴the developed model is based on maintenance activities on only these type of infra objects

Moreover, as long as the level crossing is out of order, not only the railway tracks cannot be used, but the crossing path also has an obstruction. Particularly the routes of the emergency services (ambulances etc.) should be considered. This means that the scheduling of a maintenance activity on the level crossing in fact is more complicated than scheduling maintenance activities that only obstruct the railways. For instance, when the diversion is blocked by roadworks, the original route cannot be blocked.

Level crossings are also used for setting the machines in the railway tracks that are needed for the maintenance activities.

2.8.2 Catenary

The definition of *catenary equipment* is the following:

Catenary equipment is the total of bearing constructions, wires and accessories serving to supply energy for the electric traction

The goal of the catenary is to supply electrical energy to the train. The energy is obtained from local energy companies. The alternating current of the energy company is transformed for trains and locomotives in the sub-station (*OnderStation*s) (OSs). The 10,000 Volt alternating current is turned into 1800 Volt direct current, see Figure 2.11.

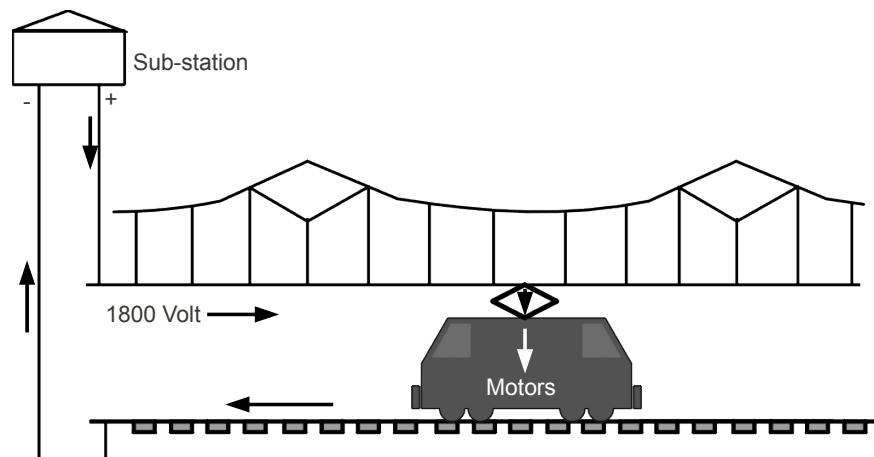


Figure 2.11: Diagram of the current from a sub-station

The definition of *catenary system* is the following:

A catenary system is the construction for the transfer of electrical power of one or more power points along the railway track to the current taker of a train. This system contains the following parts:

- catenary: all wires and lines hanging above the tracks including the movable catenary arm;
- bearing construction: the foundations, constructions and other parts that are meant for supporting the wires and lines, keeping it in their places, span and insulate (excluding the movable catenary arm);
- other: on the bearing construction fixed devices meant for switching functions, detecting and protecting.

See Figure 2.12 for a picture of a catenary system.



Figure 2.12: Catenary system

The catenary is divided into sectors. So when there is an interruption on the catenary, the interruption concerns only that sector. Especially on railway yards is this important, the sectors ensure that the other tracks remain usable. The division in sectors is achieved by placing linking stations (*SchakelStation*, SS) between the sub-stations, see Figure 2.13.

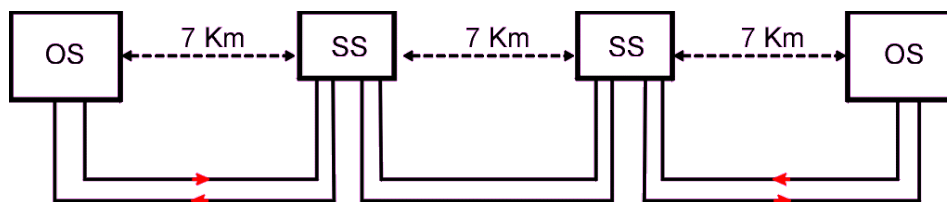


Figure 2.13: Diagram of linking stations (SS) between sub-stations (OS)

The catenary on route sections with double tracks is separated electrically. The linking stations make sure that the sectors can be separated or combined. For many maintenance activities on the catenary it is required to switch off the current, this off-switching is now possible per sector.

2.8.3 Railway tracks

The definition of railway track is the following:

Two rails constructed such that rail vehicles can run on it.

The functions of railway tracks are [22]:

- bearing and guiding of rail vehicles,
- allowing the rail vehicles to start and break,
- leading of electric currents and signals,
- detecting trains.

The structure of the railway tracks, besides the two rails, consists of sleepers for keeping the rails fixed and in the correct geometry, and ballast for keeping the rails on the correct height. The rails are part of the superstructure and lay on the substructure. Next to the railways lays an inspection path, where inspectors can walk safely to inspect the condition of the tracks. Nowadays, these inspections are done by video inspection trains (VST). The verge and the ditch are there for safety reasons, it makes it more

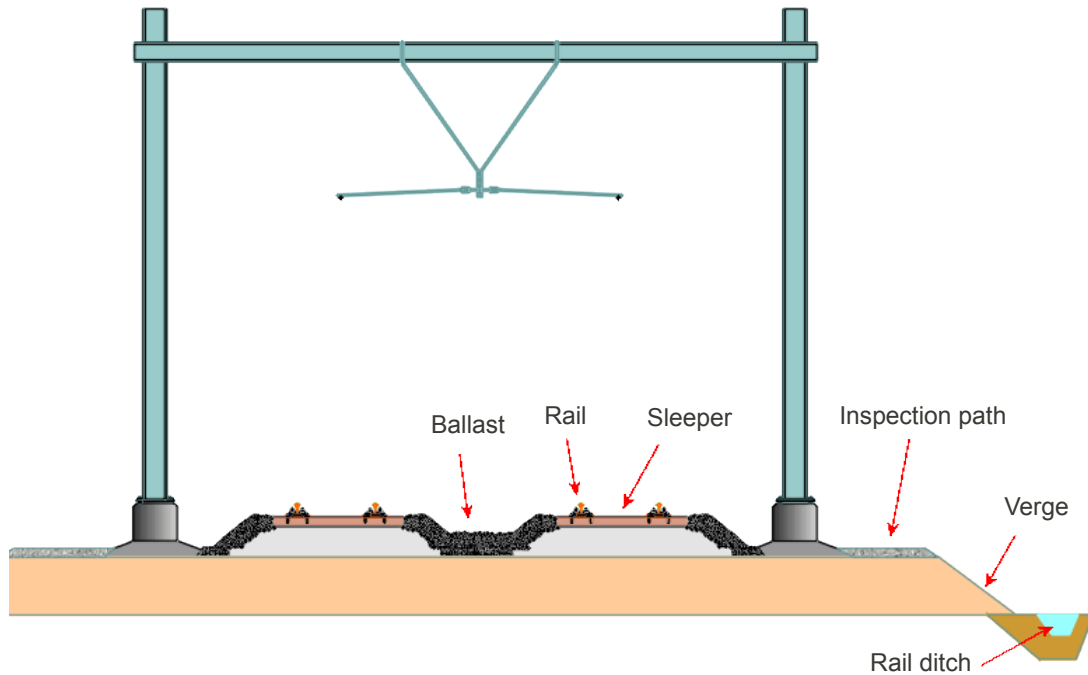


Figure 2.14: Structure of the railways

difficult to reach the railway tracks. See Figure 2.14 for an illustration of the structure of the railway tracks.

One of the most important maintenance activities on railway tracks is grinding the rails. This is done by rail-grinding trains, these trains grind the rails while they run over the railway tracks. Since the speed of this rail-grinding trains are high enough, the grinding is part of scheduling train paths instead of part of the maintenance schedule. So, grinding the rails does not need TVPs. Mechanical position maintenance on railway tracks does need TVPs, because the tampers (machines) do not run on train speed, so the railway tracks have to be out of order for a longer time. In fact, tamping the tracks has a big influence on the schedule, because the maintenance activity needs a TVP of at least 5 hours.

2.8.4 Switches

The definition of a switch is the following:

A switch is an infra object that realizes the physical branching in the railway network [16].

Another word for a switch is a point, but for clarity reasons we only use the term switch in this thesis.

There are different types of switches (see Figure 2.15), apart from the operation and the angle: normal switches, coupled switches, entire English switches and half English switches. A normal switch splits one track into two tracks. Coupled switches connect two tracks, coupled switches are controlled and shifted simultaneously, so they are always in the same position. A so-called entire English switch consists physically of a cross-over and four switches that are coupled pairwise (entire Englishman) or a cross-over with two (coupled) switches (half Englishman).

There are different angular relations (degree of deflection) possible, which then correspond to the speed a train is allowed to run over the switch in curve position (deviated). Common angular relations are 1:9 (40 km/h), 1:15 (80 km/h), 1:34.7 (140 km/h). The way a switch deviates can vary: the deflecting position can be left leading or right leading, but also both in equal degree: a so-called symmetric switch.

In terms of operation there are different possibilities: centrally operated using a motorized switch mechanism, manually operated, and so-called spring switches that are in a preferred default position using



Figure 2.15: Different switch types, from top and from left to right: normal switch, coupled switches, entire Englishman, half Englishman (the red arrows indicate the impossible direction)

a spring and could be switched by running a train over it. The technology varies; for instance, modern spring switches are not physically equipped with a spring, but they are operated by a motor. Also the coupling of switches influences the operation: the two switches always shift simultaneously in the configured positions [16].

A switch includes the switch construction, underlying stabilization construction, switches operation and switches heating elements (if any).

The functions of a switch are the same as the functions of the railway tracks as mentioned in Subsection 2.8.3, with in addition the following functions [21]:

- making possible that the rail vehicles can move from one track to another,
- allowing the rail vehicles to turn,
- controlling the locked end position of the switch.

Switches are the infra objects that require the most maintenance activities. Besides the obligatory inspections and maintenance operations which both have a high frequency, switches are also sensitive for technical malfunction. This is due to the fact that switches have moving parts, so compared with a piece of (non-moving) rails, it has more chance to malfunction. Inspections and grinding is again performed by special trains, so they do not need TVPs.

Chapter 3

Literature study

Besides getting familiar with the company, there is some literature study done to find out what has previously been done on the subject of this thesis. The most similarities are with the research of Budai-Balke [3] about Operations Research Models for Scheduling Railway Infrastructure Maintenance, see Section 3.1. In Section 3.2 two articles are described in which models for maintenance planning are developed as well. Section 3.3 describes two researches done within ProRail. Finally, in Section 3.4 the used software is described.

3.1 Thesis on Scheduling Railway Infrastructure Maintenance

The thesis of Budai-Balke [3] presents a contribution to the fields of operations research in two main areas: *Maintenance scheduling* and *Re-scheduling in the passenger railways*. I only describe the first area, because this part is much related to my Master's thesis project.

Budai-Balke could conclude from her literature study that scheduling of the preventive maintenance works on the railway infrastructure is very difficult, since there are many constraints to be considered. First, carrying out maintenance on the rail infrastructure usually involves many disturbances for travelers (e.g. delays, canceled trains), and vice versa, the train operation restricts the length and the frequency of the infrastructure possession. Moreover, due to a couple of severe accidents in the last years, the safety regulations for the track workers has become very strict in the Netherlands. Furthermore, railway infrastructure maintenance costs have increased substantially in the past years too. All these facts show that there is a need for developing mathematical models and techniques that can assist the maintenance activities on the railway infrastructure.

Budai-Balke introduced the Preventive Maintenance Scheduling Problem (PMSP) where a schedule for the repetitive routine works and once-only projects has to be found for one link such that the sum of the possession costs and the maintenance costs is minimized. The possession costs are mainly determined by the possession time, i.e., the time that a track is required for maintenance and cannot be used for railway traffic. In order to reduce track possession costs, the maintenance activities are clustered as much as possible within the same period. She provided a mathematical programming formulation for the PMSP and proved that it is a \mathcal{NP} -hard¹ problem. Since the maintenance scheduling problem is a complex optimization problem, and for a large set of instances it was difficult and time consuming to solve the problem to optimality, it was necessary to develop some approximation methods, which still give solutions close to the optimal ones. Budai-Balke used Cplex, a similar solver as Gurobi that I used.

Budai-Balke continued her study on PMSP with the objective to develop better techniques than the greedy heuristics developed to solve the PMSP as written above.

Summarizing her findings for the maintenance scheduling problems, Budai-Balke says that the mathematical models and techniques developed in her thesis can assist maintenance managers in making,

¹degree of complexity of the problem

in a reasonably short time, cost-effective schedules for carrying out different preventive maintenance activities on the railway infrastructure. Moreover, the presented models are just basic models, but they can be extended to solve many types of practical problems, since in reality there are many more constraints that a maintenance planner has to take into account. She finally mentions that the mathematical models and solution techniques developed for scheduling railway maintenance can also be applied for maintenance scheduling in other public/private sectors as well.

ProRail regrets that Budai-Balke never had a look at ProRail to make her model more valuable. So that would be the first difference between the model of my project and Budai's model. There will be more differences, for instance PMSP is considering only one track/work zone/place, so the maintenance planners have to make a planning for the total railway yard and could not make distinction between the different tracks/work zones. Or they have to make this planning for each work zone separately, but then the schedules are planned totally independent of each other, which in general will be far from optimal.

3.2 Maintenance scheduling articles

There has been more research related to maintenance scheduling, two of them are mentioned in this section. Higgins et al. [8] (Subsection 3.2.1) created a model for scheduling rail track maintenance to minimize overall delays in Australia. Badr et al. [2] (Subsection 3.2.2) present constraint based scheduling models for the building maintenance scheduling problem.

3.2.1 Scheduling Rail Track Maintenance To Minimize Overall Delays

Higgins et al. wrote for the 14th International Symposium on Transportation and Traffic Theory the paper "Scheduling Rail Track Maintenance To Minimize Overall Delays" [8], which focuses on the development of a model designed to help resolve the conflicts between train operations and the scheduling of maintenance activities. The model involves scheduling maintenance activities to minimize disruptions to train services and reduce maintenance costs. The main applicability of such a model is as a decision support tool for track maintenance planners and train planners.

The track maintenance scheduling problem, which involves the allocation of maintenance activities to time windows and crews to activities, is formulated as an integer programming model. The objective is to minimize a weighted combination of expected interference delays and prioritized finishing time of activities. Minimizing the first component will ensure a minimum interference between track maintenance activities and scheduled trains when either are delayed. The heuristic solution is obtained in two steps. First, an initial solution is generated, scheduling each of the activities in decreasing order of importance of finishing time. Each activity is selected and allocated to an available permissible work crew. If there are no available permissible work crews when the activity is chosen, the earliest finishing crew will be selected. The second stage uses the tabu search heuristic.

The model presented in the paper was applied to an 89 km track corridor on the eastern coast of Australia. The schedule constructed using tabu search has a 7 percent reduction in objective function value as compared to the schedule constructed manually. The model was also used to demonstrate the effects of activity schedule and maintenance resource changes. A four day planning horizon was used the model to test. Increasing the time window by moving less important trains was shown to reduce potential delays significantly [8].

The model of Higgins has as input among others a set of track links which make up the corridor, which Budai-Balke (Section 3.1) did not implement in her model.

3.2.2 Modeling a Maintenance Scheduling Problem with Alternative Resources

Badr et al. wrote the paper "Modeling a Maintenance Scheduling Problem with Alternative Resources" [2] about building maintenance scheduling, optional activities, alternative resources and disjunctive global

constraints.

Effective management of maintenance in buildings can have a significant impact on the total life cycle costs and on the building energy use. Nevertheless, the building maintenance scheduling problem has been infrequently studied. Badr et al. present in their paper constraint-based scheduling models for the building maintenance scheduling problem, where each activity has a set of alternative resources. They consider two different models, one using basic constraints, and the other using their new and modified global constraints, which handle alternative disjunctive resources for each activity to allow propagation before activities are assigned to resources. They evaluate these models on randomly generated problems and show that while the basic model is faster on smaller problems, the global constraint model scales better [2].

The section about the problem description is among others informative about constraints which define inter-dependency relations that might occur between activities, including *concurrency*, *precedence* and *non-overlapping*.

3.3 Researches within ProRail

This section describes two related researches done within ProRail. The first one, developed a quantifying tool for the maintenance schedule [29], see Subsection 3.3.1. The second one examined OHR-norms [28], see Subsection 3.3.2.

3.3.1 Scheduling Maintenance Model

ProRail developed in cooperation with Core Counselors a *maintenance schedule quantifying tool*, short: OHR-model. This model has the goal to give the user quantitative insight in the execution of the systematic maintenance within the maintenance schedule (OHR) with respect to four KPIs:

- Safety
- Availability
- Feasibility
- Costs

The OHR-model determines the maintenance necessities on the basis of the infra in an area. The model determines whether and how the maintenance activities could be executed within or outside the maintenance schedule and scores this solution on a set indicators. There has been made use of functional possession drawings (FOTs) which give the (application of) time and capacity slots for systematic maintenance. This could be periods during the day and during the night. The model takes into account the innovative maintenance activities like the video inspection train (VST). In fact, the model is an analysis tool that gives insight objectively into the circumstances where in the systematic maintenance will be executed [29].

The fact this model also examines the maintenance necessities is interesting. The difference with my model is that this model ‘checks’ whether the current OHR satisfies the maintenance necessities by trying to fit all the maintenance activities in the current OHR, while my model tries to find the optimal TVP planning (OHR) based on these necessities, and compares this with the current OHR afterwards.

3.3.2 Maintenance schedule norms

Swier [28] determined OHR-norms: for every kind of infra object he determined how many OHR-hours are needed per year and called these number of hours OHR-norms. Therefore, he focused on railway tracks and switches, because 60% of the maintenance costs belongs to them. (He also based his results on the OPC type of contract.) Swier decomposed the infra objects and needed execution time, and

filtered the infra objects that needs the railway tracks out of order. He got his information from the Rail Case Base (RCB), the M31-list and a list made by VolkerRail (a contractor) that indicates the minimal needed TVP length per maintenance activity.

Because Swier listed the most important maintenance activities with their frequencies and the minimal needed TVP length, his research was a good starting point for me in my research on the Top 10 of determinative maintenance activities.

3.4 Software

This subsection describes the used software besides the familiar Microsoft Excel. To solve my model given in Chapter 5, I have to translate the input file (Excel) to a file in Linear Programming (LP) format which describes my model. The solution of the LP-file is given in a solution file: .sol-file. I translate that file into an Excel-file which represents the TVP-planning. The two translations are made with MATLAB [13], and the solution is found by The Gurobi Optimizer [7].

3.4.1 MATLAB

MATLAB® is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation. Using the MATLAB product, you can solve technical computing problems more handy than with traditional programming languages, such as C, C++, and Fortran.

You can use MATLAB in a wide range of applications, including signal and image processing, communications, control design, test and measurement, financial modeling and analysis, and computational biology. Add-on toolboxes (collections of special-purpose MATLAB functions, available separately) extend the MATLAB environment to solve particular classes of problems in these application areas.

MATLAB provides a number of features for documenting and sharing your work. You can integrate your MATLAB code with other languages and applications, and distribute your MATLAB algorithms and applications [13].

The key features [13] of MATLAB are given below.

- High-level language for technical computing
- Development environment for managing code, files, and data
- Interactive tools for iterative exploration, design, and problem solving
- Mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, and numerical integration
- 2-D and 3-D graphics functions for visualizing data
- Tools for building custom graphical user interfaces
- Functions for integrating MATLAB based algorithms with external applications and languages, such as C, C++, Fortran, Java, COM, and Microsoft Excel [13].

In this project, I used MATLAB for reading the input files (Excel files) and translating it to the problem formulation of my model in LP-format (see Section 5.5). And after solving the .lp-file I translated the solution file (.sol-file) again to an Excel file which represented the TVP planning. So I did not use the computational aspects of MATLAB, but I did use the language to translate the files automatically. This could also be done with other programs like AMPL (a modeling language for mathematical programming) and GAMS (General Algebraic Modeling System), but I was already familiar with MATLAB including the functions *xlsread* and *xlswrite*.

The translations are written in two .m-files: `excel_to_lp.m` and `sol_to_excel.m`, which can be found in Appendix D.

3.4.2 The Gurobi Optimizer

The Gurobi Optimizer is a state-of-the-art solver for linear programming (LP), Quadratic Programming (QP), Mixed Integer Linear Programming (MILP) and Mixed Integer Quadratic Programming (MIQP). It was designed from the ground up to exploit modern multi-core processors.

For solving LP and QP models, the Gurobi Optimizer includes high-performance implementations of the primal simplex method, the dual simplex method, and a parallel barrier solver. For MILP and MIQP models, the Gurobi Optimizer incorporates the latest methods including cutting planes and powerful solution heuristics. All models benefit from advanced presolve methods to simplify models.

Every Gurobi license allows parallel processing, and the Gurobi Parallel Optimizer is deterministic: two separate runs on the same model will produce identical solution paths.

The Gurobi Optimizer is written in C and is accessible from several computing languages. Besides a simple command-line executable and a matrix-oriented C interface, Gurobi provides object-oriented interfaces from C++, Java, Python, and the .NET languages.

The Gurobi Optimizer is available for popular computing platforms including Microsoft Windows, Linux and Mac OS X.

I used (with the Academic License) Gurobi to solve the LP-file. Therefore I called Gurobi with a Python²-file which optimizes a MILP problem. It is based on an example file that Gurobi offers. The used file (`lp_to_sol.py`) is given in Appendix E.

²a programming language

Chapter 4

Top 10 determinative maintenance activities

This chapter describes the study of finding a list of “Top 10 maintenance activities that are influencing the TVP planning in such a way that the Top 10 could determine the TVP planning”. Section 4.1 describes the first analysis on data to set up the first concept of the Top 10. This first concept is discussed with several experts. Section 4.2 introduces the experts and their opinions. Finally, I will present the adjusted Top 10 in Section 4.3.

4.1 First analysis

This Section describes how I set up the first concept of the “Top 10”.

First of all, I tried to answer the question ‘*What makes a maintenance activity an activity that will have explicit influence on the TVP planning?*’. From now on, I will use the term determinative for this property, so with a “determinative maintenance activity” I mean an activity that influences the TVP planning in such a way that it could (together with the other determinative maintenance activities) determine the TVP planning.

Two aspects seem to be important: the duration (how long does it take to execute the activity?) and the frequency (how often has the activity to be performed?) of the maintenance activity. When a maintenance activity requires a long time, the TVP also has to be long enough. When a maintenance activity requires a lot of TVPs in a year, the frequency will be found in the TVP planning.

For finding the maintenance activities that have a relatively high frequency (more than once a year) or need a long TVP (at least 5 hours), I analyzed a benchmark on the so-called M31-list [12]. The M31-list contains a lot of information about the performed maintenance activities in the OPC-contract areas. The benchmark on this list concerns approximately 70 percent of the Netherlands. Note that this information is only available for contract areas which still work under the (old) OPC-contracts. So in the future, the M31-list will not exist anymore. At this time there is no data available for the new type of contract, so I had to do this analysis on data concerning the old one. Although the maintenance approach will change in the near future, the infra objects will still need maintenance to provide the desirable performances. So, the most important maintenance activities of the past are likely to be among the most important maintenance activities of the future. It could be worthwhile to evaluate the determined Top 10 in a couple of years, when the PGO contracts are not new anymore.

For the first concept of the Top 10, I made a list of all maintenance activities that need a TVP, according to the RCB [25] and the TVP norms determined by Jan Swier [28]. The M31-list also contains maintenance activities that can be executed without causing hindrance for the train traffic, for example activities like painting a pillar at the station hall. Since I am interested in the maintenance activities that have a big influence on the TVP planning, it is obvious that the maintenance activities that can be executed without

a TVP are not interesting (because we are minimizing the railway capacity for maintenance). For the remaining list, I collected the following information:

1. mean number of units (pieces, kilometers, tons, ...) on which the activity is executed per year (from 2006 to 2010),
2. minimal needed TVP length in hours,
3. number of times the activity is executed in 2010,
4. value 2 multiplied with value 1,
5. value 2 multiplied with value 3.

I was not interested in the exact values, but I was interested in the maintenance activities that were remarkable. So for every item described above, I sorted the list from high to low. (Except for item 2, because the list contains only a few options and the item is already part of item 4 and item 5.) The maintenance activity with the highest value gets 10 rating points, the second highest gets 9 points, etc. to the tenth highest activity which gets 1 rating point. The maintenance activities are rated four times, the total sum of the rating points decided the first concept of the Top 10, see table 4.1.

Nr	Unit code	Description	(1) Mean # units	(2) TVP length	(3) # Activities 2010	(4)=(2)x(1)	(5)=(2)x(3)	Rating points (1)	Rating points (3)	Rating points (4)	Rating points (5)	Sum rating points
1	OV.0001	Major operation revision level crossings	4370	5	377	21852	1885		9	7	10	26
2	BA.0001	Unload ballast	27992	5.5	139	153954	765	9		9	4	22
3	BA.0067	Chemical weed-killing	237653	1	260	237653	260	10	1	10		21
4	KW.0001	Function inspection structures	15428	0.5	544	7714	272	6	10			16
5	BA.0006	Revision glue welds	22231	0.5	326	11116	163	7	8			15
6	BA.0062	Grinding switch	3264	5.5	202	17954	1111			6	8	14
7	BA.0065	Maintenance fire mains	14295	2	21	28589	42	5		8		13
8	BA.0055	Rolling Contact Fatigue (RCF) inspection	12587	1	325	12587	325	3	7	2		12
9	BA.0049	Inspection moulds/turn walls	27696	0.5	39	13848	20	8		3		11
10	BA.0011	Manual position maintenance timber	1550	5.5	206	8523	1133				9	9

Table 4.1: First concept of the Top 10 of determinative maintenance activities

So the first concept of the Top 10 is based purely on found data as mentioned above. The meanings of the maintenance activities and other important information are not yet considered. For instance, the number of units is counted, but without considering what the units are, you cannot fairly compare kilometers, tons and pieces with each other. Hence, I was sure this list was not the final one, but I had soon found a first list that I could use as subject of discussion.

4.2 Expert judgement

To improve the Top 10, I presented the list to several experts. I asked them what they thought about the statement that the TVP planning could be determined by a select group of maintenance activities, discussed the Top 10 determinative maintenance activities described above (Section 4.1) and had a conversation about their expertise. First, Subsection 4.2.1 introduces a contractor. Second, Subsection 4.2.2 introduces a contract manager of areas with the new type of contract (PGO).

4.2.1 Contractor

During the research, I had contact with Jan Huiskes. Jan Huiskes has a lot experience in the railway infrastructure industry. Nowadays, he works for railway contractor *VolkerRail* [31] and is principal of the measure and video trains and project manager Inspection for the inspection, monitoring and measuring company *Inspection* [11].



Figure 4.1: Logos of VolkerRail and Inspection

First of all, on the question whether there exists a top 10 with maintenance activities that could determine the TVP planning, the contractor answers immediately 'yes'. He shares the thought that a TVP planning based on a select group of maintenance activities could be satisfying for all the systematic maintenance that has to be done. He expects that many of the maintenance activities that are not in the select group ('in the Top 10') could be combined with scheduled activities.

According to the contractor, the determinative maintenance activities are:

- obligatory inspections of signaling
- inspections and replacements on catenary
- *position maintenance*: correcting longitudinal profile, cross level and alignment of track using tampers.

The obligatory inspections of signaling are determinative because of the frequency, every switch needs a so-called R-operation every 3 months. The other maintenance activities are determinative because of the duration of the activity. Besides that, every time that the tamper is used costs a lot of money, so it is cheaper to use the tamper for one long period than for several short periods.

IBP is examining whether the maintenance schedule could have a lower frequency: nowadays, every area will have a 'long' TVP of 5.5 hours every four weeks, but they are wondering whether a 'long' TVP of for instance 7 hours every eight or thirteen weeks would satisfy the systematic maintenance needs. The contractor thinks it would be possible, but he has some critical notes on it. First, the more moments there are that the contractor could do maintenance, the cheaper the work will be due to personnel costs in combination with more flexibility. Second, the called 7 hours have to be net work time to make it possible, so the real time that the area is out of order will be longer due to making the area safe and bring the machines to right places. In fact, this should also hold for the 5.5 hours of the current OHR.

The most important criticism of the contractor on the current OHR is that there are important maintenance activities that could never be scheduled in the OHR. For example, for executing maintenance activities on coupled switches there are extra TVPs outside of the OHR needed, because there is no moment in the OHR where both switches are out of order at the same time. And another example, the catenary sectors do not have the same boundaries as the work zones, but the OHR is not taking this

into account. So when the catenary sector is not totally inside the work zone that is TVP, the contractors could not do their work on the catenary. So the current OHR is not satisfying the systematic maintenance needs.

The contractor also mentioned that inspections can be interrupted every moment, in contrast with the most maintenance activities where parts are revised, replaced or maintained. Besides that, inspections are performed by trains most of the time, so they do not determine the TVP planning. Although, there are inspections on catenary where the catenary needs to be without voltage, so then that sector will be out of order (so it needs a TVP).

The contractor also helped me with the numbers for frequency, minimal needed TVP-length, number of units per hour and combination possibilities.

4.2.2 Contract manager

The PGO contract manager also shares the thought that a TVP planning based on a select group of maintenance activities could be satisfying for all the systematic maintenance that has to be performed. However, he also thinks that by the developments to the new type of contract, it will be hard to find a Top 10 that applies to the whole Dutch railway network. Due to the new type of contract, contractors will only execute the maintenance activities that are necessary, so it will be more location specific. Besides that, it would be easier to make the Top 10 within the companies of the contractors, because they have all and more specific information about the executed maintenance activities.

In the PGO contracts only the quality of the railway infrastructure is defined (think of a maximal number of interruptions and derailments in a year), except the maintenance on switches which are called the R-operations (as described above in Subsection 4.2.1). The R-operations are so important, that they have to be executed every 3 (R3), 6 (R6), 12 (R12) or 24 (R24) months. Moreover, the contract manager requires that the maximum interval is strict: when a maintenance activity needs to be done every 3 months, the maximum interval will be 90, of course he will accept 80 days, but if the interval would be 91 days the contractor has to pay a fine.

According to the contract manager, grinding of switches and RCF inspections can easily be combined with other maintenance activities, so those activities will not be determinative. Inspections on contact wires on open track can be done without a TVP, but the inspections on contact wires on railway yards do need a TVP.

4.3 Top 10

This section presents the final Top 10 of this research. With final I mean that this is the last version of this research, but the list could be improved after the research. The presented Top 10 is also the list of maintenance activities that is used as input for the model in Chapter 5.

The final Top 10 is given in Table 4.2. The numbers one to ten do not imply that number one is more determinative than the others. The list is ordered on the concerning infra objects.

The table contains more information than only the maintenance activities. The unit code corresponds with the (short) description of the maintenance operations (bundled maintenance activities) and are used in the OPC contracts, the RCB, and the M31-list. Presumably, these codes will disappear/change in the future. The table also contains parameters that are used as input for the model and will be explained later (Chapter 5).

Nr	Unit code	Description	Infra object	Unit	D/N/W	Frequency per year	Minimal TVP length (in hours)	Minimal interval (in days)	Maximal interval (in days)	# units per hour
1	OV.0001	Major operation revision level crossings	level crossing	piece		0,3	5	1160	1250	0,2
2	EV.0004	Inspection catenary railway yards	contact wire	km	D	1	5	300	365	2
3	EV.0037b	Correction activities catenary	contact wire	km	N	0,3	3	1110	1200	0,33
4	BA.0012	Mechanical position maintenance railway tracks	railway tracks	km		0,5	5	1680	1800	0,5
5	BA.0013	Mechanical position maintenance switch	switch	piece		0,3	6	1160	1250	0,5
6	BA.0032	Major operation switch	switch	piece		0,5	5	660	720	0,4
7	BA.0016	Maintenance switch R3	switch	piece		4	1	75	90	10
8	BA.0017	Maintenance switch R6	switch	piece		2	2	150	180	2
9	BA.0018	Maintenance switch R12	switch	piece		1	3	315	360	0,67
10	BA.0019	Maintenance switch R24	switch	piece		0,5	6	660	720	0,33

Table 4.2: Top 10 of determinative maintenance activities

Chapter 5

Model

The designed model for determining a TVP planning is described in this chapter. First of all, the idea of the model is given in non-mathematical language in Section 5.1. The mathematical formulation is given in Section 5.2. Section 5.3 describes the input of the model. The complexity of the designed model is defined and proved in Section 5.4. The solution approach is given in Section 5.5. Finally, the tracking to find this model is explained in Section 5.6.

5.1 Model description

This section describes the idea of the model so that the mathematical formulation is easier to understand. The reader could even decide to skip Section 5.2.

The objective of the model is to make a TVP planning such that the capacity for maintenance will be minimized. This is realized by minimizing the costs, where the costs consist of possession costs (every hour that a zone is out of order there are no train movements possible, so this costs money), maintenance costs (execution of a maintenance activity costs money) and project costs (execution of a project costs money). A distinction is made in time: the maintenance activities are cheaper during daytime than during the night (think of the salary of the employees), but the possession costs are cheaper during the night than during the day (less train movements have to be changed or skipped).

Because of the choice to minimize costs, many factors are considered. For example, every TVP will cost money (possession costs), so the number of TVPs will also be minimized. And in the same way, the total hours a work zone has a TVP are also minimized. At the same time, the model weighs whether the maintenance activities could be better scheduled during daytime or nighttime.

The model will base the TVP planning on the Top 10 maintenance activities from Chapter 4 and the concerning infra objects (level crossings, catenary wires, railway tracks and switches) of the area where the planning will be made for. Besides that, the model needs a list of the possible time moments and a list of possible TVP lengths for scheduling the TVPs. To combine the scheduling of the systematic maintenance activities and the projects (which are incidental in contrast to systematic maintenance), the user of the model could decide to add (besides the maintenance activities) a list of projects to the input, but it is not required.

The output of the model will be a list of TVPs, where every TVP consists of the work zone, the time moment, the TVP length and all the maintenance activities (and optionally projects) that are scheduled in that TVP. Besides that, all the TVPs (without the maintenance activities and projects) are given schematically in a year diagram.

The description above is shown schematically in Figure 5.1.

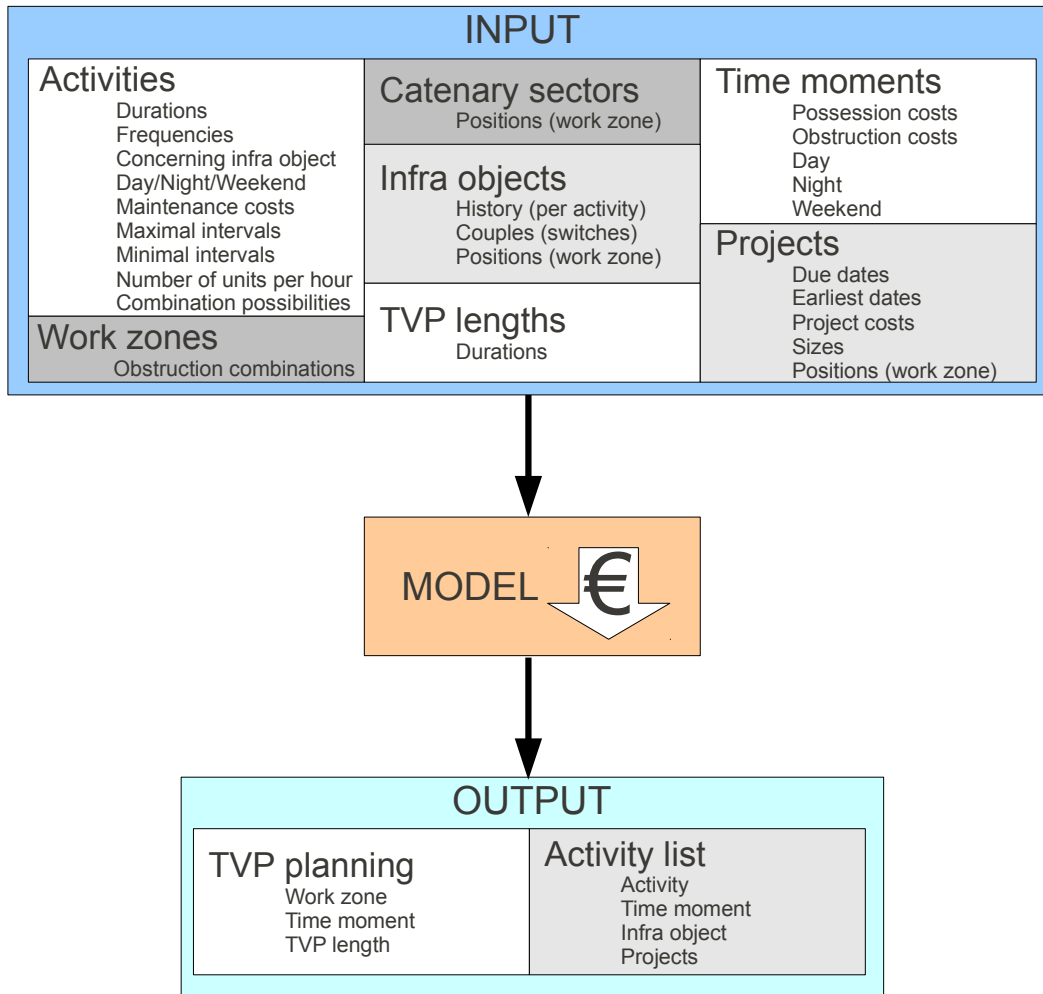


Figure 5.1: Diagram of the model

To find a feasible TVP planning, the model has to satisfy some restrictions:

- when a maintenance activity with a certain duration is scheduled at a certain time moment in a certain work zone, then the TVP at that time moment in that work zone has to have a length of at least the duration of that scheduled maintenance activity,
- when there is maintenance scheduled on a switch that is coupled with another switch (in another work zone), then the work zone of the coupled switch also needs a TVP at the same time moment, see Figure 5.2 for an illustration of this idea: left shows that only work zone A has a TVP (red) when maintenance is executed on an infra object that is not the coupled switch, right shows that work zone B also is TVP due to the maintenance on the coupled switch 1A, while no maintenance is executed in zone B,



Figure 5.2: Illustration of the effect of coupled switches on TVPs

- the interval between two successive maintenance activities (including the executed maintenance activities in the year before) on the same infra object has to satisfy the following restrictions:
 - the interval has a maximum length (in days),
 - the interval has a minimum length (in days),
 - the interval cannot start before the first moment in the planning horizon (when the planning horizon is a year, the interval cannot start before the first of January);

See Figure 5.3 for a view of the idea: at the right the maximum and the minimum are illustrated, at the left the special case (c) is illustrated.

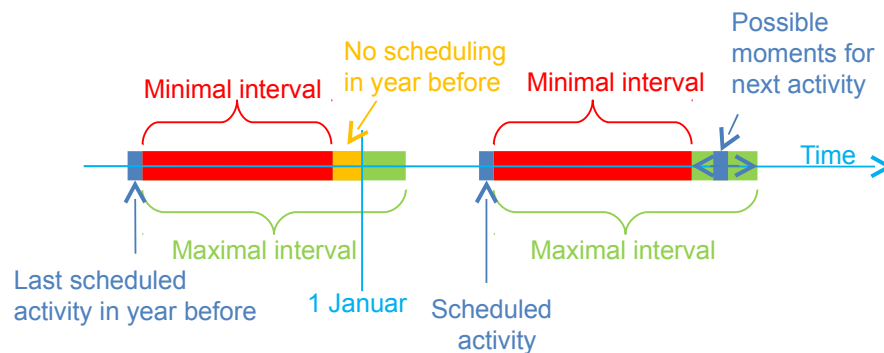


Figure 5.3: Illustration of the three restrictions on the intervals between successive maintenance activities on the same infra object

- maintenance activities that may not be combined cannot be scheduled at the same time moment,
- there is a maximum number of maintenance activities (on switches and level crossings) that can be scheduled at the same time moment in the same work zone, due to required machinery, required employees/experts or the complexity of the maintenance activity,
- there is also a maximum number of all scheduled maintenance activities possible at the same time moment in the total railway yard (to avoid too busy situations on a railway yard),
- when there are work zones having TVPs at the same time, such that the total railway yard is unreachable for trains (there are no diversions over other tracks possible), the possession costs have to increase,
- when the user of the model has also entered projects to the input, the model also schedules the projects (adding projects to the model is optional),
- when maintenance activities require a TVP during the day (or night or weekend), the model may not schedule these activities during the night (or day or working days).

5.2 Mathematical formulation

This section reformulates the model described above as a mathematical model. First Subsection 5.2.1 gives a general explanation about mathematical models. Thereafter, Subsection 5.2.2 defines the needed sets, variables and parameters of the model. Subsection 5.2.3 gives an explanation on the decision variables. Subsection 5.2.4 will then give the mathematical formulation of the model, which contains the objective function and the constraints. Finally, the objective function and constraints will need some explanation, which is given in Subsection 5.2.5.

5.2.1 Mathematical models

Mathematical models are idealized representations, expressed in terms of mathematical symbols and expressions. The laws of physics as $F = ma$ and $E = mc^2$ are familiar examples. Similarly, the **mathematical model** of a business problem is the system of equations and related mathematical expressions that describe the essence of the problem.

Thus, if there are n related quantifiable decisions to be made, they are represented as **decision variables** (say, x_1, x_2, \dots, x_n) whose respective values are to be determined. The appropriate measure of performance (e.g., profit) is then expressed as a mathematical function of these decision variables (for example, $P = 3x_1 + 2x_2 + \dots + dx_n$). This function is called the **objective function**. Any restrictions on the values that can be assigned to these decision variables are also expressed mathematically, typically by means of inequalities or equations (for example, $x_1 + 3x_1x_2 + 2x_2 \leq 10$). Such mathematical expressions for the restrictions are often called **constraints**. The constants (namely, the coefficients and right-hand sides) in the constraints and the objective function are called the **parameters** of the model. The mathematical model might then say that the problem is to choose the values of the decision variables so as to maximize or minimize the objective function, subject to the specified constraints [9].

5.2.2 Definitions of sets, variables and parameters

In the following subsections all sets, decision variables and parameters that we use in the model are defined.

Sets

\mathcal{A}	$\{\mathcal{A}_O \cup \mathcal{A}_R \cup \mathcal{A}_S \cup \mathcal{A}_W\}$ set of maintenance activities
\mathcal{A}_O	set of maintenance activities on crossings (<i>overwegen</i>)
\mathcal{A}_R	set of maintenance activities on contact wires (<i>bovenleiding rijdraad</i>)
\mathcal{A}_S	set of maintenance activities on railway tracks (<i>spoor</i>)
\mathcal{A}_W	set of maintenance activities on switches (<i>wissels</i>)
\mathcal{Z}	set of work zones
\mathcal{R}	set of catenary sectors
\mathcal{T}	set of time moments
\mathcal{L}	set of TVP lengths
\mathcal{I}	$\{\mathcal{I}_O \cup \mathcal{I}_R \cup \mathcal{I}_S \cup \mathcal{I}_W\}$ set of infra objects
\mathcal{I}_O	set of crossings (<i>overwegen</i>)
\mathcal{I}_R	set of contact wires (<i>bovenleiding rijdraad</i>)
\mathcal{I}_S	set of railway tracks (<i>spoor</i>)
\mathcal{I}_W	set of switches (<i>wissels</i>)
\mathcal{P}	set of projects

Combination sets

\mathcal{C}^{aa}	$\{(\hat{a}, \bar{a})\}$ maintenance activities \hat{a} and \bar{a} are combinable (they can be scheduled during the same time period in the same work zone), $\hat{a}, \bar{a} \in \mathcal{A}$ set of combinable maintenance activities
\mathcal{C}^{ai}	$\{(a, i)\}$ maintenance activity a concerns infra object i , $\forall a \in \mathcal{A}, i \in \mathcal{I}$ set of maintenance activity - infra object combinations
\mathcal{C}^{zi}	$\{(z, i)\}$ work zone z contains infra object i , $\forall z \in \mathcal{Z}, i \in \mathcal{I}$ set of work zone - infra object combinations
\mathcal{C}^{zp}	$\{(z, p)\}$ project p concerns work zone z , $\forall z \in \mathcal{Z}, p \in \mathcal{P}$ set of work zone - project combinations
\mathcal{C}^{zr}	$\{(z, r)\}$ work zone z is in catenary sector r , $\forall z \in \mathcal{Z}, r \in \mathcal{R}$ set of work zone - catenary sector combinations
\mathcal{C}^{zz}	$\{(z, \hat{z})\}$ work zone z and work zone \hat{z} together TVP yields a total obstruction of the railway yard/route section, $\forall z, \hat{z} > z \in \mathcal{Z}$ set of obstructing work zone combinations

Decision variables

x_{ztl}	$\begin{cases} 1 & \text{if work zone } z \text{ has a train free period at time moment } t \\ & \text{of length } l \\ 0 & \text{otherwise} \end{cases}$	$z \in \mathcal{Z}, t \in \mathcal{T}, l \in \mathcal{L}$
y_{ati}	$\begin{cases} 1 & \text{if maintenance activity } a \text{ is scheduled} \\ & \text{at time moment } t \text{ on infra object } i \\ 0 & \text{otherwise} \end{cases}$	$(a, i) \in \mathcal{C}^{ai}, t \in \mathcal{T}$
$\sigma_{z\hat{z}t}$	$\begin{cases} 1 & \text{if work zone } z \text{ and } \hat{z} \text{ both have a train free period} \\ & \text{at time moment } t \\ 0 & \text{otherwise} \end{cases}$	$(z, \hat{z}) \in \mathcal{C}^{zz}, t \in \mathcal{T}$
π_{pt}	$\begin{cases} 1 & \text{if the start of project } p \text{ is scheduled} \\ & \text{at time moment } t \\ 0 & \text{otherwise} \end{cases}$	$(z, \hat{z}) \in \mathcal{C}^{zz}, t \in \mathcal{T}$

Parameters

Δt	the time interval between each time moment (in days)	
b_a	minimal TVP length required for maintenance activity a	$a \in \mathcal{A}$
c_p^π	cost of project p	$p \in \mathcal{P}$
d_l	duration of TVP-length l	$l \in \mathcal{L}$
dd_p	due date of project p given in number of days after start moment	$p \in \mathcal{P}$
dnw_a	$\begin{cases} \text{D} & \text{maintenance activity } a \text{ needs to be performed during the day} \\ \text{N} & \text{maintenance activity } a \text{ needs to be performed during the night} \\ \text{W} & \text{maintenance activity } a \text{ needs to be performed during the weekend} \\ 0 & \text{otherwise} \end{cases}$	$a \in \mathcal{A}$
ed_p	earliest start date of project p given in number of days after start moment	$p \in \mathcal{P}$
f_a	number of times per year (frequency) of maintenance activity a	$a \in \mathcal{A}$
h_{ai}	number of days since last maintenance activity a on infra object i	$(a, i) \in \mathcal{C}^{ai}$
k_i	$\begin{cases} j & \text{if infra object } j \text{ is connected with infra object } i \\ & \text{(connected switches)} \\ 0 & \text{otherwise} \end{cases}$	$i \in \mathcal{I}_W$
ma_a	maximal interval between 2 sequential performances of maintenance activity a (in days)	$a \in \mathcal{A}$
mi_a	minimal interval between 2 sequential performances of maintenance activity a	$a \in \mathcal{A}$
mc_{at}	the maintenance costs of maintenance activity a at time moment t	$a \in \mathcal{A}, t \in \mathcal{T}$
n_a	maximum number of units that maintenance activity a can perform in one hour	$a \in \mathcal{A}$
pc_t	the possession costs of a work zone at time moment t	$t \in \mathcal{T}$
pc_t^+	extra possession costs when there is a total obstruction in the railway yard/section	$t \in \mathcal{T}$
s_p	size of the project p given in number of time moments	$p \in \mathcal{P}$
td_t	$\begin{cases} 1 & \text{if time moment } t \text{ is during the day} \\ 0 & \text{otherwise} \end{cases}$	$t \in \mathcal{T}$
tn_t	$(= 1 - td_t) \begin{cases} 1 & \text{if time moment } t \text{ is during the night} \\ 0 & \text{otherwise} \end{cases}$	$t \in \mathcal{T}$
tw_t	$\begin{cases} 1 & \text{if time moment } t \text{ is during the weekend} \\ 0 & \text{otherwise} \end{cases}$	$t \in \mathcal{T}$
y_{\max}	maximal number of maintenance activities scheduled at the same time moment in the total railway yard	

5.2.3 Explanation on the decision variables

This subsection gives a short explanation of the decision variables, because they form the base of the model. The sets and parameters build up the input and will be described in Section 5.3.

The model makes decisions about when the work zones have a TVP and of what length. To decide that, all possible time moments for every work zone and for every TVP length get a decision variable x_{ztl} , so $x_{1,2,3}$ indicates work zone 1, time moment 2 and TVP length 3. The possible values of these decision variables are 0 or 1. When $x_{ztl} = 0$, the work zone z does not have a TVP on time moment t of length l , when the value is 1, the work zone z does have a TVP on time moment t of length l . All the values of all the decision variables x determine the total TVP planning.

To decide this TVP planning, the model schedules the maintenance activities that have to be executed. For this purpose, the decision variables y_{ati} are defined. For example, $y_{1,2,3} = 1$ indicates that maintenance activity 1 is scheduled on time moment 2 on infra object 3.

To decide the values of the decision variables, an objective function is needed, which defines the target of the model. In this model, the objective function gives the model the assignment to minimize the maintenance and possession costs that follow from respectively executing the maintenance activities (decision variable y_{ati}) and possessing the work zone for maintenance (decision variable x_{ztl}). So this objective function will choose the values of the decision variables such that the corresponding costs are minimized.

Moreover, the decision variables have to satisfy the requirements translated in the constraints. So these constraints also influence the values of the decision variables.

There are two more decision variables defined. First of all, the decision variable $\sigma_{z\hat{z}t}$ is needed to add extra possession costs when multiple work zones are out of order simultaneously, such that the combination of work zones with TVPs cause an entire obstruction of the railway yard (re-routing is not possible). So when $\sigma_{1,2,3}$ is set 1 due to the constraints, the work zones 1 and 2 are both TVP at time moment 3.

The model also has the possibility to schedule some projects. Projects are irregular occurrences, so they are different from systematic maintenance activities. The decision variable π_{pt} decides the start moment t of project p , so when $\pi_{1,2} = 1$, project 1 will start on time moment 2.

5.2.4 Problem formulation

Using the sets, decision variables and parameters defined above (Subsection 5.2.2), the mathematical formulation of the model is given below (Formula 5.1 to 5.16).

$$\min \sum_{z \in \mathcal{Z}} \sum_{t \in \mathcal{T}} \sum_{l \in \mathcal{L}} d_l p c_t x_{ztl} + \sum_{z \in \mathcal{Z}} \sum_{t \in \mathcal{T}} \sum_{\hat{z} \in \mathcal{Z}: (z, \hat{z}) \in \mathcal{C}^{zz}} p c_t^+ \sigma_{z\hat{z}t} + \sum_{a \in \mathcal{A}} \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}: (a, i) \in \mathcal{C}^{ai}} m c_{at} y_{ati} + \sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}} c_p^\pi \pi_{pt} \quad (5.1)$$

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$$\sum_{l \in \mathcal{L}} x_{ztl} \leq 1 \quad \forall z \in \mathcal{Z}, t \in \mathcal{T} \quad (5.2)$$

$$y_{ati} b_a \leq \sum_{l \in \mathcal{L}} x_{ztl} d_l \quad \forall (a, i) \in \mathcal{C}^{ai}, (z, i) \in \mathcal{C}^{zi}, t \in \mathcal{T} \quad (5.3)$$

$$y_{ati} b_a \leq \sum_{l \in \mathcal{L}} x_{ztl} d_l \quad \forall a \in \mathcal{A}_W, i \in \mathcal{I}_W, \{(z, k_i) \in \mathcal{C}^{zi} : k_i > 0\}, t \in \mathcal{T} \quad (5.4)$$

$$\sum_{k=t-\lceil \frac{1}{\Delta t} m a_a \rceil + 1}^t y_{aki} \geq 1 \quad \forall t > \lceil \frac{1}{\Delta t} m a_a \rceil, \{(a, i) \in \mathcal{C}^{ai} : f_a > 1\} \quad (5.5)$$

$$\sum_{k=t-\lceil \frac{1}{\Delta t} m i_a \rceil}^t y_{aki} \leq 1 \quad \forall t > \lceil \frac{1}{\Delta t} m i_a \rceil, \{(a, i) \in \mathcal{C}^{ai} : f_a > 1\} \quad (5.6)$$

$$\sum_{t=\max(1, \lceil \frac{1}{\Delta t} (m i_a - h_{ai}) \rceil)}^{\lceil \frac{1}{\Delta t} (m a_a - h_{ai}) \rceil} y_{ati} \geq 1 \quad \{(a, i) \in \mathcal{C}^{ai} : \lceil \frac{1}{\Delta t} (m a_a - h_{ai}) \rceil \leq |\mathcal{T}|\} \quad (5.7)$$

$$y_{\hat{a}t\hat{i}} + y_{\bar{a}t\bar{i}} \leq 1 \quad \forall t \in \mathcal{T}, \{\hat{a} > a : (\hat{a}, \bar{a}) \notin \mathcal{C}^{aa}\}, (z, \hat{i}) \in \mathcal{C}^{zi} \cap (z, \bar{i}) \in \mathcal{C}^{zi} \quad (5.8)$$

$$\sum_{l \in \mathcal{L}} [d_l n_a] x_{ztl} \geq \sum_{i \in \mathcal{I} : (z, i) \in \mathcal{C}^{zi} \cap (a, i) \in \mathcal{C}^{ai}} y_{ati} \quad \forall a \in \mathcal{A}_O \cup \mathcal{A}_W, t \in \mathcal{T}, z \in \mathcal{Z} \quad (5.9)$$

$$y_{ati} \leq y_{(a-1)ti} \quad \forall a > |\mathcal{A}| - 3, t \in \mathcal{T}, \{i : (a, i) \in \mathcal{C}^{ai}\} \quad (5.10)$$

$$\sum_{a \in \mathcal{A}} \sum_{i : (a, i) \in \mathcal{I}} y_{ati} \leq y_{\max} \quad \forall t \in \mathcal{T} \quad (5.11)$$

$$\sigma_{z\hat{z}t} \geq \sum_{l \in \mathcal{L}} x_{ztl} + \sum_{l \in \mathcal{L}} x_{\hat{z}tl} - 1 \quad \forall t \in \mathcal{T}, (z, \hat{z}) \in \mathcal{C}^{zz} \quad (5.12)$$

$$\sum_{t \in \mathcal{T}} \pi_{pt} = 1 \quad \forall p \in \mathcal{P} \quad (5.13)$$

$$\pi_{pt} \leq x_{z(t+u)1} \quad \forall (z, p) \in \mathcal{C}^{zp}, u \in \{0, 1, \dots, s_p - 1\}, \{t \in \mathcal{T} : \frac{ed_p}{\Delta t} < t < \frac{dd_p}{\Delta t}\} \quad (5.14)$$

$$y_{ati} = 0 \quad \forall t \in \mathcal{T}, \{(a, i) \in \mathcal{C}^{ai} : dnw_a = \mathbf{D} \cap td_t = 0 \cup dnw_a = \mathbf{N} \cap tn_t = 0 \cup dnw_a = \mathbf{W} \cap tw_t = 0\} \quad (5.15)$$

$$x_{ztl}, y_{ati}, \sigma_{z\hat{z}t}, \pi_{pt} \in \{0, 1\} \quad \forall (a, i) \in \mathcal{C}^{ai}, z \in \mathcal{Z}, t \in \mathcal{T}, l \in \mathcal{L}, (z, \hat{z}) \in \mathcal{C}^{zz}, p \in \mathcal{P} \quad (5.16)$$

5.2.5 Explanation on the constraints

This subsection explains the mathematical formulation of the objective function and the constraints of the model.

• 5.1 - Objective function

The model minimizes the costs, which consist of four terms:

- The first term sums up the possession costs for the single work zones: for every time t a work zone z is TVP ($x_{ztl} = 1$), the duration (d_l) of the TVP (in hours) is multiplied with the possession costs (pc_t) for one hour for that time moment t , and is added to the total sum of costs.
- The second term adds extra possession costs (pc_t^+) to the total sum of costs when the combination of work zones z and \hat{z} causes a total obstruction of the railway yard.
- The third term stands for the maintenance costs: every time t that maintenance activity a is scheduled on infra object i ($y_{ati} = 1$), the cost of executing the maintenance activity (mc_a) is added to the total sum of costs.

- The last term sums up the project costs of all the projects p that are scheduled ($\pi_{pt} = 1$). The sum will be equal to zero when the model is used without projects.

- **Constraints 5.2 - One TVP-length**

For every time moment t and work zone z there are $|\mathcal{L}|$ decision variables x_{ztl} , but at most one of them could be set to 1 (one TVP cannot have two different lengths).

- **Constraints 5.3 - TVP length**

When maintenance activity a is scheduled at time moment t on infra object i ($y_{ati} = 1$), there is a TVP needed in the work zone(s)¹ z where infra object i is in $((z, i) \in \mathcal{C}^{zi})$. This gives the constraints

$$y_{ati} \leq \sum_{l \in \mathcal{L}} x_{ztl}.$$

The added multipliers b_a and d_l enforce that the TVPs have the correct length: the duration of the TVP (d_l) has to be at least the minimal required TVP length of the maintenance activity (b_a).

Note that the maintenance activities a are only scheduled on the infra objects i that need that maintenance, for example switches do of course not receive correction activities on catenary, so only the a, i -combinations in \mathcal{C}^{ai} provide constraints like these.

- **Constraints 5.4 - Coupled switches**

These constraints look similar to constraints 5.3. These are extra constraints and represent the extra requirements with coupled switches, as explained and illustrated in Section 5.1 and Figure 5.2.

When a maintenance activity a is performed on switch i (infra object), which is coupled with another switch $j = k_i$, then the coupled switch j cannot be used either, so the work zone z that contains switch j ($(z, j) \in \mathcal{C}^{zi}$) also needs a TVP at that moment t . So for every activity a and infra object i concerning switches ($a \in \mathcal{A}_{\mathcal{W}}, i \in \mathcal{I}_{\mathcal{W}}$) with a coupled switch (when $j = k_i > 0$, by definition $k_i = 0$ when the switch is not coupled) there are constraints added like constraints 5.3.

- **Constraints 5.5, 5.6 and 5.7 - Intervals: maximum, minimum and first**

These constraints represent the interval requirements as described in Section 5.1 and illustrated in Figure 5.3.

The constraints about the maximum and the minimum intervals are only set up in the cases that the maintenance activity a has a frequency higher than one ($f_a > 1$), or: the maintenance activity needs to be scheduled more than once a year. The constraints about the first interval are only set up when the maintenance activity a on infra object i needs to be scheduled in the planning horizon (for instance, a year): the maximum interval ma_a of the maintenance activity a minus the number of days since the last execution before the planning horizon h_{ai} , divided by the time interval Δt , gives the number of time moments within which the next execution needs to be scheduled. When this number is larger than the cardinality of the time moments ($|\mathcal{T}|$), the activity could be scheduled in a following planning horizon.

For the constraints 5.5: for every interval of ma_a days, there is at *least* one execution of maintenance activity a on infra object i , so every interval of that size ($\lceil \frac{1}{\Delta t} ma_a \rceil$) is added up in the sum that has to be at least one. Constraints 5.6 are set up in the same way, but then with the minimum interval mi_a and with the requirement that the interval may have at *most* one execution. Constraints 5.7 add one more constraint per maintenance activity a - infra object i combination. This constraint adds up all the time moments where (a, i) can be scheduled, taking into account the moment of the last execution before the planning window, the minimum interval and the maximum interval, and requires this sum to be at least one, so the activity has to be scheduled in one of those time moments.

- **Constraints 5.8 - Combinable maintenance activities**

Some maintenance activities cannot be executed at the same time in the same work zone. When a maintenance activity combination cannot be executed at the same time ($((\hat{a}, \bar{a}) \notin \mathcal{C}^{aa})$) and one of them (\hat{a} or \bar{a}) is scheduled at a certain time moment t on a certain infra object \hat{i} or \bar{i} in work zone z ($y_{\hat{a}\hat{i}} = 1$ or $y_{\bar{a}\bar{i}} = 1$), the other maintenance activity may not be scheduled at the same time moment on any other infra object in the same work zone. So the sum of all the $(\hat{a}, \hat{i}) - (\bar{a}, \bar{i})$ combinations, such that \hat{i} and \bar{i} are in the same work zone ($(z, \hat{i}) \in \mathcal{C}^{zi} \cap (z, \bar{i}) \in \mathcal{C}^{zi}$), has to be at most one.

¹an infra object can be in more work zones, for instance a contact wire that is spanned over more work zones

- Constraints 5.9 - **Maximum number of maintenance activities**

For every maintenance activity in every work zone at every time moment, there are limits to how many activities can be performed in one TVP. For the activities for the level crossings and the switches it is known how many units can be done in one hour (n_a), so n_a multiplied with the length of the TVP gives the maximum number of units that can be done in that TVP.

The righthandside of the formula sums up all scheduled maintenance activities a on all the concerning infra objects i ($(a, i) \in \mathcal{C}^{ai}$) in the work zone z ($(z, i) \in \mathcal{C}^{zi}$).

- Constraints 5.11 - **Maximum total number of maintenance activities**

Besides constraints 5.9, the user of the model could also give a value to parameter y_{max} that indicates the total number of maintenance activities that can be scheduled in one time moment t . This total number makes no distinction in work zones, so it concerns the total number of maintenance activities in the whole railway yard at the same time moment. So for all time moments t all possible maintenance activity - infra object combinations are summed up ($\sum_{a \in \mathcal{A}} \sum_i i : (a, i) \in \mathcal{I}y_{ati}$) and this sum may not be larger than y_{max} .

- Constraints 5.10 - **R-activities for switches - special constraints**

These constraints are special, because it is specific for a set of maintenance activities. In fact, the maintenance activities BA.0016 to BA.0019 are the same activities, that are so-called R-activities. See also Figure 5.4. Every 3 months this activity is needed for every switch (R3). However, twice

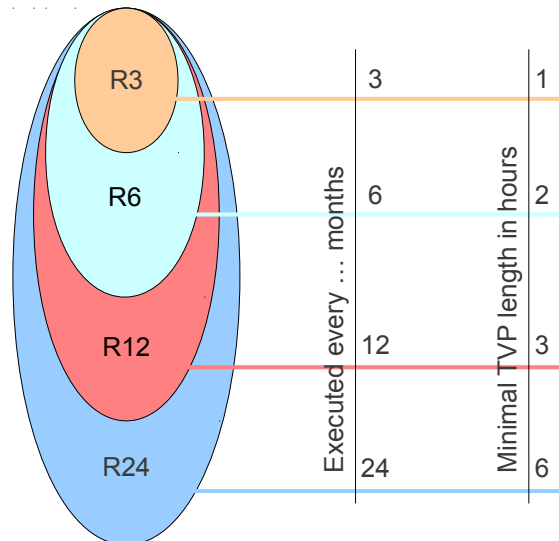


Figure 5.4: Illustration of the so-called R-activities

a year, the maintenance activity contains a little more work than the other times (R6). Next, once a year, there is still more time needed (R12) and at last, once in two years is the biggest maintenance activity needed (R24). In other words, R3 is part of R6, which is part of R12, which is part of R24. This is incorporated into the model by requiring that when R24 is scheduled, maintenance activities R3, R6 and R12 have to be scheduled too.

To realize this, the list of maintenance activities in the input file has to end with these last 4 maintenance activities, in the order R3, R6, R12 and R24. Now $\forall a > |\mathcal{A}| - 3$ indicates that these last 4 maintenance activities are considered. The formula will now provide the following constraints for every (a, i) -combination for these four maintenance activities and for all time moments t : $y_{|\mathcal{A}|,ti} \leq y_{|\mathcal{A}|-1,ti} \leq y_{|\mathcal{A}|-2,ti} \leq y_{|\mathcal{A}|-3,ti}$.

- Constraints 5.12 - **Extra possession costs**

These constraints determine when the decision variable σ has to be equal to one: when both work zone z and \hat{z} are TVP at time moment t and the work zone combination causes a total obstruction of the railway yard ($(z, \hat{z}) \in \mathcal{C}^{zz}$), then σ is forced to take value one according to its definition. The formula provides this, as you can see: the righthandside is only equal to 1 when both work zone

z and \hat{z} have a TVP at time moment t , so only in that case σ will be forced to be at least one. Because the positive coefficients of the σ s in the objective function and the minimization of the objective function, the model will choose the value of σ to be equal to zero in all the other cases.

- **Constraints 5.13 and 5.14 - Projects**

When the user chooses to integrate projects in the planning, these constraints are necessary. When the input contains no projects, these constraints are not part of the model. First of all, constraints 5.13 ensure that every project is scheduled exactly once. Constraints 5.14 ensure that for every work zone the project hits ($\forall (z, p) \in \mathcal{C}^{zp}$), the work zone has a TVP as long as the project lasts: from the time moment t until time moment $t + s_p - 1$. Note that the length of the TVP is the first length of the input (l_1), that length will be equal to the time interval Δt , but then in hours (when $\Delta t = 0.5$ days, then $l_1 = 12$). The projects require certain periods to be scheduled, for example in the first half of the year. So the constraints are only set up for the time moments in that period, starting with the earliest possible start date ed_p and finishing at the due date dd_p . The factors are divided by the time interval to get the number of time moments.

- **Constraints 5.15 - Day/Night/Weekend requirements**

When a maintenance activity a has a D/N/W-requirement (dnw_a) other than zero, the maintenance activity has to be scheduled on all the concerning infra objects i at respectively day (D), night (N) or in the weekend (W). So all the time moments that are *not* day ($td_t = 0$), night ($tn_t = 0$) or weekend ($tw_t = 0$) are moments where the activity may not be scheduled on ($y_{ati} = 0$). Because the type of the constraints, these constraints can be formulated as bounds.

- **Constraints 5.16 - Binary**

All decision variables x , y , σ and π have to be 0 or 1, as defined. So the model does not allow fractions, because for example, a maintenance activity a will be scheduled totally ($y_{ati} = 1$) or not (y_{ati}), and not something between. So the formulated problem is an Integer Programming (IP), all decision variables have to be integer.

5.3 Input

This section describes all the input needed, including where I derived the input from and which numbers are real and which are fictional. The input is categorized in the following subjects: maintenance activities (Subsection 5.3.1), work zones (Subsection 5.3.2), catenary sectors (Subsection 5.3.3), time moments (Subsection 5.3.4, TVP lengths (Subsection 5.3.5), infra objects (Subsection 5.3.6), projects (Subsection 5.3.7) and combination sets (Subsection 5.3.8).

5.3.1 Maintenance activities

The list of maintenance activities that I used in the model contains the maintenance activities that are mentioned in Chapter 4 in the Top 10. The set \mathcal{A} consists of these maintenance activities a .

The parameters concerning these maintenance activities a are listed below, including their explanations and sources. The parameters marked by an asterisk are not followed by a notation, they will come back in the combination sets in Subsection 5.3.8.

- *Duration* d_a : the minimal necessary TVP length needed for this maintenance activity has several sources, both the normunit list of the Rail Case Base [25] and the research of Jan Swier [28]. Moreover, the contractor provided me with information based on experience.
- *Frequency* f_a : the number of times that the activity has to be performed on each infra object every year has the same sources as duration d_a .
- *Corresponding infra objects**: every maintenance activity is executed on one kind of infra object, this is by definition of the maintenance activities, but the model needs this information to connect the maintenance activities to the right infra objects.

- *Day/Night/Weekend dnw_a* : the information regarding to when the activity has to be executed at day, night or weekend, is acquired from the normunit list of the RCB [25]. Although the contractor pointed out that these requirements possibly do not hold anymore. This statement could be examined, if it is true, this requirement could be deleted from the model.
- *Maintenance costs mc_{at}* : the costs of executing the maintenance activity at day, night and weekend, are acquired from the Rail Case Base. Furthermore, I chose to give precedence to the night, followed by the weekend: for instance, executing a maintenance activity during the night from Saturday to Sunday will cost the same amount as for executing the activity during the night, while executing a maintenance activity during the day on Saturday will cost the amount for executing the activity at weekend. Of course, the costs also depend on the maintenance activity.
- *Maximal intervals ma_a* : the maximal number of days between two successive activities on the same infra object are based on the frequencies, there is not much margin accepted on the maximum interval, so the maximum interval multiplied with the frequency will be very close to 365.
- *Minimal intervals mi_a* : the minimal number of days between two successive activities on the same infra object is invented by myself, to prevent that two executions of the same activity on the same object are scheduled too close to each other.
- *Number of units per hour n_a* : the number of objects that can be maintained in one hour is estimated by the contractor. In reality, it depends on many factors, for example, the number of switches that can be executed in one hour depends among others on the distance between the switches.
- *Combination possibilities**: the possibilities and impossibilities of combining two different maintenance activities are invented by me and checked by the contractor.

5.3.2 Work zones

The model makes use of work zones: zones that can get TVPs in the TVP planning. ProRail has divided the total railway network in work zones in such a way that a work zone is the smallest possible infra possession. These work zones are the default input, but the user of the model could also make other decisions. The set \mathcal{Z} contains all the work zones z that the user lists in the input file.

I chose to test the model on the railway yard Hoorn. Hoorn is not a very big railway yard compared to Amsterdam CS or Utrecht CS, but it has 6 tracks and a lot of switches to make it interesting enough for this model. (The railway yard has a so-called Route Section Value (*BaanVakWaarde*) (BVW) of 5 on a scale of 1 to 15.) Hoorn actually has more tracks, but these tracks are for the steam locomotive and are not managed by ProRail, so I left these tracks out of consideration.

I used two types of input in relation to the work zones. First of all, I used the default work zones of Hoorn. Hoorn has geocode 626, so all work zones starting with *626 were used as input. The work zones are shown in Figure 5.5. The figure is a part of the total diagram to show only the work zones of Hoorn.

The contractor told me that it is not possible to work in a single work zone like work zone *b626 p33* in Figure 5.5 when only that work zone has a TVP, because the needed machinery is not able to reach that work zone. The machines can be set in the rails at level crossings or other special “set-in-places”, so there is a TVP route needed from such a place to the work zone where the work has to be done. The model does not make these routes, so with the default work zone input as described above, the TVP planning will not be achievable. The reason that I not realized this problem while creating the model, is that I asked the contractor earlier whether I should take these routes into account, but he said that it was not necessary. The miscommunication was that he did not realize that I used these small work zones, whereas he based himself on the assumption that the TVPs were of the size he knows from his experience. Moreover, the contract manager I spoke with, told me that these work zones are chosen to be the smallest *possible* infra possessions: in fact it is possible to have these small work zones TVP, but in reality it is often unreachable for work men and machinery.

To deal with this new insight, I made a second type of work zone input, namely a group of defined work zones of Figure 5.5 together, such that all the new work zones has a set-in-place: in this case a level

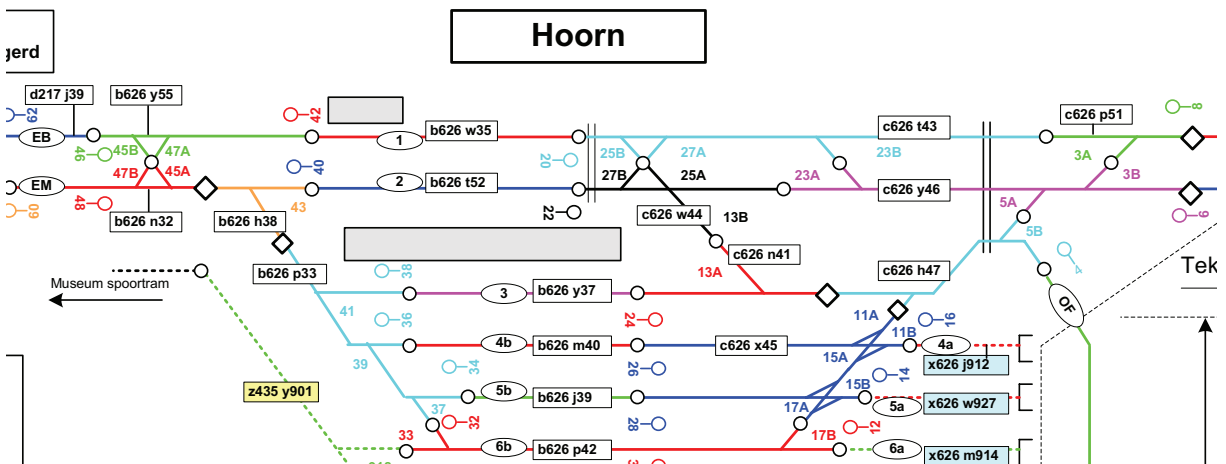


Figure 5.5: Diagram work zones Hoorn

crossing or work zone *b626 p42*. (Track 9 (not on the diagram) is an official set-in-place, from there it is possible to bring the machines via track 6b (work zone *b626 p42*) into the railway yard.) See Figure 5.6 for these new work zone classification.

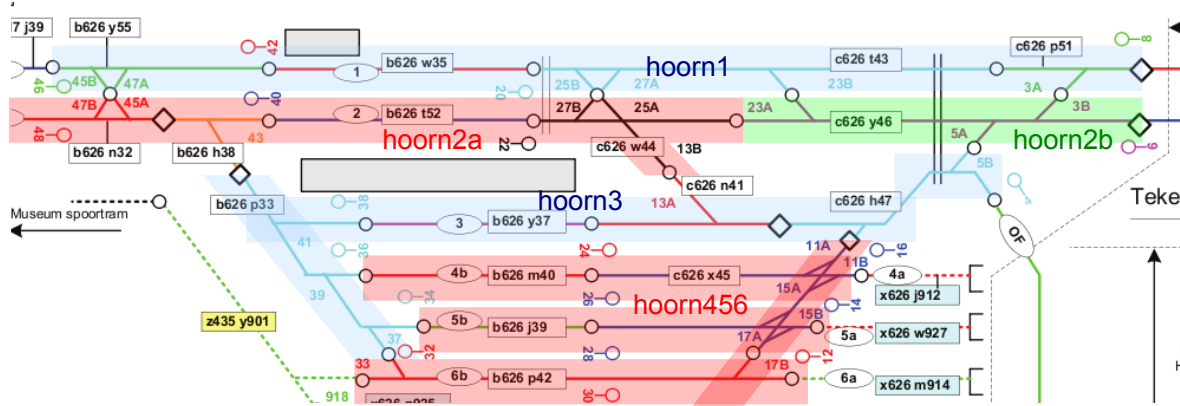


Figure 5.6: Classification of second type of work zones

The parameters concerning work zones are mostly part of the combination sets, because the model needs to know in which work zone the infra objects lay and which zones are part of the project. These are explained amply in Subsections 5.3.6 and 5.3.7. One combination set is left:

- *Obstruction combinations**: the combinations of work zones that cause a total obstruction of the railway yard when both zones are TVP, are invented by me. For every combination of two work zones I wondered whether a train could run into the railway yard and run out of the railway yard on the other side, possibly via other tracks than originally scheduled. When this is not possible for a certain combination (work zone z and work zone \hat{z}), I called this combination an obstruction combination: $(z, \hat{z}) \in \mathcal{O}^{z\hat{z}}$.

5.3.3 Catenary sectors

As mentioned in Subsection 2.8.2, the catenary is divided into sectors. Every sector can be switched off separately. For maintenance activities on catenary, the switching off of the electrical current is necessary. So when the model schedules a maintenance activity on the catenary, the whole catenary sector

needs to be switched off, so all the work zones laying under the catenary sector are out of order. Because the boundaries of the catenary sectors are different from the work zones, there can be more work zones under one catenary sector and the reverse, there can be more catenary sectors above one work zone.

The catenary sectors are presented in the diagram of catenary sectors, Figure 5.7 shows the catenary sectors of railway yard Hoorn. These catenary sectors r are listed in the input, together they form the set \mathcal{R} .

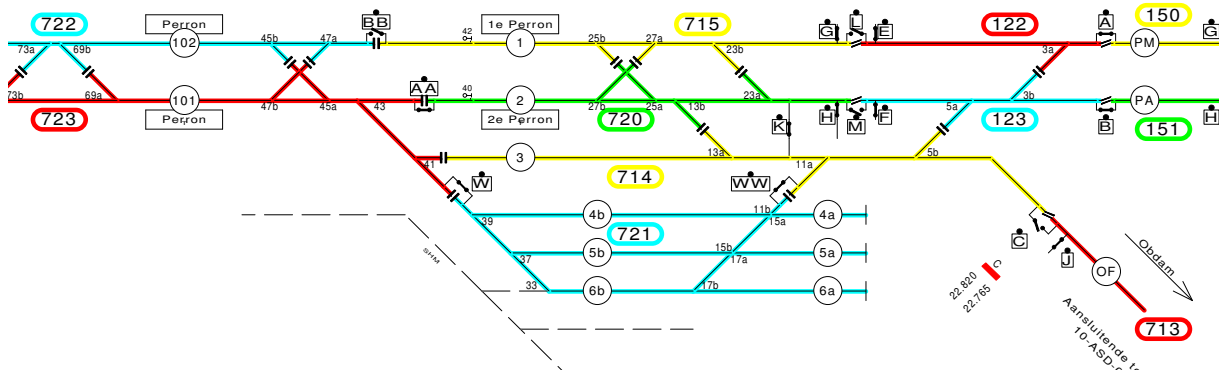


Figure 5.7: Diagram catenary sectors Hoorn

The only parameters concerning the catenary sectors are the positions of the sectors with respect to the work zones:

- *Positions**: the work zone(s) that the catenary sector is in, are determined by comparing the diagrams of the work zones and the catenary sectors. Sometimes some guesses are made, but most of the times the drawings are clear enough to determine which work zones are under the catenary of the concerning sector. Unfortunately, there is no file available with this information, so it has to be work by hand.

5.3.4 Time moments

The time moments part within the input is decided by the user of the model. For example, the user wants to make a planning with a length of one year. He wants to have the possibility to schedule maintenance at day or at night, so the time between every time moment (time interval Δt) is half a day. Then the set of time moments \mathcal{T} consists of $365 \times 2 = 730$ time moments t that the model can schedule maintenance activities. So the set \mathcal{T} consists of a list of time moments t that the model can choose from to schedule the maintenance (and projects).

It is also possible to decide to have a non-regular time interval, for example, a planning of one year, two moments per day, but without the weekends. The model can handle this in the following way: add all the time moments with the regular time interval (half a day), but set all the weekend moments in the input not available. (There is a column in the input file called 'Meenemen?', which makes this filter, every moment with 'Meenemen?'=0 is not used in the TVP planning.) Advantage is that the cardinality of the set \mathcal{T} will decrease, which will decrease the size of the total problem tremendously.

The models of Budai-Balke [3], Higgins [8] and Badr [2] use time intervals that are smaller than most of the maintenance activity lengths (for example hours), so a maintenance activity has often to be scheduled over more than one time moment². In my model, the time moments indicate the time period a given activity has to be scheduled (in my test instances it will be half a day) and the time moments are longer than the maintenance activities last. In fact, the method of Budai, Higgins and Badr is more exact (it will

²they often use the term time window instead of time moment

give a more exact schedule), but for my objective it would be too expensive (in computation time) to use smaller time values (hours). Moreover, my model is such that using hours will not increase the value of the model. Concerning the projects, that is different: the projects could last longer than the length of a time interval, so the approach to schedule the projects is similar to the approach of Budai, Higgins and Badr.

For every time moment $t \in \mathcal{T}$ the model needs the following parameters:

- *Day/Night/Weekend* $td_t/tn_t/tw_t$: the kind of time moment (day, night and/or weekend) is given by the user of the model by filling in the following columns in the input file: 'Nacht?' (night) and 'Weekend?', where a 1 stands for 'yes' and 0 for 'no'.
- *Possession costs* pc_t : the costs of one hour TVP of a work zone in a given time moment, is based on the LifeCycleManagement tool of ProRail. In the current input file there are only three values given: costs for one hour TVP at day, costs for one hour TVP at night and costs for one hour TVP in the weekend. With the help of the day/night/weekend-parameters described above, these costs are linked to all time moments t .
The costs are obtained from the LCM-tool and are specific for Hoorn. I assumed for these costs a possession such that trains can run into and out of the railway yard, but perhaps they need to run over other tracks, which can lead to a short delay of 15 minutes. The tool takes into account among others the number of trains per hour, the estimated number of passengers per train, the average price of one passenger, and the economical value of 15 minutes delay. The tool says that in this situation one hour TVP costs EUR 3,286.- at day, EUR 339.- at night and EUR 2,273.- at the weekend days.
- *Obstruction costs* pc_t^+ : the extra costs for one hour TVP in this time moment in case of a total obstruction of the railway yard are also based on the LCM-tool. Now the situation is considered that the railway yard is obstructed by the combination of TVPs, so that trains cannot pass through the railway yard. So when passengers want to pass Hoorn, they have to take the bus that is rented for this situation. The delay can easily raise to one hour. The tool takes into account the factors described above (but then for 60 minutes), but calculates also extra costs for the busses. I reached the following values for one hour obstructing TVP: EUR 9,481.- at day, EUR 885 at night and EUR 5,182.- at the weekend days. For every work zone that is scheduled a TVP, the possession costs are already added to the total costs sum, so the obstruction costs only have to be the surplus value.

The goal of using costs was to give weights to the TVPs, with distinction in day, night and weekend. That goal is now reached with these values. The correctness of these values is less important.

5.3.5 TVP lengths

The user of the model decides what lengths the TVPs can have. The input file lists these lengths from long to short. When projects are used, the length of the time interval is given as the first length (l_1). So the set \mathcal{L} consists of the possible TVP lengths l .

The only parameter of the TVP length is the length itself:

- *Durations* d_l : the length in hours of these TVP lengths is chosen by the user, so in this case by myself. I chose for three different scenarios: 3 and 6 hours (based on the current OHR, but then rounded, because the model does not work well with broken numbers), 4 and 7 hours (based on the research of Twynstra Gudde [6]) and 2, 4 and 7 hours. The minimum length of a TVP is one hour, due to efficiency reasons [27].

5.3.6 Infra objects

The maintenance activities \mathcal{A} are related to level crossings, contact wires, railway tracks and switches, so only these infra objects are considered in this model and subsection. The sets of level crossings,

contact wires, railway tracks and switches are called³ \mathcal{I}_O , \mathcal{I}_R , \mathcal{I}_S and \mathcal{I}_W respectively. The set \mathcal{I} is the union of these four sets and contains all important infra objects i .

The level crossings and the switches are obtained from SAP, the database that contains all infra objects. The level crossings are obtained per flooring, so a level crossing over three tracks contains three level crossing floorings and provides three infra objects i for the set \mathcal{I}_O . According to the contractor, the level crossings that just are paths (in Dutch: *overpad*) do not have to be considered, because they are of another type that needs less or no maintenance. The list of switches also contains cross-overs, but they are also not considered in this model, because the maintenance activities on cross-overs are not part of the Top 10. Moreover, for every Englishman obtained from SAP, the user of the model needs to enter the switch two times in the input, because an Englishman needs the maintenance of two switches.

Regarding the railway tracks: the model makes for every work zone one railway track infra object, so $|\mathcal{I}_S| = |\mathcal{Z}|$. In the same way, the model makes for every catenary sector one contact wire infra object, so $|\mathcal{I}_R| = |\mathcal{R}|$. This was a choice to make the implementation of the railway tracks and the contact wires less complicated. A disadvantage is that the two types of used work zone classifications as described in Subsection 5.3.2 have a different number of railway tracks, which makes comparing the different scenarios more complicated.

Every infra object needs the parameters described below:

- *Kind of object**: the kind of objects speak for themselves, but are needed for the model to make the (a, i) combinations in Subsection 5.3.8.
- *History h_{ai}* : the last time when all maintenance activities concerning the infra object have been executed on the object, for all (concerning) activities, are all randomly chosen by Microsoft Excel. There are two scenarios made: the first scenario chooses for every infra object, for every concerning maintenance activity, a random number between the maximum interval of that maintenance activity and one. The second scenario chooses a random number between the maximum interval and the maximum interval minus 365, to obtain that every infra object needs all concerning maintenance activities in the planning year, so it is the worst case scenario. Unfortunately, actual figures were not available.
- *Couples k_i* : it is easy to see on the diagrams which switches are connected with each other, so this information is given by the user to the input file.
- *Positions**: in the same way it is easy to see which work zone the infra object lays in, so this information is also given by the user of the model. Disadvantage is that it is a lot of work by hand, but unfortunately, ProRail does not have a file that connects the infra objects to the work zones. SAP does provide the geocode and the place in kilometers, but not the work zone.

5.3.7 Projects

\mathcal{P} is the set of projects p to be scheduled. It is the only set that may be empty (is optional). The projects used in this research are totally fictional. So all the values of the parameters described below are fictional.

- *Due dates dd_p* : the number of days from the beginning of the planning window when the project has to finish.
- *Earliest dates ed_p* : the number of days after the beginning of the planning window after which the project may start.
- *Project costs c_p^π* : the costs of executing the project.
- *Sizes s_p* : the size of the project in time moments, so a project of three days lasts 6 time moments when the time moments are half a day.
- *Positions**: the work zones the project hits.

³The letters are based on the Dutch translations, respectively *overwegen*, *rijdraad*, *spoor* and *wissels*.

5.3.8 Combination sets

The combination sets are sets that give relations between two sets. They are set up to decrease the number of variables and constraints, for instance, for a maintenance activity a on a level crossing, a decision variable y_{ati} with i a switch, is not needed. So the notation $(a, i) \in \mathcal{C}^{ai}$ contains less variables than $a \in \mathcal{A}, i \in \mathcal{I}$, so there are less constraints needed to formulate the problem. The sets \mathcal{C}^{aa} and \mathcal{C}^{zz} give relations between the elements of the sets \mathcal{A} and \mathcal{Z} respectively.

The combination sets that are defined are given in Subsection 5.2.2 and the sources of the needed information to create these sets are given above in this section.

5.4 Complexity

This section proves the complexity of the problem. Subsection 5.4.1 gives a short description of the complexity classes. In Subsection 5.4.2 we prove that the problem is *NP-hard*, one of the complexity classes.

5.4.1 Complexity classes

There are a lot of optimization problems that have a ‘fast’ algorithm to solve the problem, for example the Shortest Path Problem, for which the Shortest Path algorithm (Dijkstra’s algorithm) will always find the shortest path (the optimum) in polynomial time (polynomial in the size of the input of the problem). However, there are many more problems that do not have (yet) an algorithm that always finds an optimal solution in polynomial time. When there is a ‘new’ optimization problem, like the problem formulated in Subsection 5.2.4, it is useful to know something about the complexity of the problem. Therefore, the complexity of the problem will be classified before trying to find a solution.

To develop a method of classification, just four concepts are needed [32]:

- A class \mathcal{C} of legitimate problems to which the theory applies,
- A nonempty subclass $\mathcal{C}_A \subseteq \mathcal{C}$ of “easy” problems,
- A nonempty subclass $\mathcal{C}_B \subseteq \mathcal{C}$ of “difficult” problems,
- A relation “not more difficult than” between pairs of legitimate problems.

This immediately leads to the following proposition that can be used to classify a legitimate optimization problem [32]:

Proposition 5.4.1. (*Reduction Lemma*) *Suppose that P and Q are two legitimate problems. If Q is “easy” and P is “not more difficult than” Q , then P is “easy”. If P is “difficult” and P is “not more difficult than” Q , then Q is “difficult”.*

The basic idea about classifying an optimization problem is given above. Unfortunately, the theory does not exactly address optimization problems in the usual form. To define the class of legitimate problems, it is appropriate to pose decision problems having YES-NO answers. Thus an optimization problem:

$$\min\{cx : x \in S\} \tag{5.17}$$

for which an instance consists of: $\{c$ and a “standard” representation of $A\}$ is replaced by the *decision problem*:

$$\text{Is there an } x \in S \text{ with value } cx \leq k? \tag{5.18}$$

for which an instance consists of $\{c, \text{ a “standard” representation of } S, \text{ and an integer } k\}$.

Before dividing the decision problems into classes, two definitions [32] are considered that address the complexity of a problem.

Definition 5.4.1. *For a problem instance X , the length of the input $L = L(X)$ is the length of the binary representation of a “standard” representation of the instance.*

Definition 5.4.2. Given a problem P , an algorithm A for the problem, and an instance X , let $f_A(X)$ be the number of elementary calculations required to run the algorithm A on the instance X . $f_A^*(l) = \sup_X \{f_A(X) : |X| = l\}$ is the running time of algorithm A . An algorithm A is polynomial for a problem P if $f_A^*(l) = O(l^p)$ for some positive integer p .

Now we can define the class of “legitimate” problems [32].

Definition 5.4.3. \mathcal{NP} is the class of decision problems with the property: for any instance for which the answer is YES, there is a “short” (polynomial) proof of the YES.

In other words, \mathcal{NP} is the class of decision problems that are verifiable in polynomial time. Note that if a decision problem associated to an optimization problem is in \mathcal{NP} , then the optimization problem can be solved by answering the decision problem a polynomial number of times (by using bisection search on the object function value.)

Now we can define the class of “easy” problems [32].

Definition 5.4.4. \mathcal{P} is the class of decision problems in \mathcal{NP} for which there exists a polynomial algorithm.

Next, we give the formal definition of “is not more difficult than” that we need [32].

Definition 5.4.5. If $P, Q \in \mathcal{NP}$, and if an instance of P can be converted in polynomial time to an instance of Q , then P is polynomially reducible to Q . Notation: $P \propto Q$.

Note that this means that if we have an algorithm for problem Q , it can be used to solve problem P with an overhead that is polynomial in the size of the instance.

We now define the class of “most difficult” problems [32].

Definition 5.4.6. \mathcal{NPC} , the class of \mathcal{NP} -complete problems, is the subset of problems $P \in \mathcal{NP}$ such that for allocated $Q \in \mathcal{NP}$, Q is polynomially reducible to P ($Q \propto P$).

It is a remarkable fact that the set of decision problems in \mathcal{NPC} also has, in addition to the property that until now nobody has found a polynomially algorithm for the problems, another property in common: they are all among the *hardest problems* in \mathcal{NP} .

Definition 5.4.7. An optimization problem is called \mathcal{NP} -hard if the corresponding decision problem is \mathcal{NPC} .

Conceptually, it is not hard to prove that a problem is \mathcal{NPC} , because Stephen Cook and Leonid Levin have proven that the Satisfiability Problem (SAT) is \mathcal{NPC} [26]. To prove that a certain optimization problem P is \mathcal{NP} -hard, it has to be proven that the corresponding decision problem belongs to the class \mathcal{NP} and that SAT (or another problem that is \mathcal{NPC}) reduces to P . In practice, such a proof can be very technical.

Figure 5.8 illustrates the relations between the described complexity classes.

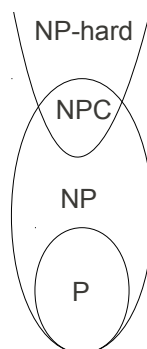


Figure 5.8: Illustration of the relation between the complexity classes

$\mathcal{P} = \mathcal{NP}$ is not yet proven or disproved, it is one of the famous ‘Millennium problems’ of the Clay Mathematics Institute [4]. If $\mathcal{P} = \mathcal{NP}$, all problems in $\mathcal{P} = \mathcal{NP}$ are polynomially solvable. The common expectation is that $\mathcal{P} \neq \mathcal{NP}$.

5.4.2 Proof of \mathcal{NP} -hardness of the problem

To prove that the optimization problem formulated in Subsection 5.2.4 is \mathcal{NP} -hard, according to Definition 5.4.7, we need to prove that the corresponding decision problem is \mathcal{NPC} . We prove this in a similar way as Budai-Balke [3] did in her thesis research: with a polynomial reduction from the k -colouring problem (k -COL).

It is well known that the k -COL problem is \mathcal{NPC} , see Garey and Johnson [5]. The problem is the following:

Given an undirected graph G and a positive integer k , decide whether G can be coloured with k colours such that no edge is incident to vertices of the same colour.

An example of a 3-coloured graph is given in Figure 5.9. The graph is a YES-instance for the 3-colouring problem (which is shown in the figure), but it is a NO-instance for the 2-colouring problem: the graph cannot be coloured with just 2 colours without violating the constraints.

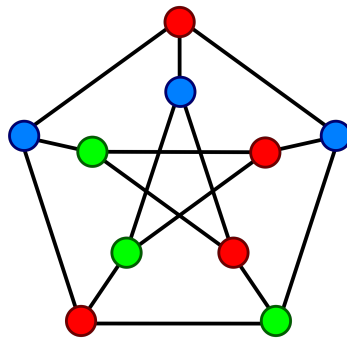


Figure 5.9: Example of a graph that is colored with 3 colors.

The decision problem X corresponding to the optimization problem of this research, is the following:

Does the optimization problem have a solution with objective value 0 (i.e. a 0 cost solution)?

Note that this is indeed a decision problem, the only possible answers are YES and NO. The decision problem is \mathcal{NP} , because it is polynomially verifiable whether a solution is indeed a YES instance, by filling in the solution in the objective function and the constraints and checking the values. So now we only need to find a polynomial reduction from k -COL to the decision problem X .

The reduction is described below. To make it more clear, a simple example of a reduction is illustrated in Figure 5.10. The figure shows a simple graph G , that is a YES-instance for the 3-coloring problem. The reduction creates a YES-instance of the problem X . Conversely, when the instance of problem X is a YES-instance, the graph will also be a YES-instance.

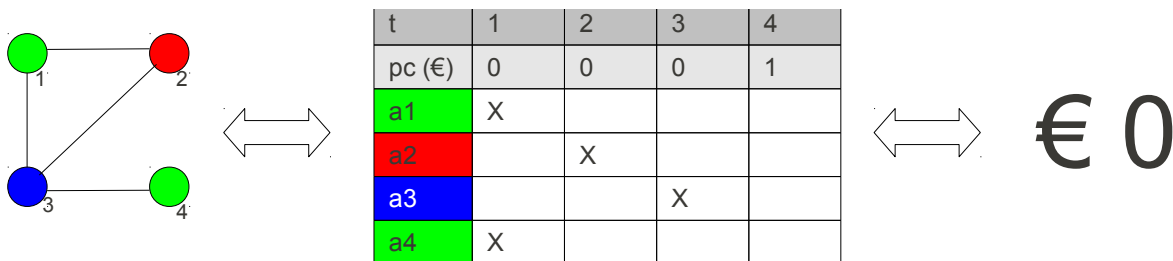


Figure 5.10: Example of reduction

Consider a graph $G = (V, E)$ and let $n = |V|$ be the number of vertices. We assume that $V = \{1, \dots, n\}$. We construct an instance of X with $|T| = n$, $\Delta t = 1$, with n maintenance activities a ($|\mathcal{A}| = n$), each of

them having $ma_a = n$, $b_a = f_a = n_a = 1$ and $h_{ai} = mi_a = dnw_a = 0$, with one work zone, one catenary sector, one TVP length (with $d_l = 1$) and one infra object ($|\mathcal{Z}| = |\mathcal{R}| = |\mathcal{L}| = |\mathcal{I}| = 1$) and without projects ($|\mathcal{P}| = \emptyset$). There is one infra object, so $k_i = 0$. $(a, \hat{a}) \in \mathcal{C}^{aa}$ if $a-\hat{a}$ is not an edge in G . The maintenance costs are zero. The first k time moments have possession cost 0, the remaining $n - k$ moments have possession costs 1. We have $(a, i) \in \mathcal{C}^{ai}$ for all maintenance activities, and of course $(z, i) \in \mathcal{C}^{zi}$ and $(z, r) \in \mathcal{C}^{zr}$ for the only work zone z , catenary sector r and infra object i . \mathcal{C}^{zp} and \mathcal{C}^{zz} are not applicable. Because there is just one work zone, no projects and no day/night/weekend-requirements, all parameters that are not mentioned yet, are also not applicable.

Now we created an instance of X based on the graph G , the size of the construction is clearly polynomial in the size of the graph G . We claim this instance has a solution with objective value zero if and only if graph G can be colored with k colors. Indeed, suppose that G has a k -coloring. If a vertex has color c , assign the corresponding maintenance activity to the c -th period. Then we obtain an assignment without conflicts. This assignment has zero cost. Conversely, consider a zero-cost solution of problem X . Then each routine work is scheduled for any of the first k periods. Color a vertex of G by color c if its corresponding routine work is scheduled for the c -th period. This yields a k -coloring of graph G . \square

So we can conclude that the decision problem X is \mathcal{NP} , because the problem is at least as hard as the problem k -COL, that is proven \mathcal{NP} . So by Definition 5.4.7, the optimization problem formulated in Subsection 5.2.4 is \mathcal{NP} -hard.

5.5 Solution approach

Since we proved in Section 5.4 that the problem is \mathcal{NP} -hard, it is not likely that there exists an algorithm that solves the problem in polynomial time. Therefore, there are enumerative techniques that consider all possibilities implicitly. One of these techniques is the method *branch-and-bound*. Because of the \mathcal{NP} -hardness, considering all possibilities and therefore finding the optimum can require exponentially many steps. However, the method considers all possibilities in a smart manner; using upper and lower bounds of subsets of sustained solutions it prunes branches of solutions. The algorithm to find a solution is described in Subsection 5.5.1. To apply this solution approach, I used various software. Subsection 5.5.2 describes this software used to find a solution of the problem.

It is also possible to try heuristics to find a feasible solution that approximates an optimal solution. Budai-Balke [3] developed some heuristics, but her problem is somewhat different from the problem of this research. Maybe it would be worthwhile to study her heuristics to find a good heuristic for the problem of this research. Because the solver Gurobi worked well enough for this project, finding such a heuristic fell beyond the scope of the research.

5.5.1 The Branch-and-bound algorithm

We are dealing with a minimization problem, which implies that the value of each feasible solution provides an upper bound on the optimum. We can determine a lower bound using a relaxation: a relaxation \hat{P} of problem P is such that \hat{P} contains the feasible region of P . Typically, the feasible region of P is strictly larger than that of \hat{P} . A relaxation of an integer optimization problem is obtained by dropping the integrality constraints on the variables (e.g. Constraints 5.16 of the developed model, see page 61). This relaxation is called the LP-relaxation. Notice that a solution to the LP-relaxation is in general not feasible for the original integer problem.

An upper bound of the optimum z^* is represented by \bar{z} and a lower bound with \underline{z} . In Figure 5.11 an example is presented graphically.

The higher the lower bound and the lower the upper bound, the smaller the interval within which z^* can be, and the faster the method typically converges to the optimal solution. The branch-and-bound algorithm will always converge to the optimum, although this can take exponentially many steps.

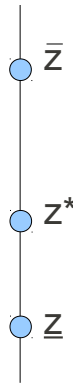


Figure 5.11: Upper bound, optimum and lower bound of a minimization problem

Thus, the lower bound (obtained by a relaxation), and the upper bound (a feasible solution) are important for the expected speed of the branch-and-bound method. To correctly define the branch-and-bound method, the upper bound and the relaxations will be treated first.

Upper bound

Recall that every feasible solution to a minimization problem yields an upper bound. One way to obtain an initial upper bound is by *greedy heuristics*. The idea of these heuristics is to construct a solution from an empty set by choosing the item providing the ‘best’ immediate profit in every step.

If a feasible solution with value \bar{z} is found, we will try to further improve this solution. A heuristic for that goal is a *local search heuristic*. The idea of this heuristic is to define a so-called neighborhood of solutions that are somewhat close to the current solution, and determine the best solution within that neighborhood. If this best solution has a value better than \bar{z} , it replaces \bar{z} and the procedure can be repeated. If \bar{z} remains the best solution value, this is ‘locally optimal’ with respect to the neighborhood. In this case the procedure stops [32].

Relaxations

Lower bounds are determined with relaxations. First, the definition of relaxations is treated. An obvious relaxation is the linear programming relaxation (LP-relaxation), which will be treated as well. After that, one more theorem will be treated regarding relaxations and that will be used in the branch-and-bound method.

Definition of relaxation

The idea of a relaxation is to substitute a ‘difficult’ minimization (maximization) ILP-problem by an easier optimization problem, whose optimal value is less (greater) than or equal to z^* . To give this ‘relaxed’ problem this feature, there are 3 possibilities:

1. Increase the set of feasible solutions to optimize over a larger set.
2. Substitute the minimizing (maximizing) objective function by another objective function that always produces the same or smaller (larger) values.
3. A combination of 1 and 2.

This can be summarized in Definition 5.5.1 [32]:

Definition 5.5.1. A problem $(RP) z_R = \min\{f(x) : x \in T \subseteq \mathbb{R}^n\}$ is a relaxation of $(IP) z^* = \min\{c(x) : x \in X \subseteq \mathbb{R}^n\}$ when:

1. $X \subseteq T$, and

$$2. f(x) \leq c(x) \quad \forall x \in X.$$

Now we can prove the next proposition (Proposition 5.5.1) [32]:

Proposition 5.5.1. *If RP is a relaxation of an IP-problem (minimization), then $z_R \leq z^*$.*

Proof If x^* is an optimal solution of IP, then $x^* \in X \subseteq T$ (follows from Definition 5.5.1:1) and $z^* = c(x^*) \geq f(x^*)$ (follows from Definition 5.5.1:2). Because $x^* \in T$ and $f(x^*)$ is an upper bound on z_R , then $z_R \leq f(x^*) \leq z^*$ applies. \square

Now the question is whether interesting relaxations can be constructed. Among the most useful and natural relaxations is the linear programming relaxation: the LP-relaxation.

LP-relaxation

The idea of the LP-relaxation is to omit the integer postulation of the IP-problem. This increases the set of feasible solutions: instead of admitting just integer solutions, non-integer solutions are feasible as well. (The set \mathbb{Z}^n is extended to \mathbb{R}^n). The linear relaxation is polynomially solvable, so by omitting the integer postulation we obtained an efficiently solvable problem.

This is formulated mathematically in Definition 5.5.2 [32]:

Definition 5.5.2. *For the IP problem $z_{IP} = \min\{c(x) : x \in P \cap \mathbb{Z}^n\}$ with formulation $P = \{x \in \mathbb{R}_+^n : Ax \leq b\}$ the LP-relaxation is the LP-problem $z_{LP} = \min\{c(x) : x \in P\}$.*

Because $P \cap \mathbb{Z}^n \subseteq P$ and the objective function is unchanged ($c(x) = c(x)$), this is obviously a relaxation.

One more result

The branch-and-bound method uses Proposition 5.5.2:

Proposition 5.5.2. *Let RP a relaxation.*

1. *If RP does not have any feasible solutions, then the original IP-problem also has no feasible solutions.*
2. *Let x^* be an optimal solution of RP. If $x^* \in X$ and $f(x^*) = c(x^*)$, then x^* also is an optimal solution of the original IP-problem.*

Proof x^* optimal in LP means $z_R = f(x^*)$. According to the assumption $f(x^*) = c(x^*)$ also applies, so $z_R = f(x^*) = c(x^*)$. x^* feasible in X means $z \leq c(x^*)$. So, for x^* applies $z \leq z_R$, but we know that for all $x \in X$ applies $z_R \leq z$ and therefore we can conclude that x^* is optimal for the IP-problem. \square

Branch-and-bound

To deal with \mathcal{NP} -hard problems, a smartly constructed enumerative method is used: the branch-and-bound method. This method, and variations, are applied successfully to several Operations Research problems, but it is widely known for its application on IP-problems [9].

The basic concept on which the branch-and-bound method is based, is *branch and prune*. As the original problem is too large and too difficult to solve directly, it is subdivided into smaller subproblems until these subproblems can be 'pruned'. The pruning is done by determining how good the optimal solution of the subset can be, after which the subset can be rejected when those bounds indicate that the optimal solution of the subset cannot be the optimal solution of the original problem [9].

These 3 steps (branch, bound and prune) are all treated, but first the start of the method is described.

The first step to be taken is to solve a relaxation, mostly the LP-relaxation, of the IP-problem. The relaxation is 'quickly' solvable. Because the LP-relaxation omits the integer condition, it can produce a non-integer solution, i.e. an infeasible solution for the original IP-problem. Of course, the optimal solution of the LP-relaxation can be integer by coincidence. Whenever that happens, we are finished, because

when the optimal solution of all solutions (including non-integer) is integer, the optimal solution of the subset integer solutions is the same. This is true because the set of integer solutions is a subset of the set of all solutions, see Proposition 5.5.2, point 2. It is possible that the (LP-)relaxation produces no solutions. Then it automatically follows that the original IP-problem cannot have any solutions and so the method stops, see Proposition 5.5.2, point 1. So, there are 3 possibilities when the LP-relaxation of the original problem is solved: there is an integer solution or there is a non-integer solution, or the LP-relaxation has no solution. In the first case, the optimal solution is already found, so the method is of no further use. In the second case, the branch-and-bound method is started. In the last case, there is no feasible solution, so the algorithm terminates. So only in the second case, the branch-and-bound method is continued.

Moreover, when there is not yet an upper bound available, we set the upper bound to $\bar{z} = \infty$.

Branching

When the LP-relaxation of the IP-problem within the set of all feasible solutions produces a non-integer solution, we split the set into two subproblems. Since we developed a binary integer problem (i.e. all decision variables can only be 0 or 1), we can choose one decision variable (let us call it y_k) and create two subsets: the first subset contains all feasible solutions with this variable $y_k = 0$ and the second subset contains all feasible solutions with this variable $y_k = 1$. Please note that the subsets complement each other. Which, not yet fixed (non-integer), variable y_k is set to 0 and 1, is not important (except for the non-integrality property). One will lead to the optimal solution quicker than the other, but often this cannot be determined in advance. There are several methods of putting them in order. Often, it is sensible to choose a variable as close to 0.5 as possible, because it could be interesting to see what the effect is on the objective function.

In Figure 5.12 a graphical representation of this branching is presented.

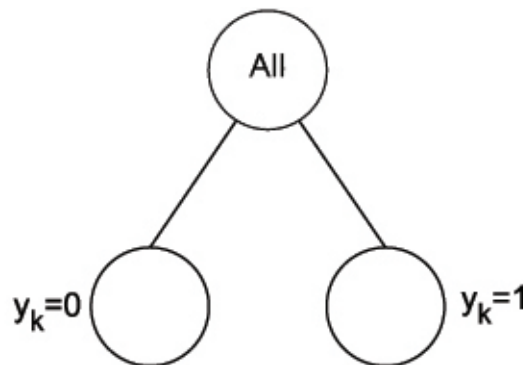


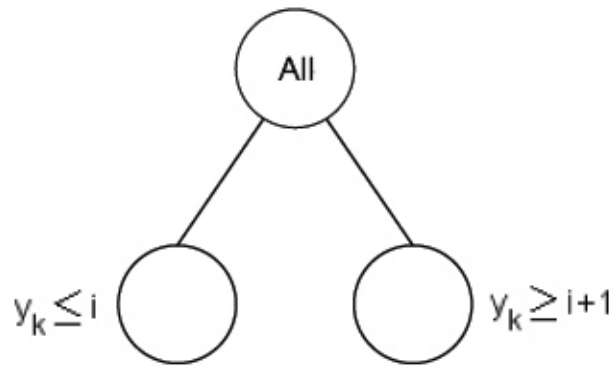
Figure 5.12: Solution tree for the 1st iteration of the binary integer problem (0-1-problem)

The upper part shows the node corresponding with the whole problem with the set of all feasible solutions. That problem splits into 2 new nodes: 2 subproblems, each containing a subset of the feasible solutions. Every new node obviously can be further split, until all variables are defined and there are no variables left to split. When all nodes are split as far as possible, a whole tree is grown, a so-called solution tree that contains every feasible solution. However, we want to avoid having to track all possibilities this way. In the figure the first iteration of a solution tree is presented.

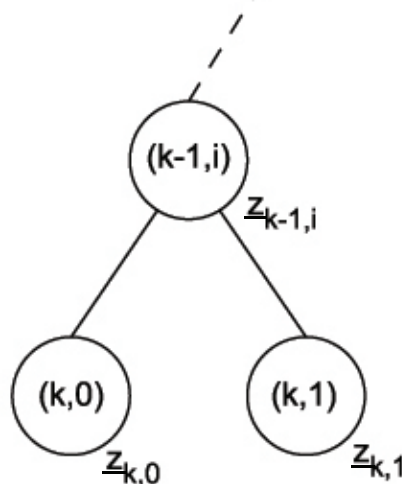
When the IP-problem is not a 0-1-problem, but the variables can have more values, a node branches into 2 branches as well, where one branch corresponds with $y_k \leq i$ and the other with $y_k \geq i + 1$, where $i = \lfloor \bar{y}_k \rfloor$ with $\lfloor \bar{y}_k \rfloor$ the value of \bar{y}_k rounded down in the current LP-relaxation. See Figure 5.13.

Bounding

For every one of the obtained subproblems we again solve the corresponding LP-relaxation. The obtained optimal value of this LP-relaxation is called $z_{k,i}$, where the k corresponds with the variable y_k on which the split is made and i is the value of y_k (in the 0-1-problem i is then equal to 0). $z_{k,i}$ again can be

Figure 5.13: Solution tree for the 1st iteration of an IP-problem

either integer or non-integer. When $z_{k,i}$ is non-integer, we make it integer by rounding it up, so $\lceil z_{k,i} \rceil$. If we assume that all objective function coefficients c_{ij} and f_i are integer, the originating thought is logical: when the optimal (minimal) value of all solutions of the set (including non-integer) is for example 16.3, then the integer optimal value of the subproblem will never be smaller than 16.3. Thus we set the lower bound at the first integer number above 16.3 which in the example is 17. This way, every subproblem acquires a lower bound $\lceil z_{k,i} \rceil$. See Figure 5.14.

Figure 5.14: Lower bounds of nodes (k, i)

Pruning

Now that the considered node has a lower bound $\lceil z_{k,i} \rceil$, this value can determine what should be done: 'prune' or 'do not prune'. Prune means that the solution tree is not further branched on that node. There are 3 cases when the solution tree is pruned at node (k, i) : (the 'prune test')

1. if $\lceil z_{k,i} \rceil \geq \bar{z}$,
2. if the LP-relaxation in node (k, i) contains no feasible solutions (is infeasible),
3. if the LP-relaxation in node (k, i) has an integer solution.

In case 1 an LP-solution is produced that has a higher value (higher costs) than an already produced feasible solution \bar{z} . It can then be concluded that the subset of feasible solutions does not contain the optimal solution. It is not useful to run through other options within that subset. Therefore the node can be pruned.

In case 2, by Proposition 5.5.2:1, we can prune due to infeasibility.

In case 3 an optimal solution is found within the subset of all solutions (including non-integer), that is integer. The set of integer solutions is a subset of all solutions, so the found solution is also an optimal solution for the integer solutions set. In this case further investigating the branch is not useful either, because for the whole branch the optimal solution is already found. The branch can be pruned at this node as well. This case was proven in Proposition 5.5.2:2.

If a node cannot be pruned using any of these three arguments, the node must be included in the branch-and-bound algorithm and will be branched further.

When case 3 applies, we have to consider whether the newly feasible solution has a better value than the best earlier feasible solution. If that is true, we define a new upper bound: $\bar{z} = \lceil z_{k,i} \rceil = z_{k,i}$.

When no node can be branched on anymore, because the branch is fully investigated or pruned, the algorithm is completed. The then resulting \bar{z} is the optimal value of the IP-problem.

Summary of the branch-and-bound method

Start:

Set $\bar{z} = \infty$. Apply the steps *bound* and *prune* and the optimality test to the whole problem, as described below. Whenever there is no pruning, classify this problem as the only left 'subproblem' to perform the first complete iteration.

Steps for each iteration:

1. *Branch:* from the remaining subproblems, choose the most recently created or the one with the lowest bound. Branch the node of this subproblem into two new subproblems by setting a currently fractional variable (y_k) to 0 and 1.
2. *Bound:* determine for every new subproblem its lower bound by solving the (LP-)relaxation. Round up the value $z_{k,i}$: $\lceil z_{k,i} \rceil$.
3. *Prune:* if any of the pruning tests is satisfied, then prune the search tree at the current subproblem. Possibly set $\bar{z} = z_{k,i}$.

Optimality test: Stop when there are no subproblems left; the solution that is corresponding with the current \bar{z} is the optimal solution⁴. Otherwise, perform another iteration [9].

5.5.2 Transitions

Gurobi can read LP-files: files that formulate the optimization problem in the LP-format (see [7]). To make these LP-files, the user of the model has to enter all the parameters in the input file in Excel, named 'NAME_input.xls'. With running the MATLAB-file 'excel_to_lp.m', the LP-file corresponding with the input is made: 'NAME.lp'. In the cases of the tested scenarios, the writing of the LP-files is done within 3 minutes and created files of approximately 300 Mb. With the help of programming language Python, Gurobi is called to read the LP-file and optimize the problem. This is done with the Python file 'lp_to_sol.py', that also gives Gurobi the assignment to write the solution in a solution file: 'NAME.sol'. The MATLAB-file 'sol_to_excel.m' translates this to the Excel-files 'NAME_planning.xls' and 'NAME_schema.xls', that represents the TVP planning. The planning-file lists all TVPs with all the scheduled activities, the schema-file illustrates the TVP planning in a diagram. This diagram is more clear, but does not contain the scheduled activities. The process from the input file to the planning as described above, is shown in Figure 5.15.

⁴ If there is no feasible optimal solution, then the conclusion is that the IP-problem is infeasible.

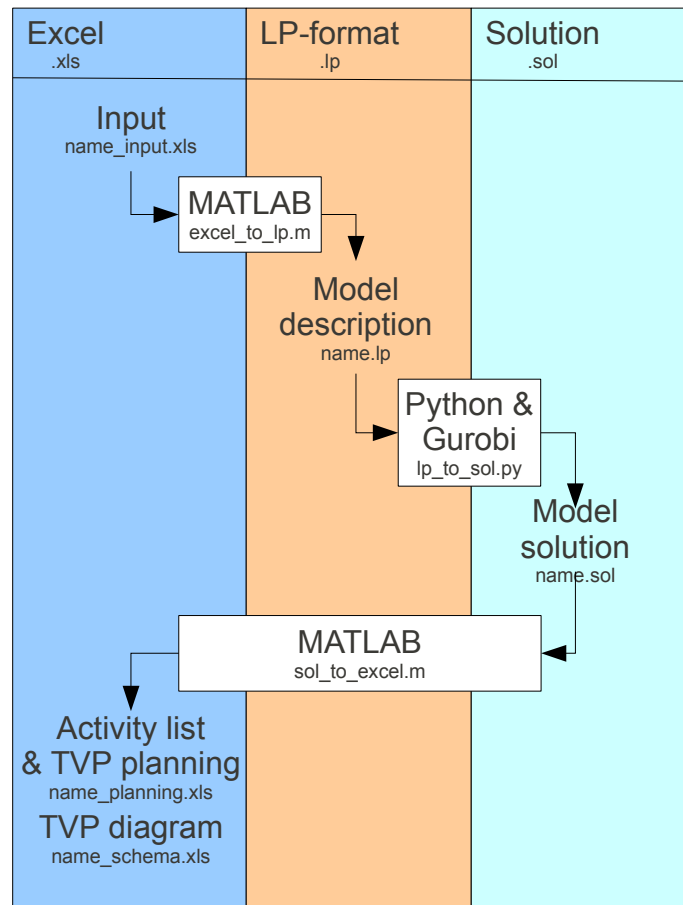


Figure 5.15: Diagram of all the transitions to solve the problem

5.6 Tracking the model

Now that the model is described, this section describes how the model came into existence. The first concept of the model was totally invented by me, to make sure that the model contains fresh, logic and 'own' ideas. Moreover, this first concept contained less parameters and constraints, because I started with a simplified version of the problem. Gradually, I added more and more requirements (such as coupled switches) to the model. Besides that, when the first concepts were made, I did look at the literature as described in Chapter 3. When I compared the model of this research to other models, I noticed matches and differences.

Gradually, my model matched more and more with the model of Budai-Balke [3]: both models handle both systematic maintenance and projects, have the same constraints for (not) combining maintenance activities, use frequency and maximum intervals and have objective functions that consist of possession costs and maintenance costs. Budai-Balke's model differs at the following (among others) points: the model makes use of smaller time windows, such that the routine maintenance works last longer than these time moments, which provides a more detailed schedule, but also makes the problem instances larger. Besides, Budai-Balke's model does not consider different work zones, so the model makes a schedule for one area, without considering the effects on and the maintenance in the neighbouring areas. An advantage of the model of Budai-Balke is that she implemented extra decision variables and constraints to prevent the "end of planning horizon effect": the model optimizes a planning for the given time window, without considering the future, but the future will be there in the reality, so it could give wrong interpretations. For example, the model could decide to schedule activity a not in this year, because then the costs for this year will rise, but due to the maximum interval, now the activity a has to be

scheduled on the 1st of January in the next year, what can be more expensive than scheduling on the 30th of December, because of the maintenance costs during the weekend. But the model does not take that into account, so it does not schedule the activity on the 30th of December.

The model of Higgins et al. [8] show some similarities because it did use a set of track links that make up the corridor. The main difference is that the model makes use of a set of scheduled trains on the corridor, which is another approach. And it makes use of a set of crews available to work on maintenance activities, which could be very useful, because that is a serious problem nowadays: the contractors get their employees from out of the country to make all the work possible. The article of Badr et al. helped me to create constraints that give different relations between activities.

There are two more important developments while tracking the model. First of all, the problem formulation contains a lot of variables, parameters and constraints. Due to the parameters, many of the decision variables are already set to zero: for instance, all the variables y_{ati} for maintenance activity a concerning level crossings have to be zero for all infra objects i that are not level crossings. Or all the variables y_{ati} for a maintenance activity a that can only be executed during the night have to be zero for all time moments t that are at day. To decrease the size of the instances, all these variables that are zero anyway, are not part of the problem and not written in the LP-file. This is also the reason that the formulation gives constraints for $(a, i) \in \mathcal{C}^{ai}$ instead of $a \in \mathcal{A}, i \in \mathcal{I}$.

The second development concerns filtering the time moments, as described in Subsection 5.3.4 (the irregular time interval). Allowing all time moments in the model creates an LP-file that is much larger than an LP-file based on the same instance but then with a fraction of all the time moments. This is because all constraints in the model are set up for all time moments t or sums up all time moments, so when all time moments are allowed (in this case there are then 728 time moments), the LP-file will become large: too large for my computer to enable Gurobi to read the file. For now, this was no problem, because the results (TVP plannings) are good enough with only this six possible time moments per week. I assume that the solution did not suffer under this development.

Chapter 6

Results

This chapter reports on tests of the developed model with the found “Top 10” on a chosen railway yard, and gives the result in the form of a TVP planning for one year. The model is tested with different scenarios (Section 6.1), and different output values are given (Section 6.2). The output is reflected and compared in Section 6.3.

6.1 Test scenarios

This section describes the 24 scenarios that are used as test input for the developed model.

First of all, all scenarios concern the railway yard Hoorn. (Unfortunately, using an additional railway yard or route section fell beyond the scope of this research. It is recommended to test the model on more railway yards and route sections in further research.) Section 5.3 described where the input of the railway yard came from.

Table 6.1 shows the titles (letters) of all the 24 scenarios.

Titles		small work zones		large work zones	
		random previous executions	high random previous executions	random previous executions	high random previous executions
3 and 6 hours TVP lengths	without projects	A	B	C	D
	with projects	E	F	G	H
4 and 7 hours TVP lengths	without projects	I	J	K	L
	with projects	M	N	O	P
2, 4 and 7 hours TVP lengths	without projects	Q	R	S	T
	with projects	U	V	W	X

Table 6.1: Titles of 24 scenarios

There are four distinctions made in the scenarios:

- **work zones:** as described in Subsection 5.3.2, there are two types of work zones used. The smallest possible infra possessions, which are really called work zones, and the larger work zones which all have a set in place for machinery.

- **previous executions of maintenance:** as described in Subsection 5.3.6, the parameter h_{ai} is chosen randomly by Microsoft Excel, in two different ways. First the parameters are chosen ‘just’ randomly and secondly randomly in a higher range¹, the last one is chosen such that the scenario indicates a *worst case scenario*: all activities have to be scheduled in the planning.
- **TVP lengths:** as described in Subsection 5.3.5, there are three types of length inputs used. First, the rounded lengths of the old OHR are used, the second type corresponds to the result of the research of Twynstra Gudde [6], the last type is the second type with in addition an extra length of two hours.
- **projects:** as described in Subsection 5.3.7, projects are excluded and included.

So there are in total $2 \times 2 \times 3 \times 2 = 24$ scenarios.

To give an indication of the size of these scenarios, the number of constraints, the number of decision variables and the number of parameters that are nonzero are given in Table 6.2. (For the mathematical reader: this corresponds to the number of rows, the number of columns and the number of nonzeros respectively.) Gurobi provides these values after reading the input file.

Sizes # constraints; # decision variables; # nonzero parameters		small work zones		large work zones	
		random previous executions	high random previous execu- tions	random previous executions	high random previous execu- tions
3 and 6 hours TVP lengths	without projects	3939613; 200616; 10404783	3939666; 200616; 10408363	5454369; 153504; 13367290	5454413; 153504; 13369982
	with projects	3939993; 206021; 10566320	3940046; 206021; 10569900	5454674; 155165; 13484373	5454718; 155165; 13487065
4 and 7 hours TVP lengths	without projects	3939613; 200616; 10404783	3939666; 200616; 10408363	5454369; 153504; 13367290	5454413; 153504; 13369982
	with projects	3939993; 206021; 10566320	3940046; 206021; 10569900	5454674; 155165; 13484373	5454718; 155165; 13487065
2, 4 and 7 hours TVP lengths	without projects	3939613; 205920; 10549551	3939666; 205920; 10553131	5454369; 155064; 13478986	5454413; 155064; 13481678
	with projects	3939993; 211325; 10711088	3940046; 211325; 10714668	5454674; 156725; 13596069	5454718; 156725; 13598761

Table 6.2: Sizes of 24 scenarios

6.2 Output

Solutions of the 24 scenarios are found by the solution approach described in Section 5.5. We gave every scenario 3 hours computing time. In some cases the optimal solution was found, in other cases solutions were found but it is not proven whether they are optimal or not. The objectives are given in Table 6.3, which represent the costs. The **bold** values are proven optimal and are followed by the computing time in seconds. The other values are not proven optimal, the followed percentage gives the gap between this solution and the found lower limit: the solver indicated that the optimal value will not be smaller than this lower limit.

¹random in the interval $[ma_a - 365, ma_a]$ instead of $[0, ma_a]$

Objectives objective; computation time (if not 10800s) gap (if not 0.00%)		small work zones		large work zones	
		random previous executions	high random previous execu- tions	random previous executions	high random previous execu- tions
3 and 6 hours TVP lengths	without projects	655034 ; 465.10s	1192560; 0.13%	410340 ; 4510.37s	820601; 1.75%
	with projects	778307 ; 434.64s	1326990; 1.02%	483804 ; 3601.83s	907050; 2.45%
4 and 7 hours TVP lengths	without projects	736175 ; 564.74s	1291224; 0.97%	453171 ; 5179.67s	871468; 2.18%
	with projects	855819 ; 721.19s	1422993; 1.15%	521989 ; 3929.57s	957446; 1.75%
2, 4 and 7 hours TVP lengths	without projects	709308 ; 453.07s	1259277 ; 5462.31s	437916 ; 2032.13s	857512; 1.08%
	with projects	828952 ; 465.37s	1391097; 0.20%	506734 ; 2604.39s	942794; 1.67%

Table 6.3: Objectives of the solutions of the 24 scenarios

In fact, the output of the model is besides the value of the objective, the TVP planning. The model creates two files, as described in Section 5.5. One of these files creates an overview of the TVP planning. As an example, the TVP planning of scenario A is given in Figure 6.1.

Appendix F contains the overviews of the TVP plannings of all the scenarios. Each overview lists all time moments where a TVP takes place. The number indicates the length of the TVP at the corresponding time moment (row) and in the corresponding work zone (column). For every work zone, the number of TVPs and the total number of TVP hours are given. For every time moment, the maximum of the TVP lengths is given, to indicate how long (a part of) the railway yard is out of order. Per week and quarter, the sum of these maxima is given. Of course, the total sums are also given. The colours of the work zones correspond to the colours of the figures of the work zones (Figure 5.5 and Figure 5.6). The grey-coloured cells indicate nights.

Since the total number of hours that the railway yard contains a TVP in a year, or the number of TVPs that the railway yard contains in a year, could be more interesting than the costs (objectives), these values are shown in Tables 6.4 and 6.5.

Hoorn scenario A		Werkzone	b626 y35	b626 w35	c626 t43	c626 p51	b626 n32	b626 n38	b626 t52	c626 w44	c626 y46	b626 p33	b626 y37	c626 n41	c626 t47	b626 n40	c626 x45	b626 t39	b626 n42	0	Weeksom	13-weeksom			
Q	Week	Dag																							
		1	di/wo	6			6				6						6					6	18	84	
		1	wo/do								6											6			
		1	za			6	6															6			
		2	di/wo			6				6	6			6	6		6		6		6	6	6		
		2	5	di/wo				6				6										6	6		
		2	6	di/wo			6					6				6		6		6		6	12		
		2	6	za/zo													6		6		6	6			
		2	7	za/zo			6				6											6	12		
		2	7	zo	6	6	6															6	6		
		2	8	di/wo						6												6	6		
		2	10	di/wo	6				6													6	12		
		2	10	za/zo									6			6		6				6			
		2	12	di/wo	6				6				6						3			6	12		
		2	12	wo/do			6				6		6		6							6	6		
		2	15	di/wo			6				6	3		6	6	3						6	6		
		2	16	wo/do				6				6										6	12		
		2	16	za										6	6	6						6			
		2	17	di/wo			3					3					3					3	3		
		2	17	za/zo			3															3	9		
		2	18	zo					6	6	6	6										6	6		
		2	19	di/wo												3		3			6	6	6		
		2	21	di/wo							3											3	3		
		2	23	di/wo	3							3										3	9		
		2	23	wo/do									6			3		3				6	6		
		2	24	za/zo			6				6	6			3							6	6		
		2	25	di/wo	6				6													6	6		
		2	27	za					6	6			6									6	6		
		2	28	di/wo			3	3				3	3			3	3					3	3		
		2	30	wo/do			3					3										3	3		
		2	32	di/wo												3		3			3	3	6		
		2	32	za/zo						3												3			
		2	34	wo/do	6				6							3		6		6		6	9		
		2	34	za/zo									3									3	6		
		2	36	wo/do							6				6							6	6		
		2	38	wo/do					3	3			3									3	3		
		2	39	zo									6			6	6	6	6	6		6	6		
		2	40	wo/do									6									6	6		
		2	41	di/wo			6	3				3	3			3	3					6	6		
		2	43	za/zo						3												3	3		
		2	45	di/wo												6		6			3	6	6		
		2	46	wo/do	3																	3	3		
		2	47	di/wo									3									3	3		
		2	48	di/wo							6				6							6	12		
		2	48	za/zo	6				6													6			
				Total hours	48	6	66	24	51	30	6	60	48	63	12	45	54	6	60	6	42		225		
				Number	9	1	13	5	10	7	1	12	10	12	2	9	13	1	12	1	8		44		

Figure 6.1: TVP planning Hoorn Scenario A

Total hours TVP in a year		small work zones		large work zones	
		random previous execu- tions	high random previous execu- tions	random previous execu- tions	high random previous execu- tions
3 and 6 hours TVP lengths	without projects	225	312	177	201
	with projects	258	360	195	222
4 and 7 hours TVP lengths	without projects	279	397	209	254
	with projects	306	423	227	273
2, 4 and 7 hours TVP lengths	without projects	264	358	182	227
	with projects	264	369	207	264

Table 6.4: Total hours Hoorn has TVPs in a year of all 24 scenarios

Number of TVPs in a year		small work zones		large work zones	
		random previous execu- tions	high random previous execu- tions	random previous execu- tions	high random previous execu- tions
3 and 6 hours TVP lengths	without projects	44	60	32	39
	with projects	45	64	31	37
4 and 7 hours TVP lengths	without projects	45	64	32	41
	with projects	46	64	31	39
2, 4 and 7 hours TVP lengths	without projects	46	61	30	39
	with projects	42	59	30	41

Table 6.5: Number of TVPs in a year of all 24 scenarios

6.3 Reflections

This section reflects upon the results. First, it compares the different scenarios and reports on some conclusions (Subsection 6.3.1). Also a comparison is made between the original OHR of Hoorn and the TVP planning as result of the model (Subsection 6.3.2). Subsection 6.3.3 describes some findings about the output in general. Finally, Subsection 6.3.4 describes some reactions of other parties inside and outside ProRail.

6.3.1 Comparisons between the different scenarios

This subsection describes some comparisons between the different scenarios. The first comparisons are between the work zone differences, followed by the previous executions of the maintenance activities, the TVP lengths and finally the projects.

Work zones

Small work zones: A, B, E, F, I, J, M, N, Q, R, U and V.
Large work zones: C, D, G, H, K, L, O, P, S, T, W and X.

Costs

Observation: it appears that large work zones are cheaper than small work zones.

Explanation: the costs for possessing a work zone are the same in both scenarios. So, in this model, scheduling two small work zones TVP is more expensive than scheduling one large work zone TVP. So it is not useful to compare the costs of scenarios with small work zones with the costs of scenarios with large work zones.

Total hours TVP & Number of TVPs

Observation: large work zones have scheduled less hours and less TVPs than small work zones.

Explanation: to clarify this phenomenon, an example is given. Consider the areas in Figure 6.2, containing two railway tracks and 4 coupled switches (1A, 1B, 2A and 2B). The left figure has four “small” work

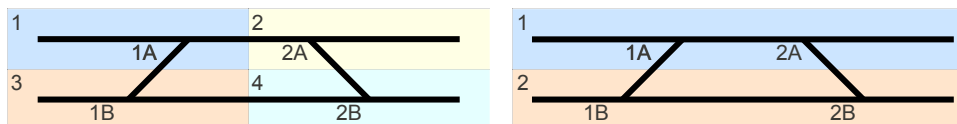


Figure 6.2: Example of railway area with different work zone division

zones, the right figure has two “large” work zones. Imagine that the model wants to schedule a maintenance activity on switch 1A and on switch 2A. The situation with the large work zones will schedule them at the same time moment (if possible), because then one TVP is needed and that is cheaper than two separate TVPs. In the situation with the small work zones, scheduling the maintenance activities at the same time moment, or at separate time moments, will not differ in costs, because in both cases there are two TVPs needed. So for the same costs, the railway area could have more TVPs and more hours. In fact, the model should take into account that when a work zone has a TVP, the costs for a TVP in the next work zone as well should be lower. So, the model as it is now, approximates the reality better with the large work zones than with the small work zones.

Previous executions of maintenance

Random previous executions of maintenance: A, C, E, G, I, K, M, O, Q, S, U and W.
High random previous executions of maintenance: B, D, F, H, J, L, N, P, R, T, V and X.

Optimality

Observation: All scenarios of type random previous executions of maintenance are solved optimally, there is only one scenario of the type high random previous executions of maintenance which is solved optimally.

Explanation: The scenarios of the type high random previous executions of maintenance have to schedule more maintenance activities than the other type, this causes larger problem instances, which could increase the computation time.

Costs

Observation: The scenarios with the high random previous executions of maintenance (worst case scenarios) are always more expensive than the scenarios with a (lower) random previous executions of maintenance.

Explanation: This is obvious, because more maintenance activities have to be scheduled, so this needs more TVPs (which leads to more possession costs) and it is clear that it leads to more maintenance costs.

Total hours TVP & Number of TVPs

Observation: The scenarios with the high random previous executions of maintenance (worst case scenarios) almost always have more hours TVP and more TVPs than the scenarios with lower random previous executions of maintenance.

Explanation: It is logical that more TVPs (and more hours) are needed to schedule more maintenance activities. The “normal” random scenarios are random, so theoretically, they can be higher than the forced high random numbers, but it seems that it is not the case.

TVP lengths

3 and 6 hours: A, B, C, D, E, F, G and H.

4 and 7 hours: I, J, K, L, M, N, O and P.

2, 4 and 7 hours: Q, R, S, T, U, V, W and X.

Costs & Total hours TVP

Observation: 3&6 hours is the cheapest/shortest scenario type, 4&7 is the most expensive/longest scenario type, 2&4&7 lies in between.

Explanation: The duration of the TVPs is in the second case (4 and 7 hours) longer than in the first case, so it is not strange that the costs/total hours are higher in the second case than in the first case. The third case has also the possibility to schedule short TVPs, which will decrease the possession costs compared to the second case. Apparently, the third case is more expensive/longer than the first case; presumably this is caused by the need of a lot of ‘long’ TVPs. I think it is not a surprising observation, because the minimal needed TVP length (b_a) of the input are lengths that are used nowadays, so there is no activity that needs longer than 6 hours, so the 7th hour looks like superfluous. However, when the 7 hours are used in the future, the contractors will be very happy, because they have to overrun less often and can combine more maintenance activities. Maybe we can conclude that this result is a consequence of the input: because the input contains no maintenance activities of 7 hours, the TVP length of 7 hours will never be the optimal one. Moreover, the model itself has also influence on this result, because the model cannot (yet) schedule maintenance activities serial, so two maintenance activities cannot follow up each other during the same night or day. If the model could schedule maintenance activities serial, a maintenance activity of 3 hours and one of 4 hours could be combined in a TVP of 7 hours.

Number of TVPs

Observation: There is not a distinction as clear as the distinctions in the observations described above. The first and the second cases need sometimes the least number of TVPs, the second case never needs the least number of TVPs.

Explanation: I do not yet see a logical explanation for this phenomenon.

Projects

Without projects: A, B, C, D, I, J, K, L, Q, R, S and T.

With projects: E, F, G, H, M, N, O, P, U, V, W and X.

Costs

Observation: Scenarios with projects are more expensive than scenarios without projects.

Explanation: Obviously, the project costs are added, so the objective will increase. Moreover, more TVP hours are needed, so the possession costs will also increase.

Total hours TVP

Observation: Scenarios with projects need more TVP hours than scenarios without projects, except for scenario Q and U, they need the same time.

Explanation: That the scenarios need more hours when projects are also included, is logical, because the added projects need more time than a systematic maintenance activity. Scenario U shows that it could be worthwhile to integrate the scheduling of the systematic maintenance and the projects.

Number of TVPs

Observation: Sometimes the scenarios with projects need more TVPs, sometimes the scenarios without projects need more TVPs, or the number of TVPs is the same.

Explanation: This also shows the benefits of integrating projects in the systematic maintenance scheduling.

6.3.2 Comparisons between model output and current OHR

For comparing the results of the model with the current OHR, I do have the following information:

1. the OHR-idea: the current OHR makes every area of the Dutch railway network available for systematic maintenance for a total of 136.5 hours divided over 39 moments (13×5.5 hours and 26×2.5 hours),
2. the OHR for Hoorn [19]: the moments that railway yard Hoorn has capacity available for maintenance are on Wednesday day and night, Thursday day, Saturday night and Sunday day,
3. published WBIs on Hoorn in 2010 [20]: there were 397 WBIs published with a total of 1159 hours, there were 226 WBIs published with a length of at least one hour, with a total of 1095 hours.

However, I do not have the following information:

1. which TVPs of the OHR are used,
2. what is done within the WBIs, so I do not know how many of the WBIs are used for systematic maintenance (and projects).

So I cannot conclude how many TVPs and how many hours there have been in Hoorn in one year for the systematic maintenance. The OHR and the idea of the OHR give an idea about the available capacity for maintenance in Hoorn, but states nothing about the realization. The WBIs state more about the realization, but that information cannot state which of the WBIs are used for systematic maintenance.

However, when we consider the output of the model of the scenarios with the large work zones (because they are the most similar to the areas that are set out of order in the OHR), the number of TVPs will not be more than 39, except for some large problem instances which are called the worst case scenarios. However, even then the number of TVPs will not increase by much. The total hours the model has scheduled a TVP on the railway yard Hoorn is a little more than 136.5.

Another interesting fact is the following, apparently for the railway yard Hoorn it satisfies to only schedule on 6 time moments, so the choice to only use 6 of 14 time moments per week was not a bad one.

6.3.3 Findings on output in general

Finally, some findings about the TVP plannings in general are given here.

- Many times there are more TVPs during the same time moment, unless the inserted decision variable σ which causes more costs when combinations of work zones are TVP such that a train can not run into and out of Hoorn. This could be explained by the connected switches: when a maintenance activity is performed on a switch which is connected to another switch, then that other switch cannot be used either, so the work zone in which the connected switch lays has to be TVP as well. However, when that work zone has a TVP, then the model schedules as many maintenance activities as possible to minimize the possession costs. However, that maintenance

activity could again concern a connected switch, which is connected to another work zone. And so on.

For example, in week 15 during the night between Tuesday and Wednesday: work zone **c626 n41**² is TVP for a maintenance activity on switch 13A, which is connected with switch 13B, so work zone **c626 w44** has to be TVP too. However, then that activity could also be scheduled on switch 27B and 25A, which are also in that work zone. In the same way that maintenance activity is scheduled on the same moment for switches 25B, 27A and 23B in work zone **c626 t43**. And so work zones **c626 y46**, **c626 p51**, **c626 h47**, **c626 x45** and **b626 p42** follow.

- It is remarkable that the first quarter of the planning is the busiest quarter in all scenarios. I guess it is caused by the randomness of the previous executions of maintenance of the maintenance activities: it causes a high chance that some maintenance activities have to be scheduled in the first quarter, and due to combination benefits and coupled switches, as described in the bullet above, more activities are scheduled at the same time moment.
- In the scenarios with 2, 4 and 7 hours TVP lengths, it is remarkable that the model chooses the length of 4 hours just a few times, or even not at all. So I guess that in the case of only 4 and 7 hours, most of the TVPs that last 4 hours are longer than needed and ask a lot capacity. Moreover, TVPs of 2 hours are easier to schedule than TVPs of 4 hours. Disadvantage is the fact that TVPs of 2 hours are not efficient for the contractors, so such short TVPs will be relatively expensive.
- The scheduling of the projects is nicely integrated in the scheduling of the maintenance activities, but it is not yet integrated into the model whether the maintenance activities could be or could not be combined with the projects. When the project scheduling would be integrated with the scheduling of the systematic maintenance, the model needs adjustments such that the input tells the model which maintenance activities of the Top 10 could be combined with the project, and the model has to use that information.
- The work zones that do not contain switches and level crossings, only need a few TVPs a year (in many cases, one TVP a year is enough). In the scenarios with the large work zones, all work zones have 6 switches, except zone **hoorn2b**, that contains 3 switches. That zone always needs the least TVPs per year. So we can conclude that the number of switches in a work zone has a lot of influence on the maintenance schedule.
- Almost all work is scheduled at night: so the maintenance cost for night work does not outweigh the possession cost for day work.
- The TVPs that are scheduled during the day contain a maintenance activity that can only be performed during the day. Moreover, the day work is scheduled in the weekend, because it is cheaper. The only exceptions are caused by the projects that are scheduled during the week. Because of the projects, some work zones have TVPs during the project. Sometimes, neighbouring work zones also have TVPs, because of the catenary that are out of order and do not have the same boundaries as the work zones. Because the maintenance costs are cheaper during the day than during the night, the model schedules maintenance activities in the work zones that have to be TVP during the project.

6.3.4 Reactions

The results are discussed with several parties inside and outside ProRail: the contractor, the manager of IBP, the region manager of IBP and the substitute tracing manager of railway yard Hoorn.

Many employees of ProRail have a great need for a model that give more insights in the needed capacity for (systematic) maintenance. Until now, ProRail has no argued reasons for it. While discussing our developed model, I noticed that this model could answer to this need. When this model develops to a usable tool, ProRail can calculate how many capacity is needed (approximately) for systematic maintenance and can better imagine the needed capacity. Apparently, many people in ProRail want that. It is

²The colours correspond with the colours in the work zone diagram in Figure 5.5 on page 66.

remarked that ProRail has detailed researches concerning money (think of the LCM-tool), but that there are no researches on time (capacity), while time (capacity) is becoming more and more scarce. Hence, some wish that this project gets a continuation. Therefore, Chapter 8 gives some recommendations on the implementation of this model.

The fact that projects could be integrated is found interesting. This led to the thought to make a very large maintenance activity bundle and see this as a project. The model could calculate some different scenarios, so ProRail could conclude whether this has benefits for the capacity. However, the model is designed for the systematic maintenance, so when this is one of the main goals of the model, maybe the model should be adjusted some more.

Also, some new insights are given. For instance, the model makes no distinction in the difference of the railway tracks that are used for train traffic (track 1, 2 and 3 in railway yard Hoorn) and the railway tracks that are mainly used during the night for setting up the trains (track 4, 5 and 6 in railway yard Hoorn). It could be cheaper to maintain the 'set up tracks' during the day, because these tracks are needed at night.

Since the model needs some developments, in the discussions, the focus lay on the possibilities of the model. Moreover, the results (the TVP plannings) did give insights about how the model works. However, the results are also discussed shortly. The proposition that the developed Top 10 could determine the TVP planning is reliable according to each discussion partner. Only the instances with the larger work zones seem to provide realizable TVP plannings, because (almost) every TVP needs a 'set in place' for the machinery. The frequencies are higher than the frequencies Twynstra Gudde advices, what made the discussion partners doubting on the result of Twynstra Gudde. Our conclusion that the scheduling of the projects could be integrated with the scheduling of the (systematic) maintenance, is received enthusiastically. It even brought new ideas about maintenance scheduling, that can be tested by our model with new scenarios.

Summarizing, the discussion partners were more enthusiastic about and interesting in the (further) developing and the possibilities of the model, than in the results of the current model. However, also some of our conclusions were received enthusiastically.

Chapter 7

Conclusion

The future Dutch railway infrastructure capacity will become more and more scarce due to increased transport, increasing safety requirements and an increasing number of projects. This is why ProRail concluded that the current maintenance schedule is not future-proof and started the program Maintenance Model 2020 (OHM2020) to give a new interpretation to performing and scheduling maintenance.

The current maintenance schedule is based on the longest lasting systematic maintenance activity and on traffic wishes: maintenance is scheduled such that the disturbance to the traffic will be minimized. Under OHM2020, the question is whether a maintenance schedule based on the essential maintenance necessities of the infra objects will be better (in terms of capacity and costs) than the current maintenance schedule. To execute maintenance and projects, the train table needs *train-free periods*: TVPs.

The main problem investigated in this research was to find a TVP planning, based on the maintenance necessities of the infra objects, including the possibility to integrate the planning of the projects.

Top 10

The first research question was '*Which 10 systematic maintenance activities are determining the TVP planning the most? And why?*' To answer this question a first analysis is done on a benchmark on realization data, to determine a first concept of the Top 10. This first concept is discussed with experts, that resulted in the Top 10 in Table 4.2 (page 53). The factors that determined which maintenance activities are part of the Top 10, are a high frequency and/or a high minimal needed TVP length. We do not claim that the given Top 10 is definitive, but we believe that it approximates the reality, so it is used in the rest of the research. Moreover, this Top 10 is based on the old type of contract (Output Process Contract), so the Top 10 will probably have to be adjusted in the future.

So, the 10 systematic maintenance activities that are determining the TVP planning the most, are given in Table 4.2. These are determining the TVP planning because of their high frequency and/or a high minimal needed TVP length.

Model

The second research question was '*What is an (approximately) optimal TVP planning for a specific route section/railway yard based on the maintenance needs of the infra objects, using the Top 10 from the first question?*' To answer this question, a mathematical optimization model is developed. The model formulates an objective function and constraints (restrictions) and tries to find the combination of decision variables that satisfies the constraints and minimizes the objective function.

The objective of the model is to make a TVP planning such that the capacity for maintenance will be minimized. This is realized by minimizing the costs: possession costs, maintenance costs and project costs. A distinction is made in time: possession costs are cheaper during the night than during the day, while maintenance activities during the night are more expensive than during the day. Constraints used in the model concern TVP lengths, coupled switches, intervals between two successive maintenance activities, combination possibilities, maximum number of executable maintenance activities at the same time, extra possession costs when the total railway yard is obstructed, projects and day/night/weekend-requirements. Besides the Top 10, the model will base the TVP planning on the concerning infra objects of the corresponding area, a list of possible time moments, a list of possible TVP lengths and (optionally)

a list of projects.

We proved that the developed model is in the complexity class \mathcal{NP} -hard, so it is not likely that there exists an algorithm that solves the problem in polynomial time. Hence, other techniques are necessary, in this case the solver Gurobi, that makes use of the branch-and-bound method, is used.

The obtained model is most similar to the model of Budai-Balke [3], but my model considers more work zones instead of just one area.

So, based on the maintenance needs (Top 10) of the infra objects of railway yard Hoorn, the model gives approximately optimal plannings, in terms of capacity and cost.

Results

The model is used to make a TVP planning for the railway yard Hoorn. Unfortunately, the parameters of the previously executed maintenance activities are fictional. Moreover, the model needs some improvements before it can be used for real. However, the results suggest how the model works and what the results look like, and can be used for giving insights into innovative ideas.

The model is tested with 24 scenarios, with distinctions in work zones (smaller and larger), range in randomness of previous executions of maintenance (random scenario and ‘worst case scenario’), TVP lengths (current maintenance schedule versus an advice as result of another research) and projects (including and excluding).

The results show that larger work zones are more approximating the reality, that maintenance activities are mainly scheduled during the night, that integrating the scheduling of the projects into the scheduling of the systematic maintenance is worthwhile, and that switches and level crossings have a big influence on the capacity. Other remarkable facts are that the most of the work is scheduled in the first quarter, and that adding the option of TVPs of just 2 hours are worthwhile. However, the efficiency of 7 hours versus 2 hours (due to personnel and safety costs) is not taken into account in this model. Moreover, the model also does not schedule serially, so two not-combinable maintenance activities with a length of 2 hours could not be scheduled in the same night in this model, while in practice this is possible in 4 hours.

The results are discussed with several parties inside and outside ProRail. Those gave some new insights into the model, which resulted in adding scenarios with larger work zone division, and in more recommendations. The general reaction to the model consists of great expectation when the model is developed further. People expect that they can get more insight into the needed capacity for maintenance, and can use arguments in the capacity allocation. The Top 10 and the TVP plannings were also discussed shortly: the Top 10 is found plausible, the TVP plannings with smaller work zones are not realizable and integrating projects into the scheduling seems interesting.

Conclusions

Summarizing, as result of this research:

- we developed a mathematical optimization model to find a TVP planning for ProRail that minimizes the capacity for systematic maintenance,
- the model needs some developments before it could be implemented and applied (see also the recommendations (Chapter 8):
 - it should be possible to schedule the maintenance activities serially during the same night or day,
 - combination (im)possibilities between projects and maintenance activities should be taken into account,
 - distinctions can be made between tracks used for traffic and tracks used for setting up trains during the night,
 - the efficiency of the length of the TVPs could be added to the model,
 - safety costs per TVP could be added,
- however, we have seen that using mathematics for finding such a TVP planning is advantageous,
- we have seen that it is possible to determine a Top 10 of the most determinative maintenance activities, although the determined Top 10 is not definitive,

-
- given the made assumptions (such as the fictional/random input), the results of the current model gave some insights:
 - weighing the maintenance costs and the possession costs, executing maintenance during the night will be cheaper than during the day,
 - integrating the scheduling of projects into the scheduling of systematic maintenance is valuable,
 - the smallest possible work zones (defined by ProRail) are not realizable, the larger work zones (defined in this research) are realizable (and similar to the current TVPs),
 - the scenarios with TVP lengths of 3 and 6 hours, based on the current maintenance schedule, seem to be the best, but that could be consequence of the input and the fact that the model cannot (yet) schedule serially,
 - the TVP plannings all have far more than four times per year a 'large' TVP, so it could be doubted whether the result of the research of Twynstra Gudde will satisfy the maintenance needs,
 - because of the necessary developments of the model, and the made assumptions, the conclusions made in the bullet above should be handled carefully,
 - the expectations of the model are high.

Chapter 8

Recommendations

In conclusion, this chapter gives some recommendations for further research on the Top 10 (Section 8.1) and on the model (Section 8.2). It also gives recommendations for the company ProRail in general (Section 8.3) and for implementation of the model (Section 8.4).

8.1 Top 10

The determined Top 10 is one based on expert judgement on a small scale. The following recommendations are for improving the Top 10:

- Expert judgement can be done on a larger scale (for example other contractors).
- Maybe the determined Top 10 based on expert judgement can be validated with realization data.
- The contractor mentioned that some maintenance activities often overrun the TVP. It could be examined whether this is true, for which maintenance activities this holds, and which needed TVP lengths would be better.
- The current Top 10 is based on the old type of contract (OPC), but it will be replaced by the new type of contract (PGO). It will be hard to find a general Top 10 for the whole country, when it is based on PGO contracts, because due to the PGO contracts the executed maintenance will differ more between each location. I think that it will be possible to set up such a Top 10 (maybe in cooperation with the contractors) for the different areas. Then the location specific Top 10s will be a good input for the model that makes a TVP planning for that area. Because of this new contract type, it will be harder to determine frequencies, but when there can be made a good estimation of the frequencies of the coming year, it will be enough for the model.

8.2 Model

If further research is done on the model, I have some suggestions for improvements of the model:

- Since it was impossible to get all the right (and needed) input, one of the important improvements should be that ProRail has to find or gather more and better data. For example, it was impossible to get the data on the previous executions of the maintenance activities. I guess this will stay hard, but there could be made better estimations than the random values we chose. It could also be considered whether the frequencies and minimal needed TVP lengths are still correct. Moreover, sometimes we had to guess in which work zone a certain infra object was, and we made the larger work zone division by ourselves.
- Additional on the previous statement, a lot of input is entered by hand. For example, I could load all switches of the area, I entered all catenary sectors and work zones by hand, and finally I had to make the connection between these objects, sectors and zones by myself. This is quite intensive, especially when this should be done for the entire country. So it would be worthwhile to think of

which steps could be automated. For professional use I recommend to automate as many steps as possible. Moreover, maybe there is more profit to win by having all asset data more connected and organized.

- (As mentioned in Subsection 6.3.1.) All the maintenance activities that are scheduled at one TVP moment are scheduled 'parallel'. It could be worthwhile to consider serial scheduling of maintenance activities. For example, when two not-combinable maintenance activities with each a length of 3 hours are scheduled after each other (serial) at the same day or night, there is only one TVP needed with a length of at least 6 hours, instead of two TVPs of at least 3 hours. I think it is not easy to implement it in this model, because the basic idea of the model did not take this into account. However, I think it will be possible. Maybe, one way to this could be to adjust the constraints of the combinable maintenance activities such that not-combinable maintenance activities could be scheduled together when the sum of both TVP lengths is at most the length of the TVP.
- (As mentioned in Subsection 6.3.3.) Projects are integrated in the model, but the model does not check whether the maintenance activities that are scheduled at the same time moments as the projects, could actually be combined with the projects. When the model is used for making the TVP planning, this improvement is necessary. One way to implement this in the model is in the same way as with the (not-)combinable maintenance activities.
- (As mentioned in Subsection 6.3.4.) Some railway tracks are used for setting up the trains in the night, so they are available during the day for maintenance. It would be profitable for costs as well as capacity to implement this fact into the model. One way to do this is to give other possession costs to 'set-up-tracks' than to 'run-tracks'.
- (As mentioned in Subsection 6.3.3.) It could be worthwhile to add efficiency into the model: TVPs of 2 hours are less efficient than TVPs of 7 hours (work men have to be paid for 8 hours). One way to handle this, is to make the 7th hour of a TVP cheaper than the 2nd hour of a TVP. This efficiency is particularly worthwhile in combination with the serial scheduling.
- It could be worthwhile to add costs for making a work zone a safe work place. Those costs will rise the objective function for every single TVP, but is not multiplied with the length of the TVP. So adding these costs will cause that the model also minimizes the number of TVPs. The situation outlined in Subsection 6.3.1 with Figure 6.2 will also disappear when this is added to the model.
- If the contractors require a certain percentage of the work scheduled during the day, it could be considered to formulate a constraint that corresponds with this requirement. (The contractors also have to have work during the day, because they will lose their employees otherwise.)
- It could be an interesting research to find out how the model could deal with condition based maintenance (maintenance that takes place when the infra object reached a certain condition). Condition based maintenance has no frequencies, but maybe with some probability analysis and robust optimization, this kind of maintenance could also be taken into account.
- (As mentioned in Subsection 6.3.3.) The results (TVP plannings) show that most of the work is done within the first quarter. My assumption is that it is a consequence of the randomness of the parameters about the previous executions of the maintenance, but it is worth to find out whether this is true.
- Although the model takes more work zones into account than the model of Budai-Balke [3], the model does not communicate with the neighbouring work zones that are not part of the input. Further research should consider whether this is a problem or not, and how to deal with that fact.

8.3 ProRail

According to the results, I would recommend ProRail the following things:

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- Because ProRail came up with the idea to integrate the project scheduling into the systematic maintenance scheduling, I also made scenarios that included projects. The results were positive: the number of TVPs and the total of TVP hours did not always increase, while we asked the model to schedule more and longer lasting activities. So my advice to ProRail is to continue their research to integrate the project scheduling into the maintenance scheduling, because I assume it will be valuable.
- Twynstra Gudde advised to perform maintenance four times per year in 7 hours, but my model indicated that these four times would not be enough. My advice to ProRail is to examine whether these 7 hours four times a year satisfy the maintenance needs or not.
- The larger work zones approximate reality more than the smaller work zones, so I advice to use the larger work zones. However, I grouped the smaller work zones into larger work zones based on the current OHR, so it could be worthwhile to investigate whether this division is the best one.

8.4 Implementation

If ProRail decides to continue this research with as goal to implement the more developed model, I have some additional suggestions:

- First of all, I used many transitions and software to find solutions (as described in Subsection 5.5.2). It was instructive for me, but it is sensitive to errors and takes a lot of work. There are programs that contain all steps: it saves the input, contains the model description, solves the model and can show the results. To install such a program, someone that understands the model is needed, but this knowledge is not necessary for using the program. When the model will be developed into a tool, I will advise ProRail to use a program like this. Examples of such programs are AIMMS or GAMS.
- I would like to advice ProRail to define what the goal of the tool would be. When the tool is meant for getting more feeling and arguments for ideas and discussions, the tool is easier to construct, because it is easier to define and apply a scope. For a model that makes the real TVP planning model, the model has to be investigated more detailed and will be more complex. I assume the first will be more worthwhile, because ProRail does not schedule when which maintenance activity will be planned, but only when the TVPs take place, the contractor will decide what maintenance will be done within that TVPs.

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Appendices

Appendix A

Regions

Figure A.1 shows the Railway Network of ProRail, divided in the four regions. KEYRAIL is a special one, they control the systematic maintenance by themselves and is beyond my scope.

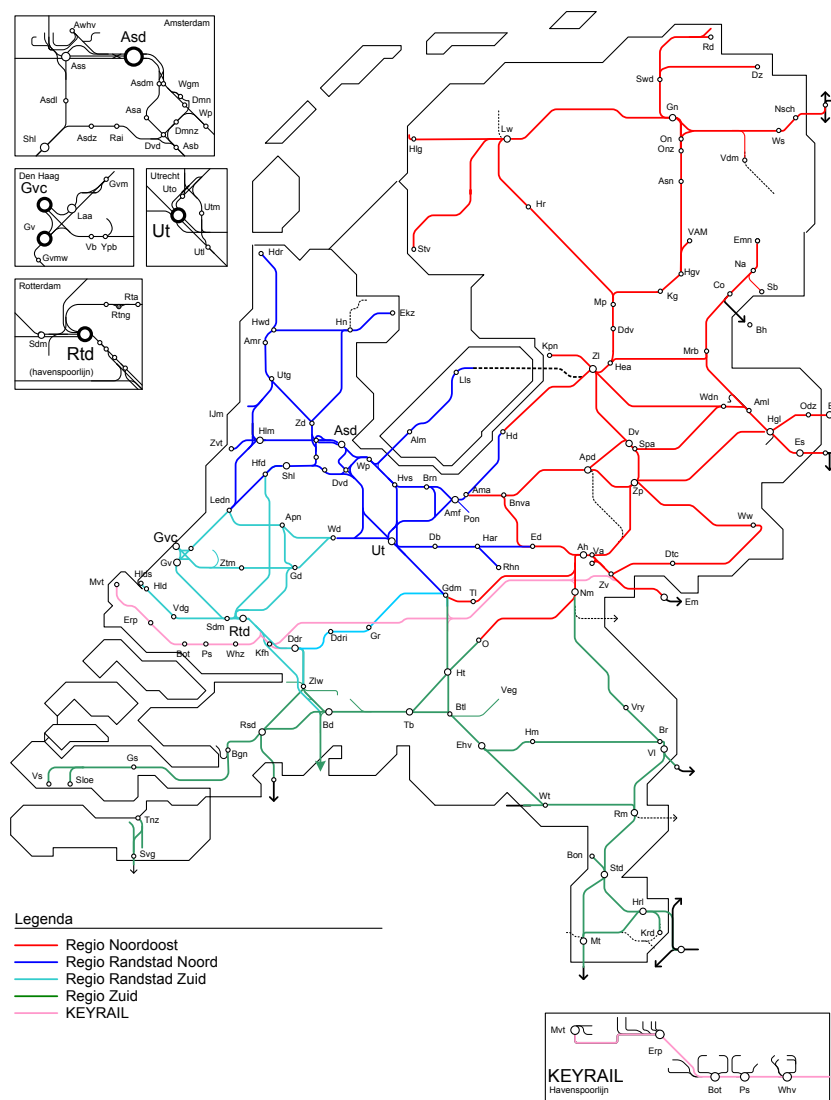


Figure A.1: The railway network divided into regions

Appendix B

Maintenance schedule

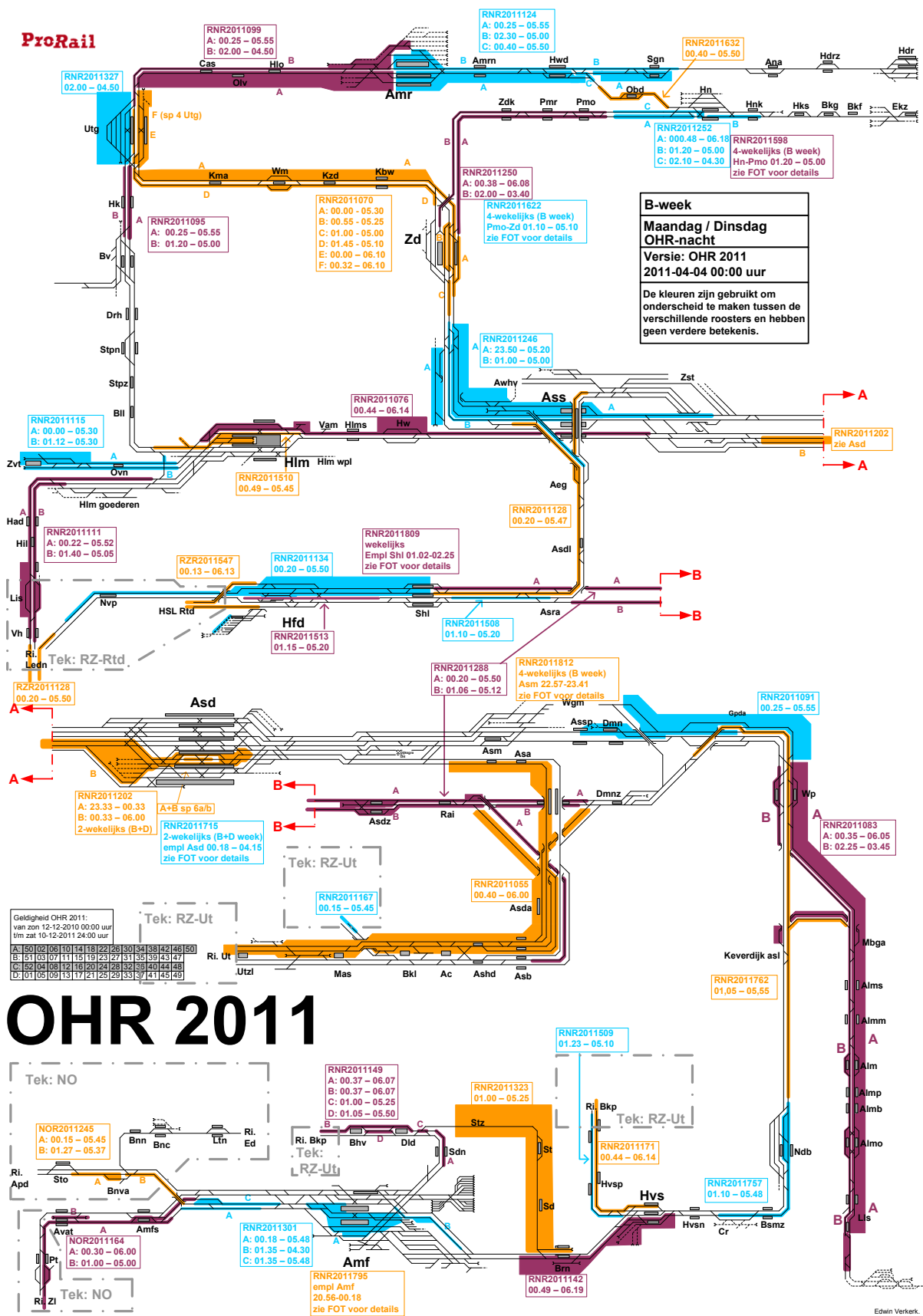


Figure B.1: OHR 2011 region RN Monday/Tuesday night week B

An optimization model for a TVP planning for ProRail based on maintenance needs of the infrastructure
 Rianda Jenema - TU Delft

Appendix C

Capacity allocation

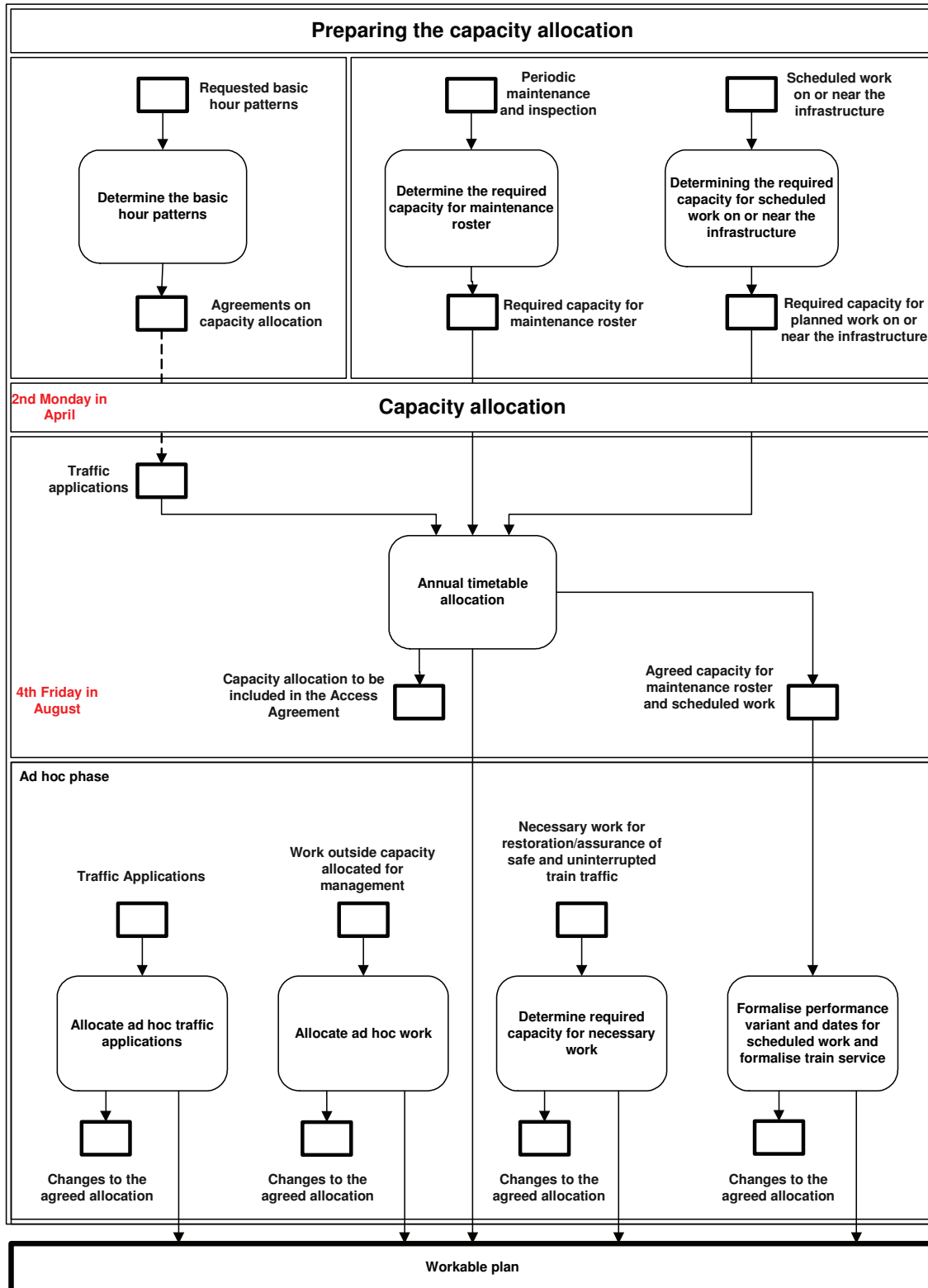


Figure C.1: Capacity allocation processes

Appendix D

MATLAB codes

This appendix gives both MATLAB codes used for the translation of the Excel and solution files.

D.1 Excel to lp.m

```
%This file translates the input excel file to an .lp-file which can be used
%as input for the solver Gurobi
clc %Clear everything done before
clear
tic

%easy to change input
name = 'hoorn_scenarioT'; %name of .lp file to create
%names of sheets to read
sheetA = 'Activiteiten';
sheetR = 'Bvl-groepen';
sheetZ = 'Werkzones';
sheetT = 'Tijdsmomenten';
sheetL = 'TVP-lengte';
sheetIW = 'Wissel';
sheetIO = 'Bevloering';
sheetO = 'Overig';
sheetPC='Bezettingskosten';
sheetMC='Onderhoudskosten';
sheetP='Projecten';

status = 'start is made'

%reading xls.file
inputtitle = strcat(name, '_input.xlsx');
[numA,txtA,rawA] = xlsread(inputtitle, sheetA);
[numT,txtT,rawT] = xlsread(inputtitle, sheetT);
[numL,txtL,rawL] = xlsread(inputtitle, sheetL);
[numIW,txtIW,rawIW] = xlsread(inputtitle, sheetIW);
[numIO,txtIO,rawIO] = xlsread(inputtitle, sheetIO);
[numZ,txtZ,rawZ] = xlsread(inputtitle, sheetZ);
[numR,txtR,rawR] = xlsread(inputtitle, sheetR);
[numO,txtO,rawO] = xlsread(inputtitle, sheetO);
[numPC,txtPC,rawPC] = xlsread(inputtitle, sheetPC);
[numMC,txtMC,rawMC] = xlsread(inputtitle, sheetMC);
[numP,txtP,rawP] = xlsread(inputtitle, sheetP);
```

```

status = 'file is read'

%parameters
    timestep = num0(1);
%cardinalities
    cardAO = numA(2,2); cardAR = numA(2,4); cardAS = numA(2,6); cardAW = numA(2,8);
    cardA = numA(1,2); cardT = numT(1,2); cardL = numL(1,2); %filter cardinalities
% from data
    if(numP(1,1)==0)
        cardP=0;
    else
        cardP = numP(1,2);
    end
    s=size(numZ); cardZ = s(1,1);
    s=size(numR); cardR = s(1,1);
    s=size(numIW); cardIW = s(1,1);
    s=size(numIO); cardIO = s(1,1);
    s=size(numMC); cardMC = s(1,1);
    s=size(numPC); cardPC = s(1,1);
    cardIR=cardR; cardIS=cardZ;
    cardI=cardIW+cardIR+cardIO+cardIS;
%startnumbers: the index of the first activity or object of a specific kind
    sAO=1; sIO=1;
    sAR=sAO+cardAO; sIR=sIO+cardIO;
    sAS=sAR+cardAR; sIS=sIR+cardIR;
    sAW=sAS+cardAS; sIW=sIS+cardIS;
%check
    if(cardA~=cardAW+cardAR+cardAO+cardAS)
        cardA='wrong'
    end
    if(cardI~=sIW+cardIW-1)
        cardI = 'wrong'
    end
    if(cardA~=sAW+cardAW-1)
        cardA='wrong2'
    end
    end

%y_max: maximaal aantal activiteiten per tijdsmoment
    ymax=num0(2,1);

%d_l: duration of TVP of length l
    for l=1:cardL
        d(l)=numL(l+3,2);
    end

%b_a: the minimal length of a TVP for activity a
%f_a: frequency of activity a
%mi_a/ma_a: minimal/maximal interval between two sequential performances of
%activity a on an object i
%n_a: maximum number of units performed in one hour
%dnw_a: requirements for the activities for time moments
    for a=1:cardA
        b(a)=numA(a+3,8);
        %check
        if b(a)>max(d)

```

```

        'error: there is an activity which needs more time than the
maximal TVP-length'
        end
        f(a)=numA(a+3,7);
        mi(a)=numA(a+3,9);
        ma(a)=numA(a+3,10);
        n(a)=numA(a+3,11);
        dnw(a)=txtA(a+3,6);
    end

%k_i: the objectnumber of the switch which is connected with switch i,
% 0 if not connected
    for i=sIW:sIW+cardIW-1
        k(i)=numIW(i-sIW+1,81);
    end
%lrs_i = the size of the objects in case of rijdraad and spoor
    for i=sIR:sIR+cardIR-1
        lrs(i)=numR(i-sIR+1,5);
    end
    for i=sIS:sIS+cardIS-1
        lrs(i)=numZ(i-sIS+1,6);
    end

%s_p: size/length of project p
%cpi_p: costs of project p
%ed_p: earliest start moment
%dd_p: due date
    for p=1:cardP
        ss(p)=numP(p+3,4);
        cpi(p)=numP(p+3,5);
        ed(p)=numP(p+3,6);
        dd(p)=numP(p+3,7);
    end

%cai_ai: activity a concerns infra object i?
    cai=zeros(cardA,cardT,cardI);
    cai(sA0:sA0+cardA0-1,sI0:sI0+cardI0-1)=ones(cardA0,cardI0);%set c(a,i)=1
%for all combinations a=overweg and i=overweg
    cai(sAR:sAR+cardAR-1,sIR:sIR+cardIR-1)=ones(cardAR,cardIR);%set c(a,i)=1
%for all combinations a=rijdraad and i=rijdraad
    cai(sAS:sAS+cardAS-1,sIS:sIS+cardIS-1)=ones(cardAS,cardIS);%set c(a,i)=1
%for all combinations a=spoor and i=spoor
    cai(sAW:sAW+cardAW-1,sIW:sIW+cardIW-1)=ones(cardAW,cardIW);%set c(a,i)=1
%for all combinations a=wissel and i=wissel

%czi_zi: infra object - work zone combinations
    czi=zeros(cardZ,cardI);
    for z=1:cardZ
        for i=sI0:sI0+cardI0-1
            if strcmpi(txtI0(i+1,2),txtZ(z+1,3))==1
                czi(z,i)=1;
            end
        end
    end
    for i=sIR:sIR+cardIR-1
        if numZ(z,4)==numR(i-sIR+1,2)
            czi(z,i)=1;
        end
    end

```

```

        end
        if numZ(z,5)==numR(i-sIR+1,2)
            czi(z,i)=1;
        end
        if numZ(z,6)==numR(i-sIR+1,2)
            czi(z,i)=1;
        end
        if numZ(z,7)==numR(i-sIR+1,2)
            czi(z,i)=1;
        end
        end
        for i=sIW:sIW+cardIW-1
            if strcmpi(txtIW(i+2-sIW,2),txtZ(z+1,3))==1
                czi(z,i)=1;
            end
        end
        end
        czi(1:cardZ,sIS:sIS+cardIS-1)=eye(cardIS);

%czp_zp: project-zone combinations
czp=zeros(cardZ,cardP);
s=size(txtP);
maz=s(1,2)-7;%max aantal zones
for zz=1:maz
    for p=1:cardP
        for z=1:cardZ
            if strcmpi(txtP(p+3,7+zz),txtZ(z+1,3))==1
                czp(z,p)=1;
            end
        end
    end
end
end

%czr_zr: workzone-catenary group combinations
for z=1:cardZ
    for r=1:cardR
        if numZ(z,4)==numR(r,2)
            czr(z,r)=1;
        else
            czr(z,r)=0;
        end
    end
end
end

%czz_zz: workzone-combinations which cause total block with combined
%TVP's
czz=zeros(cardZ);
for z=1:cardZ
    for zz=z:cardZ
        if strcmpi(txtZ(zz+1,3),txtZ(z+1,8))==1;
            czz(z,zz)=1;
            czz(zz,z)=1;
        end
        if strcmpi(txtZ(zz+1,3),txtZ(z+1,9))==1;
            czz(z,zz)=1;
            czz(zz,z)=1;
        end
    end
end

```



```

        end
        if strcmpi(txtZ(zz+1,3),txtZ(z+1,10))==1;
            czz(z,zz)=1;
            czz(zz,z)=1;
        end
    end
end

%caa_aaa: combination possibilities between the maintenance activities
caa=eye(cardA);
[nr,nc]=size(numA);
starta=nr-cardA;
startaa=nc-cardA;
for a=1:cardA
    for aa=1:cardA
        if a~=aa
            caa(a,aa)=numA(starta+a,startaa+aa);
        end
    end
end

%h_ai: if c_ai=1, when was the last time that activity a was performed on i
s=size(numIO); first_hIO=s(1,2)-cardA0+1;
for a=1:cardA0
    for i=1:cardIO
        h(sA0+a-1,sIO-1+i)=numIO(i,first_hIO+a-1);
    end
end
s=size(numR); first_hIR=s(1,2)-cardAR+1;
for a=1:cardAR
    for i=1:cardIR
        h(sAR+a-1,sIR+i-1)=numR(i,first_hIR+a-1);
    end
end
s=size(numZ); first_hIS=s(1,2)-cardAS+1;
for a=1:cardAS
    for i=1:cardIS
        h(sAS+a-1,sIS-1+i)=numZ(i,first_hIS+a-1);
    end
end
s=size(numIW); first_hIW=s(1,2)-cardAW+1;
for a=1:cardAW
    for i=1:cardIW
        h(sAW+a-1,sIW-1+i)=numIW(i,first_hIW+a-1);
    end
end

%time properties
for t=1:cardT
    if numT(t+3,4)==0
        td(t)=1;
        tn(t)=0;
    else
        td(t)=0;
        tn(t)=1;
    end
end

```

```

        if numT(t+3,5)==1
            tw(t)=1;
        else
            tw(t)=0;
        end
    end

%costs
%possession costs for simple TVP
for t=1:cardT
    if tn(t)==1
        pc(t)=numPC(2,2);
    else
        if tw(t)==1
            pc(t)=numPC(2,3);
        else
            pc(t)=numPC(2,1);
        end
    end
end

%possession costs for totale blokkade
for t=1:cardT
    if tn(t)==1
        ppc(t)=numPC(1,2)-2*numPC(2,2);
    else
        if tw(t)==1
            ppc(t)=numPC(1,3)-2*numPC(2,3);
        else
            ppc(t)=numPC(1,1)-2*numPC(2,1);
        end
    end
end

%maintenance costs
for a=1:cardA
    for t=1:cardT
        if tn(t)==1
            mc(a,t)=numA(a+3,13);
        elseif tw(t)==1
            mc(a,t)=numA(a+3,14);
        else
            mc(a,t)=numA(a+3,12);
        end
    end
end

%timemomentfilter f
for t=1:cardT
    filter(t)=numT(t+3,6);
end

% filter for pi(p,t)
pfilter=zeros(cardP,cardT);
for p=1:cardP
    for t=1:cardT-ss(p)+1
        if filter(t+ss(p)-1)==1 & filter(t)==1 & t>ed(p)/timestep &
t<dd(p)/timestep
            pfilter(p,t)=1;
        end
    end
end

```

```

        end
    end
end

status = 'parameters are read'

%used matrix
used = zeros(cardA,cardT,cardI);

%writing .lp-file
lptitle = strcat(name, '.lp');%adding .lp extension to lp title
lp = fopen(lptitle,'w'); %open .lp file

%objectfunction
fprintf(lp, 'Minimize\r\nobj: '); %create first lines
for z = 1:cardZ
    for t=1:cardT
        if filter(t)==1
            for l=1:cardL
                fprintf(lp,' + %d x_%d_%d_%d ',d(l)*pc(t),z,t,l);
            end
        end
    end
end
for z=1:cardZ
    for t=1:cardT
        if filter(t)==1
            for zz=z+1:cardZ
                if czz(z,zz)==1
                    fprintf(lp,' + %d s_%d_%d_%d% ',ppc(t),z,zz,t);%kosten
                end
            end
        end
    end
end
end
for a = 1:cardA
    for t = 1:cardT
        if filter(t)==1
            if isnan(mc(a,t))==0
                for i = 1:cardI
                    if cai(a,i)==1
                        fprintf(lp, ' + %d y_%d_%d_%d ',mc(a,t),a,t,i);
                        used(a,t,i)=1;
                    end
                end
            end
        end
    end
end
end
for p=1:cardP
    for t=1:cardT
        if pfilter(p,t)==1
            fprintf(lp, ' + %d p_0_%d_%d ',cpi(p),p,t);
        end
    end
end
end

```



```

        end
    end
status = 'first and maximum interval is written'

%combination possibilities
for t=1:cardT
    if filter(t)==1
        for z=1:cardZ
            for i=1:cardI
                for ii=1:cardI
                    if czi(z,i)==1 & czi(z,ii)==1
                        for a=1:cardA
                            for aa=a+1:cardA
                                if caa(a,aa)==0
                                    fprintf(lp,'con_comb_%d_%d_%d_%d_%d_%d:
+ y_%d_%d_%d + y_%d_%d_%d <= 1\r\n',a,aa,z,t,i,ii,a,t,i,aa,t,ii);
                                end
                            end
                        end
                    end
                end
            end
        end
    end
end
status= 'combinations is written'

%number of overwegen en wissels constrictions
for a=1:cardA
    if a<=cardA0 | a>=sAW
        for t=1:cardT
            if filter(t)==1
                for z=1:cardZ
                    fprintf(lp,'con_number_%d_%d_%d: ',a,z,t);
                    for l=1:cardL
                        fprintf(lp,'+ %d x_%d_%d_%d ',floor(n(a)*d(l)),z,t,l);
                    end
                    for i=1:cardI
                        if czi(z,i)==1
                            fprintf(lp,'- y_%d_%d_%d ',a,t,i);
                        end
                    end
                    fprintf(lp,'>= 0 \r\n');
                end
            end
        end
    end
end
status='numbers is written'

%y_max
for t=1:cardT
    if filter(t)==1
        fprintf(lp,'con_ymax_%d: ',t);
        for a=1:cardA
            for i=1:cardI

```

```

        if cai(a,i)==1
            fprintf(lp,'+ y_%d_%d_%d ',a,t,i);
        end
    end
end
end
fprintf(lp, '<= %d\r\n',ymax);
end
end

%sigma
for z=1:cardZ
    for t=1:cardT
        if filter(t)==1
            for zz=z+1:cardZ
                if czz(z,zz)==1
                    fprintf(lp,'con_sigma1_%d_%d_%d: ',z,zz,t);
                    fprintf(lp,' - s_%d_%d_%d ',z,zz,t);
                    for l=1:cardL
                        fprintf(lp,'+ x_%d_%d_%d + x_%d_%d_%d ',z,t,l,zz,t,l);
                    end
                    fprintf(lp,'<= 1 \r\n');
                end
            end
        end
    end
end
end
status='sigmas are written'

%possession for projects
for p=1:cardP
    for t=1:cardT
        if pfilter(p,t)==1
            for z=1:cardZ
                if czp(z,p)==1
                    for u=0:ss(p)-1
                        fprintf(lp, 'con_posproj_%d_%d_%d_%d: + p_0_%d_%d - x_%d_%d_%d
<= 0\r\n',p,z,t,u,p,t,z,t+u,1);
                    end
                end
            end
        end
    end
end
end
status='possession for projects is written'

%one project
for p=1:cardP
    fprintf(lp,'con_1proj_%d: ',p);
    for t=1:cardT
        if pfilter(p,t)==1
            fprintf(lp,'+ p_0_%d_%d ',p,t);
        end
    end
    fprintf(lp, '= 1\r\n');
end
status = '1 project is written'

```

```

%R-beurten - speciaal geval
for a=cardA-2:cardA
    for t=1:cardT
        if filter(t)==1
            for i=1:cardI
                if cai(a,i)==1
                    fprintf(lp,'con_R_%d_%d_%d: + y_%d_%d_%d - y_%d_%d_%d
<= 0\r\n',a,t,i,a,t,i,a-1,t,i);
                end
            end
        end
    end
end
end
status='R-beurten are written'

%bounds
fprintf(lp,'Bounds\r\n');
for a=1:cardA
    if strcmpi(dnw(a),'D')==1
        for t=1:cardT
            if filter(t)==1
                if td(t)==0
                    for i=1:cardI
                        if cai(a,i)==1
                            if used(a,t,i)==1
                                fprintf(lp,' y_%d_%d_%d = 0\r\n',a,t,i);
                            end
                        end
                    end
                end
            end
        end
    end
end
if strcmpi(dnw(a),'N')==1
    for t=1:cardT
        if filter(t)==1
            if tn(t)==0
                for i=1:cardI
                    if cai(a,i)==1
                        if used(a,t,i)==1
                            fprintf(lp,' y_%d_%d_%d = 0\r\n',a,t,i);
                        end
                    end
                end
            end
        end
    end
end
if strcmpi(dnw(a),'W')==1
    for t=1:cardT
        if filter(t)==1
            if tw(t)==0
                for i=1:cardI
                    if cai(a,i)==1
                        if used(a,t,i)==1

```



```

        end
status = 'binary pi is written'

        fprintf(lp, '\r\n');

        fprintf(lp, 'End\r\n'); %create last line
        fclose(lp); %close .lp file

status = 'done'

toc

```

D.2 Sol_to_excel.m

```

%This file translates the output .sol-file from Gurobi to two .xls-files
%that contain a list with TVPs and the scheduled maintenance activities
%and a matrix that gives an overview of the TVP planning

```

```

clc %Clear everything done before
clear %Clear everything done before

```

```

%easy to change input

```

```

    name = 'hoorn_scenarioA'; %name of .lp file to create
    %names of sheets to read
    sheetA = 'Activiteiten';
    sheetR = 'Bvl-groepen';
    sheetZ = 'Werkzones';
    sheetT = 'Tijdsmomenten';
    sheetL = 'TVP-lengte';
    sheetIW = 'Wissel';
    sheetPC='Bezettingskosten';
    sheetMC='Onderhoudskosten';
    sheetIO = 'Bevloering';
    sheetO = 'Overig';
    sheetP='Projecten';

```

```

status = 'start is made'

```

```

%reading xls.file

```

```

    inputtitle = strcat(name, '_input.xlsx');
    [numA,txtA,rawA] = xlsread(inputtitle, sheetA);
    [numT,txtT,rawT] = xlsread(inputtitle, sheetT);
    [numL,txtL,rawL] = xlsread(inputtitle, sheetL);
    [numIW,txtIW,rawIW] = xlsread(inputtitle, sheetIW);
    [numIO,txtIO,rawIO] = xlsread(inputtitle, sheetIO);
    [numZ,txtZ,rawZ] = xlsread(inputtitle, sheetZ);
    [numR,txtR,rawR] = xlsread(inputtitle, sheetR);
    [numO,txtO,rawO] = xlsread(inputtitle, sheetO);
    [numPC,txtPC,rawPC] = xlsread(inputtitle, sheetPC);
    [numMC,txtMC,rawMC] = xlsread(inputtitle, sheetMC);
    [numP,txtP,rawP] = xlsread(inputtitle, sheetP);

```

```

%reading the .sol-file: the first line (with the objective) has to be
%removed so that all lines are of the form
%character_double_double_double double

```

```

sol = fopen(strcat(name, '.sol')); %open sol-file
C = textscan(sol, '%c %c %d %c %d %c %d %d'); %read sol-file
fclose(sol); %close sol-file
sizeC = size(C{1});
n=sizeC(1,1); %number of readed lines

status = 'file is read'
%cardinalities
cardAO = numA(2,2); cardAR = numA(2,4); cardAS = numA(2,6);
cardAW = numA(2,8); cardA = numA(1,2); cardT = numT(1,2);
cardL = numL(1,2); %filter cardinalities from data
    if(numP(1,1)==0)
        cardP=0;
    else
        cardP = numP(1,2);
    end
s=size(numZ); cardZ = s(1,1);
s=size(numR); cardR = s(1,1);
s=size(numIW); cardIW = s(1,1);
s=size(numIO); cardIO = s(1,1);
s=size(numMC); cardMC = s(1,1);
s=size(numPC); cardPC = s(1,1);
cardIR=cardR; cardIS=cardZ;
cardI=cardIW+cardIR+cardIO+cardIS;
%startnumbers: the index of the first activity or object of a specific kind
sAO=1; sIO=1;
sAR=sAO+cardAO; sIR=sIO+cardIO;
sAS=sAR+cardAR; sIS=sIR+cardIR;
sAW=sAS+cardAS; sIW=sIS+cardIS;

%combination sets
%czi_zi: infra object - work zone combinations
czi=zeros(cardZ,cardI);
for z=1:cardZ
    for i=sIO:sIO+cardIO-1
        if strcmpi(txtIO(i+1,2),txtZ(z+1,3))==1
            czi(z,i)=1;
        end
    end
    for i=sIR:sIR+cardIR-1
        if numZ(z,4)==numR(i-sIR+1,2)
            czi(z,i)=1;
        end
    end
    for i=sIW:sIW+cardIW-1
        if strcmpi(txtIW(i+2-sIW,2),txtZ(z+1,3))==1
            czi(z,i)=1;
        end
    end
end
czi(1:cardZ,sIS:sIS+cardIS-1)=eye(cardIS);

%making the TVP planning
titles = {'TVP_id', 'Work zone', 'Week', 'Day', 'TVP_length', 'Activities'};
excel=strcat(name, '_planning.xls');
schema=strcat(name, '_schema.xls');

```

```

xlswrite(excel,titles);
row=2;
id=1;
tvptimes=[];
actsatt=[];

for i=1:n
    if C{8}(i)==1
        if C{1}(i)=='x'
            startcell=strcat('A',int2str(row));
            z=char(txtZ(C{3}(i)+1,3));
            weeknr=numT(C{5}(i)+3,2);
            weekdag=char(txtT(C{5}(i)+3,3));
            l=numL(C{7}(i)+3,2);
            output={id,z,weeknr,weekdag,l};
            xlswrite(excel,output,1,startcell);
            tvptimes(id)=C{5}(i);
            tvpzone(id)=C{3}(i);
            actsatt(id)=1;
            id=id+1;
            row=row+1;
            invulling(C{3}(i),C{5}(i))=1;
        end
        sizeT=size(tvptimes);
        m=sizeT(1,2);
        if C{1}(i)=='y'
            for j=1:m
                if(C{5}(i)==tvptimes(j))
                    if czi(tvpzone(j),C{7}(i))==1
                        i
                        objectnumber=C{7}(i);
                        if objectnumber <=cardIO
                            object=char(txtIO(objectnumber+1,14));
                        elseif objectnumber > cardIO &
objectnumber <= cardIO+cardIR
                            object=char(strcat('rijdraad bvl-groep ',
int2str(numR(objectnumber-cardIO,2))));
                        elseif objectnumber > cardIO+cardIR & objectnumber
<= cardIO+cardIR+cardIS
                            object=char(strcat('spoor werkzone ',
txtZ(objectnumber-cardIO-cardIR+1,3)));
                        elseif objectnumber > cardIO+cardIR+cardIS
                            object=char(txtIW(objectnumber-cardIO-cardIR-cardIS+1,16));
                        end
                        act(j,actsatt(j)) = {strcat(' (Act: ',char(txtA(C{3}(i)+3,2)),
',Obj: ',object,')')};
                        actsatt(j)=actsatt(j)+1;
                    end
                end
            end
        end
        if C{1}(i)=='p'
            for j=1:m
                if(C{7}(i)==tvptimes(j))
                    projectnumber=C{5}(i);
                    ss=numP(projectnumber+3,4);

```

```
        project=char(strcat('project: ',txtP(projectnumber+3,2)));
        for u=0:ss-1
            act(j+u,actsatt(j+u))= {project};
            actsatt(j+u)=actsatt(j+u)+1;
        end
    end
end
end
end
matrix = strcat('F',int2str(2));
xlswrite(excel,act,1,matrix);
xlswrite(schema,invulling.',1,'D3');
```


Appendix E

Using Gurobi

This appendix gives the Python code `lp_to_sol.py` which is used to call Gurobi that optimizes the problem formulated in the LP-file.

```
# Copyright 2010, Gurobi Optimization, Inc.

# This example reads a MIP model from a file, solves it and
# writes the solution in a solution file

import sys
from gurobipy import *

if len(sys.argv) < 4:
    print 'Usage: mip2.py inputfilename timelimit solutionfilename'
    quit()

# Read and solve model

model = read(sys.argv[1])

if model.IsMIP == 0:
    print 'Model is not a MIP'
    exit(0)

model.Params.TimeLimit = int(sys.argv[2])
model.optimize()
model.write(sys.argv[3])

if model.Status == GRB.Status.OPTIMAL:
    print 'Optimal objective:', model.ObjVal
elif model.Status == GRB.Status.INF_OR_UNBD:
    print 'Model is infeasible or unbounded'
    exit(0)
elif model.Status == GRB.Status.INFEASIBLE:
    print 'Model is infeasible'
    exit(0)
elif model.Status == GRB.Status.UNBOUNDED:
    print 'Model is unbounded'
    exit(0)
else:
    print 'Optimization ended with status', model.Status
    exit(0)
```


Appendix F

24 TVP plannings

This appendix gives all 24 TVP plannings, alphabetically from A to X.

Horn scenario A		Werkzone	b626 y35	b626 w35	c626 t43	c626 p51	b626 n32	b626 n38	b626 t52	c626 w44	c626 y46	b626 p33	b626 y37	c626 n41	c626 t47	b626 n40	c626 x45	b626 t39	b626 n42	0	Weeksom	13-weeksom			
Q	Week	Dag																							
		1	di/wo	6			6					6						6				6	18	84	
		1	wo/do									6										6	6		
		1	za			6	6															6	6		
		2	di/wo			6				6	6			6	6			6			6	6	6		
		5	di/wo				6					6											6		6
		6	di/wo			6						6				6		6			6	6	6		12
		6	za/zo															6			6	6	6		6
		7	za/zo				6				6												6		12
		8	zo	6	6	6																	6		6
		10	di/wo	6				6															6		6
		10	za/zo										6			6		6					6		12
		12	di/wo	6				6					6									3	6		12
		12	wo/do			6					6	6	6		6								6		6
		15	di/wo			6					6	3		6	6	3							6		6
		16	wo/do				6					6											6		12
		17	za										6	6	6								6		6
		17	di/wo			3						3					3						3		3
		18	za/zo			3																	3		9
		18	zo						6	6	6	6											6		6
		19	di/wo													3		3				6	6		60
		21	di/wo								3												3		3
		23	di/wo	3								3											3		9
		23	wo/do										6			3		3					6		6
		24	za/zo			6					6	6			3								6		6
		25	di/wo	6				6															6		6
		27	za					6	6				6										6		6
		28	di/wo			3	3					3	3			3	3						3		3
		30	wo/do			3						3											3		3
		32	di/wo													3		3				3	6		42
		32	za/zo																				3		3
		34	wo/do	6				6								3		6			6	6	9		9
		34	za/zo										3										3		3
		36	wo/do								6				6								6		6
		38	wo/do					3	3				3										3		3
		39	zo										6			6	6	6	6	6	6	6	6		6
		40	wo/do										6										6		6
		41	di/wo			6	3					3	3			3	3						6		6
		43	za/zo																				3		3
		45	di/wo													6		6				3	6		6
		46	wo/do	3																			3		3
		47	di/wo										3										3		3
		48	di/wo								6				6								6		12
		48	za/zo	6				6															6		6
		Total hours		48	6	66	24	51	30	6	60	48	63	12	45	54	6	60	6	42			225		
		Number		9	1	13	5	10	7	1	12	10	12	2	9	13	1	12	1	8			44		

Figure F.1: TVP planning Hoorn Scenario A

Hoorn scenario B		Werkloze	b626 y35	b626 w35	c626 h43	c626 p51	b626 n32	b626 h38	b626 t52	c626 w44	c626 v46	b626 p33	b626 y37	c626 n41	c626 h47	b626 m40	c626 v45	b626 p39	b626 n42	0	Weeksom	13-weeksom		
Q	Week	Dag																						
1	1	di/wo	6				6														6	12	120	
	1	za/zo			6					6				6			6			6	6			6
	1	di/wo				6				6	6	3		6		3	3	3	3	3	6			6
	2	wo/do	6				6						6											6
	2	za			6	6																		6
	2	za/zo										6												6
	4	di/wo				6					6				6									6
	4	wo/do										6												6
	6	wo/do			6	6				6	6										6			6
	6	za/zo							6							6								6
	7	wo/do											3	3	6		6							6
	1	8	di/wo					6																6
1		wo/do			6				6	6				6		6				6	6			
1		di/wo	6				6					6				6					6	6		
1		zo									6					6	6	6	6	6	6	6		
11		wo/do			6					6	6				6		6			6	6	6		
12		za/zo						6														6		
12		di/wo			3					3	3	3	3	3	3	3						3		
13		wo/do	3				3					6										6		
13		za/zo	6				6															6		
14		di/wo													6		6				3	6		
15		di/wo				3						3										3		
15		wo/do										3										3		
17	di/wo			6					6	3			6	3							6			
18	za									6											6			
19	di/wo			3					3					3		3				3	3			
2	20	za/zo						3													6	63		
	2	wo/do															6				6			
	23	di/wo	3				3																3	
	23	wo/do									6												6	
	24	di/wo			6					6	6			3	6								6	
	24	wo/do	3				3																6	
	25	di/wo																			6		6	
	26	di/wo										3											3	
	27	di/wo															3				3		3	
	27	za/zo	6			6	6				6												6	
	28	di/wo				6					6												6	
	28	za					6	6	6	6	6	6	6										6	
3	29	za/zo		6																		6		
	30	di/wo			3	3				3	3				3		3				3	3		
	31	wo/do						3														3		
	33	zo											6	6	6							6		
	33	di/wo	3				3															6		
	35	za/zo													6							6		
	35	zo	6																			6		
	37	di/wo			6					6	3			3	6							6		
	37	za/zo															6					6		
	39	di/wo										6										6		
	40	di/wo															6				3	6		
	41	di/wo			6	3				6	3			6	3		6				6	6		
42	di/wo						6														6			
43	za/zo											6									6			
44	di/wo	6				6															6			
4	45	za/zo										6										6		
	46	za/zo	3	3	3																	3		
	46	zo	6	6	6																	6		
	47	wo/do	3				3															3		
	48	wo/do			3					3	6			3	6							6		
	48	di/wo									3											3		
		Total hours	66	15	75	45	60	33	15	75	84	69	15	51	66	15	66	15	60			312		
		Number	14	3	15	9	13	7	3	15	17	14	3	11	13	3	13	3	13				60	

Figure F.2: TVP planning Hoorn Scenario B

Hoorn scenario C		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456	0	Weeksom	13-weeksom
Q	Week	Dag								
1	1	di/wo					6	6	12	87
		za/zo					6	6		
	2	di/wo	6	6		6		6	6	
		di/wo	6		6			6		
	3	wo/do			6	6		6	18	
		zo	6					6		
	6	di/wo					6	6	18	
		wo/do	6		6	6	6	6		
	8	di/wo	6	6		6		6	6	
		di/wo	6	6				6		
10	za/zo				6	6	6	12		
	di/wo					3	3			
12	za				6		6	9		
	wo/do	6	6		6		6			
13	zo	6					6	6		
	di/wo	6	6	6	3		6			
16	di/wo	6	6	6	3		6	6		
	za/zo	3		3	3	6	6			
17	za		6	6			6	6		
	di/wo	3	3				3			
21	di/wo				6	3	6	6		
	za/zo	6	6	6	3		6			
23	di/wo					3	3	3		
	za/zo	3		3	3	3	3			
24	za		6		6		6	9		
	di/wo	6	6				6			
29	di/wo	6	6				6	12		
	za/zo		3		3	6	6			
34	za/zo	3	3		3		3	3		
	za/zo	6	6		6		6			
35	za/zo	6	6		6		6	6		
	za/zo	3		3	3	6	6			
36	za/zo	3		3	3	6	6	6		
	di/wo					3	3			
40	di/wo					3	3	3		
	za/zo	3	6		6	6	6			
41	za/zo	3			6	6	6	6		
	zo				6	6	6			
46	di/wo					6	6	6		
	za/zo	3	6		6	6	6			
48	di/wo					6	6	6		
	zo					6	6			
		Total hours	90	75	45	93	78	177		
		Number	18	14	9	19	15	32		

Figure F.3: TVP planning Hoorn Scenario C

Hoorn scenario D		Weekzone	hoorn1	hoorn2a	hoorn2b	hoorn3	0	Weeksom	13-weeksom	
Q	Week	Dag								
1	1	wo/do				3	3	3	90	
		za/zo		6		6	6	6		
		zo	6					6		
	2	wo/do	6		6			6		6
		di/wo	6	6	6	6		6		
	3	wo/do	6	6				6		12
		di/wo	6	6				6		
	5	wo/do			6	6	6	6		12
		di/wo	6		6			6		
	6	wo/do				6	6	6		12
		di/wo	6		6			6		
	7	di/wo	3					3		3
		za/zo		6		6	6	6		6
	10	di/wo	6	6				6		6
di/wo		6	6	6	6	6	6	6		
11	za/zo				6		6	12		
	za				6	6	6	6		
14	di/wo					3	3	9		
	zo			6			6			
15	di/wo	6	6	3			6	9		
	wo/do		3	3	3		3			
16	di/wo	6	6	6	3	3	6	6		
	wo/do	3		3			3	3		
21	di/wo	3					3	3		
	di/wo				6	3	6	6		
22	wo/do	6	6	6	6	6	6	15		
	za/zo				3		3	6		
26	za		6	6	6		6	6		
	di/wo				3	3	3	3		
28	di/wo	3	3	3	3		3	3		
	za/zo	6	6	6	3	6	6	6		
33	za	6					6	6		
	za/zo					3	3	15		
34	zo				6		6	6		
	di/wo	3	3	3	6	6	6	6		
40	za/zo	3					3	9		
	di/wo	6	6				6	6		
44	za	6					6	6		
	di/wo	6	6	6	6		6	6		
45	za/zo				3	6	6	12		
Total hours			114	93	81	108	78	201		
Number			22	17	16	22	16	39		

Figure F.4: TVP planning Hoorn Scenario D

Hoorn scenario E		Werkzone	b626 v55	b626 w35	c626 t43	c626 p51	b626 n92	b626 h38	b626 t52	c626 w44	c626 v46	b626 p33	b626 v37	c626 n41	c626 h47	b626 m40	c626 x45	b626 p39	b626 p42	0	Weeksom	13-weeksom		
Q	Week	Dag																						
1	1	di/wo	6			6					6					6				6	6	12	96	
		wo/do									6					6				6	6	6		
	2	di/wo		12					6	12			6	12		6		6				12		18
		zo	6	6	6	6																6		6
	5	di/wo				6					6											6		6
	6	wo/do			6						6				6		6		6			6		6
	7	wo/do					6									6		6				6		6
		za/zo			6				6													6		6
	10	di/wo	6				6															6		6
		za/zo									6			6		6		6				6		6
	11	di/wo										6										6		6
		wo/do										6										6		6
	12	di/wo	6				6															6		6
		wo/do									6											6		6
	13	di/wo			6				6				6									6		6
15	di/wo			6				6	3			6	6	3							6	6		
	zo										6	6	6								6	6		
	di/wo	12	12			6				6											12	12		
16	wo	12	12																		12	12		
	wo/do	12	12			6															12	12		
	zo						6	6	6	6											6	6		
2	17	di/wo			3					3				3							3	3		
	di/wo			3						3				3			3				6	6		
	za/zo						3														3	3		
23	di/wo	3					3					6									6	6		
	wo/do													3		3					3	3		
25	di/wo			6				6	6				3		3						6	6		
28	di/wo			3	3				3	3			3	3							3	3		
	di/wo										6										6	6		
	wo/do			3					3												3	3		
32	di/wo													3		3					3	3		
	wo/do																				3	3		
33	za					6	6				6										6	6		
34	wo/do	6				6								3		6		6			6	6		
35	di/wo					3	3				3										3	3		
	di/wo										3										3	3		
36	za/zo	6				6															6	6		
37	wo/do									6			6								6	6		
41	di/wo			6	3				3	3			3	3							6	6		
43	wo/do							3													3	3		
45	di/wo													6		6					6	6		
46	za										6				6	6	6	6	6		6	6		
47	di/wo	3				3															3	3		
	di/wo									6			6								6	6		
48	za/zo										3										3	3		
		Total hours	78	42	66	24	51	30	6	60	54	63	12	45	60	6	60	6	42		258			
		Number	11	4	12	5	10	7	1	12	10	12	2	9	13	1	12	1	8		45			

Figure F.5: TVP planning Hoorn Scenario E

Hoorn scenario F		Werkzone	b626 p55	b626 w35	c626 d43	c626 d51	b626 p32	b626 b38	b626 p57	c626 w44	b626 y46	b626 p33	b626 p37	c626 r41	b626 r47	c626 m40	b626 y45	b626 p39	b626 p42	0	Weeksom	13-weeksom				
Q	Week	Dag																								
1	1	di/wo							6		6		6								6	12	129			
		za/zo																				6		6		
	2	di/wo			6						6	3				3	3	3	3			6		12		
		wo/do	6			6																		6	6	
	3	di/wo		6	6	6				6	6			6										6	18	
		za/zo	6				6																		6	6
	4	di/wo				6					6				6										6	12
		wo/do										6				6									6	6
	5	za/zo										6													6	6
	6	di/wo										3												3	9	
		wo/do			6					6	6											6			6	6
	7	di/wo											3	3	6	6	6								6	6
	wo/do						6							6		6							6	6		
8	di/wo						6																6	6		
	wo/do							6															6	6		
9	di/wo	6				6																	6	6		
	wo/do																						6	6		
10	di/wo		6																				6	12		
	wo/do				6				6														6	6		
11	za/zo			12					6	12				12		6		6				12	18			
12	di/wo							6															6	6		
	di/wo										6												6	6		
13	di/wo																					3	3	3		
	wo/do	3																					3	3		
14	za/zo										6				6	6	6	6					3	15		
	di/wo				3					3	3		3	6		6							6	15		
	wo/do										3												3	15		
15	za/zo			6					6				6										6	6		
16	di/wo									6	3												6	6		
	wo/do				6																6		3	9		
19	di/wo					3	3	3	3	3	3												6	9		
	wo/do																						3	9		
20	di/wo																					6	6	9		
	wo/do																						3	3		
22	di/wo				3					3	3			3									3	3		
	wo/do	12	12			3																	12	12		
23	za/zo																						12	36		
	di/wo																						12	12		
25	wo/do				3	3																6	6	9		
	di/wo										3												3	3		
26	wo/do																						6	15		
	za/zo					6	6	6	6	6	6												6	6		
27	di/wo																					3	3	3		
	wo/do	6				6																	6	9		
28	di/wo				6	6				3	6			3	3								6	12		
	zo	6																					6	6		
30	di/wo														3		3					3	3	3		
	wo/do																						3	3		
34	di/wo				3						3	3					6						6	6		
	di/wo	3				3																	3	3		
37	za/zo															6	6	6					6	6		
39	di/wo										6												6	6		
	di/wo	3				3																	6	6		
40	za/zo				6					6				6		6							6	12		
	di/wo				6	3				6	3		3	3		6						3	6	6		
42	di/wo								6														6	6		
	za/zo	6				6																	6	18		
43	zo	6	6	6																			6	6		
	za/zo													6									6	6		
44	wo/do										6												6	6		
	wo/do																						6	6		
45	di/wo					3					3	6				6							6	6		
	wo/do	3	3	3																			3	3		
46	di/wo																						3	3		
52	di/wo																						3	3		
		Total hours	93	45	87	45	60	33	15	78	87	69	15	48	72	15	69	15	60			360				
		Number	15	5	16	9	13	7	3	16	17	14	3	10	13	3	14	3	13			64				

Figure F.6: TVP planning Hoorn Scenario F

Hoorn scenario G		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456	0	Weeksom	13-weeksom
Q	Week	Dag								
1	1	di/wo					6	6	12	75
		za/zo					6	6		
	2	di/wo	6	6		6	6	6	6	
		di/wo	12		12	12		12		
	3	wo/do	6		6	6	6	6	6	
		za	6					6		
	6	za/zo					6	6	6	
		di/wo	6	6		6		6		
	8	di/wo	6	6		6		6	6	
		di/wo	6	6				6		
	10	za/zo				6	6	6	6	
		di/wo					3	3		
	12	di/wo							6	
wo/do		6	6		6		6			
13	di/wo	12	6	6	6	3		12		
	wo	12					12		42	
16	wo/do	12					12	6		
	za		6	6			6			
2	17	za				6	6	12		
		za/zo	3		3	3	6		6	
	21	di/wo	3	3				3	3	
23	di/wo				6	3	6	6		
	za/zo	6	6	6	3		6			
3	29	di/wo	3		3	3	3	3	3	
		zo		6		6		6		
	34	di/wo	6	6				6	6	
		za/zo	3	3		3	6	6		
36	di/wo	6	6		6		6	6		
	di/wo		3		3		3			
	di/wo	3		3	3	3	3		3	
40	di/wo	3		3	3	3	3	6		
	zo				6	6	6			
4	45	di/wo	3	6		6	6	6	6	
		di/wo					6	6		
	47	di/wo	3	6		6	6	6	6	
50	di/wo					6	6			
Total hours			120	75	45	99	78		195	
Number			19	14	8	19	15		31	

Figure F.7: TVP planning Hoorn Scenario G

Hoorn scenario H		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456				
Q	Week	Dag					0	Weeksom	13-weeksom		
1	1	za/zo		6		6	6	6	93		
		zo	6					6			
	2	di/wo	6	6				6			
		wo						0			
	3	wo/do	6		6	3	3	6			
		wo/do	6	6	6	6		6			
	5	wo/do				6	6	6			
		za/zo	12	6	12	12		#			
	9	di/wo					6	6			
		za/zo		6		6	6	6			
	10	di/wo	6	6	6			6			
		zo			6			6			
	11	di/wo	6	6	6	6	6	6			
		za/zo				6		6			
	12	di/wo	3					3			
		zo				6	6	6			
	14	wo/do					3	3			
		di/wo	6	6	3	3		6			
	16	di/wo		3	3	3	3	3			
		za/zo	3	3	3	3		3			
	22	di/wo	12	6			3	#			
		wo	12					#			
	22	wo/do	12	6	6	6	6	#			
		za/zo			3	3		3			
	23	za/zo	3					3			
		di/wo				6	3	6			
	27	za	6					6			
		za/zo	6	3	6	3		6			
	3	zo		6	6	6		6			
		di/wo				3		3			
	33	za/zo	6	6	3	3	3	6			
		wo/do	3					3			
	38	zo				6		6			
		di/wo	3	3	3	6	6	6			
	41	di/wo	6	6			6	6			
		di/wo	6	6	6	6		6			
	4	45	za/zo			3	6	6			
		48	za	6				6			
	Total hours			141	96	84	117	78		222	
	Number			22	18	16	23	16		37	

Figure F.8: TVP planning Hoorn Scenario H

Hoorn scenario I		Werkzone	b626 v85	b626 w35	c626 t43	c626 p31	b626 n32	b626 h38	b626 t37	c626 w44	c626 v46	b626 p33	b626 v37	c626 n41	c626 h47	b626 m40	c626 x45	b626 l39	b626 p42	Q	Week	Dag	Weeksom	13-weeksom		
1	1	di/wo	7																				7	21	112	
		wo/do																								7
	za			7	7																		7	7		
	3	di/wo																						7		7
		wo/do																						7		7
	5	di/wo																						7		7
		wo/do																						7		7
	6	za/zo																						7		14
		di/wo																						7		7
	8	wo/do																						7		21
		zo																						7		7
	10	di/wo																						7		14
za/zo																							7	7		
11	wo/do																						7	7		
	di/wo																						7	14		
12	za																						7	7		
	di/wo																						7	7		
13	di/wo																						7	7		
	wo/do																						7	14		
16	za/zo																						7	7		
	di/wo																						7	14		
17	wo/do																						7	7		
	za/zo																						7	7		
19	di/wo																						4	4		
	za																						7	7		
20	di/wo																						4	4		
	wo/do																						4	11		
23	za/zo																						7	7		
	di/wo																						7	14		
24	wo/do																						7	7		
	za/zo																						7	14		
27	zo																						7	7		
	di/wo																						4	4		
29	wo/do																						4	4		
	za/zo																						4	4		
31	di/wo																						4	4		
	wo/do																						7	11		
32	za/zo																						4	4		
	di/wo																						7	14		
34	wo/do																						7	7		
	za/zo																						7	11		
35	di/wo																						4	4		
	wo/do																						4	11		
36	za/zo																						7	7		
	di/wo																						4	4		
40	wo/do																						4	4		
	za/zo																						7	14		
42	di/wo																						7	7		
	wo/do																						4	4		
44	za/zo																						4	4		
	di/wo																						4	4		
45	wo/do																						4	4		
	za/zo																						7	7		
46	di/wo																						7	7		
	wo/do																						7	7		
47	za/zo																						4	4		
	di/wo																						4	4		
48	wo/do																						4	4		
	za/zo																						4	4		
Total hours		57	7	79	29	61	37	7	83	54	75	14	50	59	7	76	7	50					279			
Number		9	1	13	5	10	7	1	14	9	12	2	8	11	1	13	1	8					45			

Figure F.9: TVP planning Hoorn Scenario I

Hoorn scenario J		Werkzone	b626 p5	b626 w35	c626 t43	c626 p51	b626 n32	b626 l38	b626 s7	c626 w44	c626 y46	b626 p33	b626 v37	c626 m41	c626 t47	b626 m40	c626 x45	b626 l39	b626 m42	0	Weeksom	13-weeksom			
Q	Week	Dag																							
1	1	di/wo	7			7															7	14	169		
		za/zo																				7			
	2	di/wo	7			7	7				7											7		11	
		wo/do									4				4	4	4	4				4			
	3	di/wo			7					7		7	7											7	14
		za			7	7																		7	
	4	wo/do				7					7	7												7	7
		di/wo										7												7	
	5	wo/do			7	7					7	7			7									7	21
		za/zo			7						7													7	
	6	wo/do																						7	7
		za/zo																						7	
	7	wo/do											4	4	7		7							7	14
		za/zo							7															7	
	8	wo/do													7		7		7					7	14
		za/zo							7															7	
	9	di/wo																						7	
		za																						7	21
		za/zo				7						7					7	7	7	7				7	
	10	di/wo	7				7																	7	7
		wo/do				7					7	7			7		7		7					7	
	11	zo										7												7	14
		di/wo											7											7	
	13	wo/do	4				4																	4	18
		za/zo	7				7																	7	
	14	di/wo															7		7					4	7
		di/wo																						4	
	15	wo/do																						4	8
		di/wo																						4	
	16	wo/do																						4	15
		za/zo																						4	
	17	wo/do																						4	7
		wo/do																						7	7
	18	wo/do																						7	7
		di/wo																						4	4
	19	di/wo																						4	4
		di/wo																						4	4
	20	di/wo																						4	4
		za/zo																						7	7
	21	di/wo																						7	7
		za/zo																						4	4
	22	di/wo																						4	4
		za/zo																						4	4
	24	di/wo																						4	4
		za/zo																						7	7
	26	di/wo																						4	4
		wo/do																						7	7
	27	di/wo																						4	4
		za																						7	11
	28	di/wo																						4	7
	zo																					7	7		
29	di/wo																					4	4		
	wo/do																					7	11		
30	wo/do																					7	7		
	wo/do																					4	4		
31	wo/do																					4	4		
	di/wo																					4	4		
33	di/wo																					4	4		
	di/wo																					4	4		
35	di/wo																					4	4		
	di/wo																					4	4		
39	di/wo																					4	4		
	di/wo																					4	4		
40	di/wo																					4	4		
	zo																					7	14		
41	di/wo																					4	7		
	di/wo																					4	7		
42	di/wo																					7	7		
	za/zo																					7	7		
43	za/zo																					7	7		
	wo/do																					7	7		
44	wo/do																					7	7		
	za/zo																					7	14		
45	di/wo																					7	7		
	di/wo																					4	4		
46	di/wo																					4	4		
	zo																					7	7		
47	zo																					7	7		
	di/wo																					4	4		
49	di/wo																					4	4		
	wo/do																					4	4		
		Total hours	80	18	101	50	73	40	18	90	97	83	18	58	83	18	79	18	73			397			
		Number	14	3	17	8	13	7	3	15	16	14	3	10	14	3	13	3	13			64			

Figure F.10: TVP planning Hoorn Scenario J

Hoorn scenario K		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456		Weeksom	13-weeksom
Q	Week	Dag								
1	1	wo/do					7	7	7	102
		di/wo	7	7		7		7	14	
	2	wo/do					7	7	14	
		di/wo			7	7		7	14	
	3	wo/do	7		7			7	7	
	5	zo	7					7	7	
		di/wo	7		7	7	7	7	21	
	6	wo/do					7	7	21	
		za/zo					7	7	7	
	8	di/wo	7	7				7	7	
		di/wo	7	7		7		7	14	
	10	za/zo				7	7	7	14	
		di/wo					4	4	11	
	12	za				7		7	11	
	13	wo/do	7	7		7		7	7	
	15	zo	7					7	7	
	di/wo	7	7	7	4		7	14		
16	zo		7	7			7	14		
2	18	di/wo	4		4	4	7	7	7	46
	21	di/wo	4	4				4	4	
	23	wo/do				7	4	7	7	
	25	di/wo	7	7	7	4		7	7	
	28	zo		7		7		7	7	
	29	di/wo	4		4	4	4	4	4	
3	34	di/wo	7	7				7	14	36
		za/zo		4		4	7	7	14	
	36	di/wo	4	4		4		4	11	
		wo/do	7	7		7		7	11	
4	41	wo/do	4		4	4	4	4	4	25
	42	zo				7	7	7	7	
	47	di/wo	4	7		7	7	7	7	
	48	wo/do					7	7	7	
Total hours			108	89	54	112	93	209		
Number			18	14	9	19	15	32		

Figure F.11: TVP planning Hoorn Scenario K

Hoorn scenario L		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456	0	Weeksom	13-weeksom	
Q	Week	Dag									
1	1	di/wo				4	4	4	18	102	
		za	7					7			
	2	za/zo		7			7	7			7
		wo/do	7		7						7
	3	di/wo	7	7							7
		wo/do	7	7	7	7					7
	5	wo/do	7	7							7
		za/zo	7		7	7					7
	6	wo/do				7	7	7			7
		wo/do				7	7	7			7
	9	za/zo						7			7
		di/wo	7	7							7
	11	wo/do	7	7	7						7
		za/zo			7	7					7
13	za				7	7	7	7			
	wo/do		7		7	7	7	7			
14	za/zo	4						4			
	di/wo	7	7	4				7			
15	za/zo		4	4	4	4		4			
	zo			7				7			
16	di/wo	7	7	7	4			7			
	di/wo	4		4	4			4			
19	di/wo				4	4	4	4			
	wo/do	4						4			
22	di/wo				7	7	7	7			
	za/zo	7	7	7	7			7			
26	za		7	7	7			7			
	di/wo					4	4	4			
27	za/zo				4			4			
	di/wo	4	4	4	4			4			
32	di/wo				4	4	4	4			
	za/zo	7	7	7	4			7			
34	di/wo					7	7	7			
	za	7						7			
36	za				7			7			
	di/wo	4	4	4	7	7	7	7			
40	za/zo	7	7					7			
	zo	7						7			
44	di/wo				4	7	7	7			
	wo/do	7	7	7	7			7			
48	di/wo	4						4			
	Total hours		136	110	97	138	86		254		
	Number		22	17	16	24	14		41		

Figure F.12: TVP planning Hoorn Scenario L

Hoorn scenario M		Werkzone	b626 v35	b626 w35	c626 t43	c626 p51	b626 n32	b626 h38	c626 t52	c626 w44	b626 v46	b626 p33	c626 v37	c626 n41	b626 h47	c626 m40	b626 x45	b626 l39	b626 o42	Q	Week	Dag	Weeksom	13-weeksom			
1	1	di/wo	7			7					7				7								7	21	128		
		wo/do									7															7	
	za/zo														7								7				
	2	di/wo							7			7											7			7	
	3	di/wo			7				7	7				7												7	14
		zo	7	7	7	7																				7	
	5	di/wo				7					7															7	7
		di/wo			12						12			12		7		7								12	19
	6	za/zo														7		7								7	19
		di/wo							7																	7	14
	8	wo/do			7				7																	7	14
		di/wo	7				7																			7	21
	10	wo/do									7	7														7	21
		za/zo												7		7										7	7
	11	wo/do									7															7	7
		di/wo	7				7				7															7	11
	12	wo/do																					4			4	11
		di/wo			7				7			7														7	7
	13	di/wo				7			7			7														7	7
		di/wo	12	12	7	7			7	7		7	4													12	12
	16	wo	12	12																						12	36
		wo/do	12	12			7																			12	12
	18	di/wo			4					4			4		4	4		4					7			7	14
		zo										7	7	7												7	14
	19	di/wo			4				4																	4	15
		za/zo						4																		4	15
	23	zo					7	7	7	7																7	7
		di/wo	4				4					7														7	11
	24	wo/do											4		4	4										4	11
		za/zo			7				7	7		4														7	7
	29	di/wo			4	4			4	4			4		4	4		4								4	4
		di/wo			4				4																	4	4
	31	di/wo					4																			4	4
		di/wo									4															4	4
	34	wo/do	7				7						4		4	7		7								7	11
		di/wo					4	4			4															4	11
	35	wo/do									7															7	18
		za					7	7			7															7	18
	36	di/wo							4			4														4	11
		za/zo	7				7																			7	11
	39	zo									7				7	7	7	7								7	7
		za/zo			7	4			4	4			4		4	4	4									7	7
	42	di/wo							7			7														7	7
		wo/do							4																	4	4
	45	za/zo													7		7									7	7
		wo/do	4				4				4															4	4
	47	di/wo							7			7														7	7
Total hours		86	43	77	29	61	37	7	83	59	75	14	50	64	7	76	7	50					306				
	Number	11	4	12	5	10	7	1	14	9	12	2	8	11	1	13	1	8					46				

Figure F.13: TVP planning Hoorn Scenario M

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Hoorn scenario O		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456	0	Weeksom	13-weeksom
Q	Week	Dag								
1	1	di/wo					7	7	14	98
		wo/do					7	7		
	2	di/wo	7	7		7		7	7	
		di/wo	12		12	12		#		
	3	za	7					7		
		di/wo	7		7	7	7	7		
	6	wo/do					7	7	21	
		za/zo					7	7		
	8	di/wo	7	12		7		#	12	
		za/zo				7	7	7		
	10	za/zo				7	7	7	7	
		zo				7		7		
	12	di/wo					4	4	4	
wo/do		7	7		7		7			
13	di/wo	12	7	7	4		#	7		
	wo	12					#			
16	wo/do	12	7				#	43		
	za		7	7			7			
17	za/zo	4		4	4	7	7	7		
	di/wo	4	4				4			
21	di/wo	4	4				4	4		
	wo/do				7	4	7			
23	wo/do				7	4	7	7		
	za/zo	7	7	7	4		7			
24	za/zo	7	7	7	4		7	7		
	za		7		7		7			
27	za		7		7		7	7		
	di/wo	4		4	4	4	4			
29	di/wo	4		4	4	4	4	4		
	di/wo	7	7				7			
34	di/wo	7	7				7	14		
	za/zo		4		4	7	7			
36	di/wo	4	4		4		4	11		
	za/zo	7	7		7		7			
40	di/wo	4		4	4	4	4	11		
	za				7	7	7			
47	di/wo	4	7		7	7	7	7		
	za/zo					7	7			
49	di/wo	4	7		7	7	7	7		
	za/zo					7	7			
Total hours			128	94	52	117	93	227		
Number			18	14	8	19	15	31		

Figure F.15: TVP planning Hoorn Scenario O

Hoorn scenario P		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456	0	Weeksom	13-weeksom	
Q	Week	Dag									
1	1	di/wo				4	4	4	18	114	
		za/zo	7	7	7	7	7	7			
		zo	7					7			
	2	wo/do	7		7				7		11
		za/zo	4					4			
	3	wo/do	12	7		7		#	12		
		wo/do	12		12	12		#			
	4	wo/do				7	7	7	14		
		za/zo	7	7	7			7			
	5	zo				7	7	7	7		
		wo/do				7	7	7			
	6	za/zo				7	7	7	7		
		di/wo	7	12				#			
	7	di/wo	7	7	7	7	7	7	14		
za/zo					7		7				
8	wo/do					4	4	4			
	di/wo	7	7	4	4		7				
9	zo			7			7	14			
	di/wo		4	4	4	4	4				
10	di/wo	12	4	7			#	36			
	wo	12					#				
11	wo/do	12	7	4			#	11			
	di/wo					4	4				
12	di/wo	7	7	7	7	7	7	11			
	za/zo				4		4				
13	wo/do	4					4	4			
	di/wo	4			7	4	7				
14	di/wo	4	4	4	4		4	11			
	zo		7	7	7		7				
15	zo	7					7	7			
	za/zo					4	4				
16	za/zo	7	7	7	4	7	7	7			
	di/wo	4	4	4	7	7	7				
17	za/zo	7	7				7	14			
	za				7		7				
18	wo/do	4					4	4			
	wo/do	4					4				
19	za/zo				4	7	7	7			
	di/wo	7	7	7	7		7				
20	za/zo	7	7				7	14			
	di/wo	4	4	4	7	7	7				
21	za/zo	7	7				7	7			
	za				7		7				
22	wo/do	4					4	4			
	wo/do	4					4				
23	za/zo				4	7	7	7			
	di/wo	4	4	4	7	7	7				
24	za/zo	7	7				7	14			
	za				7		7				
25	wo/do	4					4	4			
	wo/do	4					4				
26	za/zo				4	7	7	7			
	di/wo	7	7	7	7		7				
27	za/zo	7	7				7	7			
	zo	7					7				
28	za/zo					4	4	4			
	za/zo	7	7	7	4	7	7				
29	di/wo	4	4	4	7	7	7	14			
	za/zo	7	7				7				
30	za				7		7	7			
	wo/do	4					4				
31	za/zo				4	7	7	7			
	di/wo	7	7	7	7		7				
32	za/zo	7	7				7	7			
	zo	7					7				
33	za/zo					4	4	4			
	za/zo	7	7	7	4	7	7				
34	di/wo	4	4	4	7	7	7	14			
	za/zo	7	7				7				
35	za				7		7	7			
	wo/do	4					4				
36	za/zo				4	7	7	7			
	di/wo	7	7	7	7		7				
37	za/zo	7	7				7	7			
	zo	7					7				
Total hours			171	109	102	131	94	273			
Number			23	17	16	21	16	39			

Figure F.16: TVP planning Hoorn Scenario P

Hoorn scenario Q		Werkzone	b626 y55	b626 w35	c626 v43	c626 v51	b626 n32	b626 n38	b626 t52	c626 w44	c626 v46	b626 p33	b626 v37	c626 n41	c626 h47	b626 m40	c626 x45	b626 p39	b626 p42	0	Weeksom	13-weeksom	
Q	Week	Dag																					
1	1	di/wo	7			7					7										7	14	121
		wo/do									7										7	7	
	2	di/wo		7					7	7			7	7		7		7			7	7	
		za/zo				7					7										7	14	
	4	zo	7	7	7	7															7	7	
	6	wo/do			7						7				7		7		7		7	7	
	7	di/wo					7														7	14	
		wo/do															7		7		7	7	
	8	di/wo		7					7												7	7	
	9	di/wo										7									7	7	
	di/wo	7			7					7										7	7		
10	za/zo													7		7				7	21		
	zo	7																		7	7		
	di/wo															2				2	2		
	wo/do	7			7					7										7	7		
12	za										7	7	7							7	23		
	za/zo									7										7	7		
13	wo/do		7					7					7							7	7		
15	di/wo		7					7	2			7	2							7	7		
16	wo/do				7				7											7	7		
17	wo/do		2						2				2							2	2		
	wo/do					2														2	2		
18	za					7	7	7	7											7	9		
19	di/wo			2				2					2		2		7			7	7		
23	di/wo	2			2					7										7	9		
	wo/do												2		2					2	7		
24	za/zo		7					7	7			2								7	7		
27	wo/do	7			7															7	7		
28	di/wo		2	2				2	2			2	2							2	2		
30	di/wo					2														2	4		
	wo/do		2					2												2	2		
32	di/wo												2		2		2			2	2		
33	za				7	7					7									7	7		
	di/wo												2		7		7			7	7		
34	wo/do	7			7															7	14		
	di/wo										2									2	6		
36	za/zo				4	4				4										4	7		
37	wo/do							7				7								7	7		
	di/wo											7								7	7		
39	wo/do	7			7															7	21		
	zo													7	7	7	7			7	7		
41	di/wo		7	2				2	2			2	2							7	7		
42	wo/do					2														2	2		
45	di/wo													7		7			2	7	7		
46	di/wo	2			2															2	2		
49	di/wo							7		2		7								7	7		
		Total hours	60	7	64	25	57	31	7	64	50	71	14	48	51	7	64	7	46		264		
		Number	10	1	12	5	10	7	1	12	10	12	2	9	13	1	12	1	8		46		

Figure F.17: TVP planning Hoorn Scenario Q

Hoorn scenario S		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456				
Q	Week	Dag						0	Weeksom	13-weeksom	
1	1	wo/do						7	7	21	93
		za/zo	7	7		7	7	7			
		zo	7						7		
	3	di/wo	7		7				7	14	
		wo/do			7	7	7	7			
		wo/do	7		7	7	7	7			
	6	za/zo						7	7	14	
		di/wo	7	7					7		
		zo	7						7		
	8	di/wo	7	7		7			7	7	
		zo	7						7		
		di/wo	7	7					7		
10	za/zo				7	7	7		14		
	di/wo					2	2				
	zo				7			7			
13	di/wo	7	7		7			7	7		
	di/wo	7	7	7	2			7			
	di/wo	2		2	2	7	7				
20	za		7	7				7	7		
	di/wo	2	2					2			
	wo/do				7	2	7				
24	za/zo	7	7	7	2			7	7		
	di/wo	2		2	2	2	2				
	wo/do							4			
30	wo/do		4		4			4	4		
	zo		7		7			7			
	di/wo	7	7					7			
34	di/wo	2	2		2	7	7		7		
	wo/do	7	7		7			7			
	zo				7	7	7				
40	di/wo	2		2	2	2	2		2		
	di/wo	2	7		7	7	7				
	di/wo				2	2	2				
47	di/wo	2	7		7	7	7		7		
	di/wo				2	2	2				
Total hours			96	85	48	102	80	182			
Number			18	14	9	20	15	30			

Figure F.19: TVP planning Hoorn Scenario S

Hoorn scenario T		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456	0	Weeksom	13-weeksom
Q	Week	Dag								
1	1	di/wo	7	7	7	7		7	14	105
		za/zo					7	7		
	2	di/wo	7		7	4	4	7	14	
		za/zo	7	7				7		
	3	di/wo	7	7	7	7		7	14	
		zo	7					7		
	5	za/zo	7	7	7	7		7	7	
		wo/do				7	7	7		
	6	wo/do				7	7	7	7	
		za				7	7	7		
7	wo/do				7	7	7	7		
	wo/do					7	7			
8	di/wo		7				7	14		
	wo/do	7	7				7			
9	di/wo	7	7	7	7	7	7	14		
	za/zo				7		7			
10	di/wo					2	2	2		
	di/wo	2	2	2	2		2			
11	di/wo	7	7	7			7	14		
	za/zo				7		7			
12	di/wo						2	2		
	di/wo	2	2	2	2		2			
13	di/wo	7	7	7			7	14		
	zo			7			7			
14	wo/do	2	2	2	2		2	2		
	di/wo		4	4	4		4			
15	wo/do		7		7	7	7	11		
	di/wo				2	2	2			
16	di/wo	4					4	4		
	za/zo	7	7	7	7		7			
17	di/wo					2	2	2		
	di/wo	2	2	2	2		2			
18	zo		7	7	7		7	9		
	di/wo				2	2	2			
19	zo		7	7	7		7	7		
	di/wo					7	7			
20	za/zo	7	7	7	2		7	7		
	di/wo						7			
21	zo				7		7	7		
	di/wo	2	2	2	7	7	7			
22	di/wo	4			2	7	7	7		
	za/zo	7	7				7			
23	za	7					7	7		
	wo/do	7	7	7	7		7			
24	wo/do				2		2	2		
	di/wo						2			
25	zo						7	7		
	di/wo	2	2	2	7	7	7			
26	di/wo	4			2	7	7	7		
	za/zo	7	7				7			
27	za	7					7	7		
	wo/do	7	7	7	7		7			
28	wo/do				2		2	2		
	di/wo						2			
29	zo						7	7		
	di/wo						7			
30	za/zo	7	7	7	2		7	7		
	di/wo						7			
31	zo						7	7		
	di/wo						7			
32	za/zo	7	7	7	2		7	7		
	di/wo						7			
33	zo						7	7		
	di/wo	2	2	2	7	7	7			
34	di/wo	4			2	7	7	7		
	za/zo	7	7				7			
35	za	7					7	7		
	wo/do	7	7	7	7		7			
36	wo/do				2		2	2		
	di/wo						2			
Total hours			121	110	89	122	82	227		
Number			21	19	16	24	15	39		

Figure F.20: TVP planning Hoorn Scenario T

Hoorn scenario U		Werkzone	b626 y55	b626 w35	c626 t43	c626 p51	b626 m32	b626 h38	b626 t52	c626 w44	c626 v46	b626 p33	b626 y37	c626 m41	b626 h47	b626 m40	c626 x45	b626 p39	b626 p42	0	Weeksom	13-weeksom		
1	1	di/wo	7			7					7					7				7	7	21	96	
		wo/do									7					7				7	7	7		
		zo	7	7	7	7																7		
	2	di/wo		12					7	12			7	12								12		12
	4	za/zo			7					7												7		7
	6	wo/do			7					7				7		7		7		7	7	7		14
		za/zo					7									7		7		7	7	7		
	7	za/zo			7				7													7		7
	10	di/wo	7				7					7				7		7				7		14
		za/zo										7			7		7					7		7
		di/wo	7				7					7					2					7		7
	12	za										7	7	7	7							7		21
		za/zo			7				7	7	7	7	7	7								7		7
	15	di/wo			7				7	2			7	2								7		7
		di/wo	12	12		7	7			7												12		12
	16	wo	12	12																		12		36
	wo/do	12	12																		12	12		
2	17	di/wo			2				2		7		2								7	7		
		za/zo						2													2	2		
		zo					7	7	7	7											7	7		
	19	di/wo											2		2		7				7	7		
		wo/do			2				2													2	9	
	23	di/wo	2			2																2	9	
		wo/do									7			2		2						7	7	
	24	za/zo			7				7	7			2			2						7	7	
	28	di/wo			2	2			2	2			2	2								2	4	
		za/zo					2															2	2	
	30	di/wo			2				2													2	2	
	31	di/wo									7											7	7	
	32	di/wo												2		2		2			2	2	9	
		zo					7	7			7											7	7	
	34	di/wo					4	4			4			2		7		7			7	7	14	
		wo/do	7				7															7	7	
35	za/zo									2											2	2		
36	di/wo							7				7									7	7		
37	di/wo	7				7															7	7		
40	wo/do							2													2	2		
41	di/wo			7	2			2	2			2	2								7	7		
42	za									7				7	7	7	7	7			7	7		
45	di/wo													7		7		2			7	9		
	za/zo			2																	2	2		
47	di/wo							7		2		7									7	7		
Total hours		82	43	69	25	57	31	7	64	55	71	14	48	56	7	64	7	46			264			
Number		11	4	12	5	10	7	1	12	10	12	2	9	13	1	12	1	8			42			

Figure F.21: TVP planning Hoorn Scenario U

Hoorn scenario V		Werkzone	b626 v25	b626 w35	c626 t43	c626 p51	b626 n32	b626 n38	c626 t52	c626 w44	c626 v46	b626 p33	b626 v37	c626 n41	c626 h47	b626 n40	c626 v45	b626 t39	b626 n42	0	Weeksom	13-weeksom	
Q	Week	Dag																					
1	1	za/zo																			7	14	149
	2	di/wo	7																		7	11	
		wo/do									4					4	4	4	4		4	14	
	3	di/wo	7																		7	14	
		za/zo																			7	14	
	4	di/wo																			7	14	
		wo/do																			7	21	
	6	wo/do																			7	7	
	7	za/zo																			7	19	
		di/wo																			7	14	
	8	di/wo																			7	7	
		wo/do																			7	14	
	9	za																			7	14	
	10	di/wo	7																		7	14	
	11	wo/do																			7	7	
		zo																			7	14	
13	wo/do																			7	2		
	za/zo	7																		7	7		
14	di/wo	2																		2	7		
	wo/do																			7	2		
15	di/wo																			2	2		
16	za/zo																			4	4		
17	di/wo																			7	14		
	wo/do																			7	7		
19	di/wo																			7	2		
20	wo/do																			2	2		
21	wo/do																			7	7		
23	di/wo	2																		2	2		
24	di/wo																			7	7		
25	di/wo	2																		2	9		
	wo/do																			7	12		
	di/wo	12	12																	12	36		
26	wo	12	12																	12	9		
	wo/do	12	12																	12	2		
	di/wo																			2	7		
27	di/wo																			7	7		
	za																			7	2		
28	di/wo																			7	2		
30	di/wo																			2	9		
	di/wo																			2	7		
31	zo	7																		7	14		
	zo																			7	14		
33	zo																			7	7		
	di/wo	2																		2	9		
36	za/zo																			7	7		
37	di/wo																			7	7		
39	di/wo																			7	14		
40	di/wo																			7	14		
	za/zo																			7	7		
41	di/wo																			7	7		
	za	7	7	7																7	7		
42	di/wo																			7	7		
43	za/zo																			7	7		
44	wo/do	7																		7	7		
45	wo/do	4	4	4																4	7		
48	di/wo																			7	7		
49	di/wo	2																		2	2		
52	di/wo																			2	36		
		Total hours	99	47	91	46	63	36	18	82	96	77	18	54	76	18	73	18	63	369			
		Number	16	5	16	8	13	7	3	15	17	14	3	11	13	3	13	3	13	59			

Figure F.22: TVP planning Hoorn Scenario V

Hoorn scenario W		Werkzone	hoorn1	hoorn2a	hoorn2b	hoorn3	hoorn456	0	Weeksom	13-weeksom	
Q	Week	Dag									
1	1	di/wo						7	7	21	89
		za/zo	7	7		7		7	7		
		zo	7						7		
	2	di/wo						7	7	7	
		3	di/wo	12		12	12	7	12	12	
	6	di/wo	7		7	7	7	7	7	7	
		7	wo/do					7	7	7	
			8	di/wo	7	12		7		12	
		10	za/zo				7	7	7	7	
			11	za				7		7	
		12	wo/do					2	2	2	
			za/zo	7	7		7		7	7	
16			di/wo	12	7	7	2		12	12	
2		16	wo	12					12	36	
			wo/do	12	7				12	12	
	17	za		7	7			7	7		
	18	di/wo	2		2	2	7	7	7		
		21	di/wo	2	2				2	2	
	23	wo/do				7	2	7	7		
		24	za/zo	7	7	7	2		7	7	
	29	di/wo	2		2	2	2	2	2		
30		wo/do		4		4		4	11		
3	30	zo		7		7		7	7		
		34	di/wo	7	7				7	7	
	35	za/zo	2	2		2	7	7	7		
		36	di/wo	7	7		7		7	7	
4	39	zo				7	7	7	7		
		42	di/wo	2		2	2	2	2		
	46	za/zo	2	7		7	7	7	7		
		47	di/wo				2	2	2		
	Total hours			116	90	46	107	80		207	
Number			18	14	8	20	15		30		

Figure F.23: TVP planning Hoorn Scenario W

Hoorn scenario X		Werkzone					0	Weeksom	13-weeksom	
Q	Week	Dag	hoorn1	hoorn2a	hoorn2b	hoorn3				hoorn456
1	1	za/zo		7			7	7	7	118
	2	di/wo	7		7				7	
		wo/do					4	4	4	
	3	di/wo		7			7		7	
		wo/do	12	7	12	12			12	
	4	zo	7						7	
		za/zo	7	7					7	
	5	wo/do					7	7	7	
		za/zo	7		7	7			7	
	8	wo/do						7	7	
		za/zo		7			7	7	7	
	9	zo					7	7	7	
		di/wo	7	7	7				7	
	11	di/wo	4						4	
wo/do		7	7	7	7	7	7	7		
12	di/wo		7			7		7		
	zo			7				7		
14	wo/do						2	2		
	di/wo	2		2				2		
16	di/wo	2	2		2	2	2	2		
	za/zo	7	7	2	2			7		
19	wo/do		4	4	4			4		
	di/wo						2	2		
22	di/wo	12	7	7	7	7	7	12		
	wo	12						12		
23	wo/do	12						12		
	di/wo			2	2			2		
27	di/wo					7	2	7		
	za		7	7	7			7		
28	za/zo	7	7	7	2			7		
	za	7						7		
29	di/wo		2		2			2		
	di/wo	2	2	2	2	2	2	2		
37	za					7		7		
	za/zo	7	7					7		
40	di/wo	2	2	2	7	7	7	7		
	di/wo					7	7	7		
45	di/wo	7	7	7	7	7	7	7		
	di/wo				2	7	7	7		
46	wo/do	4	2					4		
	za	7						7		
47	za	7						7		
Total hours			148	112	89	132	84	260		
Number			22	20	16	24	16	41		

Figure F.24: TVP planning Hoorn Scenario X