MASTER

An aggregate planning for preventive maintenance of bogies by NedTrain

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An Aggregate Planning for Preventive Maintenance of Bogies by NedTrain

by

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I. Preface

This report is the results of my research project conducted in corporation with NedTrain, done to finalize the Master Operations Management and Logistics at the Eindhoven University of Technology (TU/e). During this project I had the opportunity to work with many inspiring people both from the TU/e and from NedTrain and I would like to thank those people for this experience.

From the TU/e I would like to thank multiple people for their guidance and enthusiasm during my project. First of all I would like to thank my mentor and first supervisor from the TU/e, Ir.dr. S.D.P. Flapper. During the many discussions we had on the different subjects concerning my thesis your critical view stimulated me to keep the bigger picture in mind while working out the details. Also, my thanks for your sincere interest and enthusiasm for my project, this made our meeting very enjoyable. Further, I would also like to thank my second supervisor from the TU/e, Prof.dr.ir. G.J. van Houtum. Thank you for making time to discuss my work and asking critical questions that helped me improve my work. Last, I would like to thank Joachim Arts. From the very beginning of my project the discussions with you helped me to get a clear view on the processes at NedTrain and translate this into mathematical formulas.

At NedTrain I also worked with many inspiring people. First of all, my thanks go to Bob Huisman, the initiator of the project and my supervisor at NedTrain. I believe you have two opposite inspiring sides. One side is your enthusiasm for the challenges of the different processes at NedTrain, this is very contagious and it inspires to look behind the horizon. The second side is your practical side, which helped me define good boundaries for my project, to match the amount of work with the time available. Furthermore, I would like to thank Michel Wilson for his time and advice concerning my ICT related problems during my thesis. And last, I would like to thank the other students and employees at NedTrain that made time to discussions, coffee or walks; this made my time at NedTrain much more enjoyable for many reasons.

Finishing this thesis also means saying goodbye to my life as a student. The last seven years would not have been as amazing as they were without my family and friends, I want to thank all of you for your interest and support. Special thanks go to my parents, your infinite believe in me and the knowledge that you would support me no matter what decision I made meant the world to me. I would also like to thank my sister, despite your ‘stupid’ choice to go study in Groningen, you have always been there for me. Last, I would like to thank all of my friends for making the last seven years unforgettable!

Karin

II. Abstract

In academic literature multiple studies have been done on the planning of preventive maintenance of machine that have an inter-revision deadline; a maximum time between two revisions that may not be exceeded. However, all of the studies only look at a fleet of machines with only one type of machines and plan only one revision per machine. It is unknown whether the models created in these studies still would hold when the fleet would consist of multiple types of machines going through the same revisions capacity with multiple revisions that have to be planned per machine. In this research, this extension on the existing models is made and a field study is done on the revisions of different types of bogies at NedTrain. An additional challenge at NedTrain has been the disproportionally distributed demand for revisions. The results show that it is possible to flatten the peaks in demand for revisions created by the disproportionally distributed demand by pushing revisions backward in the planning horizon. In addition, scenario analysis shows that there might be different possibilities to decrease the total costs for revisions.

III. Management Summary

Availability of the fleet of a rolling stock company is an important and noticeable aspect for customers of these companies, which makes this availability a key aspect for the success. An important part of maintaining availability is by executing preventive maintenance of the rolling stock, since this decreases the probability of break downs and makes the system more predictable.

During the course of this research project, a model has been created for the planning of preventive maintenance for bogies in the refurbishment and overhaul workshop (ROW) in Haarlem at NedTrain. There are two challenges identified in planning this preventive maintenance at NedTrain. The first challenge is to deal with peak loads that lead to capacity problems in the ROW. These peak loads originate from the fact that all bogies from a specific type need revision at approximately the same moment in time because they also come into the field at approximately the same time. The second challenge is that bogies have an inter-revisions deadline, which causes that a revision can only be pushed backward in time and not forward. Furthermore, if a revision is pushed backwards, this pushes all subsequent revision backwards as well.

The different challenges at NedTrain lead to the following problem statement: how to deal with the shortage of different types of capacity during peak loads in the ROW caused by a disproportionately distributed demand for maintenance of main spare parts?

To solve this problem a mathematical model has been created. This model plans the revisions of different types of bogies over the total lifetime of the bogies while minimizing the total life cycle costs of all revisions in the ROW during a planning horizon of 30 years. The costs that are included are the investment costs, holding costs, transport costs, and processing costs. The investment costs are the costs of purchasing the bogies. The holding costs are the costs of holding a bogie in inventory during a period of time. The transport costs are the costs of transporting bogies from the MD to the ROW and vice versa. The processing costs are the costs for replacing a bogie in the MD or revision of a bogie in the ROW. In fact, these are the costs for the time mechanics are actually working on the maintenance and the materials used.

The scope of this created model is shown in Figure 1. Approximately once every three months the rolling stock comes into the MD (arrow 0 in Figure 1). In the MD (point 2 in Figure 1), when necessary bogies are replaced. All bogies that are taken out of rolling stock in the MD are

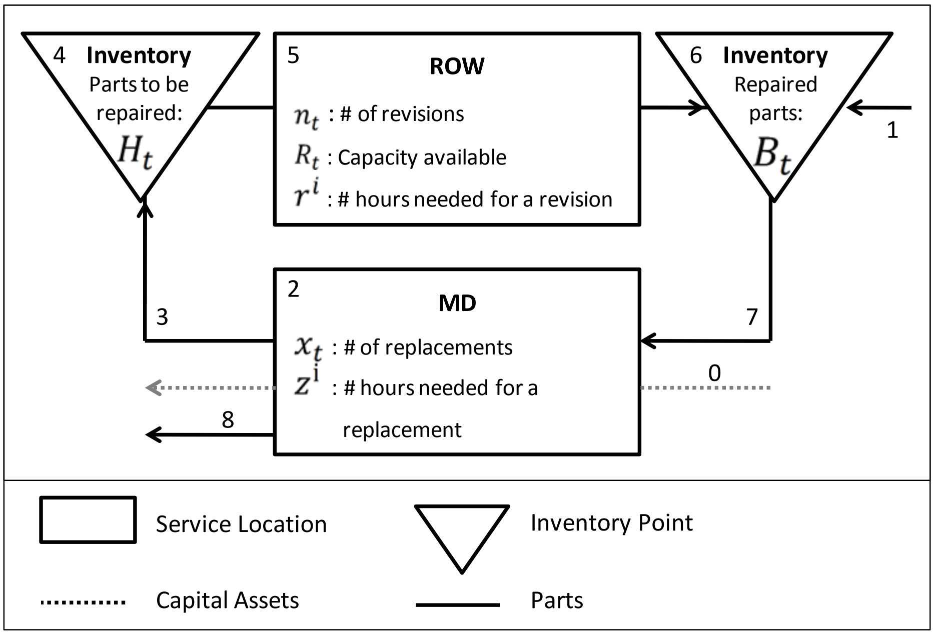

Figure 1: Project Scope

transported to the ROW (arrow 3 in Figure 1). In the ROW (point 5 in Figure 1) the bogies are revised. Once the bogies are revised they are transported to the MD when needed (arrow 7 in Figure 1).

The model created needs multiple parameters for which the values are not researched before at NedTrain and therefore the values are not currently available. The consequence for the results is that they might not match reality exactly. However, although the results might differ from reality, the effects of different types of decisions can still be derived from the results. Before concrete decisions can be made based on the model, the data for the different estimated parameters has to be collected.

The model demonstrates that it is possible to flatten the peaks in demand for revisions by pushing revisions backward in the planning horizon. The planning has been made while minimizing the total costs for revisions. These total costs are calculated in two different ways. First the costs are calculated with a discounting factor of 0% and then with a discounting factor of 5% per year. When minimizing these costs over a planning horizon of 30 years for the 0% and 5% discounting factor, these costs are €541,246,922.- and €268,213,286.- , respectively. The resulting utilization of the capacity in the ROW is shown in Figure 2.

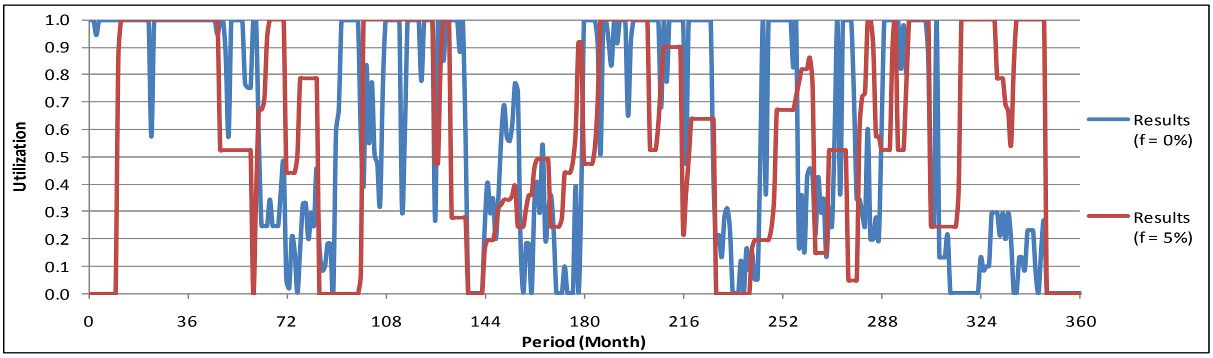

Figure 2: Utilization Capacity ROW (R=12,220)

While analyzing the model, three relevant observations have been made.

Firstly, several types of bogies that are currently in use have inter-revisions deadlines that are close together. The consequence of the clustering of inter-revision deadlines is that multiple periods where the capacity in the ROW is totally used are alternated with multiple periods where almost no capacity used. If it would be possible to spread inter-revisions deadlines equally over time it would be easier for NedTrain to use the capacity in the ROW more efficient.

Secondly, approximately 63% of all bogies that are currently in use will go out of the field between 2022 and 2030. Because such a large percentage of bogies go out of the field in a relatively short period, there are significantly less revisions necessary in this time period. If it would be possible to spread the periods that the different types of bogies go out of the field over a longer period, it would be easier for NedTrain to use the capacity in the ROW more efficient.

Thirdly, currently the planning of revisions is mostly done manually. Engineers decide on the planning of the revisions for the different types of bogies based on the upcoming inter-revision deadlines and a raw estimate of the available capacity in the ROW. This method is mostly short term based, as it does not take the revisions later in the lifetime of the bogies into account. As a result of the developed method, revisions are normally planned as late as possible, intuitive it makes sense not to do a revision until it is necessary. As said, many of the inter-revision deadlines of the different types of bogies are clustered closely together in time. The model created here shows that for the long term it might be better to push some revisions backward within the planning horizon, to divide the different peak loads over the horizon. Planning earlier creates more flexibility to push revisions backward and decreases capacity and the number of spare bogies over time.

To obtain more managerial insights, three different scenario analyses have been done.

Firstly, the effect of changing capacity in the ROW on the total costs for revisions has been investigated. The initial results showed that the capacity in the ROW can be decreased with as much as 22% until it becomes infeasible to plan all necessary revisions. When the capacity is decreased with 22%, the total costs decrease with 12%. Further research shows that the first five years of the planning horizon are a bottleneck for the decrease of the capacity in the ROW. When the capacity in the first five years is decreased with 21%, the capacity year 6 to 30 can be decreased further with as much as 39% until it becomes infeasible to plan all necessary revisions. In this scenario, the total costs decrease with 20%. For this situation the utilization of the capacity of the ROW is shown in Figure 3.

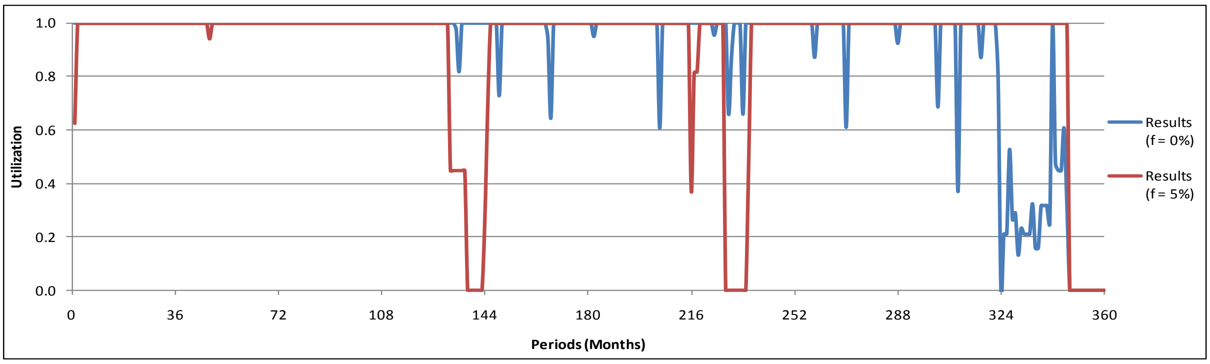

Figure 3: Utilization Capacity ROW (R[1,...,60}=9,660, R[61,...,361]=7,580)

Secondly, the effect of changing the number of spare bogies on the total costs for revisions has been analyzed. Currently, 7.5% of the total population of bogies is spare bogies, which can be decreased with 50% before it becomes infeasible to plan all necessary revisions on time. When the number of spare bogies is decreased with 50%, the costs are decreased with approximately 5%. Another finding is that the effect on the change in total costs is different for the different types of rolling stock. The effect is caused by different costs, different numbers of bogies per type of rolling stock and different inter-revision deadlines for the different types of rolling stock. It has been demonstrated that the VIRM has the most influence on the change in total costs and the SLT the least.

Thirdly, the effect of changing the inter-revision deadlines of bogies on the total costs for revisions has been researched. The result is that increasing the inter-revision deadline decreases the total costs for revisions, which is caused by the fact that less revisions are necessary in the total lifetime of a bogie when the inter-revisions deadline increases. However, this is not a linear relationship, as not all increases of the inter-revision deadlines have an effect on the total costs. For example, when a type of bogie has to be revised every 7 year in a period of 30 years, it needs 4 revisions in its total lifetime. When the inter-revisions deadline for this type of bogie changes to 7.2 years, the bogie still needs 4 revisions in its total lifetime.

After the individual scenario analyses, a combination of the above scenarios show that an even higher decrease in total costs is possible. When a capacity decrease of 21% for the first five years and up to 39% for year 6 to 25 is combined with a decrease of 50% in the number of spare bogies for all types of bogies that come into the field during the planning horizon, it is still possible to plan all necessary revisions before the inter-revision deadline. The total cost decrease for this situation with approximately 25%.

Taken all the above conclusions into account, the five most important recommendations for NedTrain are:

- To actively incorporate the most important lessons of this research project when planning preventive maintenance for bogies. An Example is, explicitly considering to execute revisions earlier when there is an expected peak load of due dates coming up in the ROW. To incorporate the lessons of this research project successfully, it is important that the engineers at NedTrain are familiar with the consequences of their decisions, especially the long term consequences. When the engineers truly understand how all of the little decisions they make daily concerning the planning of the revisions relate to each other, they can make more substantiated decisions.
- To use the lessons learned from this research project for the preventive maintenance of other main parts at NedTrain. For all parts that have a similar maintenance program, only the input parameters have to be changed to use the model to plan the maintenance. For parts with a different maintenance program it can be analyzed if it is profitable to adjust the model.
- To collect the actual values of the data for the input parameters for the created model. This research shows that there are multiple ways to deal with the disproportionately distributed demand for the revision of bogies and that this leads to possibilities to reducing the total costs of the revision of bogies. To discover how large the advantages of changing the parameters can be for NedTrain and make adequate decisions, the values of the parameters in the current situation have to be determined more precisely.
- To start calculating the exact costs of preventive maintenance under the current system. When the exact data on the current costs is known, the real advantages of the new way of planning can be discovered. Only when this data is known, conclusion can be drawn on the desired values of the different parameters.
- Once the exact values for the parameters in the basic model are researched, the extensions suggested in Chapter 8 could be further developed. Expansion of the model with the suggested extensions will get the model closer to reality.

IV. Table of Contents

1. Introduction

This chapter will give an introduction in the problem researched in this thesis and elaborates an outline for this report.

1.1 Introduction to the Problem

The economic position of companies that provide public transportation can be very vulnerable, since this position depends, probably more so than for companies in other industries, on image. The performance of public transportation is criticized by the whole society and regularly spoken about in the media. Besides the society and media, in the Netherlands also the government has a lot of influence on rolling stock companies, for example by legislations and performance agreements.

An aspect of companies providing public transport that is seen by society every day is the availability of the fleet and this makes this a key aspect for success of rolling stock companies. An important part of keeping up performance is the preventive maintenance of the rolling stock, since this decreases the probability on break downs and makes the system more predictable. Preventive maintenance on rolling stock will be the subject researched in this report. Besides the theory, this research will also look at a field study, which was done at NedTrain; a Dutch company that has specialized in rolling stock maintenance, servicing, cleaning and overhaul.

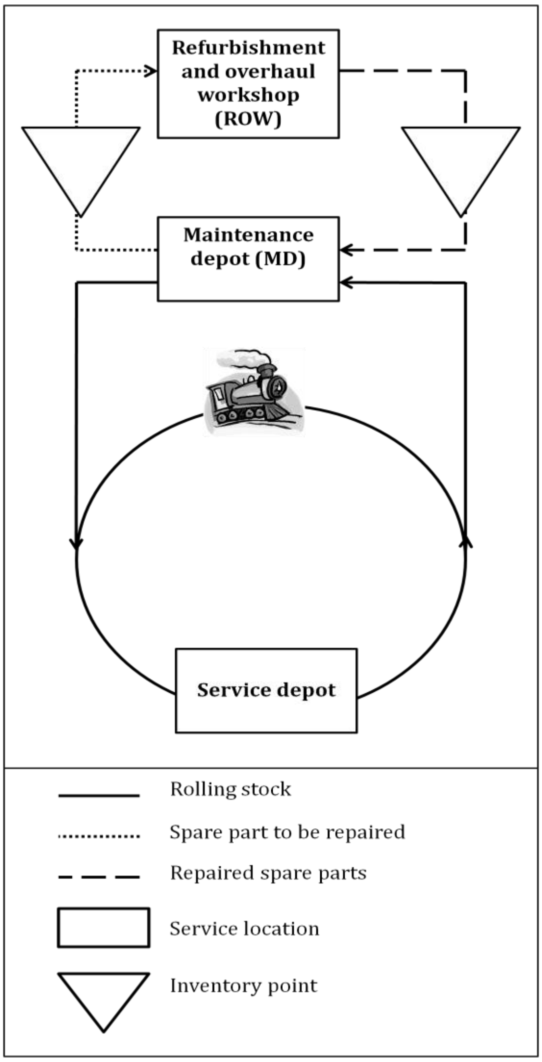

Figure 4: Maintenance Supply Chain NedTrain

The maintenance supply chain of NedTrain is divided in three types of maintenance locations (as can be seen in Figure 4); the service depot, the maintenance depot (MD) and the refurbishment and overhaul workshop (ROW). Daily, the rolling stock goes to the service locations, where the rolling stock is cleaned and some small tests are done to check for failure in the system. Approximately once every three months the rolling stock goes into the MD, where maintenance on the rolling stock is done. All the repairable spare parts that are taken out of the rolling stock in the MD are transported to the ROW, where the spare parts are repaired.

The initial problem given by NedTrain is: *"Main parts require Long Cycle Maintenance (LCM) a number of times during their total lifetime. Since several trains of a rolling stock type are taken into use at approximately the same time, the main parts are also ready for LCM at approximately the same moment in time. This leads to a peak load for the maintenance capacity. Performing this major maintenance for main parts earlier has the disadvantage that the number of revisions during the life cycle time increases and that the technical lifetime (technical lifetime is here defined as the maximum number of kilometers before a main part* *needs revision) of the main parts is not totally used. The assignment is to make a quantitative model that can be used to support decisions around these problems."* (Huisman, 2010)

Combining the initial problem given by NedTrain and the conversations with Bob Huisman and Joachim Arts from NedTrain, the problem that will be addressed in this report is how to deal with the shortage of different types of capacity during peak loads in the ROW caused by a disproportionately distributed demand for maintenance of main spare parts.

To get more insights in how disproportionately distributed the demand is, some estimates have been made about the demand for revisions in the upcoming years, this is shown in Figure 5. Even though the numbers are estimates, the pattern becomes clear; multiple periods with (almost) no demand alternating with periods with high demand.

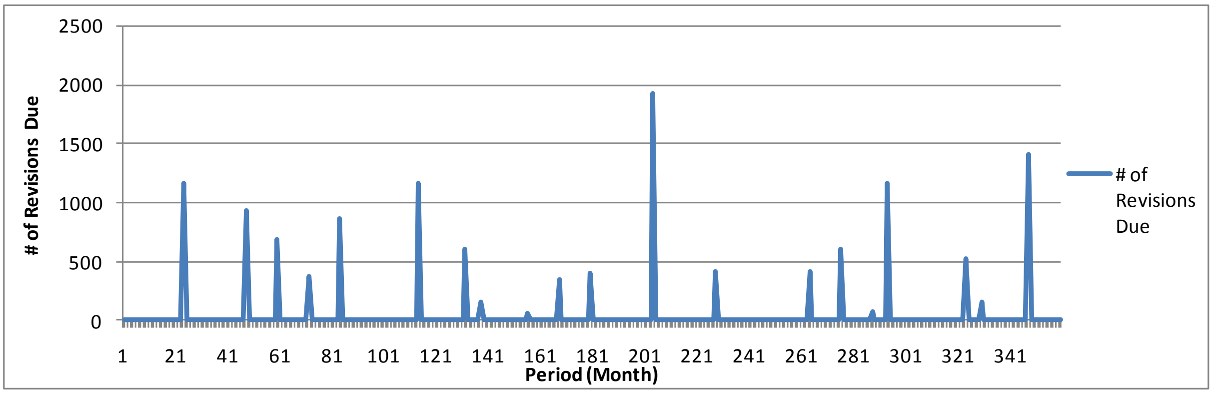

Figure 5: Distribution Revisions in the ROW

For NedTrain an efficient method to plan the preventive maintenance of the main parts is very important, especially because there are large numbers of rolling stock and main spare parts involved. The total fleet of NedTrain consists of about 3000 carriages, one of those carriages costs about €2.500.000,-. If the main parts are not managed correctly, the result is that the waiting lines in the maintenance depots will grow and this will decrease the service level. The service level is here defined as the percentage of time that a train comes into the maintenance depot with a main part that has to be replaced and everything that is needed is available to replace the main part immediately. The result of a decreased service level could be that there won't be enough rolling stock available to cover the total public transport network.

As mentioned in the article of Joo (2009), there are three different solutions for a problem like this; 1) changing the capacity by the purchase of new spare parts and/or hiring new employees 2) leaving rolling stock in the waiting line 3) repairing main parts earlier than the due dates. NedTrain will initially try to solve this problem without purchasing new main spare parts and/or hiring new people, so the first solution is not considered further. The second solution, leaving rolling stock in the waiting line is not an option either, because NedTrain has an agreement on a service level with the company NS Reizigers. This means that the solution should be found in the third solution option, repairing main parts earlier than the due dates.

1.2. Outline of the Report

The outline of the remaining of this report is given in Figure 6. After this introduction, chapter 2 will start by explaining some general concepts concerning maintenance on rolling stock. The second part of chapter 2 will explain the specific problem discussed in this report and a literature review is presented containing the literature already written on the problem.

Chapter 3 contains an analysis on the company that will be used as field study for this research, NedTrain. First some general information about NedTrain is given, followed by an analysis of the supply chain structure.

Chapter 4 presents the research approach for the project. The chapter starts with a problem statement, followed by the project scope. The research conducted in this project is part of a broader innovation project performed at NedTrain; the last section of chapter 4 will discuss the position of this research in the total innovation project.

Chapter 5 discusses the mathematical model created to solve the problem. This chapter starts with general information on the model and then the model assumptions will be explained. After this the mathematical model will be given.

Chapter 6 presents information on the case study, NedTrain. In this chapter more detailed information on the case study is given and the model assumptions are justified. In the last section, the selection of the software is discussed and then the mathematical model is programmed in the software and validated.

Chapter 7 gives the results of this research project. First the general results will be explained and then the results of multiple scenario analysis will be discussed.

Chapter 8 explains multiple possible extensions on the mathematical model.

Chapter 9 discusses the conclusions and recommendations. In the first part the conclusions of this research project will be explained. The second part will give recommendations for further research and for NedTrain.

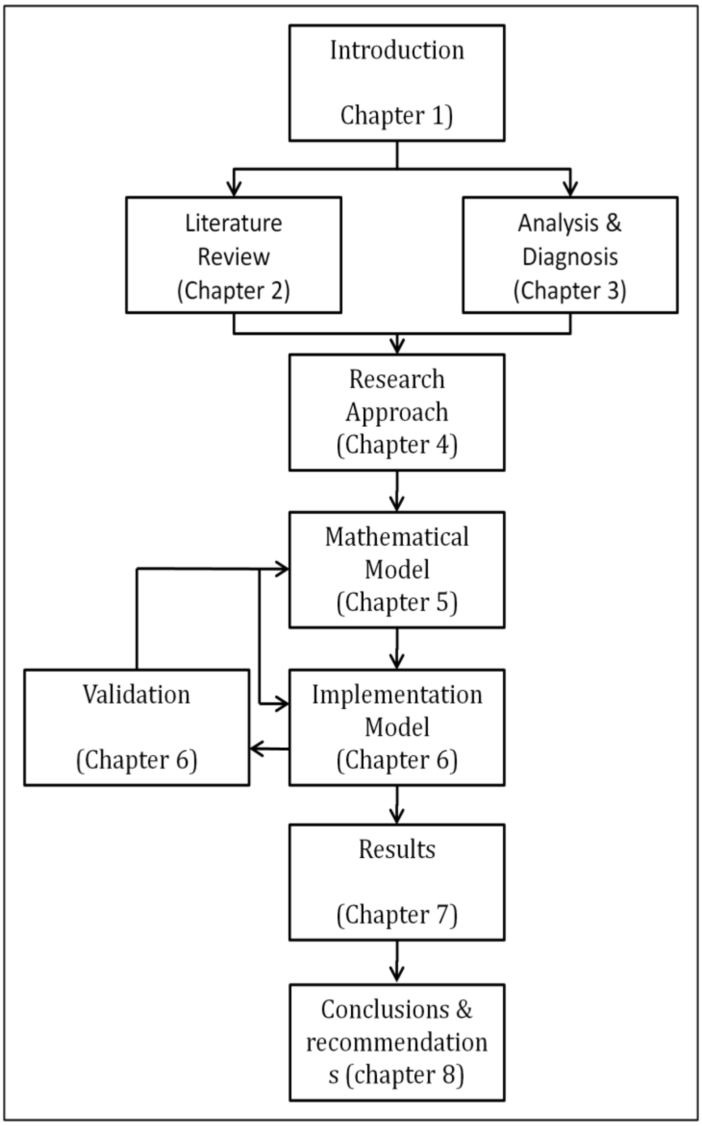

Figure 6: Outline Report

2. Literature Background

This chapter contains the literature background for this report. In the first two sections some important concepts are explained, to provide a general understanding of the problems in maintenance for rolling stock. In the third section the specific problem addressed in this research is explained. In the fourth section a review of the literature that has already been written on this problem is given.

2.1. Maintenance and Spare Parts

The goal of maintenance is to keep an asset up at minimal cost; this is done by repairing failed parts and/or by improving the quality. In the literature, different distinctions are made to describe different types of maintenance. One of those distinctions is corrective maintenance versus preventive maintenance. Corrective maintenance is failure-based maintenance. This means that the maintenance is done after the part has failed (Vliegen, 2010). Preventive maintenance “is servicing equipment on regular basis, for example, an interval or operation time” (Joo, 2009, p. 512). This means that maintenance will be done after a predefined amount of a specific variable, such as time or kilometers. Since the period after which the part has to come back for maintenance is fixed, the maintenance is more predictable and can be scheduled easier. A special type of preventive maintenance is condition based maintenance; this kind of maintenance requires that there is a failure indicator. This means that this type of maintenance aims to repair the part in advance of the breakdown. This is done by inspection to predict failures.

The research of Paz & Leigh (1994) indicates that in general maintenance requires three resources; manpower, equipment and material. The lack of availability of any of those three recourses can cause capacity constraints on the problem. Manpower is here defined as the person(s) needed to perform the maintenance. The equipment is the tool(s) needed to perform the maintenance. Materials are the subpart(s) that are needed to perform the maintenance. Fortuin & Martin (1999) define two kinds of spare parts; consumable and repairable. The consumable spare parts are the parts that are disposable, which means that those parts are only used once. After they are removed during maintenance they are disposed. The repairable spare parts on the other hand are recoverable, which means that they can be repaired and reused after they are removed during maintenance.

2.2. Rolling Stock Maintenance

The problem described in this report will have a specific environment; it will be in a company providing public transportation and more specifically rolling stock. Rolling stock is defined as all the vehicles that move on a railway, this includes powered and unpowered vehicles. A reason why this is an interesting environment for this research is that in general companies owning rolling stock, don’t own only one train, but an entire fleet of rolling stock. This means that maintenance decisions also have to be made for the entire fleet.

According to Genser (1982) there are multiple facts that a company must be aware of and can use in its advantage when responsible for maintenance planning in rail transportation. One of those facts is that most public transportation companies both own and maintain their own fleet, instead of having two different companies handling this. As a result, the objective function for a public transportation company becomes “the smallest investment in, and commitment of, workshop and operational equipment, like rolling stock” (Genser, 1982, p. 35). This means that instead of just looking at maintenance costs, total life cycle costs should be taken into consideration.

Another important point that Genser & Grassl (1974) make is that the reliability level of public transportation must be set high because of very high standards of official regulation. This means that "reliability is a principal objective for railway management" (Genser & Grassl, 1974, p. 156). These regulations are not the only reason for public transportation companies to keep their reliability, availability and safety levels high. Since delays and/or accidents will generally directly be published in the media, this can cause significant image damage for the company. The last reason to keep reliability high is because research suggests that this is in the long run the most economic strategy (Genser, 1982). As explained in the last section, when the goal is to prevent faults, preventive maintenance can be very effective, so this is why this is an interesting environment for the problem of this report.

A problem in the maintenance of rolling stock is that in general spare parts of critical systems of the rolling stock are expensive and have long lead times when bought after the purchase of the train (Arts, 2011). For some types of spare parts it is even impossible to buy new spare parts, because they are simply no longer produced. Since rolling stock has a long lifetime, it is likely that the producer already sells a newer version before the old ones are taken out of the field. For this reason the purchase of spare parts for rolling stock can be seen as a final lot size problem. Inderfurth & Mukherjee (2008, p. 21) refer to the final lot size as "production of additional spare parts at the time of manufacturing the last of the final lot of production at the end of product life cycle." For companies who own rolling stock this means that they have to decide early in the lifetime of the rolling stock how much spare parts they are going to need to be able to maintain the rolling stock until the end of their life time.

A last factor that complicates the maintenance planning of rolling stock is that new rolling stock normally comes into the field in batches. Since all rolling stock from the same batch will need maintenance after approximately the same amount of time, this can create capacity problems in the maintenance depots. (Huisman, 2010)

2.3. Specific Type of Problem Addressed in this Project

The problem that will be addressed in this project is a combination of the topics and environment discussed in section 2.1 and 2.2. The problem is the planning of preventive maintenance in the public transportation sector, more specifically rolling stock. As described above, in this kind of company preventive maintenance is not only effective, but necessary to meet official legislations and run the company in an economically advantageous way. This is the reason why preventive maintenance will be the main focus of this research.

As described before, maintenance requires manpower, material and equipment. In this problem at least one of those three will be limited, which will cause capacity restrictions. The spare parts considered in this research will be repairable spare parts with a finite life time, which means that when they are removed from the rolling stock they will stay in the system to be repaired and reused. After a specific amount of time the spare parts will go out of the system (finite lifetime).

The objective of this research will be to find the way to plan preventive maintenance given the constraints above with the lowest costs. The costs that will be researched will be total life cycle costs. During this research a special interest will go to the problem that rolling stock from the same batch will approximately need preventive maintenance at the same time and this is a challenging combination with the limited capacity that is researched in this report.

2.4. Literature

This section will describe the most important literature that is already written on the problem described in this report. In the first section a literature review will be presented which summarizes the research already done on this type of problem and in the second section conclusions will be drawn.

2.4.1. Literature Review

A summary of the most interesting articles read for the literature review is given in appendix A. During the search the conclusion could be drawn that there is only a limited amount of literature on the problem described in this report. To find some more background on the problem the search was made a little wider by also searching for articles focused on only a few of the components of the total problem.

The most interesting articles found in the search are given in table 1 and 2 of appendix A. In table 1 the articles are given that focus only on part of the components, where in table 2 the articles can be found that describe a situation similar to the total problem described in this report.

2.4.2. Literature Review Conclusions

After examining the literature available on the problem described in this report, an interesting conclusion is that the most similar situations to the one described here are not necessary in rolling stock. Especially aircrafts and helicopters have similar maintenance problems. As can be seen in the tables of appendix A, there are two articles that describe all the aspects of the problem described in this report; Everingham et al. (2008) and Joo (2009).

The situation described in the article of Everingham et al. (2008) is interestingly similar to the problem described in this report. Unfortunately, this article does not include the model used to solve the problem, which makes it less useful for this literature review. Since this article is an overview article the underlying articles are examined as well. Interesting here is the article of Deshpande et al. (2006), which describes part of the problem described in Everingham et al (2008) mathematically. However, in this article some assumptions have been made that are different than the ones made in the overview article. The most important difference is that the focus is not on the planning of parts, but on the choice whether or not to outsource work in the MD. This makes that this situation looks less like the situations described in this report and makes the article less useable for this literature review.

The article of Joo (2009) on the other hand, gives a mathematical model of a situation very similar to the one described in this report. The differences between the two situations are:

1. The article of Joo (2009) takes only a single revision in the future into account. In this research a total life cycle perspective is taken, which means that multiple revisions in the future will be taken into account.
2. In the article of Joo (2009) there is only one type of module for repair, while the problem described here consists of multiple different types of parts that have to be repaired. In all the articles found with case studies similar to the problem described here, only one type of part is examined. The interesting part about examining multiple different types of parts is that they have to share the same repair capacity.
3. The article of Joo (2009) only takes module capacity constraints into account and no labor capacity constraints. However, since the modeling of labor capacity constraints can probably be

done in the same way as the parts capacity constraints, this difference shouldn’t change the model too much. Also, again the article of Chen et al. (2010) is interesting here, since they do model labor capacity constraints.

4. In the article of Joo (2009), purchasing new modules is an option, in the research conducted here purchasing new spare parts is not an option.
5. In the article of Joo (2009) doing maintenance earlier than strictly required results in higher replacement costs. In the problem discussed here this is not necessary the case, the costs will only increase if the part needs extra maintenance in its total lifetime because of the rescheduling of the maintenance.

The conclusion that can be drawn is that there is useful literature available, especially the article of Joo (2009). But the total problem as described in this report hasn’t been researched before. There are two gaps found in the literature around this problem. The biggest gap is the planning of the revision of multiple different spare parts with a revision deadline that have to go through the same revision capacity, where the revision capacity is restricted. In literature, articles are found on either the planning of multiple different spare parts going through the same revision capacity or on the planning of revision for parts that have a revision deadline, but the combination hasn’t been made yet.

There is a second gap in the literature found during this review; in all the articles found about planning preventive maintenance for parts with a revision deadline the researcher only plans one revision in the future. In this research on the other hand, multiple revisions per part will be planned in the planning horizon.

3. Company Analysis

In chapter 2 the theoretical problem that will be researched in this report is described. This theoretical problem is also found in practice, for example within the company NedTrain. NedTrain will be used as a field study within this research and this chapter will provide an overview of the current situation of NedTrain.

In the first section of this chapter a general description is given of NedTrain. The second section, explains the structure of NedTrains supply chain, this gives a better understanding of environment around the problem.

3.1. Company Description

In 1839 the first Dutch railroad was constructed and this is also where the history of NedTrain starts, although NedTrain did not operate under this name yet. The name NedTrain came years later, in 1999 when NedTrain was founded as a subsidiary of the NS, the Dutch railway transport provider. The organization of the NS holding is explained in Figure 7.

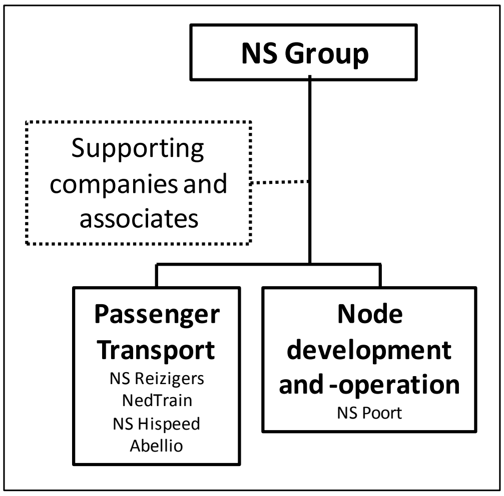

Figure 7: Organization NS Holding

NedTrain "has specialized in rolling stock maintenance, servicing, cleaning and overhaul, they maintain railroad passenger cars and locomotives 24/7" (www.nedtrain.nl). Rolling stock is, in this case, defined as all the vehicles that move on a railway, this includes powered and unpowered vehicles. NedTrain counts their fleet of rolling stock in carriages, since trains can have different numbers of carriages. The total fleet of NedTrain consists of about 3000 carriages, one of those carriages costs about €2.500.000,-. On average there are five carriages per train, so this means approximately 600 trains. Those 3000 carriages are not all the same, they are divided into 12 different types.

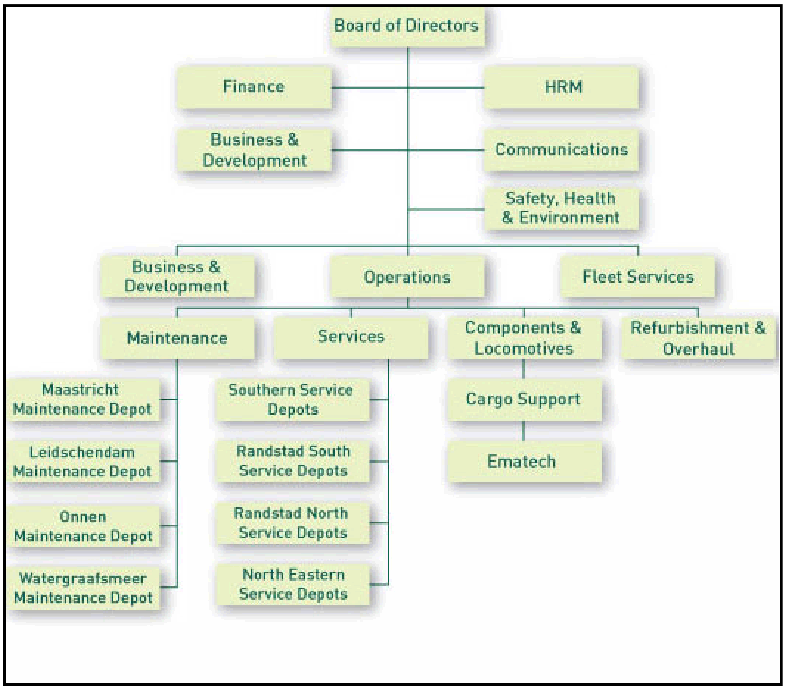

Figure 8: Organization NedTrain

The NedTrain headquarter is located in Utrecht and over 40 more sites of NedTrain are strategically located around the Dutch railroad network. The goal of those sites is to get the highest possible level of rolling stock availability and reliability, achieved 24/7 at the lowest possible costs. Over the years, NedTrain has become one of Europe's leading rolling stock maintenance and revision companies for both passengers and freight carriers, with 3100 employees and a turnover of 450 million euro in 2010. The organization of NedTrain is given in Figure 8.

3.2. Supply Chain Structure

NedTrain has a total of 50.000 different types of spare parts in use. Of those different types of spare parts, there are around 12.000 actively used throughout the year, the others are only used sporadically. NedTrain has classified three different categories of parts that all kinds of rolling stock have: consumable, repairable and main parts.

Consumable parts are parts that cannot be repaired and reused after having become defective. Repairable and main parts are both reusable parts, the difference is that main parts are individually identifiable during their lifecycle, while the repairable parts are only monitored per type. The main parts are in general the significantly more expensive parts; they are also the more critical components of the rolling stock. Parts become main parts for one of three reasons; it is legally required, it is economically attractive (main parts have their own maintenance schedule and this can make it more profitable for specific parts to be categorized main part) or the customer demands it. The focus of this project will be on main parts.

As said before, main parts have an individual maintenance schedule; this means that every main part has a maximum amount of time or kilometers before they need maintenance, this is called the technical lifetime of the spare part. If this deadline has past, the part can not be used until maintenance has been done. The remaining amount of time or kilometers before they need maintenance of all individual main parts is kept in a database. The total remaining amount of kilometers for a specific type of main parts for the total fleet can be calculated as well; this is summation of all the individual remaining times or kilometers of all the main parts of a specific type. This calculation becomes particularly interesting as the end of the total lifetime of a main part becomes closer, because the objective would be to have the total remaining amount of times or kilometers as low as possible at the end of the total lifetime of the part.

3.2.1. Different Kind of Service Locations

NedTrain divides the maintenance, servicing, cleaning and overhaul of rolling stock into three different types of activities; service, maintenance and ‘refurbishment and overhaul’. Each type has its own physical locations where the work is done. A schematic representation of the maintenance structure is already given in Figure 4. The different service locations in Figure 4 are explained in the following sections.

Service Depot

The first type of activities is the service; this is done in one of the service depots. All these locations where all rolling stock stays overnight if it is not in maintenance or used in the night shift. During the night, the rolling stock is cleaned and some small tests are done to check for failure in the system. Small repairs are done in the service depot during the same night. If during the checks problems are detected that are too complicated for the service depot to handle, the rolling stock will be scheduled to visit the maintenance depot. The service depot will be outside of the scope of this project.

Maintenance Depot (MD)

The second type of location is the maintenance depot. There are three reasons why rolling stock can go to the MD:

1. All rolling stock goes to the MD after a certain amount of time or kilometers driven (this is preventive maintenance).
2. If during one of the checks in the service depot problems are detected that the service depot can not repair themselves, the rolling stock is moved to the MD (this is corrective maintenance).
3. If the rolling stock breaks down in the field (this is also corrective maintenance).

Under normal circumstance (which means that there is no corrective maintenance necessary) the rolling stock goes to the MD approximately once every three months. Besides the planned rolling stocks that come in for preventive maintenance, there is also a possibility that there is rolling stock that needs corrective maintenance because they broke down when active in the field. Different types of rolling stock are repaired in different locations of the MDs. There are four different MD located across the Netherlands. All types of rolling stock are only sent to one, mostly two different locations of the MDs.

In the MD all the parts that need to be replaced are removed from the rolling stock and replaced. For the consumable and repairable spare parts, the decision whether they need to be replaced or not is based on the condition of the parts. For the main parts, general rules have been made by a maintenance engineer and the production planner acts within these rules.

Every main part has an individual registration number and the maintenance engineer links this to a maximum number of time or kilometers that the part can be in the rolling stock before revision is necessary. When the rolling stock comes in the MD, the production planner calculates how much more kilometers a main part can make and if the rolling stock will be back in the MD before this time has passed the main part won't be replaced, otherwise it will be replaced. The main parts are on average replaced after 3 to 10 years.

If there is no repaired or new spare part available for the part that is taken out of the rolling stock, then the rolling stock will be put in the waiting line until a part becomes available. Only in very exceptional cases can a rolling stock go back into the field with parts that should have been replaced, but where no parts were available for, this is called 'release outside tolerance'. 'Release outside tolerance' can only be done with the permission of a maintenance engineer. All the repairable spare parts that are removed from the rolling stock will be sent either to a warehouse or directly to the refurbishment and overhaul workshop.

Refurbishment and Overhaul Workshop (ROW)

The third type of location is the refurbishment and overhaul workshop. Part of the main parts that need to be repaired in the ROW are collected in a central warehouse, because the ROW does not have enough space to store all parts. When the ROW has repaired parts they will be sent back to the warehouse, from where the parts will be distributed over the different MDs in the country. The ROW also has the power to declare a part as irreparable, this practically happens for repairable parts, but never for main parts.

There are two ROWs in the Netherlands, one in Haarlem and one in Tilburg. All the repairable spare parts are sent to the depot in Tilburg, except for the main parts, which are sent to the depot in Haarlem. Since the main parts will be the focus of this project, only the depot in Haarlem will be inside the scope of this project.

4. Problem Definition and Scope

This chapter discusses the problem definition and scope of the project. In the first section the problem definition is given, followed by the project scope for the research. This project will be part of a broader project within NedTrain and the third section will explain the position of this project within the total project.

4.1. Problem Definition

As described in the previous chapters the problem that will be researched in this report is how to deal with the shortage of different types of capacity during peak loads in the ROW caused by a disproportionately distributed demand for maintenance of main spare parts. To solve this problem a mathematical model will be created. The objective of this model will be two fold; to assist NedTrain with the planning of the revisions of main parts and to provide insights in the consequences of long-term decisions in the planning of revisions of main parts in the ROW. For providing the insides three different scenarios will be analyzed, the different scenarios will be explained in the following subsections.

4.1.1. Capacity ROW

A constraint in the planning of the revisions of the main parts in the ROW is the capacity (here described as the maximum number of main parts that can be revised in one period). The decision that will be made by NedTrain is the amount of capacity that will be available per period of time for the revision of main parts. Increasing or decreasing the capacity of the ROW will have both financial and practical consequences for NedTrain. The scenario analysis that will be done with the created mathematical model can give the following insights:

1. The flexibility in the capacity of the ROW, the range that the capacity in the ROW can have where all the revisions necessary in the planning horizon are feasible.
2. The changes in total cost when the capacity of the ROW increases or decreases.

4.1.2. Number of Spare Parts

A constraint in the planning of the revisions of the main parts in the ROW is the number of extra main parts that is purchased at the beginning of the lifetime of a series of rolling stock. This limits the number of revisions that can be done per period of time. The decision that has to be made at NedTrain is the amount of spare parts that will be purchased at the beginning of the lifetime of a series of rolling stock. The insight that can be obtained here is how the costs change when the number of spare parts increases or decreases. The expectation is that purchasing of more parts will increase the total investment and holding costs of the main parts and decrease the total revision and replacement cost.

4.1.3. Inter-Revision Deadlines

A constraint in the planning for the revisions of the main parts in the ROW is the inter-revision deadline. This inter-revision deadline indicates the maximum time a main part may be in use between two consecutive revisions. By past experience NedTrain knows that there is a possibility that these deadlines can be increased. However, researching those possibilities costs money and time and it is not known how much increasing the inter-revision deadlines can gain. The decision that has to be made is whether or not it would be profitable to spend money on research that can lead to increasing the maximum time between two revisions; this can be done by a scenario analysis with the model created in this research.

4.2. Project Scope

As explained in section 3.2., NedTrain uses three types of spare parts; consumable, repairable and main parts. Only the main parts will be inside the scope of this project. Main parts are individually identifiable and they belong to a specific type of rolling stock. One type of main parts can be used in all the rolling stock of a specific type, but they are not exchangeable between types of rolling stock.

The main parts that are taken out of the rolling stock in the MD are transported to the ROW. The main parts are mainly repaired in the ROW in Haarlem; Tilburg repairs mostly the non-main repairable spare parts. For this reason the choice has been made to focus on the ROW in Haarlem and so this will be the only ROW within the scope of the project.

The ROW in Haarlem has three different departments where they perform different types of revision: one for the revision of carriages, one for revision of bogies and one for the revision of wheel sets. The three departments work as independent business units. The organizational structure of the ROW in Haarlem is schematically given in Figure 9.

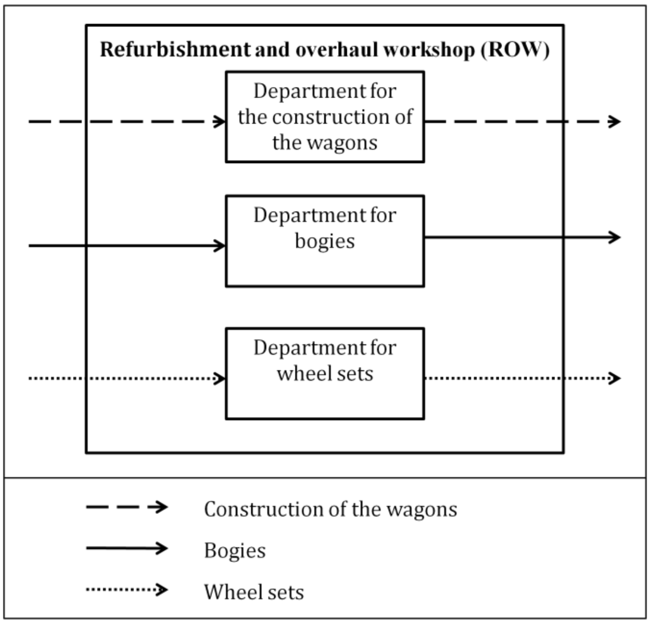

Figure 9: Schematically Representation of Department in ROW Haarlem

This project only makes a model for one of the departments; this is done because the revision capacity is independent over the different types of main parts. This means that a model created for one type of main parts can probably, with some adjustments and different data, also be used for the other types of main parts.

The revisions of the wheel sets don't fit into the problem discussed here. Even though the revisions of wheel sets are officially after a fixed inter-revision deadline, in practice it turns out that they almost never make it to the revision deadline. This means that these revisions are actually condition based maintenance. Both the carriages and the bogies would be suitable main parts to use for this research, the revisions for both parts are preventive and have a fixed inter-revision deadline. However, the construction of the carriages only has a revision once in the lifetime of the rolling stock and normally the revisions for the different carriages of one type are not planned individual. The bogies have revisions multiple times in their lifetime and are planned individual, wherefore they are expected to be a more interesting case and are chosen for this research (an example of a bogie is shown in Figure 10). From here on when this report

Figure 10: Example of a Bogie

speaks of the ROW, only the department for bogies is meant.

Rolling stock has a finite lifetime and the types of main parts that belong to that type of rolling stock have the same finite lifetime. The consequence is that all main parts of a specific type go out of the system as soon as the corresponding type of rolling stock goes out of the system.

All the main parts have besides their finite lifetime also an inter-revision deadline; this is the maximum amount of time or kilometers driven between two revisions. This amount of time or kilometers is a given amount per type of main parts.

The maintenance process of NedTrain can be divided into different types of activities, and corresponding locations, as explained in section 3.2.1.; the service depots, the MD's and the ROW's. All the activities done in the service depots will be outside the scope of this project. As explained earlier in this section, only the ROW in Haarlem will be inside the scope of the project. All the MD's will be in the scope of the project. In Figure 11 a graphical representation of the scope of the project is given.

The focus of the mathematical model to be made will be the ROW, because the capacity problems that are explained in the problem definition occur here. The model that will be generated will assist the asset manager parts to make an aggregate planning for the maintenance of main parts over the whole lifetime of a rolling stock type. The only input for ROW is bogies that need to be repaired. These bogies come from the MD's. Inside the ROW, the bogies are revised. The output of the ROW is ready-for-use bogies.

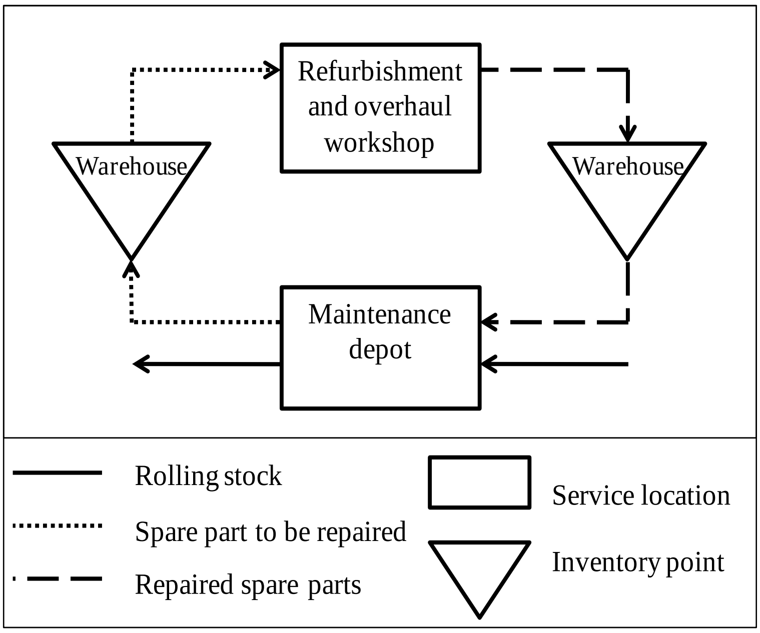

Figure 11: Scope of the Project

If, because of space limitation in the ROW, the bogies can not be transported to the ROW, they are transported to a warehouse and stored there until space becomes available. After the bogies are repaired in the ROW, they are normally transported to the warehouse, where they will be stored until use. There are two possible reasons to make exceptions on this rule. First, if a bogie is necessary in one of the MDs in the coming period, then the bogie is transported to that MD directly. The other exception occurs if the bogie is exclusively for a series of rolling stock that is only repaired in one location and they have enough space in their warehouse. Then the bogie is transported to that specific MD directly after the revision.

The MD's have two inputs: rolling stock that arrives here approximately once every three months, and the ready-for-use bogies from the ROW. Inside the MD, maintenance is done on the rolling stock. There is more work done here than only the replacement of bogies, but replacing main parts always has priority over the other work. The MD has two outputs that are inside the scope of this report; repaired rolling stock and bogies that need to be repaired.

The costs that will be considered in this project are the total life cycle costs of bogies, consisting of investment costs, holding costs, transport costs, and processing costs. The investment costs are the costs of purchasing the bogies. The holding costs are the costs of holding a bogie in inventory during a period of time. The transport costs are costs for transporting bogies from the MD to the ROW and vice versa. The processing costs are the costs for replacing a bogie in the MD or revision of a bogie in the ROW, this is the costs for the time mechanics is working on the maintenance.

4.3. Position of this Project in the Total Innovation Project of NedTrain

NedTrain is working on an innovation project for the maintenance of rolling stock. This is done in corporation with students and staff of three Dutch universities; Eindhoven University of Technology, University of Twente and Delft University of Technology. New technologies make it possible to measure the condition of parts of the rolling stock during the time they are in the field, this gives information useful for the timing of maintenance. The research question for the total project is to see if the maintenance program that is used now at NedTrain should change or stay the same when information on the state of the parts is know earlier and more accurately.

An overview of the total innovation project is given in Figure 12; here you can see three different levels; strategic, tactical and operational. The problem discussed in this report will be on tactical level, since it is on the planning of maintenance jobs (in figure 8 this is the arrow between 'tactical resource and spare parts planning' and 'operational maintenance job scheduling', which is highlighted in yellow). The output of the report will be input for the operational units.

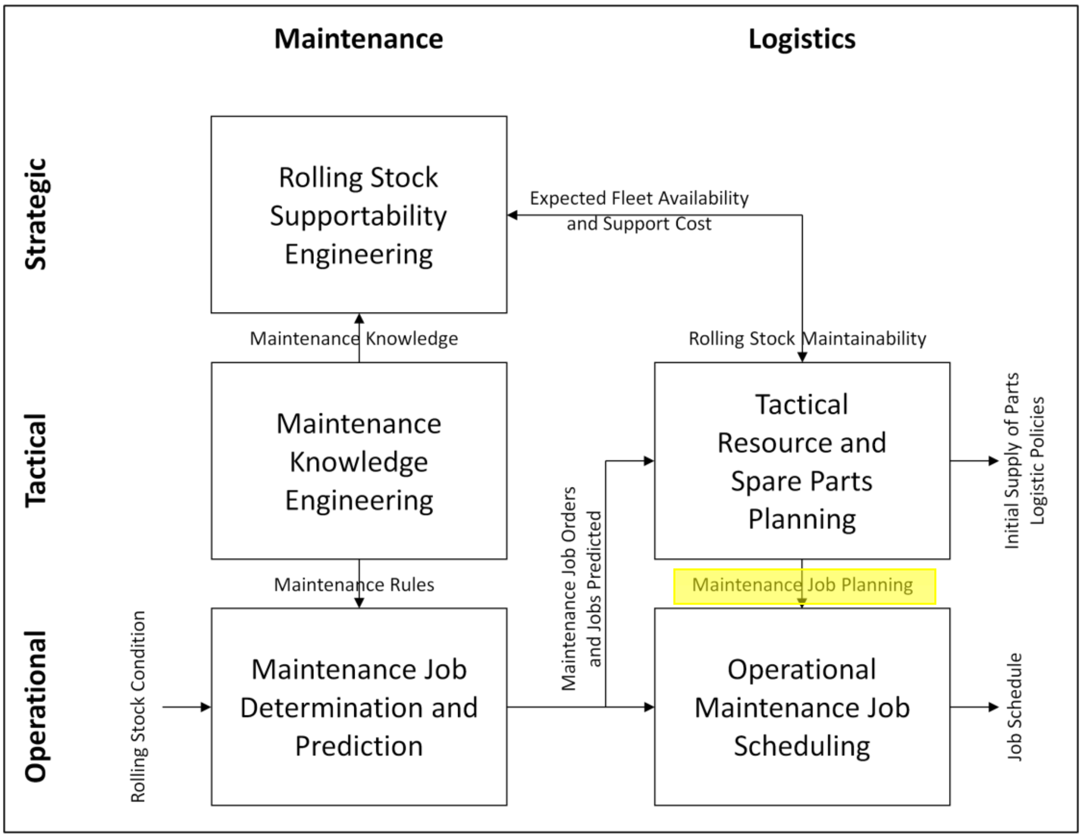

Figure 12: Overview Total Innovation Project of NedTrain

5. Mathematical Model

This chapter will explain the mathematical model created to solve the problem discussed in the previous chapters. In the first section, the different indexes, parameters and variables that will be used in the model will be defined. In section 2, a general overview is given to explain the environment of the model. Section 3 will discuss the planning horizon. In section 4 the different costs of the model will be explained and in section 5 the model assumptions and their justification will be discussed. The sixth section contains the mathematical model.

5.1. Sets, Parameters and Variables

In this sections the different first sets are defined, then the decision variables, the variables and finally the parameters.

Sets:

I : Set of all different types of parts considered in the model, $i \in \{1,2,3,\dots,|I|\}$.

T : Set of all periods considered in the planning horizon, $t \in \{1,2,3,\dots,|T|\}$.

I_t : Set of all types of parts that are in the field in period t.

Parameters:

a^i : For all part types that are already in use before the first period of the planning horizon this parameter is set 1. For all part types that are not in use before the first period of the planning horizon this parameter is set to the period in the planning horizon that part type i first goes into the field.

b^i : For all part types that are in use before the first period of the planning horizon this parameter indicates the number of ready-for-use parts type i in inventory at the beginning of the first period of the planning horizon. For all part types that are not in use before the first period of the planning horizon this parameter is the number of extra parts of type i that are purchased and are ready-for-use in the first period that part type i comes into the field.

c_c^i : The cost for purchasing one part of type i.

c_h^i : The cost of holding one part type i in inventory for one period.

c_f : The cost of one mechanic when working on the replacement of a part for one hour in the MD.

c_l : The cost of one mechanic for one hour in the ROW, independent of whether the mechanic is working on the revision of a part or not.

c_m^i : The cost of materials required for the revision of one part type i in the ROW.

c_{w1}^i : The cost of transporting one part from the MD to the ROW.

c_{w2}^i : The cost of transporting one part from the ROW to the MD.

d_{t}^i : Number of replacements of parts type i due in period t, $t \in \left\{\mathrm{a}^{\mathrm{i}},\dots,\min\left(\mathrm{p}^{\mathrm{i}},\left(a^i+q^i-1\right)\right)\right\}$.

f : Interest rate per period.

g^i : This parameter shows whether or not a part type i was already in the field before the planning horizon. This parameter is zero if part type i was already in the field before the planning horizon and one if the type or part comes into the field during the planning horizon.

h^i : For all part types that are already in use before the first period of the planning horizon this parameter indicates the number of parts type i waiting for revision in inventory at the beginning of the first period of the planning horizon. For all part types that are not in use before the first period of the planning horizon this parameter is set zero.

p^i : For all part types that go out of the field before the last period of the planning horizon, this parameter indicates the period on the planning horizon that part type i is taken out of the field. For all part types that don't go out of the field before the last period of the planning horizon the value of this parameter is set the last period in the planning horizon.

q^i : The inter-revision deadline, i.e. the maximum usage maximum allowed between two consecutive revisions of part type i (in periods).

r^i : The number of labor hours necessary for the revision of one part type i in the ROW.

R_t : The number of hours of labor capacity available for preventive maintenance in the ROW in period t.

z^{i} : The number of labor hours necessary for replacing one part of type i in the MD.

Decision variables:

$n_t^i: t \geq a^i, t \leq p^i$: The number of parts of type i that will undergo revision in the ROW in period t, for all types of parts that are in the field in period t.

$x_t^i: t \geq a^i, t \leq p^i$: The number of parts of type i that will be replaced in the MD in period t, for all types of parts that are in the field in period t.

Variables:

$B_t^i: t \geq a^i, t \leq p^i$: The number of ready-for-use parts type i in inventory at the beginning of period t.

$H_t^i: t \geq a^i, t \leq p^i$: The number of parts of type i that need revision before they can be used for replacement in inventory at the beginning of period t.

$W_t^i: \forall i \in I: (\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}) \leq \mathrm{p}^{\mathrm{i}}, \forall t \in \{(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}), \dots, \mathrm{p}^{\mathrm{i}}\}$: Number of replacements of parts type i due in period t.

5.2. Description Situation

An overview of the mathematical model is given in Figure 13, this section will discuss the different parts of the figure.

Arrow 1 in Figure 13 represents the new parts that come into the system. These parts enter the system through the ready-for-use inventory.

Arrow 0 in Figure 13 represents the rolling stock visiting the MD. In the MD (location 2 in Figure 13) the parts are replaced. A replacement can only be done if ready-for-use parts are available. After the replacement the rolling stock leaves the MD.

The parts that are taken out of the rolling stock are transported to the inventory point (point 4 in Figure 13) in front of the ROW, where the parts that are replaced in the MD are revised. This is represented by arrow 3. When the parts are planned to be revised, they go to the ROW (point 5 in Figure 13). For the ROW the optimal set of revisions per period has to be estimated, taking into account the labor capacity in the ROW and the number of parts in the inventory in front of the ROW. Once the parts are revised they go to inventory point 6 in Figure 13. From there they will be transported to the MD (arrow 7 in Figure 13).

Arrow 8 in Figure 13 represents the used parts that are taken out of the field.

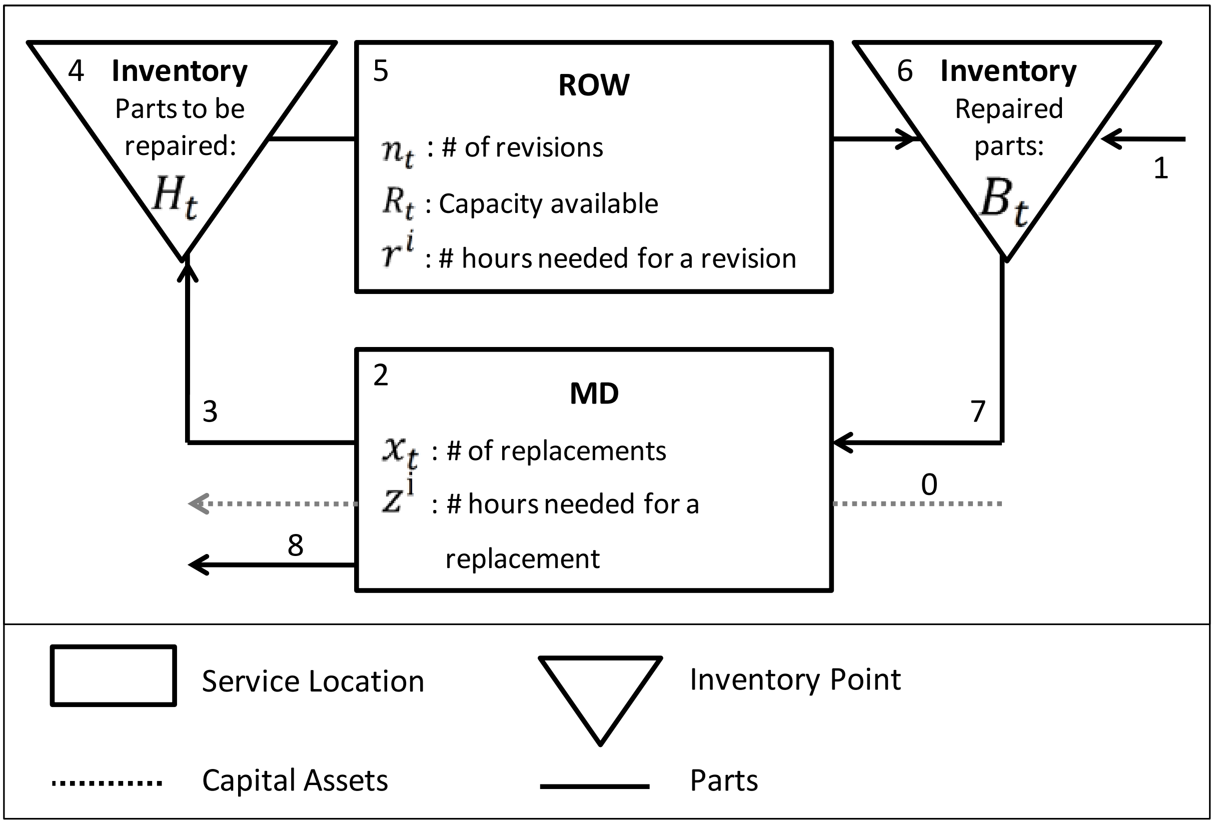

Figure 13: Scope of the Mathematical Model

5.3. Time

The finite lifetime of rolling stock is an important issue. To take this issue into account, the planning horizon in the model ends at the end of the year that the last type of rolling stock that is currently active is planned to go out of the field.

As explained before, every part has an inter-revision deadline and needs to be revised before a given revision deadline. When a part is revised before the revision deadline, this also changes the next revision deadlines for that part. For the first revision in the planning horizon the maximum amount of time left until the next revision will be given. The model will calculate the next revision deadline based on when the last revision has been executed. The part that has the shortest time until the revision deadline out of all the parts of the same type is replaced first.

The above explanation on the planning horizon is further clarified in Figure 14 and Figure 15. Figure 14 represents a planning horizon with 10 periods. The blue line is a type of part that comes into the field at the beginning of period 1 and goes out of the field at the end of period 10. The assumption has been made that this type of part has an inter-revision deadline of five periods, which means that it needs to be revised every five periods. The first revision deadline of the horizon is known, the revision has to be done before the end of period 5 (green line in Figure 14). To realize this deadline, the part has to be replaced at least latest in period 5. When this part is revised in period 5, it can be used again in the beginning of period 6 (yellow line in Figure 14), which means that it can stay in the rolling stock until the end of the planning horizon. For all the revisions after the first one, the model will calculate the revision deadlines based on when the last revision has been executed.

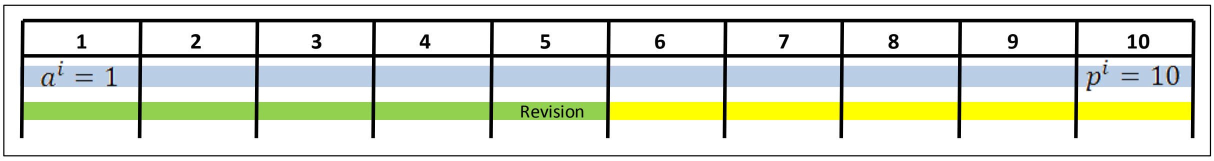

Figure 14: Planning Horizon

In Figure 15 the importance of including the finite lifetime is clarified. The same example is used as in figure 10, a planning horizon of 10 periods with a type of part that comes into the field in period 1, goes out of the field in period 10 and has an inter-revision deadline of 5 periods. If all the revisions can be done at the latest point possible (represented by situation 1 in Figure 15), there is only one revision necessary in the total lifetime of the part. Ideally, the revision will be done in period 5 and at the beginning of period 6 the part can be used again. It is only 5 more periods until the end of the planning horizon, so the part does not need any more revisions. However, if the part can not be revised in period 5 and the revision will be moved one period backward (represented by situation 2 in Figure 15), the part will need two revisions in the planning horizon.

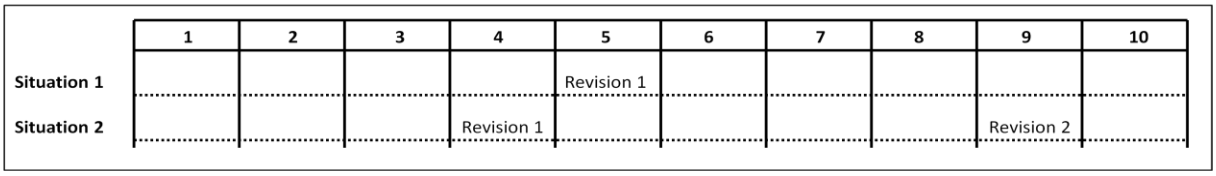

Figure 15: Importance Finite Lifetime

5.4. Costs

The objective of the model will be to minimize the total costs of preventive maintenance for the parts that are revised. The total costs of preventive maintenance considered here consist of investment costs, holding costs, transport costs, and processing costs related to the MD and the ROW. The investment costs are the costs of purchasing the parts. The holding costs are the costs of holding a part in inventory during a period, where it is assumed that there is no difference in costs for the ready-for-use parts and the parts that still need revision. The transport costs are the costs for transporting the parts from the MD to the ROW and vice versa. The processing costs are the costs for replacing a part in the MD or repairing a part in the ROW. All the different costs that are included in the model are shown in Figure 16, based on Figure 13.

The investment costs for the types of parts that are already in the field when the planning horizon starts are not included in the model, since these are sunk cost that can not be changed anymore. There is no possibility to buy new parts after a type of parts has gone into the field. The investment costs for the parts that belong to the rolling stock that come into the field during the planning horizon will be included (arrow 1 in Figure 16), since the amount of spare parts bought then still can be decided on. Initially, it is not possible to buy new parts for the types of parts that are already in the field at the beginning of the planning horizon.

The holding costs (point 4 and 6 in Figure 16) are initially not significant, since the system is a closed loop supply chain without any possibility to buy parts during the lifetime of the rolling stock and the initial amount of parts bought is outside the scope of the project. This means that in all different situations the holding costs will be the same. However, they will be included since this creates the opportunity to use the model for a broader range of analysis.

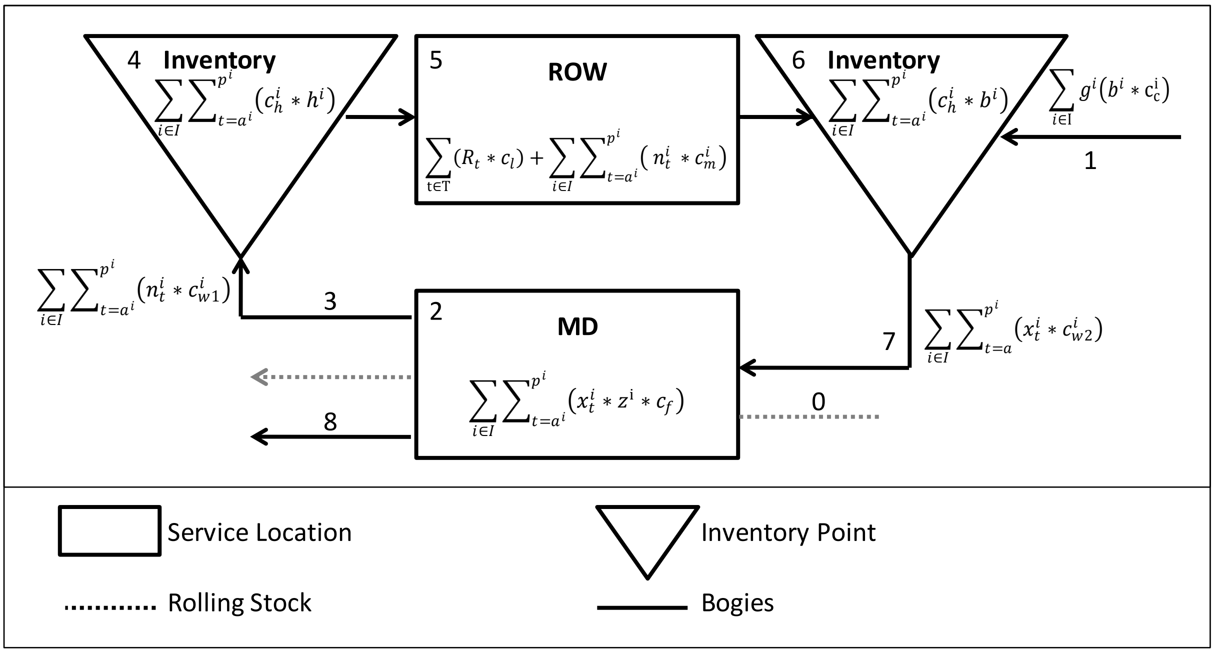

Figure 16: Cost Related to the Mathematical Model

As discussed in section 2.2, Paz & Leigh (1994) explained in their research that processing costs can be divided into three parts; equipment cost, material cost and labor cost. For the MD the equipment and material costs are not included in the model. All the equipment that is used is present, whether or not a part will be replaced. There are no extra costs for using equipment. There are no materials used to replace the parts. The labor costs (point 2 in Figure 16) for the MD are significant. They depend on the time that the mechanics use for replacing the parts, how much time they can use for other work, like replacing other kind of spare parts and helping the service depots.

In the ROW (point 5 in Figure 16) the processing costs are fixed. Repairing parts is the only activity done and since mechanics don't have flexible hours, spending less time on revisions does not decrease the labor costs. Of course, if the amount of hours could decrease permanently, the number of mechanics working in the ROW could change. In the ROW the equipment costs are also insignificant and will not be included in the model. The material costs on the other hand are significant for the ROW. During the revision of a part multiple subparts in the part are replaced. The material costs for one part are calculated by summing the costs of the subparts that need to be replaced for one revision per type of part.

The transport cost (arrows 3 and 7 in Figure 16) for parts between the MD and ROW are taken into account. To be able to do a revision, a part has to be transported from the MD to the ROW. To be able to do a replacement, a part has to be transported from the ROW to the MD.

In general, it is more profitable to spend money as far in the future as possible. As long as companies don't spend money they can get interest on it. In this model, the difference between taken this issue into account and not taking this issue into account could be that when the model does not include differences in costs for the different periods and it can plan a revision or replacement in two different periods it will plan randomly, while the model that takes cost changes into account will do it as late as possible. To include this into the model all the different values of future cost should be converted to present values, using the discounted cash flow (DCF) method. As French & Gabrielli

(2005) say in their article, the DCF method is “to determine the present value of a future cash flow”. In the case presented in this report, this would mean that the holding, labor, material and transport costs during the planning horizon would be converted to present values. The net present value of an incoming or outgoing cash flow at t $= \frac{Future\ Value_t}{(1+f)^t}$, where f is the interest rate and N is the moment in time that the future cash flow occurs.

5.5. Model Assumptions

In this section the model assumptions are given, the structure is based on Figure 13.

New types of parts coming into the field (arrow 0 in Figure 13)

In this section all assumptions are given that concern the new parts that come into the field during the planning horizon.

1. All the individual parts have a preset deterministic moment in time that they come into the field.
2. It is only possible to buy new parts in the period that a part first goes into the field.
3. The investment costs are fixed linear costs per type of part.

Capital Assets (arrow 1 in Figure 13)

In this section all assumptions are given that concern the rolling stock.

4. All the inter-revision deadlines for the different types of parts are fixed deterministic deadlines of at least one period, given in periods.
5. Every individual part can be replaced in any period in the planning horizon.

MD (point 2 in Figure 13)

In this section all the assumptions will be explained concerning the MD.

6. The hourly wage for mechanics in the MD is a fixed linear amount over the planning horizon.
7. The amount of hours needed to replace a part in the MD is fixed per type of part for the planning horizon.
8. The MD has no capacity constraints.

Transport parts (arrows 3 and 7 in Figure 13)

In this section the assumptions concerning the transport of the parts from the MD to the ROW are explained.

9. The transport of parts between the MD and the ROW and vice versa is mutually independent.
10. Transportation capacity between the MD and the ROW is unlimited.
11. Transportation time between a MD and the ROW can be neglected.
12. Transport costs for the transport from a MD to the ROW are linear and fixed per type of part for the planning horizon.

Stock point (points 4 and 6 in Figure 13)

In this section the assumptions concerning the stock point that contains parts that need repair are explained.

13. The inventory costs are the same for parts that need revision as for ready-for-use parts.
14. There is no storage limit.
15. The holding costs are fixed linear costs per type of part over the planning horizon.

ROW (point 5 in Figure 13)

In this section all the assumptions will be explained concerning the ROW.

16. The amount of hours needed to revise a part in the ROW is fixed per type of part for the planning horizon.
17. The labor capacity in the ROW is limited.

18. Every revision for a specific type of part is the same.

Disposal of types of parts (arrow 8 in Figure 13)

In this section all assumptions are given on the disposal of parts during the planning horizon.

19. All the different types of parts have a fixed deterministic finite lifetime; the period that a specific type of parts goes out of the field is given.
20. There are no cost and/or profits associated with the disposal of the parts at the end of their lifetime.

5.6. Mathematical Model

This section explains the mathematical model created.

Objective:

$$Minimize\ \sum_{i\in \mathrm{I}} g^i\left(\frac{b^i * \mathrm{c}_\mathrm{c}^\mathrm{i}}{(1+f)^{a^i}}\right)+\sum_{\mathrm{t}\in\mathrm{T}}\left((R_t * c_l)/(1+f)^t\right)+\sum_{i\in I}\sum_{t\prime=a^i}^{p^i}\left(c_h^i\left(b^i+h^i\right)+\left(x_{t\prime}^i * z^\mathrm{i} * c_f\right)+\left(n_{t\prime}^i * c_m^i\right)+\left(n_{t\prime}^i * c_{w1}^i+x_{t\prime}^i * c_{w2}^i\right)/(1+f)^{t\prime}\right) \qquad (1)$$

(1) Objective function; being the sum of the purchase cost of all the new parts that will be bought within the planning horizon, the labor cost in the ROW, the holding cost, the labor cost in the MD, the material cost in the ROW and the transport cost from the ROW to the MD and from the MD to the ROW.

Constraints:

$$H_t^i = H_{t-1}^i + x_{t-1}^i - n_{t-1}^i\,, \qquad \forall i \in I\colon p^i \geq a^i+1, \forall t \in \left\{a^i+1,\dots,p^i\right\} \qquad (2)$$

$$H_{a^i}^i = h^i\,, \qquad \forall i \in I \qquad (3)$$

$$B_t^i = B_{t-1}^i + n_{t-1}^i - x_{t-1}^i\,, \qquad \forall i \in I\colon p^i \geq a^i+1, \forall t \in \left\{a^i+1,\dots,p^i\right\} \qquad (4)$$

$$B_{a^i}^i = b^i\,, \qquad \forall i \in I \qquad (5)$$

$$\sum_{i\in I_t}\left(n_t^i * r^i\right) \leq R_t, \qquad \forall t \in \{1,\dots,|T|\} \qquad (6)$$

$$n_t^i \leq H_t^i + x_t^i, \qquad \forall i \in I, \forall t \in a^i,\dots,p^i \qquad (7)$$

$$x_t^i \leq B_t^i, \qquad \forall i \in I, \forall t \in \left\{a^i,\dots,p^i\right\} \qquad (8)$$

$$\sum_{t\prime=\mathrm{a}^\mathrm{i}}^{\mathrm{t}} d_{t\prime}^i \leq \sum_{t\prime=\mathrm{a}^\mathrm{i}}^{\mathrm{t}} x_{t\prime}^i\,, \qquad \forall i \in I, \forall t \in \left\{\mathrm{a}^\mathrm{i},\dots,\min\left(\mathrm{p}^\mathrm{i},\mathrm{a}^\mathrm{i}+\mathrm{q}^\mathrm{i}-1\right)\right\} \qquad (9)$$

$$W_t^i = x_{t-q^i}^i, \qquad \forall i \in I\colon \left(\mathrm{a}^\mathrm{i}+\mathrm{q}^\mathrm{i}\right) \leq \mathrm{p}^\mathrm{i}, \forall t \in \left\{\left(\mathrm{a}^\mathrm{i}+\mathrm{q}^\mathrm{i}\right),\dots,\mathrm{p}^\mathrm{i}\right\} \qquad (10)$$

$$\sum_{t\prime=\mathrm{a}^\mathrm{i}}^{\mathrm{a}^\mathrm{i}+\mathrm{q}^\mathrm{i}-1} d_{t\prime}^i + \sum_{t\prime=\mathrm{a}^\mathrm{i}+\mathrm{q}^\mathrm{i}}^{\mathrm{t}} W_{t'}^i \leq \sum_{t\prime=\mathrm{a}^\mathrm{i}}^{\mathrm{t}} x_{t\prime}^i, \qquad \forall i \in I\colon p^i \geq a^i+q^i, \forall t \in \left\{\left(\mathrm{a}^\mathrm{i}+\mathrm{q}^\mathrm{i}\right),\dots,\mathrm{p}^\mathrm{i}\right\} \qquad (11)$$

$$n_t^i \geq 0,\ x_t^i \geq 0, B_t^i \geq 0, H_t^i \geq 0, \qquad \forall i \in I, \forall t \in \left\{a^i,\dots,p^i\right\} \qquad (12)$$

(2) The number of parts of type i in stock at the beginning of period t that need a revision equals the number of parts of type i in stock at the beginning of period t-1 that need a revision, plus the number of replacements of parts type i that has been done in period t-1, minus the number of revisions of parts type i that has been bone in period t-1. This constraint holds for all i where the second period that the part is in the field is lower or equal then the period that the part goes out of

the field. This constraint holds for all t from the second period that the part is in the field to the last period that the part is in the field during the planning horizon.

(3) The number of parts of type i that need revision in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of extra parts of type i that need revision that are in inventory in the first period that the type or parts goes into the field. This constraint holds for all i.

(4) The number of ready-for-use parts of type i in stock at the beginning of period t equals the number of ready-for-use parts of type i in stock at the beginning of period t-1, plus the number of revisions of parts type i that has been done in period t-1, minus the number of replacements of parts type i that has been bone in period t-1. This constraint holds for all i where the second period that the part is in the field is lower or equal then the period that the part goes out of the field. This constraint holds for all t from the second period that the part is in the field to the last period that the part is in the field during the planning horizon.

(5) The number of ready-for-use parts of type i in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of extra ready-for-use parts of type i that are in inventory in the first period that the type or parts goes into the field. This constraint holds for all i.

(6) For every period, the total amount of time to do all the planned revisions can never be more than the total available revision time in the ROW, for every period.

(7) There can never be more revisions of parts type i in period t then the number of parts of type i that need revision in stock at the beginning of the period plus the number of replacements that is done in period t. This constraint holds for all i between the beginning of the first period that the specific type of parts comes into the field until the end of the last period that the type of part is in the field.

(8) There can never be more replacements of parts type i in period t then there are revised parts of type i in stock at the beginning of the period. This constraint holds for all i between the beginning of the first period that the specific type of parts comes into the field until the end of the last period that the type of part is in the field.

(9) If t is less than or equal to the period when the part comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be equal to the total demand until the current period, for every period. This constraint holds for all i's.

(10) The demand for part type i in period t is equal to the number of replacements of part type i, τ periods ago. This constraint holds for all i's where the period when the part comes into the field plus the inter-revision deadline $\left(\mathrm{a}^{\mathrm{i}}+\mathrm{q}^{\mathrm{i}}\right)$ is less than or equal to the period that the part goes out of the field $\left(\mathrm{p}^{\mathrm{i}}\right)$. This constraint creates a rolling horizon where the number of replacements in the past create due dates for replacements in the present en future. If capacity problems occur, a replacement of a part can be pushed backwards in the planning horizon, this constraint ensures that the next replacements for that part are also pushed backwards.

(11) If t is greater than the period when the part comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be the total demand until the current period, for every period. The total demand until the current period equals the sum of the parameter D_t^i and the variable W_t^i over the period from a^{i} to t.

(12) Non-negativity constraint.

6. Case Study: NedTrain

As a case study for the model explained in the previous chapter the planning of preventive maintenance of bogies at NedTrain will be used.

As explained in section 4.2, the planning of preventive maintenance of bogies at NedTrain fits in the model created in this research. An average bogie cost around €200,000.- and is active for approximately 30 years. NedTrain has more than 5,200 bogies divided over 30 different types. The different types have different inter-revision deadlines and need to go through the same capacity in the ROW.

NedTrain plans the preventive maintenance of bogies at three different levels; strategic, tactical and operational. At a strategic level plans are made on which types of bogies will be revised in which years in the future. At a tactical level the decisions are made on how many bogies of the different types will be revised in specific months. At an operational level the day to day planning is made which bogie will be revised on which day. This model is to support the tactical level of decision making and the time units in the model are set one month.

Hereafter, it will firstly be explained how the different assumptions that have been made for the model fit NedTrains case and what extra simplifying assumptions are made. In the second subsection the different values of the input parameters for the model will be discussed. In the last section the implementation of the mathematical model in GUSEK is discussed

6.1. Justification Model Assumptions

This section will justify the different assumptions that belong to the mathematical model for the NedTrain case study. In the first subsection the different assumptions given in section 5.5 will be justified. The second subsection will discuss some extra assumptions that are specific for the NedTrain case study, these assumptions will be justified as well.

6.1.1. Model Assumptions

This subsection discusses the justification of the model assumptions given in section 5.5.

1. All the individual parts have a preset deterministic moment in time that they come into the field.

This assumption does not completely match with the reality at NedTrain. The moment in the planning horizon that the part goes into the field is often stochastic. Since the planning horizon for the model is approximately 30 years, at the moment the planning is made there are only estimates of when a new type or rolling stock will be purchased and used in the field. The moment of introduction depends among others on financial possibilities, future research on the possibilities to extend the lifetime of types of rolling stock in use and the progress in the development of new types of rolling stock. The choice has been made to use deterministic times because NedTrain does not have the exact data that can be used to calculate the variability in these planned dates.

2. It is only possible to buy new parts in the period that a part first goes into the field.

NedTrain only buys new bogies at the beginning of the lifetime of a type of rolling stock. The two most important reasons why there are no new bogies bought during the lifetime of a type of rolling stock are; first, when more bogies are necessary during the lifetime of a type of rolling stock this is usually because there are crisis situations, but the lead time of new bogies is on average too long to solve those situations. The result would be that the bogies arrive after the crisis has ended. The second reason why no new bogies are bought during the lifetime is that there are a lot of situations where it is not possible anymore to buy new bogies, because they are simply no longer produced. Since rolling stock has a long lifetime, it is likely that the producer already sells a newer version before the old ones are taken out of the field.

3. The investment costs are fixed linear costs per type of part.

Since parts can only be bought at the beginning of the lifetime of rolling stock, this purchase is at one moment in time and so there are no fluctuations in these costs over the planning horizon. There is a fixed price per part and so the costs are linear.

4. All the inter-revision deadlines for the different types of parts are fixed deterministic deadlines of at least one period, given in periods.

This assumption is reality for part of the types of bogies at NedTrain. However, some of the bogies types have an inter-revision deadline that is based on the amount of kilometres driven. To convert this to time, which is the input for the model, the total amount of kilometres a bogie can be in the field before revision is divided by the average number of kilometres driven per period. The number of kilometers driven per period is assumed to be a constant number, since the NS strives to let every train in the fleet drive on average the same amount of kilometres per period. Since the average number of kilometres driven per period can have some variability, in reality it is possible that a bogie has to be revised before the revision deadline, because it has already been used the maximum amount of kilometres.

5. Every individual part can be replaced in any period in the planning horizon.

The model only gives the amount of bogies that has to be replaced per period and assumes that that bogie is chosen that has been in the field the longest time. However, in reality it is possible that the bogie that has been in the field the longest does not come into the MD in that month, since the rolling stock is only coming in approximately once every three months. This is a constraint that has to be taken into account when the tactical planning made by the model is converted into a planning on operational level, since bogies can not stay in the field after the revision deadline.

6. The hourly wage for mechanics in the MD is a fixed linear amount over the planning horizon.

There is a fixed hourly wage per hour for the entire planning horizon and so the costs are linear.

7. The amount of hours needed to replace a part in the MD is fixed per type of part for the planning horizon.

Theoretically it is possible that the hours needed to replace a bogie in the MD decrease over time because of new improved techniques, but since there is no plausible reason to suggest that in practice right now, the assumption has been made that there is a fixed amount of hours needed for a replacement.

8. The MD has no capacity constraints.

For the MD the equipment, material and labor capacity are not included in the model. There can only be as many replacements in one period as there are ready-for-use parts available. The MD always has more equipment, material and labor capacity than needed to handle this maximum number of replacements.

9. The transport of parts between the MD and the ROW and vice versa is mutually independent.

The transportation between the MD’s and the ROW is outsourced. For NedTrain the transport in one direction is independent of the other direction, because NedTrain pays linear cost per bogie per one-way trip.

10. Transportation capacity between the MD and the ROW is unlimited.

There are no limits on the number of parts that can be transported between the MD’s and the ROW.

11. Transportation time between a MD and the ROW can be neglected.

The transportation of the bogies between the MD’s and the ROW takes on average four hours. To make the transportation more efficient, multiple main parts are transported together. The total time involved with this type of transport is at most two days. Since the periods in this model are set to months, this transportation time has been neglected.

12. Transport costs for the transport from a MD to the ROW are linear and fixed per type of part for the planning horizon.

The transportation between the MD’s and the ROW is outsourced, the cost are fixed per type of bogie per ride.

13. The inventory costs are the same for parts that need revision as for ready-for-use parts.

Inventory costs are calculated based on space that a bogie occupies in the warehouse. Bogies that need revision occupy the same space as ready-for-use bogies, which make the inventory cost equal.

14. There is no storage limit.

There is enough storage capacity to store bogies.

15. The holding costs are fixed linear costs per type of part over the planning horizon.

There is a fixed price for holding one bogie in inventory for one period and so the costs are linear.

16. The amount of hours needed to revise a part in the ROW is fixed per type of part for the planning horizon.

Theoretically it is possible that the hours needed to revise a bogie in the MD decreases over time because of new improved techniques, but since there is not plausible reason to suggest that in practice right now, the assumption has been made that there is a fixed amount of hours needed for a revision.

17. The labor capacity in the ROW is limited.

NedTrain has found that the labor capacity in the ROW is the bottleneck for the revisions in the ROW. When looking back at Figure 5 this looks reasonable, since the ROW has to keep up with the peaks in the demand for revisions.

18. Every revision for a specific type of part is the same.

In reality there are multiple types of revision for every type of bogie. Those different revisions are often combined by maintenance engineers to avoid replacing the bogies too often. Because this is done manually and on intuition there are no guidelines for how to combine. For the basic model an average revision will be created per type of bogie.

19. All the different types of parts have a fixed deterministic finite lifetime; the period that a specific type of parts goes out of the field is given.

In reality the finite lifetime of a type of bogies are usually stochastic; the planned date that a type of rolling stock is taken out of the field can vary over time during the lifetime of the rolling stock. This depends among others on future research on the possibilities to extend the lifetime of the rolling stock and the possibilities to purchase new types of rolling stock. The choice has been made to use the deterministic times because NedTrain does not have data that can be used to calculate the variability in this planned date.

20. There are no cost and/or profits associated with the disposal of the parts at the end of their lifetime.

In reality there is a small amount of money paid by a third party for the bogies at the end of their lifetime. Because the amount is flexible and unpredictable over the years and insignificant compared to all the other cost, these profits are not taken into account in the model.

6.1.2. Assumptions Related to Case Study NedTrain

For the case study at NedTrain not all exact information on the input parameters is known for the upcoming 30 years. To be able to use the model, some extra assumptions have to be made for the case study.

First, it is not exactly known what details will be on the successors of the types of rolling stock that are currently in use. The assumptions that have been made for this:

21. When the lifetime of a type of bogies ends, a new type of bogies is brought into the field in the next period in the planning horizon.

The seating capacity (this is the amount of seats available) in rolling stock necessary over the total public transport network has been stable over the last years, even increasing. So, when a type of rolling stock is taken out of the field it is plausible that there will be a new type of rolling stock coming into the field with at least as much seating capacity as the last type.

22. A new type of rolling stock that comes into the field during the planning horizon requires the same “effort” as the type or rolling stock that is taken out of the field.

When the planning is made to take a type of rolling stock out of the field in a specific period in the future, there is normally not much information available about the maintenance efforts that are needed for the new type of rolling stock, since the new type of rolling stock may not even have been designed yet. Since technology improves over time, a save assumption would be that the maintenance of a new type of rolling at least does not require more maintenance as the old type, so assuming that it takes the same effort would be a save assumption for NedTrain.

23. A new type of bogies arrives at the beginning of the same period as the corresponding type of rolling stock arrives in the field.

There is no extra delivery time for bogies that come new in the field; they arrive at the beginning of the same period as the corresponding type of rolling stock.

Second, in the model there is only one MD, NedTrain has in reality four. Chapter 2 explains why there is no significant difference in results when the situation at NedTrain is modeled as if there is one MD. An extra assumption that is needed for this:

24. The hourly wage for mechanics is the same for all MD’s.

In reality this is assumption is not completely correct. There are different labor costs for the different MD’s. But since researching how much work for which types of rolling stock is done in what MD is outside the scope of this project, the average wage has been taken as input for this model. The biggest deviation between the average and one of the MD's is 5%.

Lastly, NedTrain has years in which the different types of bogies come into the field and in reality this is done gradually over multiple periods. However, the exact distribution over the different periods is not known. The extra assumptions needed for this:

25. All bogies of one type come into the field at the beginning of the same period.

In the model all bogies of one type come into the field at the beginning of one specific period in the planning horizon. In reality, the new type of rolling stock will be brought into the field gradually over multiple periods. The choice has been made to use one period to get the new type into the field, because NedTrain currently does not have data that can be used to calculate the actual situation.

26. All bogies of one type go out of the field at the end of the same period.

In the model all bogies of one type go out of the field in the end of one specific period in the planning horizon. In reality, the rolling stock will be taken out of the field gradually over multiple periods. The choice has been made to use one period to get the type out of the field, because NedTrain does not have data that can be used to calculate the actual situation.

6.2. Model Input

The model created contains multiple parameters for which the values are not researched before at NedTrain and therefore the values are not currently available. Researching those parameters is outside the scope of this project, especially because of time constraints. The choice have been made that the values for the different unknown parameters are estimated by Bob Huisman, the maintenance development manager at NedTrain. This way the employees of NedTrain can develop an understanding in which way the model can be used and what benefits can be achieved with it. When the results are promising, more research can be done to the exact value of the different parameters.

The remaining of this section will explain how the different input parameters for the GUSEK model are gathered to simulate the situation at NedTrain. First the initial values of the parameters for the basic model will be given. In the second part of this section, the parameters for the basic model with cash flow discounting are given.

6.2.1. Initial Input Parameters Basic Model

This section will explain how the different initial input parameters have been generated. The parameters are divided into different categories; bogie types parameters, time parameters, cost parameters, labor capacity parameters and initial revision due parameters. The different categories will be discussed in the following subsections. The values for the different input parameters can be found in appendix E.

Bogie Types Parameters

First, the different types of bogies that will be considered in this model have to be determined. NedTrain has 30 different types of bogies that are currently in use and all of those types will be considered in the model. In NedTrains database the data is found about what the different kind of bogies are and how many spare bogies were bought at the beginning of the lifetime of the different types of bogies. In total, NedTrain has approximately 5200 bogies, 92.5% of those bogies are built in rolling stock, and the others are in inventory. Figure 17 shows per type of bogie the number of bogies built into rolling stock and the number of spare bogies.

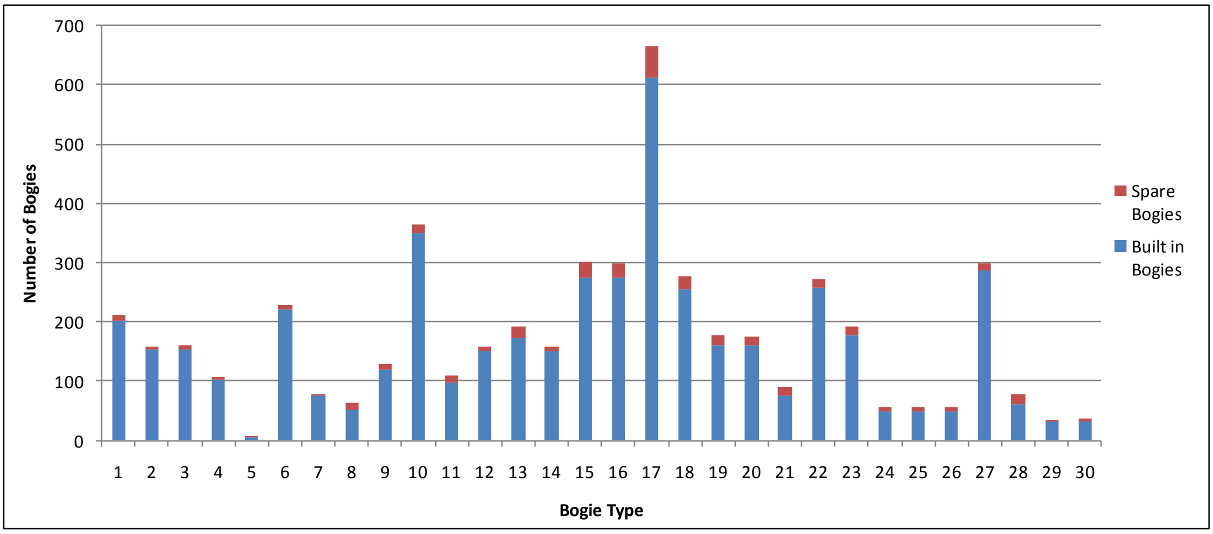

Figure 17: Number of Bogies per Bogie Type

The above information gives the values of three of the models input parameters; g^i (all these bogies are already in use, so $g^i = 0$ for all those types of bogies, b^i and h^i. The value for those different values for these 30 types of bogies can be found in Table 78 in appendix E.

Besides the 30 types of bogies that are already in the field, multiple dummy bogies have been created to replace the types of bogies that are currently in use and go out of the field before the end of the planning horizon. These dummy bogies are created because not all 30 types of bogies that are in use have the same end of their lifetime and it is not realistic that the bogies that go out of the field are not replaced by new bogies. The challenge with these dummy bogies is that there is no information available on how the maintenance will be done. The choice has been made to give the new type of bogie the same characteristics as the old type of bogie.

Time Parameters

Concerning time, every bogie type has a start period (i.e. the period in the planning horizon that the bogie comes into the field), an end period (i.e. the period in the planning horizon that the bogie goes out of the field) and an inter-revision deadline (i.e. the maximum time that a type of bogie can spend in the field between two revisions).

The start periods (a^i) are one for all types of bogies that were already in the field before the planning horizon. For the types of bogies that come into the field after the planning horizon has already started, the start period is one period after the bogie that it is replacing went out of the field. The inter-revisions deadlines are found in NedTrains database, they vary for the different types of bogies between 6 and 20 years. Figure 18 show the different inter-revisions deadlines per bogie type. NedTrain has expected end dates for all types of bogies that are already in use and those dates are used for the end periods (p^i). NedTrain hasn't specified those dates in periods; there is only an expected year available. The end period for the different types of bogies will be set equal to the last period of the expected year.

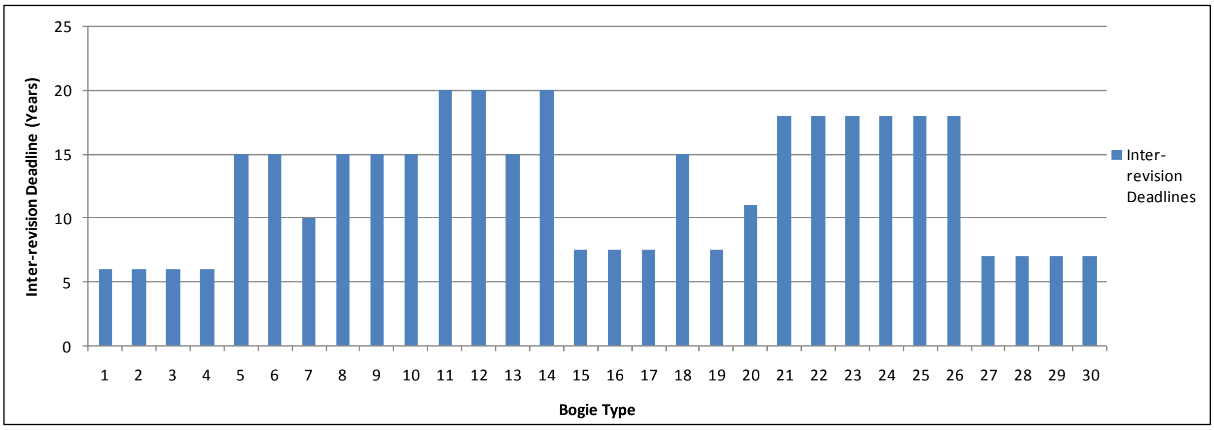

Figure 18: Inter-revision Deadlines per Bogie Type

Table 79 of appendix E shows the different start and end periods for all 56 types of bogies. In this table it can be seen that the last type of bogie to go out of the field goes out of the field in period 360, this will also be the last period of the planning horizon (t_e).

Cost Parameters

There are six different cost parameters; costs for labor in the ROW, costs for labor in the MD, purchasing costs, holding costs, material costs and transport costs.

The costs for the labor hours in the ROW (c_l) and the MD's (c_f) have been researched in an earlier study by Cretier (2011) done at NedTrain. The values for those parameters are known. As explained in section 6.1, the different cost for the different MD's are not taken into account, an average of the different labor cost per hour over all the MD's is used. The labor cost per hour in the MD is €[redacted].- and in the ROW the labor cost per hour is €[redacted].-.

The purchasing(c_c^i), holding(c_h^i), material (c_m^i) and transport$(c_{\mathrm{w1}}, c_{\mathrm{w2}})$ costs have been estimated by Bob Huisman, manager maintenance development of NedTrain. The purchasing costs for an average bogie is approximately €200,000.-. The holding costs are €40.- per bogie per period, independent of the type of bogie. The material costs for a revision are on average €10,000.- and the transport costs are approximately €1,000.- per trip from the ROW to one of the MD's or the other way around. The values for those input parameters are given in Table 80 in appendix E.

Labor Capacity Parameters

There are three parameters that are related to labor capacity: the number of hours necessary for the revision of one bogie type i in the ROW (r^i), the number of hours of labor capacity available for preventive maintenance in the ROW in period t (R_t) and the numbers of labor hours necessary for replacing one bogie of type i in the MD (z^{i}).

The number of hours necessary for the revision of one bogie type i in the ROW is dependent on two variables: the type of bogie and the type of revision. All revisions for one type of bogie are the same and for this parameter an estimate have been made for the time an average revision of a bogie takes, being on average 200 hours per revision.

The number of hours of labor capacity available for preventive maintenance in the ROW in period t has been researched by Rousseau (2010). Those values have been used, being 13,000 hours per period. However, this is the total number of hours available for revisions in the ROW, corrective and preventive maintenance together. For this research only the number of hours available for preventive maintenance will be used. For this reason the percentage of time that is spent on corrective maintenance in the ROW has to be calculated.

Only for the months January to May of the year 2011 the data was available for estimating the percentage of corrective maintenance per month. Five months of data is not enough to make a good calculation or reveal season pattern, but it gives an estimate that has been used. From the data it can be seen that in those five months on average 6% of the work done in the ROW is corrective maintenance. Therefore, the total amount of hours available in the ROW for preventive maintenance 12,220 hours per period.

The numbers of labor hours necessary for replacing one bogie in the MD (z^{i}) is dependent on the type of bogie that needs replacements. For the model an estimation has been done by Bob Huisman, this is dependent on the type of bogie 1 or 2 hours per replacement.

The values of the three parameters described in this subsection can be found in Table 81 appendix E.

Initial Revision Due Parameters

The NedTrain database contains the moment in time that the next inter-revision deadline occurs for the different types of bogies and those values have been used to set the initial revision due parameters (D_{t}^{i}). The inter-revision deadlines by NedTrain have been set at a year and not a period as is needed for this model. For the model, the inter-revision deadlines have been set the last period of the year that NedTrain has calculated for the next revision.

The values for the initial revision due parameters can be found in Table 82 appendix E.

Input Parameters Cash Flow Discounting

For the cash flow discounting extension one parameter has to be set, the discounting rate per period (f). This parameter is set 5% per year, this is the standard value that NedTrain used and that makes results obtained with the model easily comparable to other calculations NedTrain has done. In the model the periods have been set a month instead of a year, the discount factor will be adjusted for this.

6.3. Implementation of the Mathematical Model

Solving the mathematical model for a problem with the size of NedTrain is too complicated to do manually. For this reason software will be used to generate the results. How the software is selected is explained in the first subsection of this section. After this, in subsection 2, the model is validated.

6.3.1. Selection of the Software

The mathematical model created in the previous chapter is a linear programming (LP) model. There are many different software tools available to solve LP models. Preference is software that can be used without buying licences, this gives more flexibility for future use.

Initially the options for using the Excel solver have been explored, since this is available on all computers of NedTrain and employees are used to work with it. However, it turned out that the created model has more decision variables than the allowed limit in the Excel Solver.

The next step was looking at open source software that allows enough decision variables (the needed number of decision variables is for the basic model approximately; 30 part types * 360 periods * two different decision variables per period per part type = 21,600 decision variables) and can solve problems with the size of NedTrains problem in a reasonable time (the model should be solved in maximum 10 minutes). After solving the model with different software tools, the software tool GUSEK was chosen. This tool can handle the problem size of NedTrains problem within a reasonable time and has the advantage that there are already people within NedTrain working with it, which makes implementing it easier.

GUSEK can read different input languages. For this problem the choice has been made to use GMPL, since this is already used at NedTrain. The translation of the mathematical model given in the previous chapter in GMPL is given in appendix B.

6.3.2. Model Validation

In his article, Sargent (2003) discusses different methods for validation of conceptual models. Not all methods are applicable for the model created here, since for example, there is no historical data available because the planning has been done differently in the past. Methods that are applicable for this model are: event validity, comparison to other models, extreme condition test and face validity. All of these validity methods are used to validate the created model, the explanation, elaboration and results can be found in appendix C for the basic model and appendix D for the extended model. As can be seen in appendix C and D, all the different methods give the conclusion that the model is valid.

7. Case Study Results

In this chapter the results for the case study at NedTrain, obtained with the model described in the preceding chapters are given. As described in section 4.1., the first objective of the model is to assist NedTrain with the planning of the revisions of bogies. The results with respect to this objective will be discussed section 7.1. The results related to the second objective, to provide insights in the consequences of long-term decisions in the planning of revisions, will be discussed in section 7.2.

While reviewing the results, it is important to take into account that multiple input parameters for the model are based on estimations (see section 6.2), because the exact data is not currently available. The consequence for the results is that they might not match reality exactly. Even though the results might differ from reality, the effects of different types of decisions can still be derived from the results. Before concrete decisions can be made based on the model, the data for the different estimated parameters has to be collected.

Secondly, it should be kept in mind while reviewing the results that the model assumes that the last period of the planning horizon equals the final period that bogies are in the field. This means that the expected number of revisions in the last years will be lower than in reality, because the demand for ready-for-use bogies ends.

7.1. Planning Results

The model is used to generate a planning for the revision of bogies over the planning horizon, which consists of 360 periods of one month length. To show the consequences of cash flow discounting by the planning of revisions, the net present value (NPV) of the costs are calculated in two ways; for the first calculation a discounting factor of 0% is used (which equals a situation where cash flow discounting is not taken into account), the second calculation has a discounting factor of 5% (which equals the discounting factor that NedTrain generally uses). A discounting factor of 0% results in a net present value of €541,246,922.-, a discounting factor of 5% results in a net present value of €268,213,286.-.

Further analysis shows the consequences of the planning for the different service location in the supply chain. Figure 19 shows the utilization of the capacity of the ROW per period. Only the capacity of the ROW for preventive maintenance (12,220 hours) is taken into account in this figure.

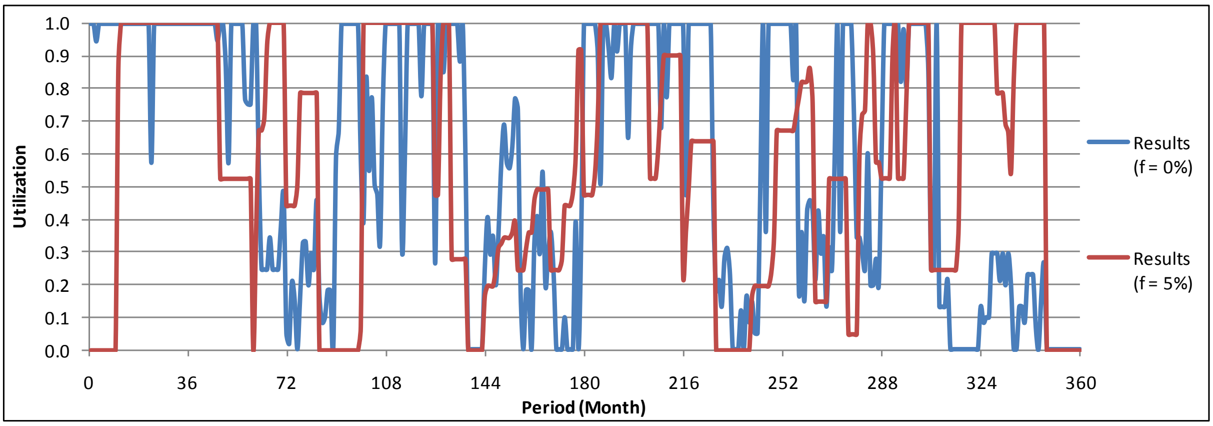

Figure 19: Utilization Capacity ROW (R=12,220)

Figure 19 shows multiple notable insights.

Firstly, both lines show the disproportionately distributed demand for maintenance of bogies (as has been described in the problem definitions). The peak loads in the demand, where the capacity is totally used for multiple periods in a row are alternated with periods where only a small part of the capacity is used. Those peaks correspond with the moments in time that types of bogies with a large population approach their inter-revision deadline.

Secondly, besides the individual peaks, also a more general trend is notable; peaks in the revision demand are a lot of the time clustered closely together. This is caused by the inter-revision deadlines of multiple different types of bogies in the fleet being close together. In the situation where the discounting factor is 5%, the peaks in revisions are clustered more often than with a discounting factor of 0%. This happens because the costs are lower for periods in the future, which means that the model tries to do all revisions as late as possible to minimize the total costs.

Thirdly, a large part of the current fleet of rolling stock is currently at half of its lifetime, which means that after approximately 15 years in the planning horizon a large part of the fleet is replaced by new rolling stock. This creates a gap in the demand for revisions, because the new types of rolling stock do not need any revisions during the first years.

Fourthly, during the first approximately 60 periods (5 years) the capacity of the ROW is almost completely used. There are two causes for this: a high number of already scheduled revisions during the first five years and inflexibility in the planning caused by a relatively short period to plan deviation from the original inter-revision deadlines. In the first years of the planning horizon there is not a lot of flexibility to spread out the revisions over time, since revisions can only be brought backward and not forward. This, in combination with the high number of scheduled revisions for the first five years, makes that these years the capacity has to be used completely to make all revisions possible. The difference between the two lines in Figure 19 originates from the fact that in the situation where the discounting factor is 0%, the capacity in the ROW is completely used from the first period on. However, in the situation where the discounting factor is 5%, in the first periods no capacity is used at all. This happens because these are the most expensive periods to perform revisions and all possible flexibility is used to push the revisions forward.

Lastly, a big difference between the two lines can be noted in the approximately last 5 years of the planning horizon. Where the discounting factor is 0%, the capacity of the ROW is not used for more than 30%. As explained in the introduction of this chapter, this is caused by the fact that the model acts as if the last period of the planning horizon is the last period in the lifetime for all types of bogies that are still in the field in that period. The model stops with the revision of the bogies, since the demand for ready-for-use bogies stops. On the other hand, where the discounting factor is 5%, the last years of the planning horizon are used almost completely. This is caused by the fact that all revisions are pushed as far backwards as possible.

Figure 20 shows the hours per period that are used in the MD’s for the replacement of the bogies. Here the same patterns can be found as was seen in the utilization of the ROW in Figure 19. This makes sense, since the replacement and revision of bogies are mutually dependent processes. Almost all revisions of one type of bogie are done in the last periods before the inter-revisions deadline and there is only a limited amount of spare bogies, so replacements have to be done in the same periods to make all revisions possible.

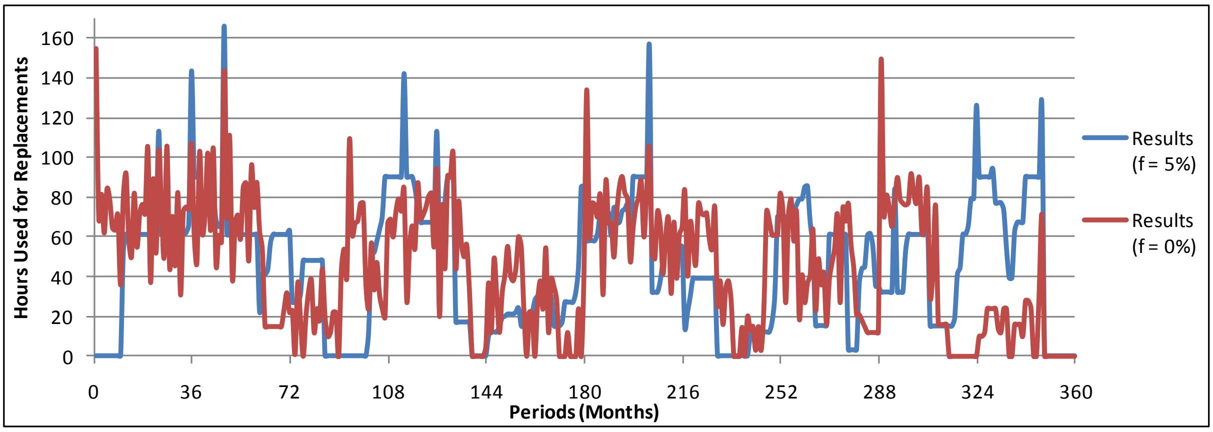

Figure 20: Hours Used in MD's (R=12,220)

Figure 20 also confirms that labor capacity in the MD's is no limitation for the revisions. The highest peak in the figure shows a little less than 170 hours of work in a period in the MD's, which equals the work of one full time mechanic in the MD. Since every MD has multiple mechanics, the labor capacity in the MD's will never be a constraint for the revisions of bogies.

7.2. Results Scenario Analyses

As explained in section 4.1 making a planning for the revision of bogies is the first objective of the model. The second objective of the model is to provide insights in the consequences of decisions in the planning of revisions of main parts in the ROW. These insights are achieved through scenario analysis with the model, as explained in section 4.1. The results of the three different scenario analyses will be discussed in the following three subsections.

7.2.1. Capacity ROW

The first scenario analysis will, as explained in section 4.1.1, provide insights in the consequences of changing the capacity of the ROW. The starting position for this scenario analysis is the situation shown in section 7.1; in this situation there are 12,220 hours dedicated to preventive maintenance and the Net Present Value is €541,246,922.- with a discounting factor of 0% and €268,213,286.- with a discounting factor of 5%.

Figure 19 already showed the peak loads in demand for revisions. The consequence of those peak loads is that the capacity in the ROW is completely used for multiple periods in a row, while in other periods only a small part of the capacity in the ROW is used. In reality, making a planning which uses the capacity completely in certain periods can cause problems, since this leaves no space for any unplanned events in those periods. Even though this is a planning for preventive maintenance, not all unplanned events can be prevented. To solve this problem, future research at NedTrain could indicate what the optimal level of utilization would be for the ROW.

To analyze what the consequences are of changing the number of hours available for revisions in the ROW the capacity has been changed gradually with steps of 160 hours (or multiple of 160 hours). The 160 hours are equal to one full time mechanic working in the ROW. The results for this analysis are shown in Table 1.

.

Table 1: Changing Capacity ROW

Capacity ROW (hours)	% Change in Capacity ROW	NPV (f = 0%)	% Change NPV (f = 0%)	NPV (f = 5%)	% Change NPV (f = 5%)
9,340	-24	Infeasable	-	Infeasable	-
9,820	-20	€480,870,602,-	-11	€238,388,755.-	-11
10,300	-16	€492,945,866.-	-9	€244,305,168.-	-9
10,780	-12	€505,021,130.-	-7	€250,254,306.-	-7
11,260	-8	€517,096,394.-	-4	€256,224,200.-	-4
11,740	-4	€529,171,658.-	-2	€262,211,507.-	-2
12,220	0	€541,246,922.-	0	€268,213,286.-	0
12,700	4	€553,322,186.-	2	€268,213,287.-	2
13,180	8	€565,397,450.-	4	€280,259,113.-	4
13,660	12	€577,472,714.-	7	€286,303,173.-	7
14,140	16	€589,547,978.-	9	€292,365,307.-	9

Table 1 shows that it is still feasible to plan the revisions for all types of bogies with up to 16% less capacity in the ROW. The peak loads are flattened by pushing revisions backwards in the planning. Table 1 also shows that the costs can be decreased when the capacity of the ROW is decreased. The results shown in Table 1 are also shown in Figure 21 and Figure 22.

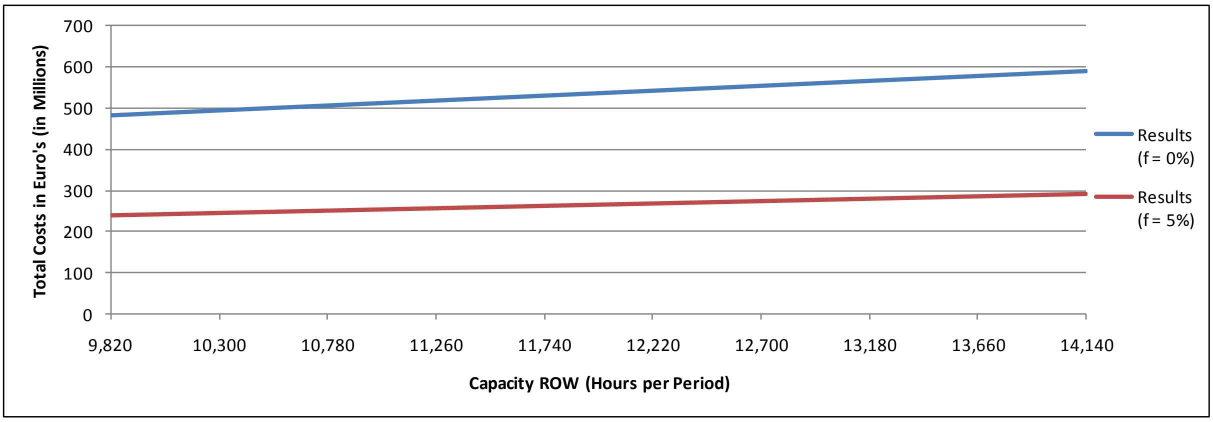

Figure 21: Change in Total Costs with Different Capacities in the ROW

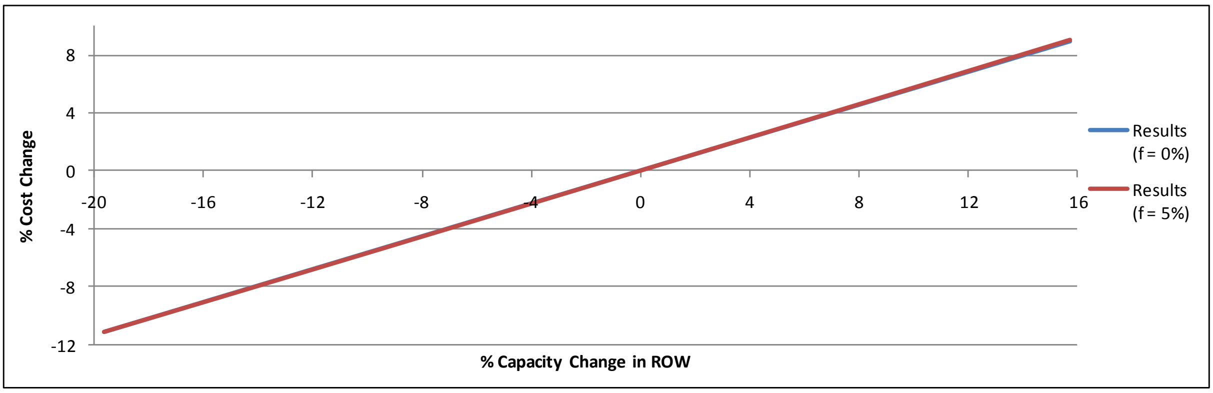

Figure 22: Percentage Change of Total Cost with Different Capacities in the ROW

As can be seen in Figure 21, the total costs decrease linearly with the decrease of the capacity of the ROW for the situation where the discounting factor is 0% as well as the situation where the discounting factor is 5%. Figure 22 shows that the percentage change in costs is exactly equal for both situations.

Further analysis of the situation where the discounting factor is 0% shows that the costs decrease equally with €12,075,264.- for every decrease of 480 hours in the capacity of the ROW. These costs equal the labor cost in the ROW; 480 hours per period multiplied with 360 periods over the planning horizon and multiplied with the hourly wage in the ROW of €[redacted].- gives €12,075,264.-. The total change in costs equals the change in labor costs because these are the only costs that change, the total amount of revisions or replacements does not change when the capacity of the ROW is changed, they are just spread differently over time.

As can be seen in Table 1, if the capacity of the ROW is decreased to 9,340 hours per period no feasible solution can be found. To find the minimum costs for this situation, the lowest capacity should be found that is still feasible. To find this point, the capacity of the ROW (R_t in the model) has been changed from a parameter to a decision variable. Moreover, an extra constraint is included in the model, to keep the capacity constant over all the periods in the planning horizon:

$$R_t = R_{t+1}, \qquad \forall t \in 1, \dots, t_e - 1 \tag{13}$$

(13) The capacity of the ROW has to be the same for all period in the planning horizon.

When this model is executed, it is found that the minimum needed capacity for a feasible solution is 9,583 hours per period. This gives a present value of €474,908,440.- for a 0% discounting factor and €235,482,980.- for a 5% discounting factor.

The utilization of the capacity in the ROW for this scenario is given in Figure 23. This figure shows that when the capacity is set 9,583 hours per period, the peaks in revisions are flattened in comparison with Figure 19. In the first half of the planning horizon, the flattening of the peaks causes that the capacity is approximately fully used. In the middle and the end of the planning horizon the capacity is still not fully used, caused by the finite lifetime of different types of bogies. In the second part of the planning horizon, the peaks are flattened, but not totally disappeared.

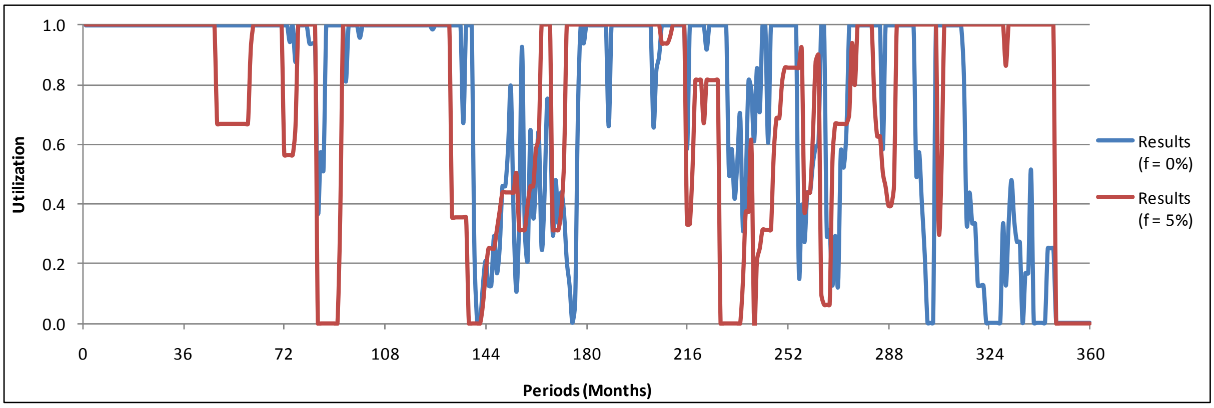

Figure 23: Utilization Capacity ROW (R=9,583)

The findings of Figure 19 and Figure 23 combined, show that in the first approximately 60 periods (5 years) of the planning horizon the planned revisions leave the model with little space to plan the revisions flexibly over time. This raises the question if the capacity could decrease even more than 9,583 if those five years are not taken into account.

In Table 2 the total costs are given for the cases where the capacity per period will decrease even more from the 6th year on. The capacity of the first five years is set 9,660, this is the closest number to 9,583 that is still a multiple from 160 hours away from 12,220 hours. The steps in which the capacity decreases from the 6th year on are set 160 hours per period, which equals one full time mechanic.

Table 2: Consequences of Changing Capacity ROW Periods 61 to 3600

Capacity ROW 2011-2015 (in Hours)	Capacity ROW 2016-2040 (in Hours)	% Change in Mechanics	NPV (f = 0%)	% Change NPV (f = 0%)	NPV (f = 5%)	% Change NPV (f = 5%)
9,660	9,660	-21	€476,845,514.-	-11.9	€236,425,792.-	-11.9
9,660	9,500	-22	€473,491,274.-	-12.5	€235,010,313.-	-12.4
9,660	9,340	-24	€470,137,034.-	-13.1	€233,598,614.-	-12.9
9,660	9,180	-25	€466,782,794.-	-13.8	€232,195,521.-	-13.4
9,660	9,020	-26	€463,428,554.-	-14.4	€230,803,283.-	-13.9
9,660	8,860	-27	€460,074,314.-	-15.0	€229,417,329.-	-14.5
9,660	8,700	-29	€456,720,074.-	-15.6	€228,039,147.-	-15.0
9,660	8,540	-30	€453,365,834.-	-16.2	€226,667,050.-	-15.5
9,660	8,380	-31	€450,011,594.-	-16.9	€225,303,383.-	-16.0
9,660	8,220	-33	€446,657,354.-	-17.5	€223,947,845.-	-16.5
9,660	8,060	-34	€443,303,114.-	-18.1	€222,604,680.-	-17.0
9,660	7,900	-35	€439,948,874.-	-18.7	€221,287,900.-	-17.5
9,660	7,740	-37	€436,594,634.-	-19.3	€220,019,789.-	-18.0
9,660	7,580	-38	€433,240,394.-	-20.0	€218,778,798.-	-18.4
9,660	7,420	-39	Infeasable	-	Infeasable	-

In Table 2 can be seen that the total costs over the planning horizon can decrease even more if the capacity per period will decrease after year 5. When a capacity of 9,660 hours per period is used for 2011 until 2015 and a capacity of 7,420 hours per period is used for the years 2016 until 2040, the total costs can decrease with approximately 20% over the total planning horizon. The utilization for the capacity in the ROW for this situation can be seen in Figure 24.

For Table 2 the same remark has to be made as earlier, that the minimum calculated here is the theoretical minimum which does not take unexpected events like sickness and holidays of mechanics into account. To set values for capacity in reality, some flexibility for these kinds of events should be taken into account.

The capacity of 7,580 hours per period can handle the peak loads of demand that have been seen in Figure 19. The fact that the capacity can stay 7,580 hours for a period of 25 years without any problems with the multiple peak demands suggests that in the periods after the planning horizon this value can be kept. This means that the capacity can be reduced permanently and without consequences for hiring new mechanics after the total planning horizon of the model has passed.

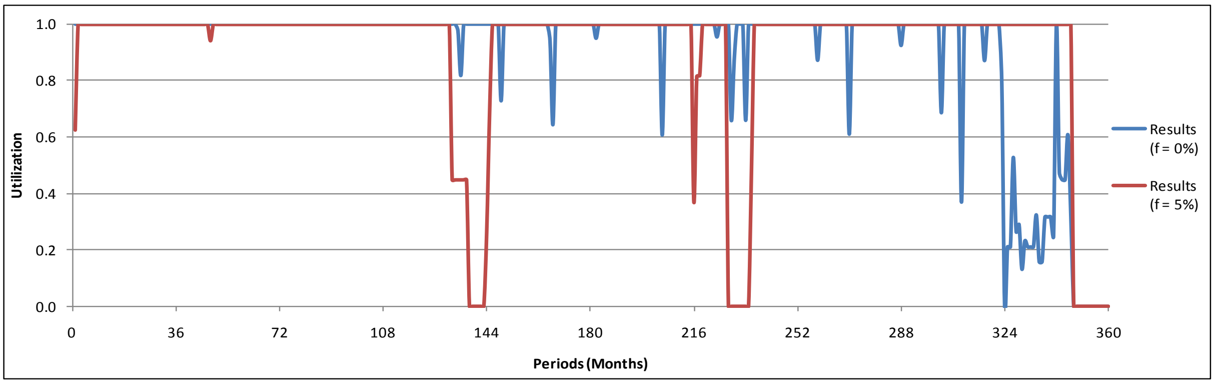

Figure 24: Utilization Capacity ROW (R[1,...,60}=9,660, R[61,...,361]=7,580)

7.2.2. Number of Spare Bogies

The second scenario analysis will, as explained in section 4.1.2, provide the insights in the consequences of the changing the number of spare bogies in the population. The number of spare bogies in the population will be decreased and increased to see what the consequences are on the total costs for revisions in the ROW.

Now, the total population of bogies consists of approximately 5,200 individual bogies, approximately 7.5% of those bogies are spare bogies. For the first analysis, the number of spare bogies over the total populations (the 7.5%) is changed. This means that when the number of spare bogies is changed with 10%, the number of spare bogies for each type of bogie is changed 10%. The results are shown in Figure 25 and Figure 26.

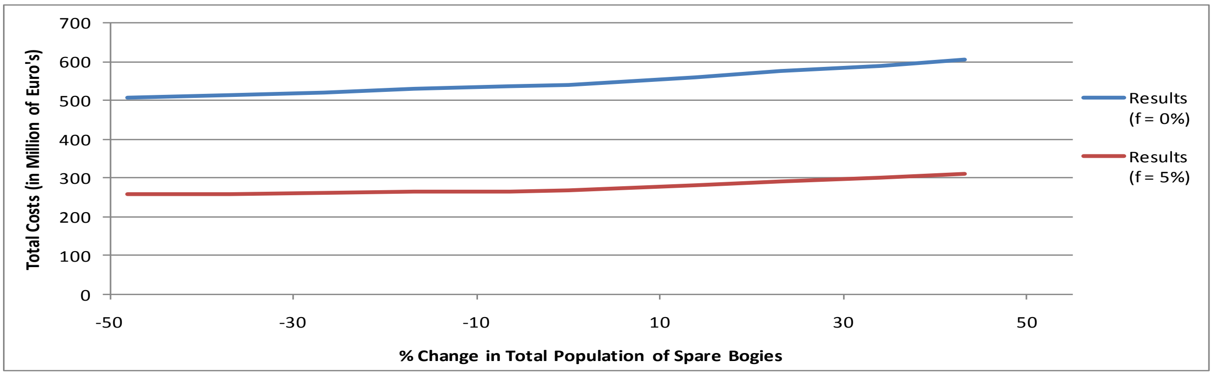

Figure 25: Change in Total Cost when Changing the Total Population of Spare Bogies

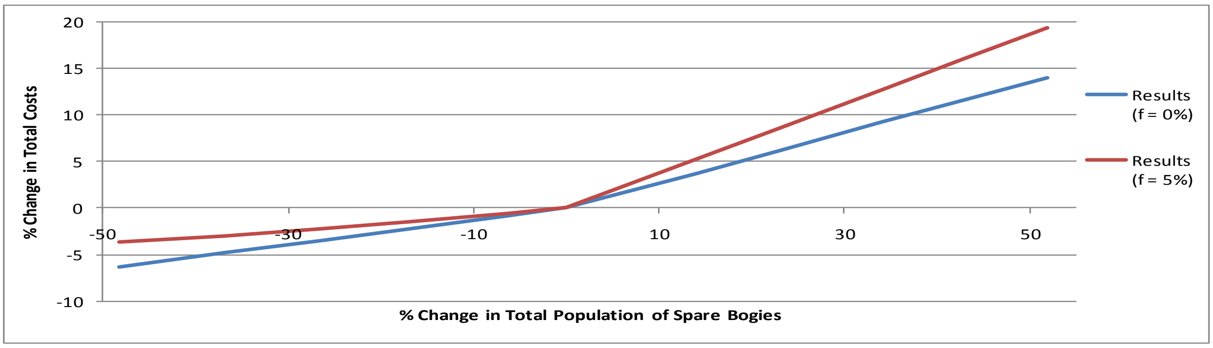

Figure 26: % Change in Total Cost when Changing the Total Population of Spare Bogies

Both lines in Figure 25 and Figure 26 show a nod, this implies that there is different relationship for the situation where the population of spare bogies is decreased or increased. This difference is caused by the investment costs for the types of bogies that are already in the field at the beginning of the planning horizon. When the population of spare bogies is decreased, the bogies for the types of bogies that were already in the field at the beginning of the planning horizon are taken out of the system without any extra costs or revenue. However, when the population of spare bogies is increased, extra spare bogies have to be bought for the types of bogies that are already in the field at the beginning of the planning horizon.

A further investigation of the results shows that when the total population of spare bogies is changed, the total number of revisions stays the same. This means that the change in total costs found in Figure 26 is meanly caused by two types of costs; the investment costs and the holding costs. When the total population of spare bogies is decreased, the investment costs change because fewer bogies have to be bought for the types of bogies that come into the field during the planning horizon. The holding costs will decrease because there are fewer bogies to keep on stock. When the total population of bogies is increased, the investment costs change because more bogies have to be bought, both for the types of bogies that are already in the field at the beginning of the horizon and for the types of bogies that come in the field during the planning horizon. The holding costs change because more bogies have to be kept in inventory.

When the total population of spare bogies is decreased more than 50%, an infeasible situation is created. The reason for this situation is that there are too little spare bogies to handle all the revisions before the inter-revision deadline.

The last notable issue in Figure 26 is the difference for the total costs calculated with a discounting factor of 0% and 5%. The percentage change in total costs is less when the costs are calculated with a discounting factor of 5% then when the discounting factor is 0%. This is caused by the investment costs for bogies that come into the field after the start of the planning horizon. Because those costs are planned in the future and so discounted when the discounting factor is 5%, they influence the total costs less proportionally.

The different types of bogies can be clustered by the type of rolling stock they belong to. NedTrain has six different types of rolling stock; SLT, SGM, ICM, VIRM, DDZ and ICRm. In the next analysis, the number of spare bogies per type of rolling stock is changed to check if the different types of rolling stock have a different effect on the total costs of revisions.

Different factors that could influence the effect of one type of bogie on the total costs are the percentage of bogies that one type of bogie has compared to the total population of bogies, the length of the inter-revision deadline and the different cost parameters. Figure 27 shows the percentage of bogies per type of rolling stock in the total fleet of bogies. The expectation is that the types of

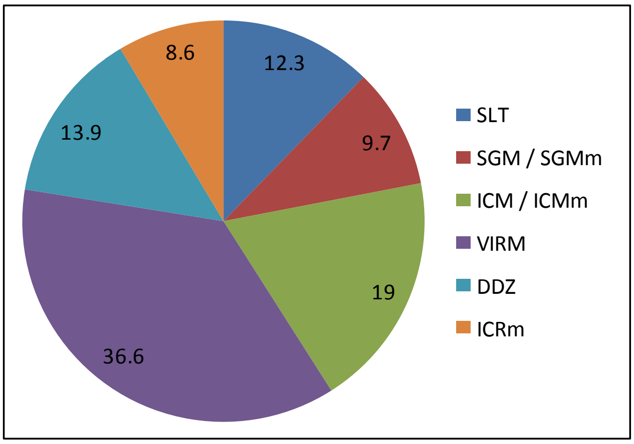

Figure 27: The Percentage of Bogies per Type of Rolling Stock in the Total Fleet of Bogies

rolling stock with a high percentage in Figure 27 have a stronger effect on the change in total costs. The percentage of bogies that one type of bogie has, compared to the total population, influences the change in total costs in two ways. First, there are more bogies that need revisions during the lifetime of a type of rolling stock, with corresponding higher expected costs for replacements and revisions. Second, when the type of bogie goes out of the field during the planning horizon, this means a new type of rolling stock has to come into the field with a corresponding high number of bogies, which causes high investment costs. Figure 28 shows the weighted average for the inter-revision deadlines for the different types of bogies that belong to the different types of rolling stock.

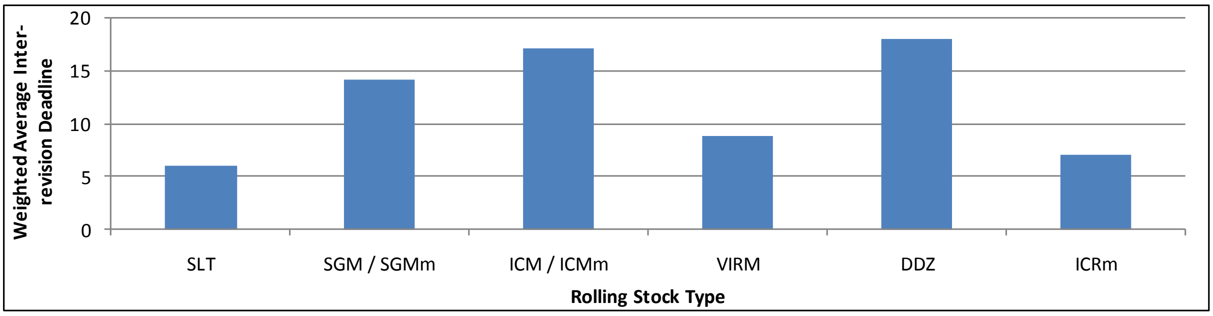

Figure 28: Weighted Average Inter-revision Deadlines per Types of Rolling Stock

The number of spare bogies per type of rolling stock is changed to see if the different types of rolling stock have a different effect on the total costs of revisions. These results can be found in Figure 29 and Figure 30, respectively for a discounting factor of 0% and 5%.

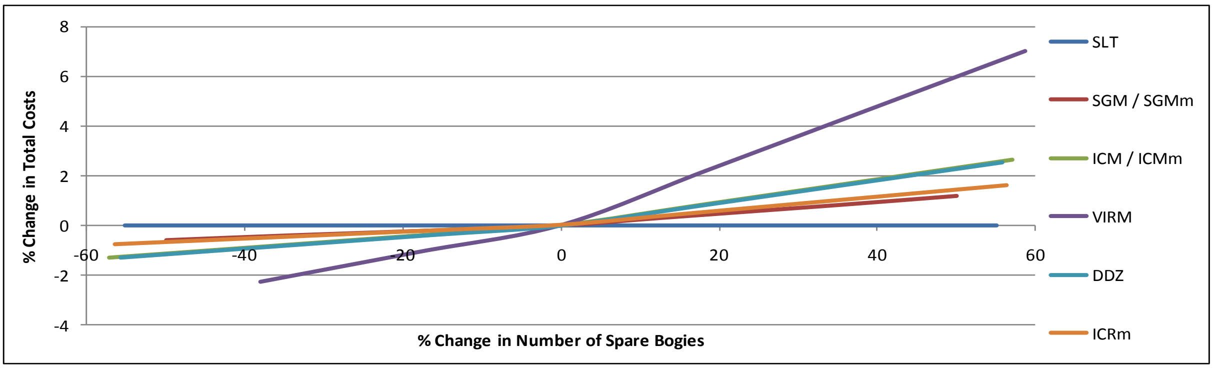

Figure 29: % Change in Total Cost when Changing the # of Spare Bogies per Rolling Stock Type (f = 0%)

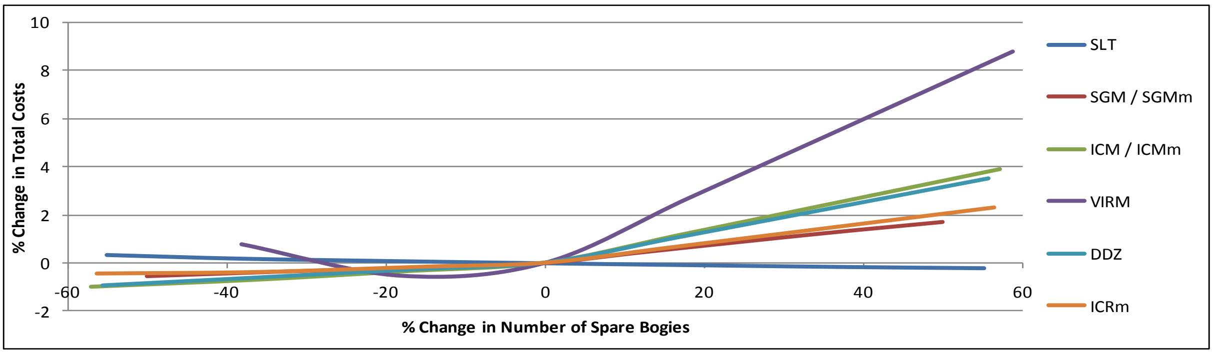

Figure 30: % Change in Total Cost when Changing the # of Spare Bogies per Rolling Stock Type (f = 5%)

Figure 29 shows that by a discounting factor of 0% a difference in the number of spare bogies for different types of rolling stock have different effect on the total costs for revisions. Figure 29 shows that the VIRM is the type of rolling stock that has the largest effect on the total costs for revisions. The fact that VIRM has a higher impact than other types of rolling stock corresponds with the expectation. First, Figure 27 shows that the VIRM has the largest part of the total fleet of rolling stock at NedTrain, as VIRM has 36.6% of all rolling stock in the current fleet. Second, Figure 28 shows that the bogies in the VIRM have a low inter-revision deadline on average.

Changing the number of spare bogies of the SLT has the smallest effect on the total costs. This can be explained by the fact that the SLT is the only type of rolling stock that is in the field during the entire planning horizon. For the SLT only the holding costs change when the number of spare bogies is changed, while for the other types of rolling stock also the investment cost for their successor is changed.

Figure 30 shows by a discounting factor of 5% multiple remarkable results. The different rolling stock types reveal different results. The shape of the lines for the SGM/SGMm, ICM/ICMm, DDZ and ICRm are linear, similar to the lines in Figure 29. The shape of the lines for the SLT and the VIRM on the other hand show different results.

The VIRM shows a non linear relationship between the changed number of spare bogies and the total costs. When the change in the number of spare bogies is between approximately -8% and +55%, the total costs decrease with the decrease in the percentage of spare bogies. When the number of spare bogies decreases with more than 8%, the total costs increase. When the number of spare bogies decreases more than 8%, the revisions have to be planned so much earlier in the planning horizon that the number of revisions over the total lifetime of the VIRM increases.

The SLT shows an opposite effect from the other types of rolling stock, when the number of spare bogies decrease, the total costs for revisions increase. However, this result is misleading. As explained in the last section, the SLT is the only type of rolling stock in the model that stays in the field during the entire planning horizon and therefore does not have a successor. This means that by increasing the number of spare bogies, no investment costs are taken into account at all.

Up to this point in the analysis, the total population of spare bogies has been changed. However, changing the number of spare bogies that is already in the field would mean that decisions from the past can be changed, which is not realistic for NedTrain. In the following analysis only the number of spare bogies is changed from the types of rolling stock that come into the field after the planning horizon has started. The results are shown in Figure 31 and Figure 32.

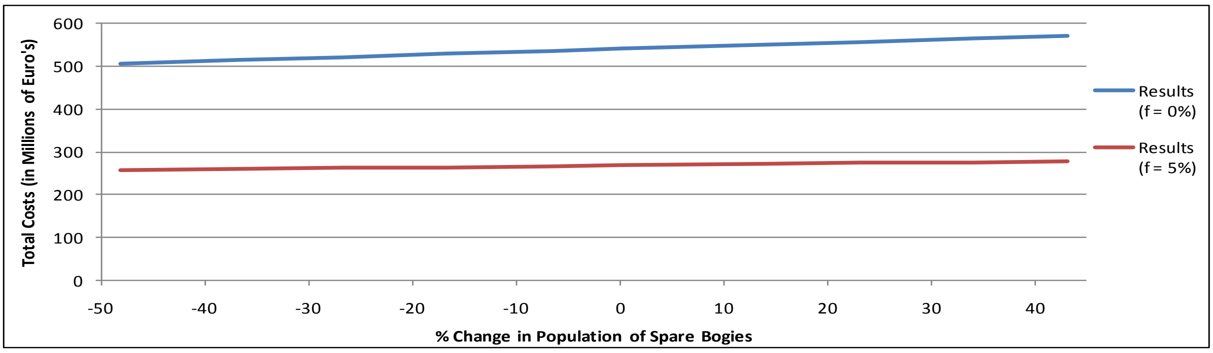

Figure 31: Change in Total Cost when Changing the Population of Spare Bogies

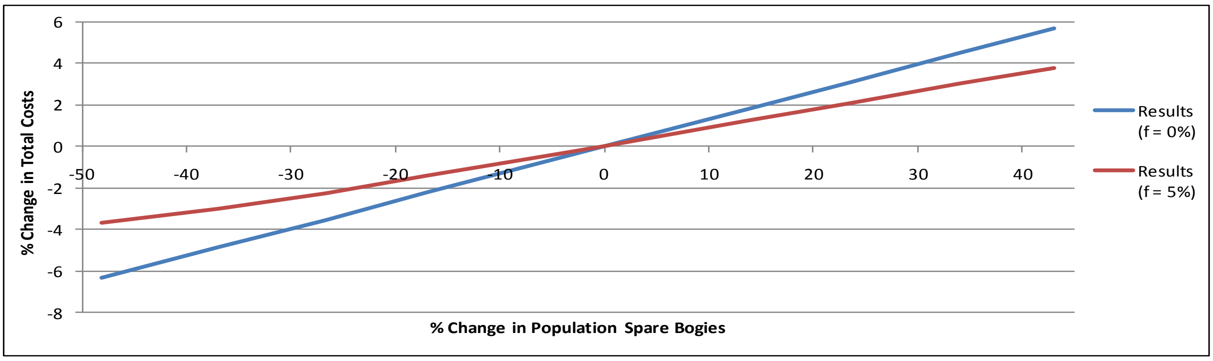

Figure 32: % Change in Total Cost when Changing the Population of Spare Bogies

Comparing Figure 31 and Figure 32 with Figure 25 and Figure 26 shows that the change in total costs is almost the same when the number of spare bogies is decreased. In both situations the mean costs that change are the investment costs and the holding costs. The investment costs change equally in both situations, because only the investment costs are taken into account of those types of rolling stock that are come into the field during the planning horizon. The holding costs change equally in both situations as well, since the same amount of bogies is in inventory in the same periods.

Comparing Figure 31 and Figure 32 with Figure 25 and Figure 26 shows that the change in total costs is different for the situation where the number of spare bogies is increased. This difference is caused by the investment costs for the extra spare bogies for the types of bogies that were already in the field.

7.2.3. Inter-Revision Deadlines

The third scenario analysis will, as explained in section 4.1.3, provide insight in the consequences of the changing inter-revision deadlines for the different types of bogies. The inter-revision deadlines will be increased to see what the consequences are on the total costs for revisions in the ROW.

First, the inter-revision deadlines of the total population of bogies are increased to show the general result of increasing inter-revision deadlines. The results of this analysis are shown in Figure 33 and Figure 34.

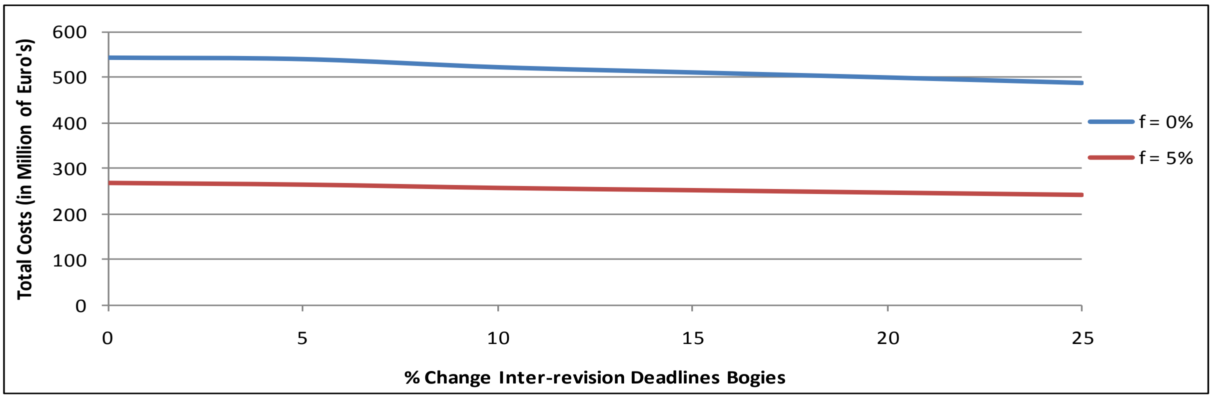

Figure 33: Total Costs Change by different Inter-revisions Deadlines

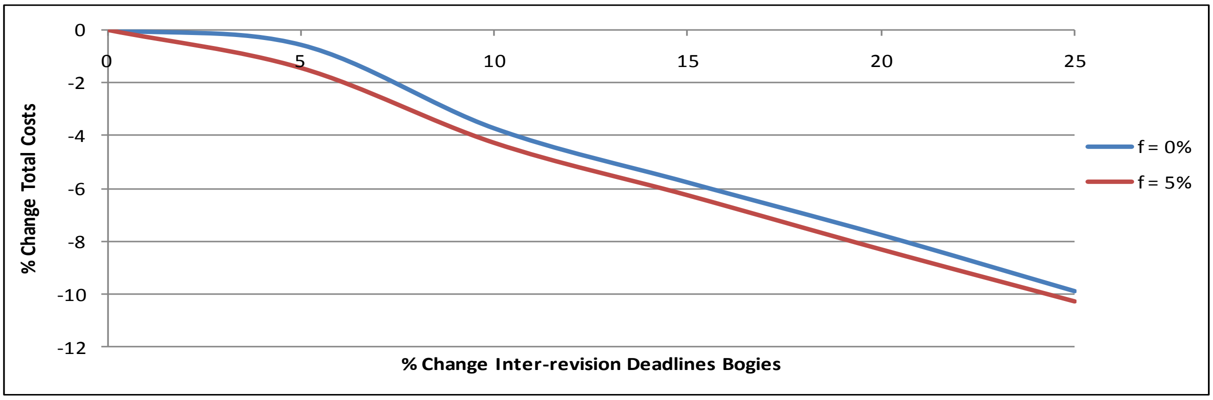

Figure 34: % Total Costs Change by different Inter-revisions Deadlines

Figure 33 and Figure 34 show that the total costs decrease when the inter-revision deadlines are increased. This makes sense, when the inter-revision deadlines increase, fewer revisions have to be done within the lifetime of a type of bogie. However, the relationship is not linear. The expectation is that not every increase of the inter-revision deadlines has an effect on the total costs. When a type of bogie has to be revised every 7 year in a period of 30 years, it needs 4 revisions in its total lifetime. When the inter-revisions deadline for this type of bogie changes to 7.2 years, the bogie still needs 4 revisions in its total lifetime.

This effect is shown in the next analysis. In this analysis, only the inter-revision deadlines of the types of bogies that belong to the SLT are changed. The SLT has four types of bogies, all with the same inter-revision deadline and end of the lifetime. The results of this analysis can be seen in Figure 35.

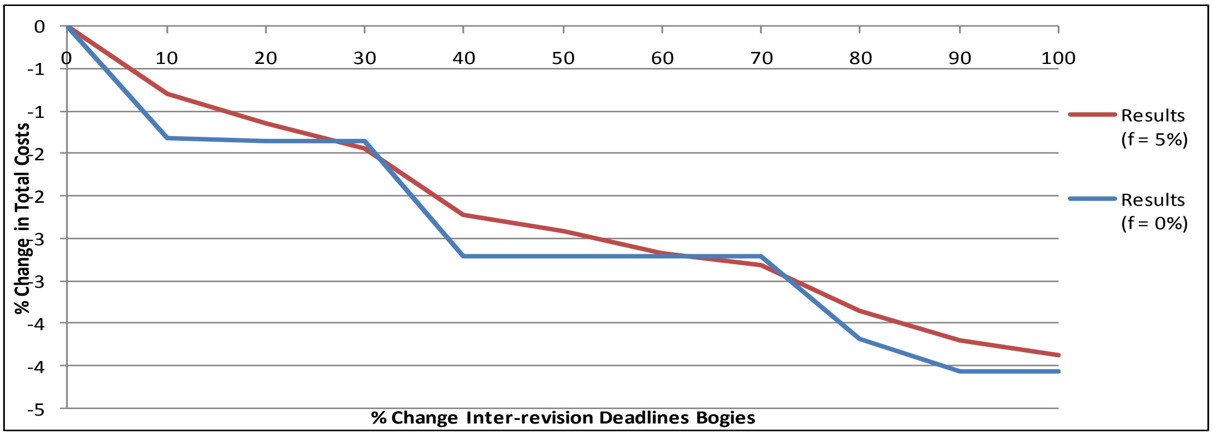

Figure 35: Change in Total Costs when Changing Inter-revision Deadlines of the SLT

Figure 35 shows that when the discounting factor is 0%, the inter-revision deadline is increased with 10%, the total costs decrease. After this, the inter-revision deadlines can be increased until 30% and no change in total costs is seen. This pattern of a decrease for a small period of time followed by a flat part is seen all over the graph.

Figure 35 also shows that he effect is higher when the discounting factor is 0% than when it is 5%. This is caused by the fact that the revisions are planned further in the future when the discounting factor is 5%. These revisions further in the future are cheaper because they are discounted and this makes their influence smaller.

7.2.4. Combinations of Scenario Analysis

The results of the three different scenario analysis show that the total costs for revisions can decrease by decreasing the capacity, decreasing the number of spare parts or increasing the inter-revisions deadlines. Next, different scenarios are combined to see if this result in a feasible solution and what this means for the total costs.

Looking at the three different scenario analyses, the inter-revisions deadlines are the hardest to change for NedTrain. NedTrain can analyze the possibilities to increase the inter-revision deadlines, but finally the inter-revision deadlines can only be decreased when it appears possible within the technical specification of the bogies. Besides this, the different inter-revisions deadlines for the different types of bogies have to be researched separately. Decreasing the capacity can also take time and money. To decrease the capacity, the mechanics working in the ROW have to be replacing elsewhere in the organization or even let go. Decreasing the number of spare bogies is easiest, because all NedTrain has to do is buy less spare bogies for future types of rolling stock.

It is not certain that increasing the inter-revision deadlines is possible for NedTrain. Decreasing the capacity and the number of spare parts is certainly possible and for this reasons those two scenarios will be combined. For the number of spare parts, only the number of spare parts will be changed that are coming into the field during the planning horizon. These are the spare bogies that still need to be purchase and therefore the number of spare parts can still be decided.

In the combined scenario the capacity for the first 5 year of the planning horizon will be set 9,660 and for the other 25 years 7,580 hours per period. The number of spare bogies for the rolling stock that comes into the field during the planning horizon will be decreased with 50%. The results show that the combination of decreasing the capacity and the number of spare bogies still creates a feasible solution. The results for the model with a 0% and a 5% discounting factor are €398,875,834.-, (26% decrease) and €206,285,617.- (23% decrease), respectively.

8. Some Extensions of the Mathematical Model

In creating the model for this research, multiple assumptions have been done. Not all of those assumptions totally fit with the reality. Most of the assumptions have been done for one of two reasons, first because currently the exact data for the reality is not available at NedTrain and collecting this data was too much work to fall inside the scope of this project. The second reason is that some assumptions have been made to keep the model more understandable for different employees of NedTrain; this makes it possible for people to see the more important relationships more clearly. This chapter explains possibilities to extend the created model to relax some of the assumptions discussed in section 5.5. For all the assumptions the possible change is discussed qualitative, for some the new formulas for the model have already been made.

8.1. Differentiation Revisions

In the basic model two assumptions have been made that make the model significantly different from the reality at NedTrain:

1. 'the amount of hours needed to revise a bogie in the ROW is fixed per type of bogie for the planning horizon"
2. "every revision for a specific type of bogie is the same"

In reality in different revisions different parts are changed and this creates different costs and different inter-revision deadlines for different revisions within the lifetime of a type of bogie.

To match the model more with reality, a model has been designed where an extra index has been created to keep track of the different revisions per type of bogie. This makes it possible to enter different input parameters for costs and time for different types of revisions per type of bogie. This mathematical model can be found in appendix G.1.

8.2. Labor Capacity in the ROW

The assumption that has been presented in the created model is; 'the available capacity for revisions in the ROW and the corresponding labor cost are fixed per period of the planning horizon'. As said before, this assumption has been made because at NedTrain the mechanics in the ROW have no other work than the revision of the bogies and the mechanics have a contract with a fixed number of hours per month.

There are two different interesting ways to release this assumption; flexible labor contracts for the mechanics in the ROW and variable labor costs in the ROW. Those two ways to release this assumption will be discussed in more detail in the following two subsections.

8.2.1. Flexible Labor Contracts for the ROW

A possibility to release the assumption 'the available capacity for revisions in the ROW and the corresponding labor cost are fixed per period of the planning horizon' is to use the hours of labor capacity during the year flexible. If a specific period contains more work than an average period, the mechanics can make a few extra hours as long as they get those hours off at another time in the year, as long as the total amount of hours worked in one year remain the same. Of course there is a limit to this flexibility.

To model this flexibility, a flexibility parameter could be built in the model. This would represent the percentage of flexibility that the ROW can use. This could be an interesting parameter for the analysis, since it will show the cost changes when the flexibility in the ROW changes. This mathematical model can be found in appendix G.2.1.

8.2.2. Variable Labor Cost for the ROW

A possibility to release the assumption 'the available capacity for revisions in the ROW and the corresponding labor cost are fixed per period of the planning horizon' is to see what would happen if the mechanics have flexible hours per month during the planning horizon. This might be possible if, for example, mechanics can be trained as all rounder's for the other departments of the ROW in Haarlem or if temporary employees were used. The results of the model would change, since there wouldn't be fixed cost per period for the ROW, but only cost for the hours that are actually spent on the revision of bogies.

For this change, only the objective function has to be changed, this mathematical model can be found in appendix G.2.2.

8.3. Cost Differentiation by MD's

One of the assumptions that have been presented in the created model is; 'the hourly wage for mechanics is the same for all MD's'. As explained in paragraph 5.5, in reality this is assumption is not totally correct; there are different labor costs for the different MD's.

At the moment NedTrain has four different MD's which have different labor costs. The model have been extended in such a way that the exact number of MD's entered can be chosen, to keep the model flexible for future changes. This mathematical model can be found in appendix G.3.

9. Conclusions and Recommendations

This chapter gives an overview of the conclusion and recommendations that can be made based on the research presented in the previous chapters. The first section will give the conclusions of the research and the second section will explain the different recommendations to both NedTrain and academic literature.

9.1. Conclusions

Two objectives were set in the beginning of this research.
The first objective was to close the two gaps in literature that were found:

1. There is no literature found on the planning of revisions for different parts with an inter-revision deadline going through the same revision capacity.
2. There is no literature found on planning multiple revisions per part within a planning horizon.

The second objective was to answer the research question for the case study at NedTrain: *How to deal with the shortage of different types of capacity during peak loads in the ROW caused by a disproportionately distributed demand for revision of bogies?*

Concerning the first objective, the created model can close both gaps. Considering the first gap, in the model different types of parts are revised at the same revision location by the same men. If the total demand for revisions in a period is higher than the total capacity for that period, the model will push revisions backward. The choice which revisions to push backward is based on the characteristics of the different types of parts, such as revision time and costs. Another reason to push revisions backwards is when there are not enough spare parts available for replacements. There can never be more replacements than there are spare parts available and the rolling stock can not ride when these parts are not available. The second gap is closed as well; the created model considers all revisions in the lifetime of a part. By taking this total lifetime of a part into consideration the flexibility within the total lifetime of a part can be used.

Concerning the second objective, the model demonstrates that it is possible to flatten the peaks in demand for revisions by pushing revisions backward in the planning horizon. The planning has been made while minimizing the total costs for revisions. These total costs are calculated in two different ways. First the costs are calculated with a discounting factor of 0% and then with a discounting factor of 5% per year. When minimizing these costs over the planning horizon of 30 years for the 0% and 5% discounting factor, theses present value of the costs are €541,246,922.- and €268,213,286.-, respectively. The resulting utilization of the capacity in the ROW is shown in Figure 36.

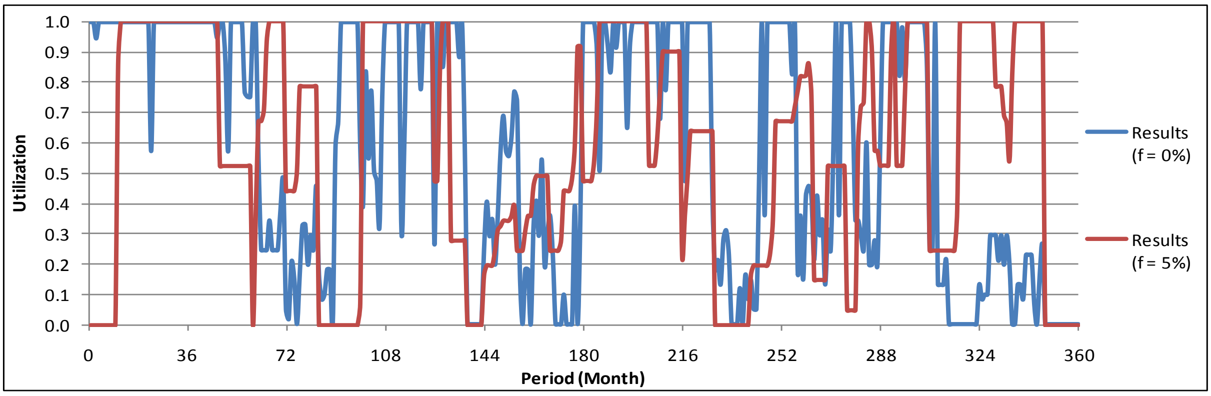

Figure 36: Utilization Capacity ROW (R=12,220)

While analyzing the model, three relevant observations have been made.

Firstly, several types of bogies that are currently in use have inter-revisions deadlines that are close together. The consequence of the clustering of inter-revision deadlines is that multiple periods where the capacity in the ROW is totally used are alternated with multiple periods where almost no capacity used. If it would be possible to spread inter-revisions deadlines equally over time it would be easier for NedTrain to use the capacity in the ROW more efficient.

Secondly, approximately 63% of all bogies that are currently in use will go out of the field between 2022 and 2030. Because such a large percentage of bogies go out of the field in a relatively short period, there are significantly less revisions necessary in this time period. If it would be possible to spread the periods that the different types of bogies go out of the field over a longer period, it would be easier for NedTrain to use the capacity in the ROW more efficient.

Thirdly, currently the planning of revisions is mostly done manually. Engineers decide on the planning of the revisions for the different types of bogies based on the upcoming inter-revision deadlines and a raw estimate of the available capacity in the ROW. This method is mostly short term based, it does not take the revisions later in the lifetime of the bogies into account. As a result of the developed method, revisions are normally planned as late as possible, intuitive it makes sense not to do a revision until it is necessary. As said, many of the inter-revision deadlines of the different types of bogies are clustered closely together in time. The model created here shows that for the long term it might be better to push some revisions backward within the planning horizon, to divide the different peak loads over the horizon. Planning earlier creates more flexibility to push revisions backward and decreases capacity and the number of spare bogies over time.

There are some values of parameters not exactly known by NedTrain and for the unknown values estimations have been made during this research. Even though this means that the exact numbers of the results might not totally match reality, the relationship between variables can give a lot of managerial insights. To obtain those managerial insights, three different scenario analyses have been done.

Firstly, the effect of changing capacity in the ROW on the total costs for revisions has been investigated. The initial results showed that the capacity in the ROW can be decreased with as much as 22% until it becomes infeasible to plan all necessary revisions. When the capacity is decreased with 22%, the total costs decrease with 12%. Further research shows that the first five years of the planning horizon are a bottleneck for the decrease of the capacity in the ROW. When the capacity in the first five years is decreased with 21%, the capacity year 6 to 30 can be decreased further up to 39% until it becomes infeasible to plan all necessary revisions. In this scenario, the total costs decrease with 20%. For this situation the utilization of the capacity of the ROW is shown in Figure 37.

Secondly, the effect of changing the number of spare bogies on the total costs for revisions has been analyzed. Currently, 7.5% of the total population of bogies is spare bogies, which can be decreased with 50% before it becomes infeasible to plan all necessary revisions on time. When the number of spare bogies is decreased with 50%, the costs are decreased with approximately 5%. Another finding is that the effect on the change in total costs is different for the different types of rolling stock. The effect is caused by different costs, different numbers of bogies per type of rolling stock and different inter-revision deadlines for the different types of rolling stock. It has been demonstrated that the VIRM has the most influence on the change in total costs and the SLT the least.

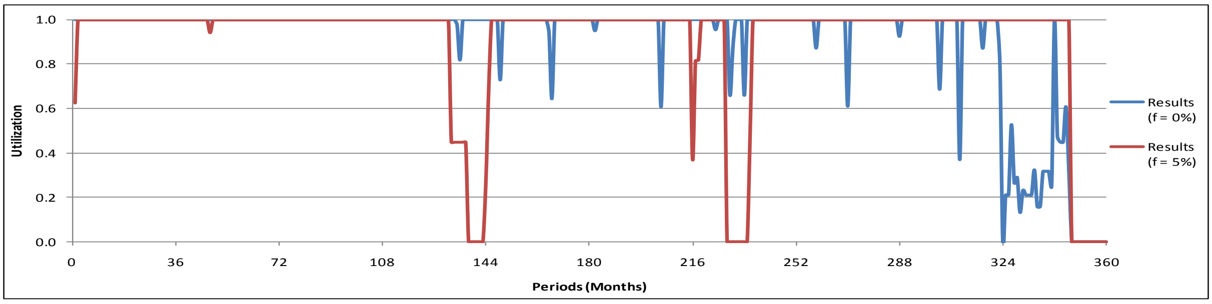

Figure 37: Utilization Capacity ROW (R[1,...,60}=9,660, R[61,...,361]=7,580)

Thirdly, the effect of changing the inter-revision deadlines of bogies on the total costs for revisions has been researched. The result is that increasing the inter-revision deadline decreases the total costs for revisions, which is caused by the fact that less revisions are necessary in the total lifetime of a bogie when the inter-revisions deadline increases. However, this is not a linear relationship, as not all increases of the inter-revision deadlines have an effect on the total costs. For example, when a type of bogie has to be revised every 7 year in a period of 30 years, it needs 4 revisions in its total lifetime. When the inter-revisions deadline for this type of bogie changes to 7.2 years, the bogie still needs 4 revisions in its total lifetime.

After the individual scenario analyses, a combination of the above scenarios show that an even higher decrease in total costs is possible. When a capacity decrease of 21% for the first five years and up to 39% for year 6 to 25 is combined with a decrease of 50% in the number of spare bogies for all types of bogies that come into the field during the planning horizon, it is still possible to plan all necessary revisions before the inter-revision deadline. The total cost decrease for this situation with approximately 25%.

Besides all analyses done in this research, in the future the created model could be used for other purposes as well. Firstly, the model can be used to do sensitivity analyses on the values of the different parameters. This can provide NedTrain with information on what influence the different parameters have on the results of the model. Secondly, by making the number of spare bogies a decision variable, the optimal number of spare parts to purchase for a new type of rolling stock can be generated.

9.2. Recommendations

This section presents the recommendations derived from the research conducted in this project. First, the recommendations for NedTrain will be given and then the recommendations for academics.

9.2.1. Recommendations for NedTrain

Taken all the conclusions into account, the five most important recommendations for NedTrain are:

The first recommendation is to actively incorporate the most important lessons of this research project when planning preventive maintenance for bogies. An Example is, explicitly considering to execute revisions earlier when there is an expected peak load of due dates coming up in the ROW. To incorporate the lessons of this research project successfully, it is important that the engineers at NedTrain are familiar with the consequences of their decisions, especially the long term consequences. When the engineers truly understand how all of the little decisions they make daily concerning the planning of the revisions relate to each other, they can make more substantiated decisions.

Secondly, the lessons learned from this research project can also be used for the preventive maintenance of other main parts at NedTrain. For all parts that have a similar maintenance program, only the input parameters have to be changed to use the model to plan the maintenance. For parts with a different maintenance program it can be analyzed if it is profitable to adjust the model.

The third recommendation for NedTrain is to collect the actual values of the data for the input parameters for the created model. This research shows that there are multiple ways to deal with the disproportionately distributed demand for the revision of bogies and that this leads to possibilities to reducing the total costs of the revision of bogies. To discover how large the advantages of changing the parameters can be for NedTrain and make adequate decisions, the values of the parameters in the current situation have to be determined more precisely.

Critical parameters to research for NedTrain are the parameters involving the timing and duration of the revisions; the exact inter-revision deadline for the different types of bogies, the exact number of labor hours necessary for the revision of one bogie type i and the exact number of hours of labor capacity available for preventive maintenance in the ROW in period t. The second category of parameters that should be researched further is the different costs in the model. The expectation is that the estimates that are used in this research at least represent the correct relationship between the different costs parameters, which results in correct choices with respect to prioritizing revisions of different types of bogies. But to calculate the real total cost for revisions, the different costs parameters should be researched more, especially since the objective of the model is to minimize the total costs. When the exact values for all the parameters in the created model are found, the model can be used to make long-term decisions about the capacity in the ROW and the number of spare bogies for future types of rolling stock.

The fourth recommendation for NedTrain is to start calculating the exact costs of preventive maintenance under the current system. When the exact data on the current costs is known, the real advantages of the new way of planning can be discovered. Only when this data is known, conclusion can be drawn on the desired values of the different parameters.

The fifth recommendation for NedTrain is that once the exact values for the parameters in the basic model are researched, the extensions suggested in chapter 8 could be further developed. Expansion of the model with the suggested extensions will get the model closer to reality.

9.2.2. Recommendations for Academics

There are different subject that would be suitable for further research.

Firstly, this research assumed that all bogies could be taken out of the rolling stock at any moment in time. In the case study and probably in many companies too, this is not the case. A specific train only comes in the MD approximately once every three months. This assumption could be relaxed when a model is created that keeps track of all individual trains in the field and the moments in time that they are planned to come in for maintenance.

Secondly, this research assumed that there is only one MD. In the case study, and probably in many companies too, this is not the case. For companies that have multiple MD’s, further research could extend the created model in this research. When the different MD’s are included, an extra extension could be to research if it would be better to keep all inventories of ready-for-use parts in the ROW or in the different MD’s and what the corresponding inventory policy should be.

Thirdly, this research assumed that all revisions can be done within one period. This is probably in many companies not the case. An interesting extension to the model would be to introduce a lead time for the revisions and/or replacements of parts.

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List of Concepts

Bogie:	Framework mounted on a set of wheels on the undercarriage of rolling stock.
Closed loop supply chain:	A supply chain where the business controls both the forward and backward shipping of the products in it.
Consumable part:	Parts that cannot be repaired and reused after being used once.
Corrective maintenance:	Maintenance policy where maintenance is done after the part has failed. Since there is no certainty about when the part will fail, it can not be scheduled.
Equipment:	The tools or machines needed for revision or replacement of bogies. Equipment can be used multiple times.
Equipment cost:	The costs associated with using equipment.
Spare bogies:	The difference in the number of bogies that is purchased at the beginning of the lifecycle and the number of bogies of that specific type that is built-in in rolling stock.
Final lot size:	Production of additional spare parts at the time of manufacturing the last of the final lot of production at the end of product life cycle.
Finite lifetime:	The end of the lifecycle of a specific product. After this moment the product is removed from the field.
Holding cost:	The costs of holding a bogie in inventory during a period of time.
Inter-revision deadline:	the maximum time a part may be in use between two consecutive revisions.
Investment cost:	The cost of purchasing a bogie.
Labor cost:	The costs for the time that a mechanic is actually working on a replacement or revision of a bogie.
Life cycle:	The complete process of change and development during the lifetime of somebody / something.
Main part:	Reusable part that is individually identifiable.
Maintenance schedule:	A schedule what every individual main spare part has that defines the moments in time that that main spare part needs maintenance.
Material cost:	The costs of material that are used for the replacement or revision of one bogie.
Planning horizon:	The total time for which a model is build.
Preventive maintenance:	Is maintaining a product on regular basis, for example, an interval or operation time
Processing cost:	The costs for a replacement or a revision of a bogie.
Repairable part:	Reusable part that is identifiable by type.
Replacement:	Substituting a part of the rolling stock that needs revision with a repaired part.
Revision:	The repair of a part, afterwards the part is as reliable as a new part.
Revision deadline:	The latest moment in time that a revision can take place.
Rolling stock:	All the vehicles that move on a railway, this includes powered and unpowered vehicles.
Technical lifetime:	The maximum number of kilometers before a main spare part needs maintenance.

List of Abbreviations

COW:	Component Overhaul Workshop (Tilburg)
DCF:	Discounted Cash Flow
DDZ:	DubbelDeks Materieel
ICM:	InterCity Materieel
ICRm:	InterCity Materieel na Modernisering
LCM:	Long Cycle Maintenance
MD:	Maintenance Depot
MSc:	Master of Science
NPV:	Net Present Value
OML:	Operations Management and Logistics
ROW:	Refurbishment and Overhaul Workshop (Haarlem)
SGM:	Stads Gewestelijk Materieel
SLT:	Sprinter Light Train
TU/e:	Eindhoven University of Technology
VIRM:	Verlengd Inter Regio Materieel

Appendix A: Literature Review

This appendix consists of two tables that summarize the articles found in the literature review.

A.1. Summery of Articles

Table 3: Articles that focus on only part of the components

Article	General	Fleet Maintenance	Preventive Maintenance	Repairable Spare Parts	Limited Capacity	Finite Lifetime	Life Cycle Cost	Interesting part
Alfares (1999)	Objective is to determine the optimum maintenance workforce schedule to satisfy growing labor requirements with minimum costs	The research is done on a fleet of 13 aircrafts and 19 helicopters	50% of the maintenance is scheduled, the other 50% is unscheduled	n.a.	Limited amount of human resources	n.a.	n.a.	Gives an model to determine the optimum maintenance workforce
Caggiano, Muckstadt & Rappold (2006)	Integrated real-time capacity and inventory allocation for repairable service parts in a two-echelon supply system	n.a.	n.a.	The defective unit is shipped back to the central repair facility, where is joins a queue of parts awaiting repair	Limited amount of spare parts and limited amount of human resources	n.a.	n.a.	Shows the significance of integrating repair and inventory allocation decisions
Christer & Waller (1984)	Investigates the effectiveness of a system of planned maintenance for a vehicle fleet	The research is on a fleet of 33 tractor units	The focus is on preventive maintenance and calculating using reliability the optimal time period before maintenance	n.a.	n.a.	n.a.	It includes cost of preventive maintenance, cost of breakdowns and cost of service repairs, but it does not include investment costs	Gives an interesting qualitative view on what happens if a company performs too much or too little preventive maintenance
Fortuin & Martin (1999)	Discusses experiences gained in case studies of practical stock control techniques	n.a.	Explanation of the difference between preventive and corrective maintenance	Explanation of the difference between repairable and consumable spare parts	Explanation of different kinds of capacity	n.a.	Explanation of different kind of costs	Qualitative explanation of different concepts used in the control of service parts
Genser (1982)	Outline of the maintenance problem for railway systems	Explains the advantages of managing an entire fleet instead of one product	n.a.	n.a.	n.a.	n.a.	Explains how the different kind of costs dealing with a fleet of rolling stock influence each other	Background on companies that work and/of own rolling stock

Genser & Grassl (1974)	Explain why reliability is a principal objective of railway management to keep ahead of competition	n.a.	Explains why this is necessary to keep reliability of rolling stock high enough	n.a.	n.a.	n.a.	n.a.	Explanation of why preventive maintenance on rolling stock is necessary to keep an economic advantage
Hertz, Schindl & Zufferey (2009)	Discusses a car fleet management problem with maintenance constraints	Maintenance on a car fleet	There is a maximum time of use that can separate two maintenances of a car	The cars are repairable	Limited number of workers available to perform maintenance	n.a.	n.a.	In the model there is a maximum time that a car can be used until maintenance is necessary
Inderfurth & Mukherjee (2008)	Discusses the cost differences between different options in a final lot situation	n.a.	n.a.	n.a.	There are different scenarios discussed, with difference in capacity restrictions	Discusses the different option for finite lifetime of parts / products	n.a.	Gives information about the final lot decision
Paz & Leigh (1994)	Discusses issues, results and research needs in maintenance scheduling	n.a.	Discusses the differences between emergency, routine and preventive maintenance	Explains what the consequences can be of repairable spare parts for the total system	Explains how capacity restrictions can influence your model	n.a.	n.a.	Gives background information about interesting facts to consider when making maintenance schedules

n.a. = not available (this means that this aspect is not mentioned in the article.

Below the terms used in table 1 are explained:

Article: This column gives the name(s) of the authors of the article discussed and the year it was published.
General: This column gives a general overview of what the article is about.
Fleet maintenance: This column explains whether or not the article describes the maintenance of a fleet and what kind of fleet it is.
Preventive maintenance: This column explains if the planning of preventive maintenance is the focus of the article and if there are interesting fact about the maintenance.
Repairable spare parts: This column says if the spare parts used in the article are repairable or consumable spare parts.
Limited capacity: This column explains which capacities in the model are limited.
Finite lifetime: This column explains if the spare parts in the model have an finite lifetime.
Life cycle cost: This column discusses which costs are taken into consideration in the article and if these are the total life cycle costs.
Interesting part: This column gives a short explanation on what makes the article interesting for this literature review.

Table 4: Articles that describe a situation similar to the total problem

Article	General	Fleet Maintenance	Preventive Maintenance	Repairable Spare Parts	Limited Capacity	Finite Lifetime	Life Cycle Cost	Method
Chen, Yan & Chen (2010)	Develops two manpower supply planning models and a solution algorithm for mass rapid transit carriage maintenance under mixed deterministic and stochastic demands	Designed for a fleet of MRT carriage, case study done on only part of the fleet	Both preventive and corrective maintenance are planned in the model	n.a.	Limited amount of manpower	n.a.	Only direct handling costs are taken into account	Mixed integer programming
Deshpande, Iyer & Cho (2006)	Improving the performance of the aircraft service parts supply chain	Designed for a fleet of more than 200 aircrafts	The aircraft is completely overhauled periodically (depot maintenance)	The broken carcass (if the part is repairable) is shipped back to the warehouse for repair and reuse	Limited availability of spare parts	n.a.	n.a.	Developed a state-dependent supply replenishment policy that uses part age information for managing the service parts supply chain
Everingham, Polaski, Riedlin, Shirk, Deshpande & Iyer (2008)	Demonstrates the value of operations research methodologies for efficient supply chain management	Designed for a fleet of 200 aircrafts	Certain life-limited parts require overhaul at predefined intervals	In most cases, the air stations replace broken parts on the aircraft and send these broken parts back to evaluate and repair locally or through outsourcing	Labour recourses are constrainted	After some predetermined life limit, ARSC retires parts from its system and destroys them to prevent their re-entry into the parts system	Only repair costs are taken into account, investment costs are not taken into account	Multiple linear programming models
Gallego (2011)	Focuses on a closed-loop supply chain	The focus is a fleet of containers	n.a.	The empty containers follow a reverse flow from the customer to the supplier. Here, empty containers are reconditioned and filled again in order to be ready for a new use cycle	The supplier will deliver n full containers only if the customer is able to give back, at the moment of delivery, exactly the same amount of empty containers	n.a.	Transport, ordering, holding, reconditioning and fleet acquisition costs are included	Multiple linear programming models

Hahn & Newman (2008)	Scheduling United States Coast Guard helicopter deployment and maintenance	Approach designed for a small fleet of helicopters	Heavy maintenance is an intensive, intrusive preventative maintenance regimen that is based primarily on flight hours accrued by each aircraft	n.a.	Limited availability of mechanics and there has to be a minimum number of helicopters available each period	n.a.	n.a.	Mixed integer linear programming model
Helm, Painter & Oakes (2002)	Comparison of three optimization methods for scheduling maintenance of high cost, long-lived capital assets	n.a.	All components have a minimum and a maximum lifetime, in between maintenance has to happen	n.a.	Limited human resource capacity	All components have a design life time	n.a.	quasi manual using standard spreadsheet technology, a modern constraint programming-based software package and a genetic program written especially for this application
Joo (2009)	Scheduling preventive maintenance for modular designed components	Approach will be the best fit to modular designed system operated in a small fleet such as aircraft, heavy machinery, medical equipment, and even space shuttles	Dynamic approach for scheduling preventive maintenance	When a module reaches its flight time limit, it is taken from the aircraft and sent to a depot for preventive maintenance	Limited availability of spare modules	After a specific amount of time the module is no longer used	Only opportunity costs due to premature overhauls are taken into account	Backward allocation algorithm
Koper & Rietra (1997)	Analysis and evaluation of the economic aspects of a reusable packaging for food trading-companies	n.a.	n.a.	After a packaging has been used it is cleaned and reused	Limited number of packaging in the system	n.a.	Costs that are taken into account are sales, transport location, handling, holding and production costs	Mixed integer linear programming model
Sriskandarajah, Jardine & Chan (1998)	Optimization of maintenance overhaul scheduling of rolling stock at the Hong Kong Mass Transit Railway Corporation	Designed for a fleet of 95 trains	A combination of running maintenance every 15 days and annual maintenance overhaul	n.a.	Minimum number of trains required and limited workforce	n.a.	n.a.	Genetic algorithm

n.a. = not available (this means that this aspect is not mentioned in the article.

In table 2 the column ‘interesting part’ is exchanged for a column ‘method’, the term method is explained as:

Method: This column tells which method is used to solve the problem.

Appendix B: Code GUSEK

This appendix contains the GMPL code that is used in GUSEK to solve the linear programming problem described in this report:

```
# NedTrain Basic Model

/* Parameters */
param T; /* end of planning horizon */
param I; /* total number of types of bogies in the system */

/* Sets */
set PERIOD:= {t in 1..T}; /* set of periods in the planning horizon */
set BOGIE_TYPE:= {i in 1..I}; /* set van different types of bogies */

/* Parameters */
param a {i in BOGIE_TYPE}; /* period that bogie type i goes into the field */
param b {i in BOGIE_TYPE}; /* number of ready to use bogies type i when bogie type i comes into the
field */
param c_c {i in BOGIE_TYPE}; /* investment cost of one bogie type i */
param c_h {i in BOGIE_TYPE}; /* holding cost for one bogie type i in period t */
param c_f; /* labor cost per mechanic per hour in MD */
param c_l; /* total labor cost in the ROW in period t */
param c_m {i in BOGIE_TYPE}; /* material cost per revision for bogie type i in period t */
param c_w1:= 1000; /* transport cost for one bogie from MD to ROW in period t */
param c_w2:= 1000; /* transport cost for one bogie from ROW to MD in period t */
param g {i in BOGIE_TYPE}; /* whether or not the bogie was in the field before planning horizon */
param p {i in BOGIE_TYPE}; /* period that bogie type i is taken out of the field */
param h {i in BOGIE_TYPE}; /* number of bogies type i waiting for repair when bogie type i comes
into the field */
param q {i in BOGIE_TYPE}; /* inter-revision time of bogie type i in periods */
param r {i in BOGIE_TYPE}; /* capacity needed in ROW for one revision of bogie type i */
param R {t in PERIOD}; /* capacity of the ROW in period t */
param z {i in BOGIE_TYPE}; /* number of labor hours necessary for replacing one bogie type i in MD
*/
param D {i in BOGIE_TYPE, t in PERIOD: t >= a[i] and t <= (a[i]+q[i]-1)}; /* demand for period a[i] to
a[i]+q[i]-1 */
param f; /* cash flow discounting factor */

/* Decision Variables */
var n {i in BOGIE_TYPE, t in PERIOD: t >= a[i] and t <= p[i]} >=0; /* # of revisions */
var x {i in BOGIE_TYPE, t in PERIOD: t >= a[i] and t <= p[i]} >=0; /* # of replacements */

/* Variables */
var B {i in BOGIE_TYPE, t in PERIOD: t >= a[i] and t <= p[i]} >= 0; /* # of ready-to-use bogies type i at
the beginning of period t */
var H {i in BOGIE_TYPE, t in PERIOD: t >= a[i] and t <= p[i]} >=0; /* # of bogies type i in stack at the
beginning of period t that need revision */
var W {i in BOGIE_TYPE, t in PERIOD: t >= (a[i]+q[i]) and t <= p[i]and (a[i]+q[i]) <= p[i]} ; /* # of
necessary replacements in at least period t*/
```

```
set PERIOD_BOGIE{t in PERIOD} := setof{j in BOGIE_TYPE: t >= a[j] and t <= p[j]}j;

/* Objective Function */
minimize y: sum{i in BOGIE_TYPE}(g[i]*((b[i]*c_c[i])/((1+f)^a[i]))) + sum{t in
PERIOD}((R[t]*c_l)/((1+f)^t)) + sum{i in BOGIE_TYPE}(sum{tt in a[i]..p[i]}(((c_h[i]*(b[i]+h[i])) +
(x[i,tt]*z[i]*c_f) + (n[i,tt]*c_m[i]) + (n[i,tt]*c_w1) + (x[i,tt]*c_w2))/((1+f)^tt)));

/* Constraints */
 s.t. StockH {i in BOGIE_TYPE, t in PERIOD: p[i] >= (a[i]+1) and t >= (a[i]+1) and t <= p[i]}: H[i,t] = H[i,t-
1] + x[i,t-1] - n[i,t-1];
 s.t. Stockh {i in BOGIE_TYPE}: H[i,a[i]] = h[i];
 s.t. StockB {i in BOGIE_TYPE, t in PERIOD: p[i] >= (a[i]+1) and t >= (a[i]+1) and t <= p[i]}: B[i,t] = B[i,t-1]
+ n[i,t-1] - x[i,t-1];
 s.t. Stockb {i in BOGIE_TYPE}: B[i,a[i]] = b[i];
 s.t. Capacity {t in PERIOD}: sum{j in PERIOD_BOGIE[t]}(n[j,t] * r[j]) <= R[t];
 s.t. MaxReplacements {i in BOGIE_TYPE, t in PERIOD: t >= a[i] and t <= p[i]}: x[i,t] <= B[i,t];
 s.t. MaxRevisions {i in BOGIE_TYPE, t in PERIOD: t >= a[i] and t <= p[i]}: n[i,t] <= H[i,t] + x[i,t];
 s.t. MeetingDemand1 {i in BOGIE_TYPE, t in PERIOD: t >= a[i] and t <= min(p[i],a[i]+q[i]-1)}: sum{tt in
a[i]..t}(D[i,tt]) <= sum{tt in a[i]..t}(x[i,tt]);
  s.t. ChangeDemand1 {i in BOGIE_TYPE, t in PERIOD: t >= (a[i] + q[i]) and t <= p[i] and (a[i] + q[i]) <=
p[i]}: W[i,t] = x[i,t-q[i]];
 s.t. MeetingDemand2 {i in BOGIE_TYPE, t in PERIOD: p[i] >= (a[i] + q[i]) and t >= (a[i]+q[i]) and t <=
p[i]}: sum{tt in a[i]..(a[i]+q[i]-1)}(D[i,tt]) + sum{tt in (a[i]+q[i])..t}(W[i,tt]) <= sum{tt in a[i]..t} x[i,tt];

  end;
```

Appendix C: Validation of the Basic Model

This appendix contains the validation of the basic model. In the four different sections different validation models are explained and applied.

C.1. Event Validity Results

This method compares results for specific predefined events from the model with the mathematical calculations of the same results. Specifically for this case the results that were compared are the total cost that are minimized and the total number of replacements and revisions over the planning horizon. In this case the results from GUSEK are compared to calculations done manually.

The different scenarios used in the event validity test are explained in more detail in the following section, followed by the results of this validity in the last section. The first scenario is a basic scenario where all capacities are set large enough so there are no limitations. In the other scenarios, parameters are changed to see the changes compared to the first scenario. The changes in scenario are highlighted in the tables with input parameters in yellow.

C.1.1. Different Scenarios

In this section the different scenarios are given. For every scenario a short introduction is given, then the input parameters are given, followed by the calculation of the results and then the results found by GUSEK.

Scenario 1

For scenario 1 a scenario is chosen with only 3 periods and 2 bogie types, since all results have to be calculated by hand as well and this becomes complicated for large scaled problems. Besides that, if the model works for this small scale there is no reason why it would be different for larger scaled problems. The input variables for scenario 1 are given in the three tables below:

Table 5: Input Basic Model, Event Validity, Scenario 1, Part 1

Parameter	Value
$\mathbf{I}$	2
$\mathbf{T}$	3
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 6: Input Basic Model, Event Validity, Scenario 1, Part 2

	Bogie Type 1	Bogie Type 2
a^i	1	1
b^i	2	4
h^i	3	4
p^i	3	3
q^i	2	1
r^i	2	3
z^i	1	2
c_c^i	100	100
c_h^i	10	10

c_m^i	15	10

Table 7: Input Basic Model, Event Validity, Scenario 1, Part 3

	Period 1	Period 2	Period 3
$\mathrm{R_t}$	100	100	100
D_t^1	2	3	
D_t^2	4		

Since the parameters are chosen in such a way that there are no capacities restrictions the expectation is that all the replacements are done in the period of the revision deadline. The number of ready-for-use bogies that are in stock at the beginning of period 1 equals the number of replacements that need to happen in period 1, this means that in period 1 at least enough bogies have to be revised to make enough for period 2, etc. Calculating like this the expected number of replacements and revision per period per bogie type can be calculated. The results are given in the table below:

Table 8: Calculated Result Basic Model, Event Validity, Scenario 1

	Period 1	Period 2	Period 3
n_t^1	3	2	0
x_t^1	2	3	2
$\mathrm{D_t^1}$	2	3	
$\mathrm{W_t^1}$			2
n_t^2	4	4	0
x_t^2	4	4	4
$\mathrm{D_t^2}$	4		
$\mathrm{W_t^2}$		4	4

The results in the table above will lead to the following total cost:

$$\sum_{i\in\{a^i>1\}}\left(b^i * c_c^i\right) + \sum_{t\in T}(c_l) + \sum_{i\in I}\sum_{t'=a^i}^{t'=p^i}\Big(c_h^i\left(b^i + h^i\right) + \left(x_{t'}^i * z^i * c_f\right) + \left(n_{t'}^i * c_m^i\right) + \left(n_{t'}^i * c_{w1} + x_{t'}^i * c_{w2}\right)\Big) = (3 * 100) + \big(30(2+3) + (7 * 1 * 5) + (5 * 15) + (5 * 10 + 7 * 10)\big) + \big(30(4+4) + (12 * 2 * 5) + (8 * 10) + (8 * 10 + 12 * 10)\big) = €1{,}320.-$$

When these parameters are put in GUSEK, the total cost of €1,320.- is found as well.

Scenario 2

This scenario will check how the model reacts if one of the bogie types only comes into the field after the planning horizon has already started. In this case bogie type 2 comes into the field in period 2. The input variables are given in the three tables below:

Table 9: Input Basic Model, Event Validity, Scenario 2, Part 1

Parameter	Value
I	2
T	3
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 10: Input Basic Model, Event Validity, Scenario 2, Part 2

	Bogie Type 1	Bogie Type 2
a^i	1	2
b^i	2	8
h^i	3	0
p^i	3	3
q^i	2	1
r^i	2	3
z^{i}	1	2
c_c^i	100	100
c_{h}^i	10	10
c_m^i	15	10

Table 11: Input Basic Model, Event Validity, Scenario 2, Part 3

	Period 1	Period 2	Period 3
$\mathrm{R_t}$	100	100	100
D_{t}^1	2	3	
D_{t}^2		4	

The expectation for this scenario is that the results will be the same as for scenario 1, except from the fact that bogie type 2 comes into the field in period 2, which eliminates the demand of 4 replacements and consequential 8 revisions. The calculated results are given in the table below:

Table 12: Calculated Result Basic Model, Event Validity, Scenario 2

	Period 1	Period 2	Period 3
n_t^1	3	2	0
x_t^1	2	3	2
$\mathrm{D_t^1}$	2	3	
$\mathrm{W_t^1}$			2
n_t^2		0	0
x_t^2		4	4
$\mathrm{D_t^2}$		4	
$\mathrm{W_t^2}$			4

The expected total cost for this scenario would be:

$$\sum_{i\in\{\mathrm{a^i}>1\}}\left(b^i * \mathrm{c_c^i}\right) + \sum_{\mathrm{t\in T}}(c_l) + \sum_{i\in I}\sum_{t'=a^i}^{\mathrm{t'}=p^i}\left(\mathrm{c_h^i}\left(b^i + h^i\right) + \left(x_{t'}^i * z^{\mathrm{i}} * c_f\right) + \left(n_{t'}^i * c_m^i\right) + \left(n_{t'}^i * c_{w1} + x_{t'}^i * c_{w2}\right)\right) = (8 * 100) + (3 * 100) + \left(30(2+3) + (7 * 1 * 5) + (5 * 15) + (5 * 10 + 7 * 10)\right) + \left(20(8+0) + (8 * 2 * 5) + (0 * 10) + (0 * 10 + 8 * 10)\right) = €1{,}800.-$$

When these parameters are put in GUSEK, the total cost of €1,800.- is found as well.

Scenario 3

Scenario 3 studies the opposite effect of scenario 2, here the different bogie types are put into the field at the same time, but bogie type 2 is taken out of the field after 2 periods.

Table 13: Input Basic Model, Event Validity, Scenario 3, Part 1

Parameter	Value
I	2
T	3
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 14: Input Basic Model, Event Validity, Scenario 3, Part 2

	Bogie Type 1	Bogie Type 2
a^i	1	1
b^i	2	4
h^i	3	4
p^i	3	2
q^i	2	1
r^i	2	3
z^i	1	2
c_c^i	100	100
c_h^i	10	10
c_m^i	15	10

Table 15: Input Basic Model, Event Validity, Scenario 3, Part 3

	Period 1	Period 2	Period 3
R_t	100	100	100
D_t^1	2	3	
D_t^2	4		

The expectation is that the results will be the same as those of scenario 1, except that there won't be any demand in period 3 for bogie type 2 anymore, which results in 4 replacements and 4 revisions less for bogie type 2. The results of the calculations are given in the table below:

Table 16: Calculated Result Basic Model, Event Validity, Scenario 3

	Period 1	Period 2	Period 3
n_t^1	3	2	0
x_t^1	2	3	2
D_t^1	2	3	
W_t^1			2
n_t^2	4	0	
x_t^2	4	4	
D_t^2	4		
W_t^2		4	

The expected total cost for this scenario would be:

$$\sum_{i\in\{a^i>1\}}\left(b^i * c_c^i\right) + \sum_{t\in T}(c_l) + \sum_{i\in I}\sum_{t'=a^i}^{t'=p^i}\left(c_h^i\left(b^i + h^i\right) + \left(x_{t'}^i * z^i * c_f\right) + \left(n_{t'}^i * c_m^i\right) + \left(n_{t'}^i * c_{w1} + x_{t'}^i * c_{w2}\right)\right) = (3*100) + \left(30(2+3) + (7*1*5) + (5*15) + (5*10+7*10)\right) + \left(20(4+4) + (8*2*5) + (4*10) + (4*10+8*10)\right) = €1{,}080.-$$

When these parameters are put in GUSEK, the total cost of €1,080.- is found as well.

Scenario 4

This scenario explores the labor capacity restriction of the ROW. In scenario 1, the total capacity is set so high, that this will never limit the model. In the below table the capacity that is used per period in scenario 1 is calculated. This is 18 hours in period 1, 16 hours in period 2 and 0 hours in period 3.

Table 17: Basic Model, Calculation Labor Capacity Scenario 1

	Period 1	Period 2	Period 3
n_t^1	3	2	0
$n_t^1 * r^1$	6	4	0
n_t^2	4	4	0
$n_t^2 * r^2$	12	12	0
$(n_t^1 * r^1) + (n_t^2 * r^2)$	18	16	0
R_t	100	100	100

In this scenario the total available capacity for the ROW will be set so that there will be a shortage in period 2 and there will be extra time in period 1. The expectation is that the model will push one revision of bogie type 2 backwards to satisfy all constraints.

The input variable for this scenario are given in the three tables below:

Table 18: Input Basic Model, Event Validity, Scenario 4, Part 1

Parameter	Value
I	2
T	3
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 19: Input Basic Model, Event Validity, Scenario 4, Part 2

	Bogie Type 1	Bogie Type 2
a^i	1	1
b^i	2	4
h^i	4	4
p^i	3	3
q^i	2	1
r^i	2	3
z^i	1	2
c_c^i	100	100
c_h^i	10	10
c_m^i	15	10

Table 20: Input Basic Model, Event Validity, Scenario 4, Part 3

	Period 1	Period 2	Period 3
R_t	20	14	0
D_t^1	2	3	
D_t^2	4		

As set before, the expectation is that the model will push one revision of bogie type 1 backwards; this is shown in the table below:

Table 21: Calculated Result Basic Model, Event Validity, Scenario 4

	Period 1	Period 2	Period 3
n_t^i	4	1	0
x_t^i	2	3	2
D_t^i	2	3	
W_t^i			2
n_t^i	4	4	0
x_t^i	4	4	4
D_t^i	4		
W_t^i		4	4

The expected total cost for this scenario would be:

$$\sum_{i\in\{a^i>1\}}\left(b^i * c_c^i\right) + \sum_{t\in T}(c_l) + \sum_{i\in I}\sum_{t'=a^i}^{t'=p^i}\left(c_h^i\left(b^i + h^i\right) + \left(x_{t'}^i * z^i * c_f\right) + \left(n_{t'}^i * c_m^i\right) + \left(n_{t'}^i * c_{w1} + x_{t'}^i * c_{w2}\right)\right) = (3 * 100) + \left(30(2+4) + (7 * 1 * 5) + (5 * 15) + (5 * 10 + 7 * 10)\right) + \left(30(4+4) + (12 * 2 * 5) + (8 * 10) + (8 * 10 + 12 * 10)\right) = €1{,}350.-$$

When these parameters are put in GUSEK, the total cost of €1,350.- is found as well.

C.1.2. Results

The calculated results and the GUSEK results for the different scenarios are given in the table below:

Table 22: Results Basic Model Event Validity

	Calculated	GUSEK Model
Scenario 1	€1,320.-	€1,320.-
Scenario 2	€1,800.-	€1,800.-
Scenario 3	€1,080.-	€1,080.-
Scenario 4	€1,350.-	€1,350.-

As can be seen in the table above, for all scenarios the calculated costs equal the cost of GUSEK.

C.2. Comparison to Other Models Results

The validation method “comparison to other models” is described by Irobi et al (2004) as a method that compares the output of the model to the output of other models. In this case the mathematical model is besides in GUSEK also made in Excel, where it can be solved using the Excel solver. Both models are made independent of each other and so comparison of the models can validate the GUSEK model.

To start the validation, the scenario's described in the previous validation method, the event validity, are also calculated using the Excel solver. After this, three more scenarios are calculated with both GUSEK and Excel to see the differences. For all the scenarios the results will be compared, specifically for this case the results that were compared are the total cost that are minimized and the total number of replacements and revisions over the planning horizon. The description and the results of scenarios 5 to 7 are given in the following sections.

C.2.1. Different Scenarios

To start the validation, the scenario's described in the previous validation method, the event validity, are also calculated using the Excel solver. After this, three more scenarios are calculated with both GUSEK and Excel to see the differences.

The different scenarios used in the comparison to other model test are explained in more detail in this section. For every scenario a short introduction is given and then the input parameters are given, followed by the results found by GUSEK and Excel. The fifth scenario is a basic scenario where all capacities are set large enough so there are no limitations. In the other scenarios, parameters are changed to see the changes compared to the first scenario.

Scenario 5

Scenario 5 is the first scenario that will only be solved by GUSEK and Excel and not by hand anymore. This has the advantage that a larger scaled problem can be solved, but to interpret the results correct it is important to keep the problem manageable. Just like scenario 1, scenario 5 is a basic scenario, to compare scenario 6 and 7 to where the parameters will be changed. The input parameters for scenario 5 are given in the three tables below:

Table 23: Input Basic Model, Comparison to Other Models, Scenario 5, Part 1

Parameter	Value
I	3
T	12
c_f	50
c_l	45
c_{w1}	10
c_{w2}	15

Table 24: Input Basic Model, Comparison to Other Models, Scenario 5, Part 2

	Bogie Type 1	Bogie Type 2	Bogie Type 3
a^i	1	1	1
b^i	5	5	5
h^i	5	5	5
p^i	12	12	12
q^i	4	2	3
r^i	3	2	4
z^i	1	1	1
c_c^i	1000	1000	1000
c_h^i	3	4	5
c_m^i	25	50	75

Table 25: Input Basic Model, Comparison to Other Models, Scenario 5, Part 3

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$\mathbf{R_t}$	60	60	60	60	60	60	60	60	60	60	60	60
D_t^1	1	0	0	8								
D_t^2	3	2										
D_t^3	3	1	2									

The total cost for this scenario are both from GUSEK and from Excel €11,130.-

Scenario 6

The only difference between scenario 5 and 6 will be that in scenario 6 the different bogie types will come into the field and go out of the field on different times compared to each other. In this scenario, bogie type 2 will only come into the field in period 4 instead of 1 and bogie type 3 will go out of the field after period 8. The input variables are given in the following three tables:

Table 26: Input Basic Model, Comparison to Other Models, Scenario 6, Part 1

Parameter	**Value**
I	3
T	12
c_f	50
c_l	45
c_{w1}	10
c_{w2}	15

Table 27: Input Basic Model, Comparison to Other Models, Scenario 6, Part 2

	Bogie Type 1	**Bogie Type 2**	**Bogie Type 3**
a^i	1	4	1
b^i	5	10	5
h^i	5	0	5
p^i	12	12	8
q^i	4	2	3
r^i	3	2	4
z^i	1	1	1
c_c^i	1000	1000	1000
c_h^i	250	300	350
c_m^i	25	50	75

Table 28: Input Basic Model, Comparison to Other Models, Scenario 6, Part 3

Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$\mathbf{R_t}$	60	60	60	60	60	60	60	60	60	60	60	60
D_t^1	1	0	0	8								
D_t^2				3	2							
D_t^3	3	1	2									

The different costs that are expected to change compared to scenario 5 are the investment cost, the holding cost, the cost for revisions and the cost for replacements. The expected value of this change will be:

Investment cost: In the planning horizon 10 new bogies type 2 has to be bought, cost increase: 10 * €1,000.- = €10,000.-.
Holding cost: In the first 3 periods no holding cost for bogies type 2 are required and in the last 4 periods no holding cost for bogies type 3 are required. The cost decrease would be: 3 * €4.- * (10+0) + 4 * €5.- * (5+5) = €320.-
Revision cost: There are 12 less revisions necessary for bogies type 2 and 8 less for bogies type 3. Cost decrease would be: 12 * €50.- + 8 * €75.- + 12 * €10.- + 8 * €10.- = €1,400.-
Replacement cost: There are 7 less revisions necessary for bogie type 2 and 8 less for bogie type 3. Cost decrease would be: 7 *1 * €50.- + 8 * 1 * €50.- + 7 * €15.- + 8 * €15.- = €975.-
Total expected cost would be: €11,130.- + €10,000.- - €320.- - €1,400.- - €975.- = €18,435.-

The total cost for this scenario are both from GUSEK and from Excel €18,435.-.

Scenario 7

The difference between scenario 6 and scenario 7 is that in scenario 7 there are less extra parts in the field for bogie type 1. Because there are only 5 spare parts in the field, it will never be possible to replace the 8 bogies of this type at once in period 4 as requested. This means that the model will have to bring some of those replacements backward, which will lead to extra replacements at the end of the planning horizon. The input parameters are given in the three tables below:

Table 29: Input Basic Model, Comparison to Other Models, Scenario 7, Part 1

Parameter	Value
I	3
T	12
c_f	50
c_l	45
c_{w1}	10
c_{w2}	15

Table 30: Input Basic Model, Comparison to Other Models, Scenario 7, Part 2

	Bogie Type 1	Bogie Type 2	Bogie Type 3
a^i	1	1	1
b^i	5	5	5
h^i	0	5	5
p^i	12	12	12
q^i	4	2	3
r^i	3	2	4
z^i	1	1	1
c_c^i	1000	1000	1000
c_h^i	250	300	350
c_m^i	25	50	75

Table 31: Input Basic Model, Comparison to Other Models, Scenario 7, Part 3

Period	1	2	3	4	5	6	7	8	9	10	11	12
R_t	60	60	60	60	60	60	60	60	60	60	60	60
D_t^1	1	0	0	8								
D_t^2	3	2										

D_t^3	3	1	2									

The different costs that are expected to change compared to scenario 5 are only the holding cost. Even though the replacements and revisions are distributed differently over the periods, there are no extra replacements or revisions necessary. The expected value of this change will be:

Holding cost: There are 5 less bogies of type 1 in inventory during the total planning horizon. The cost decrease would be: 5* 12 * €3.- = €180.-
Total expected cost would be: €11,130.- - €180.- = €10,950.-

The total cost for this scenario are both from GUSEK and from Excel €10,950.-.

C.2.2. Results

The calculated results, the GUSEK results and the Excel results for the different scenarios are given in the table below:

Table 32: Results Basic Model Comparison to Other Models

	Calculated	GUSEK Model	Excel Model
Scenario 1	€1,320.-	€1,320.	€1,320.-
Scenario 2	€1,800.-	€1,800.-	€1,800.-
Scenario 3	€1,080.-	€1,080.-	€1,080.-
Scenario 4	€1,350.-	€1,350.-	€1,350.-
Scenario 5		€11,130.-	€11,130.-
Scenario 6		€46,615.-	€46,615.-
Scenario 7		€40,505.-	€40,505.-

As can be seen in the table above, the Excel solver gives the same results as the GUSEK model and the values calculated without a solver.

C.3. Extreme Condition Test Results

This method checks how the model implemented in software deals with extreme conditions. For the model created in this report it is important that the model implemented in software will give no output when not all conditions are met.

C.3.1. Different Conditions

This section describes the different extreme conditions in further detail and gives the input parameters for the different scenarios.

Total Capacity in the ROW lower than the total capacity needed to revise all bogies.

An extreme point is taken here, where the total capacity of the ROW is zero for every period. The input parameters for this scenario are given in the three tables below:

Table 33: Input Basic Model, Extreme Conditions, Capacity ROW, Part 1

Parameter	Value
I	3
T	12
c_f	50
c_l	45
c_{w1}	10
c_{w2}	15

Table 34: Input Basic Model, Extreme Conditions, Capacity ROW, Part 2

	Bogie Type 1	Bogie Type 2	Bogie Type 3
a^i	1	1	1
b^i	5	5	5
h^i	5	5	5
p^i	12	12	12
q^i	4	2	3
r^i	3	2	4
z^i	1	1	1
c_c^i	1000	1000	1000
c_h^i	250	300	350
c_m^i	25	50	75

Table 35: Input Basic Model, Extreme Conditions, Capacity ROW, Part 3

Period	1	2	3	4	5	6	7	8	9	10	11	12
R_t	0	0	0	0	0	0	0	0	0	0	0	0
D_t^1	1	0	0	8								
D_t^2	3	2										
D_t^3	3	1	2									

As a result GUSEK says that there is no optimal solution found.

No ready-for-use bogies in inventory when the planning horizon starts, while there is demand in the first period.

In this extreme scenario the start inventory of all ready-for-use bogies for all bogie types will be put to zero, the input parameters are shown in the three tables below:

Table 36: Input Basic Model, Extreme Conditions, Capacity Ready-to-use Bogies, Part 1

Parameter	Value
I	3
T	12
c_f	50
c_l	45
c_{w1}	10
c_{w2}	15

Table 37: Input Basic Model, Extreme Conditions, Capacity Ready-to-use Bogies, Part 2

	Bogie Type 1	Bogie Type 2	Bogie Type 3
a^i	1	1	1
b^i	0	0	0
h^i	5	5	5
p^i	12	12	12
q^i	4	2	3
r^i	3	2	4
z^i	1	1	1
c_c^i	1000	1000	1000
c_h^i	250	300	350

c_m^i	25	50	75

Table 38: Input Basic Model, Extreme Conditions, Capacity Ready-to-use Bogies, Part 3

Period	1	2	3	4	5	6	7	8	9	10	11	12
R_t	60	60	60	60	60	60	60	60	60	60	60	60
D_t^1	1	0	0	8								
D_t^2	3	2										
D_t^3	3	1	2									

As a result GUSEK says that there is no optimal solution found.

No bogies that need revision in inventory when the planning horizon starts, while revision in necessary to meet future demand.

In this extreme scenario the number of bogies in inventory that need revision at the beginning of period 1 is set to zero and the number of ready-for-use bogies in inventory is set to three per type of bogie. The input parameters are given in the three tables below:

Table 39: Input Basic Model, Extreme Conditions, Capacity Bogies that need Revision, Part 1

Parameter	Value
I	3
T	12
c_f	50
c_l	45
c_{w1}	10
c_{w2}	15

Table 40: Input Basic Model, Extreme Conditions, Capacity Bogies that need Revision, Part 2

	Bogie Type 1	Bogie Type 2	Bogie Type 3
a^i	1	1	1
b^i	3	3	3
h^i	0	0	0
p^i	12	12	12
q^i	4	2	3
r^i	3	2	4
z^i	1	1	1
c_c^i	1000	1000	1000
c_h^i	250	300	350
c_m^i	25	50	75

Table 41: Input Basic Model, Extreme Conditions, Capacity Bogies that need Revision, Part 3

Period	1	2	3	4	5	6	7	8	9	10	11	12
R_t	60	60	60	60	60	60	60	60	60	60	60	60
D_t^1	1	0	0	8								
D_t^2	3	2										
D_t^3	3	1	2									

As a result GUSEK says that there is no optimal solution found.

Period that one of the bogie types is taken out of the field is outside the planning horizon.

In this extreme scenario the period that bogie type 1 is taken out of the field is set on period 15, which is three periods after the planning horizon ends. The input parameters are given in the three tables below.

Table 42: Input Basic Model, Extreme Conditions, Outside Horizon, Part 1

Parameter	Value
I	3
T	12
c_f	50
c_l	45
c_{w1}	10
c_{w2}	15

Table 43: Input Basic Model, Extreme Conditions, Outside Horizon, Part 2

	Bogie Type 1	Bogie Type 2	Bogie Type 3
a^i	1	1	1
b^i	5	5	5
h^i	5	5	5
p^i	15	12	12
q^i	4	2	3
r^i	3	2	4
z^i	1	1	1
c_c^i	1000	1000	1000
c_h^i	250	300	350
c_m^i	25	50	75

Table 44: Input Basic Model, Extreme Conditions, Outside Horizon, Part 3

Period	1	2	3	4	5	6	7	8	9	10	11	12
R_t	60	60	60	60	60	60	60	60	60	60	60	60
D_t^1	1	0	0	8								
D_t^2	3	2										
D_t^3	3	1	2									

As a result GUSEK says that there are variables out of domain.

C.3.2. Results

The four different extreme conditions that are used during this test are explained in the table below, together with the results GUSEK gave.

Table 45: Results Basic Model Extreme Condition Test

Input	GUSEK output
Total capacity in the ROW lower than the total capacity needed to revise all bogies.	No optimal solution found
No ready-for-use bogies in inventory when the planning horizon starts, while there is demand in the first period.	No optimal solution found
No bogies that need revision in inventory when the planning horizon starts, while revision in necessary to meet future	No optimal solution found

demand.	
Period that one of the bogie types is taken out of the field is outside the planning horizon.	Variable out of domain

As can be seen in the table above, the model does not give output when the input parameters are not correct or not all conditions can be met.

C.4. Face Validity

This method "has to do with asking knowledgeable people if the system model behaviour is reasonable" (Irobi, Andersson, & Wall, 2004, p. 3). In this case Bob Huisman, manager maintenance development by NedTrain, is asked to see if the results look reasonable compared to the reality.

Appendix D: Validation Extended Model

This appendix contains the validation of the basic model. In the four different sections different validation models are explained and applied.

D.1. Event Validity Results

This method compares results for specific predefined events from the model with the mathematical calculations of the same results. Specifically for this case the results that were compared are the total cost that are minimized and the total number of replacements and revisions over the planning horizon. In this case the results from GUSEK are compared to calculations done manually.

The different scenarios used in the event validity test are explained in more detail in the following section, followed by the results of this validity in the last section. The first scenario is a basic scenario where all capacities are set large enough so there are no limitations. In the other scenarios, parameters are changed to see the changes compared to the first scenario. The changes in scenario are highlighted in the tables with input parameters in yellow.

D.1.1. Different Scenarios

In this section the different scenarios are given. For every scenario a short introduction is given, then the input parameters are given, followed by the calculation of the results and then the results found by GUSEK.

Scenario 1

For scenario 1 a scenario is chosen with only 3 periods, 2 bogie types and 2 revision types per bogie type, since all results have to be calculated by hand as well and this becomes complicated for large scaled problems. Besides that, if the model works for this small scale there is no reason why it would be different for larger scaled problems. The input variables for scenario 1 are given in the three tables below:

Table 46: Input Extended Model, Event Validity, Scenario 1, Part 1

Parameter	Value
I	2
T	3
K	2
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 47: Input Extended Model, Event Validity, Scenario 1, Part 2

	Bogie Type 1		Bogie Type 2	
	Revision Type 1	Revision Type 2	Revision Type 1	Revision Type 2
a^i	1		1	
b^i	5		4	
h^i	2	2	2	2
p^i	3		3	
q^i	2	1	2	2
r^i	2	3	1	4

z^i	1		2	
c_c^i	100		100	
c_h^i	10		10	
c_m^i	10	30	20	40

Table 48: Input Extended Model, Event Validity, Scenario 1, Part 3

	Period 1	Period 2	Period 3
R_t	100	100	100
$D_t^{1,1}$	2	2	
$D_t^{1,2}$	3		
$D_t^{2,1}$	3	2	
$D_t^{2,2}$	1	1	

Since the parameters are chosen in such a way that there are no capacities restrictions the expectation is that all the replacements are done in the period of the revision deadline. The number of ready-for-use bogies that are in stock at the beginning of period 1 equals the number of replacements that need to happen in period 1, this means that in period 1 at least enough bogies have to be revised to make enough for period 2, etc. Calculating like this the expected number of replacements and revision per period per bogie type can be calculated. The results are given in the table below:

Table 49: Calculated Result Extended Model, Event Validity, Scenario 1

	Period 1	Period 2	Period 3
$n_t^{1,1}$	2	2	0
$x_t^{1,1}$	2	2	0
$D_t^{1,1}$	2	2	
$W_t^{1,1}$			0
$n_t^{1,2}$	2	0	0
$x_t^{1,2}$	3	2	2
$D_t^{1,2}$	3		
$W_t^{1,2}$		2	2
$n_t^{2,1}$	2	3	0
$x_t^{2,1}$	3	2	0
$D_t^{2,1}$	3	2	
$W_t^{2,1}$			0
$n_t^{2,2}$	1	0	0
$x_t^{2,2}$	1	1	3
$D_t^{2,2}$	1	1	
$W_t^{2,2}$			3

The results in the table above will lead to the following total cost:

$$\sum_{i\in\{a^i>1\}}\left(b^i * c_c^i\right) + \sum_{t\in T}(c_l) + \sum_{i\in I}\sum_{t'=a^i}^{t'=p^i}\left(c_h^i\left(b^i + \sum_{k\in K}\left(h^{i,k}\right)\right)\right) + \sum_{i\in I}\sum_{k\in K}\sum_{t'=a^i}^{t'=p^i}\left(\left(x_{t'}^{i,k} * z^i * c_f\right) + \left(n_{t'}^{i,k} * c_m^{i,k}\right) + \left(n_{t'}^{i,k} * c_{w1} + x_{t'}^{i,k} * c_{w2}\right)\right) = 0 + (3 * 100) + 3(10 * 9) + 3(10 * 8) + (4 * 1 * 5) + (4 * 10) + (4 * 10 + 4 * 10) + (7 * 1 * 5) + (2 * 30) + (2 * 10 + 7 * 10) +$$

$$(5 * 2 * 5) + (5 * 20) + (5 * 10 + 5 * 10) + (5 * 2 * 5) + (1 * 40) + (1 * 10 + 5 * 10) = €1{,}535. -$$

When these parameters are put in GUSEK, the total cost of €1,535.- is found as well.

Scenario 2

This scenario will check how the model reacts if one of the bogie types only comes into the field after the planning horizon has already started. In this case bogie type 2 comes into the field in period 2. The input variables are given in the three tables below:

Table 50: Input Extended Model, Event Validity, Scenario 2, Part 1

Parameter	Value
I	2
T	3
K	2
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 51: Input Extended Model, Event Validity, Scenario 2, Part 2

	Bogie Type 1		Bogie Type 2	
	Revision Type 1	Revision Type 2	Revision Type 1	Revision Type 2
a^i	1		2	
b^i	5		8	
h^i	2	2	0	0
p^i	3		3	
q^i	2	1	2	2
r^i	2	3	1	4
z^{i}	1		2	
c_c^i	100		100	
c_{h}^i	10		10	
c_m^i	10	30	20	40

Table 52: Input Extended Model, Event Validity, Scenario 2, Part 3

	Period 1	Period 2	Period 3
R_{t}	100	100	100
$D_{\mathrm{t}}^{1,1}$	2	2	
$D_{\mathrm{t}}^{1,2}$	3		
$D_{\mathrm{t}}^{2,1}$		3	2
$D_{\mathrm{t}}^{2,2}$		1	1

The expectation for this scenario is that the results will be the same as for scenario 1, except from the fact that bogie type 2 comes into the field in period 2, which eliminates the demand of 3 replacements (of bogie type 2 revision type 2) and consequential 6 revisions (5 of bogie type 2 revision type 1 and 1 of bogie type 2 revision type 2). Regarding the cost, investment cost will increase because bogies type 2 have to be bought, holding and revision costs will decrease. The calculated results are given in the table below:

Table 53: Calculated Result Extended Model, Event Validity, Scenario 2

	Period 1	Period 2	Period 3
$n_t^{1,1}$	2	2	0
$x_t^{1,1}$	2	2	0
$\mathrm{D}_t^{1,1}$	2	2	
$\mathrm{W}_t^{1,1}$			0
$n_t^{1,2}$	2	0	0
$x_t^{1,2}$	3	2	2
$\mathrm{D}_t^{1,2}$	3		
$\mathrm{W}_t^{1,2}$		2	2
$n_t^{2,1}$		0	0
$x_t^{2,1}$		3	2
$\mathrm{D}_t^{2,1}$		3	2
$\mathrm{W}_t^{2,1}$			
$n_t^{2,2}$		0	0
$x_t^{2,2}$		1	1
$\mathrm{D}_t^{2,2}$		1	1
$\mathrm{W}_t^{2,2}$			

The expected total cost for this scenario would be:

$$\sum_{i\in\{\mathrm{a}^{\mathrm{i}}>1\}}\left(b^i * \mathrm{c}_{\mathrm{c}}^{\mathrm{i}}\right) + \sum_{\mathrm{t}\in\mathrm{T}}(c_l) + \sum_{i\in I}\sum_{t\prime=a^i}^{\mathrm{t}'=p^i}\left(c_h^i\left(b^i + \sum_{k\in K}\left(h^{i,k}\right)\right)\right) + \sum_{i\in I}\sum_{\mathrm{k}\in\mathrm{K}}\sum_{t\prime=a^i}^{\mathrm{t}'=p^i}\left(\left(x_{t\prime}^{i,k} * z^{\mathrm{i}} * c_f\right) + \left(n_{t\prime}^{i,k} * c_m^{i,k}\right) + \left(n_{t\prime}^{i,k} * c_{w1} + x_{t\prime}^{i,k} * c_{w2}\right)\right) = (8 * 100) + (3 * 100) + 3(10 * 9) + 2(10 * 8) + (4 * 1 * 5) + (4 * 10) + (4 * 10 + 4 * 10) + (7 * 1 * 5) + (2 * 30) + (2 * 10 + 7 * 10) + (5 * 2 * 5) + (0 * 20) + (0 * 10 + 5 * 10) + (2 * 2 * 5) + (0 * 40) + (0 * 10 + 2 * 10) = €1{,}995.-$$

When these parameters are put in GUSEK, the total cost of €1,995.- is found as well.

Scenario 3

Scenario 3 studies the opposite effect of scenario 2, here the different bogie types are put into the field at the same time, but bogie type 2 is taken out of the field after 2 periods.

Table 54: Input Extended Model, Event Validity, Scenario 3, Part 1

Parameter	Value
I	2
T	3
K	2
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 55: Input Extended Model, Event Validity, Scenario 3, Part 2

	Bogie Type 1		Bogie Type 2	
	Revision Type 1	Revision Type 2	Revision Type 1	Revision Type 2
a^i	1		1	
b^i	5		4	
h^i	2	2	2	2
p^i	3		2	
q^i	2	1	2	2
r^i	2	3	1	4
z^i	1		2	
c_c^i	100		100	
c_h^i	10		10	
c_m^i	10	30	20	40

Table 56: Input Extended Model, Event Validity, Scenario 3, Part 3

	Period 1	Period 2	Period 3
R_t	100	100	100
$D_t^{1,1}$	2	2	
$D_t^{1,2}$	3		
$D_t^{2,1}$	3	2	
$D_t^{2,2}$	1	1	

The expectation is that the results will be the same as those of scenario 1, except that there won't be any demand in period 3 for bogie type 2 anymore, which results in 4 replacements and 4 revisions less for bogie type 2. The results of the calculations are given in the table below:

Table 57: Calculated Result Extended Model, Event Validity, Scenario 3

	Period 1	Period 2	Period 3
$n_t^{1,1}$	2	2	0
$x_t^{1,1}$	2	2	0
$D_t^{1,1}$	2	2	
$W_t^{1,1}$			0
$n_t^{1,2}$	2	0	0
$x_t^{1,2}$	3	2	2
$D_t^{1,2}$	3		
$W_t^{1,2}$		2	
$n_t^{2,1}$	2	0	
$x_t^{2,1}$	3	2	
$D_t^{2,1}$	3	2	
$W_t^{2,1}$			
$n_t^{2,2}$	1	0	
$x_t^{2,2}$	1	1	
$D_t^{2,2}$	1	1	
$W_t^{2,2}$			

The expected total cost for this scenario would be:

$$\sum_{i\in\{a^i>1\}}\left(b^i * c_c^i\right) + \sum_{t\in T}(c_l) + \sum_{i\in I}\sum_{t'=a^i}^{t'=p^i}\left(c_h^i\left(b^i + \sum_{k\in K}\left(h^{i,k}\right)\right)\right) + \sum_{i\in I}\sum_{k\in K}\sum_{t'=a^i}^{t'=p^i}\left(\left(x_{t'}^{i,k} * z^i * c_f\right) + \left(n_{t'}^{i,k} * c_m^{i,k}\right) + \left(n_{t'}^{i,k} * c_{w1} + x_{t'}^{i,k} * c_{w2}\right)\right) = 0 + (3*100) + 3(10*9) + 2(10*8) + (4*1*5) + (4*10) + (4*10+4*10) + (7*1*5) + (2*30) + (2*10+7*10) + (5*2*5) + (2*20) + (2*10+5*10) + (2*2*5) + (1*40) + (1*10+2*10) = €1{,}305.-$$

When these parameters are put in GUSEK, the total cost of €1,305.- is found as well.

Scenario 4

This scenario explores the labor capacity restriction of the ROW. In scenario 1, the total capacity is set so high, that this will never limit the model. In the below table the capacity that is used per period in scenario 1 is calculated. This is 16 hours in period 1, 7 hours in period 2 and 0 hours in period 3.

Table 58: Extended Model, Calculation Labor Capacity Scenario 1

	Period 1	Period 2	Period 3
$n_t^{1,1}$	2	2	0
$n_t^{1,2}$	2	0	0
$n_t^{1,1} * r^{1,1} + n_t^{1,2} * r^{1,2}$	10	4	0
$n_t^{2,1}$	2	3	0
$n_t^{2,2}$	1	0	0
$n_t^{2,1} * r^{2,1} + n_t^{2,2} * r^{2,2}$	6	3	0
$\left(n_t^{1,1} * r^{1,1} + n_t^{1,2} * r^{1,2}\right) + \left(n_t^{2,1} * r^{2,1} + n_t^{2,2} * r^{2,2}\right)$	16	7	0
R_t	100	100	100

In this scenario the total available capacity for the ROW will be set so that there will be a shortage in period 2 and there will be extra time in period 1. The expectation is that the model will push one revision backward to satisfy all constraints.

The input variable for this scenario are given in the three tables below:

Table 59: Input Extended Model, Event Validity, Scenario 4, Part 1

Parameter	Value
I	2
T	3
K	2
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 60: Input Extended Model, Event Validity, Scenario 4, Part 2

	Bogie Type 1		Bogie Type 2	
	Revision Type 1	Revision Type 2	Revision Type 1	Revision Type 2
a^i	1		1	
b^i	5		4	

h^i	2	2	2	2
p^i	3		3	
q^i	2	1	2	2
r^i	2	3	1	4
z^{i}	1		2	
c_c^i	100		100	
c_{h}^i	10		10	
c_m^i	10	30	20	40

Table 61: Input Extended Model, Event Validity, Scenario 4, Part 3

	Period 1	Period 2	Period 3
$\mathrm{R_t}$	20	6	0
$D_{\mathrm{t}}^{1,1}$	2	2	
$D_{\mathrm{t}}^{1,2}$	3		
$D_{\mathrm{t}}^{2,1}$	3	2	
$D_{\mathrm{t}}^{2,2}$	1	1	

As set before, the expectation is that the model will push one revision backwards; this is shown in the table below:

Table 62: Calculated Result Extended Model, Event Validity, Scenario 4

	Period 1	Period 2	Period 3
$n_t^{1,1}$	2	2	0
$x_t^{1,1}$	2	2	0
$\mathrm{D_t^{1,1}}$	2	2	
$\mathrm{W_t^{1,1}}$			0
$n_t^{1,2}$	2	0	0
$x_t^{1,2}$	3	2	2
$\mathrm{D_t^{1,2}}$	3		
$\mathrm{W_t^{1,2}}$		2	2
$n_t^{2,1}$	2	2	0
$x_t^{2,1}$	3	2	0
$\mathrm{D_t^{2,1}}$	3	2	
$\mathrm{W_t^{2,1}}$			0
$n_t^{2,2}$	2	0	0
$x_t^{2,2}$	1	1	3
$\mathrm{D_t^{2,2}}$	1	1	
$\mathrm{W_t^{2,2}}$			3

The expected total cost for this scenario would be:

$$\sum_{i\in\{\mathrm{a^i}>1\}}\left(b^i * \mathrm{c_c^i}\right) + \sum_{\mathrm{t\in T}}(c_l) + \sum_{i\in I}\sum_{t\prime=a^i}^{\mathrm{t}'=p^i}\left(c_h^i\left(b^i + \sum_{k\in K}\left(h^{i,k}\right)\right)\right) + \sum_{i\in I}\sum_{\mathrm{k\in K}}\sum_{t\prime=a^i}^{\mathrm{t}'=p^i}\left(\left(x_{t\prime}^{i,k} * z^{\mathrm{i}} * c_f\right) + \left(n_{t\prime}^{i,k} * c_m^{i,k}\right) + \left(n_{t\prime}^{i,k} * c_{w1} + x_{t\prime}^{i,k} * c_{w2}\right)\right) = 0 + (3 * 100) + 3(10 * 9) + 3(10 * 8) + (4 * 1 * 5) + (4 * 10) + (4 * 10 + 4 * 10) + (7 * 1 * 5) + (2 * 30) + (2 * 10 + 7 * 10) + (5 * 2 * 5) + (4 * 20) + (4 * 10 + 5 * 10) + (5 * 2 * 5) + (2 * 40) + (2 * 10 + 5 * 10) = €1{,}555. -$$

When these parameters are put in GUSEK, the total cost of €1,555.- is found as well.

D.1.2. Results

The calculated results and the GUSEK results for the different scenarios are given in the table below:

Table 63: Results Extended Model Event Validity

	Calculated	GUSEK Model
Scenario 1	€1,535.-	€1,535.-
Scenario 2	€1,995.-	€1,995.-
Scenario 3	€1,305.-	€1,305.-
Scenario 4	€1,555.-	€1,555.-

As can be seen in the table above, for all scenarios the calculated costs equal the cost of GUSEK.

D.2. Comparison to Other Models Results

The validation method "comparison to other models" is described by Irobi et al (2004) as a method that compares the output of the model to the output of other models. In this case the mathematical model is besides in GUSEK also made in Excel, where it can be solved using the Excel solver. Both models are made independent of each other and so comparison of the models can validate the GUSEK model.

For this validation the scenarios described in section D.1. will be put in Excel and the results will be compared to the results found in section D.1.2.. Specifically for this case the results that were compared are the total cost that are minimized and the total number of replacements and revisions over the planning horizon.

D.2.1. Results

The calculated results, the GUSEK results and the Excel results for the different scenarios are given in the table below:

Table 64: Results Extended Model Comparison to Other Models

	Calculated	GUSEK Model	Excel Model
Scenario 1	€1,535.-	€1,535.-	€1,535.-
Scenario 2	€1,995.-	€1,995.-	€1,995.-
Scenario 3	€1,305.-	€1,305.-	€1,305.-
Scenario 4	€1,555.-	€1,555.-	€1,555.-

As can be seen in the table above, the Excel solver gives the same results as the GUSEK model and the values calculated without a solver.

D.3. Extreme Condition Test Results

This method checks how the model implemented in software deals with extreme conditions. For the model created in this report it is important that the model implemented in software will give no output when not all conditions are met.

D.3.1. Different Conditions

This section describes the different extreme conditions in further detail and gives the input parameters for the different scenarios.

Total Capacity in the ROW lower than the total capacity needed to revise all bogies.

An extreme point is taken here, where the total capacity of the ROW is zero for every period. The input parameters for this scenario are given in the three tables below:

Table 65: Input Extended Model, Extreme Conditions, Capacity ROW, Part 1

Parameter	Value
I	2
T	3
K	2
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 66: Input Extended Model, Extreme Conditions, Capacity ROW, Part 2

	Bogie Type 1		Bogie Type 2	
	Revision Type 1	Revision Type 2	Revision Type 1	Revision Type 2
a^i	1		1	
b^i	5		4	
h^i	2	2	2	2
p^i	3		3	
q^i	2	1	2	2
r^i	2	3	1	4
z^i	1		2	
c_c^i	100		100	
c_h^i	10		10	
c_m^i	10	30	20	40

Table 67: Input Extended Model, Extreme Conditions, Capacity ROW, Part 3

	Period 1	Period 2	Period 3
R_t	0	0	0
$D_t^{1,1}$	2	2	
$D_t^{1,2}$	3		
$D_t^{2,1}$	3	2	
$D_t^{2,2}$	1	1	

As a result GUSEK says that there is no optimal solution found.

No ready-for-use bogies in inventory when the planning horizon starts, while there is demand in the first period.

In this extreme scenario the start inventory of all ready-for-use bogies for all bogie types will be put to zero, the input parameters are shown in the three tables below:

Table 68: Input Extended Model, Extreme Conditions, Capacity Ready-to-use Bogies, Part 1

Parameter	Value
I	2
T	3

K	2
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 69: Input Extended Model, Extreme Conditions, Capacity Ready-to-use Bogies, Part 2

	Bogie Type 1		**Bogie Type 2**	
	Revision Type 1	**Revision Type 2**	**Revision Type 1**	**Revision Type 2**
a^i	1		1	
b^i	0		0	
h^i	2	2	2	2
p^i	3		3	
q^i	2	1	2	2
r^i	2	3	1	4
z^i	1		2	
c_c^i	100		100	
c_h^i	10		10	
c_m^i	10	30	20	40

Table 70: Input Extended Model, Extreme Conditions, Capacity Ready-to-use Bogies, Part 3

	Period 1	**Period 2**	**Period 3**
R_t	100	100	100
$D_t^{1,1}$	2	2	
$D_t^{1,2}$	3		
$D_t^{2,1}$	3	2	
$D_t^{2,2}$	1	1	

As a result GUSEK says that there is no optimal solution found.

No bogies that need revision in inventory when the planning horizon starts, while revision in necessary to meet future demand.

In this extreme scenario the number of bogies in inventory that need revision at the beginning of period 1 is set to zero and the number of ready-for-use bogies in inventory is set to three per type of bogie. The input parameters are given in the three tables below:

Table 71: Input Extended Model, Extreme Conditions, Capacity Bogies that need Revision, Part 1

Parameter	**Value**
I	2
T	3
K	2
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 72: Input Extended Model, Extreme Conditions, Capacity Bogies that need Revision, Part 2

	Bogie Type 1		Bogie Type 2	
	Revision Type 1	Revision Type 2	Revision Type 1	Revision Type 2
a^i	1		1	
b^i	5		4	
h^i	0	0	0	0
p^i	3		3	
q^i	2	1	2	2
r^i	2	3	1	4
z^i	1		2	
c_c^i	100		100	
c_h^i	10		10	
c_m^i	10	30	20	40

Table 73: Input Extended Model, Extreme Conditions, Capacity Bogies that need Revision, Part 3

	Period 1	Period 2	Period 3
R_t	100	100	100
$D_t^{1,1}$	2	2	
$D_t^{1,2}$	3		
$D_t^{2,1}$	3	2	
$D_t^{2,2}$	1	1	

As a result GUSEK says that there is no optimal solution found.

Period that one of the bogie types is taken out of the field is outside the planning horizon.

In this extreme scenario the period that bogie type 1 is taken out of the field is set on period 15, which is three periods after the planning horizon ends. The input parameters are given in the three tables below.

Table 74: Input Extended Model, Extreme Conditions, Outside Horizon, Part 1

Parameter	Value
I	2
T	3
K	2
c_f	5
c_l	100
c_{w1}	10
c_{w2}	10

Table 75: Input Extended Model, Extreme Conditions, Outside Horizon, Part 2

	Bogie Type 1		Bogie Type 2	
	Revision Type 1	Revision Type 2	Revision Type 1	Revision Type 2
a^i	1		1	
b^i	5		4	
h^i	2	2	2	2
p^i	3		5	
q^i	2	1	2	2

r^i	2	3	1	4
z^{i}	1		2	
c_c^i	100		100	
c_{h}^i	10		10	
c_m^i	10	30	20	40

Table 76: Input Extended Model, Extreme Conditions, Outside Horizon, Part 3

	Period 1	Period 2	Period 3
$\mathbf{R}_{\mathrm{t}}$	100	100	100
$D_{\mathrm{t}}^{1,1}$	2	2	
$D_{\mathrm{t}}^{1,2}$	3		
$D_{\mathrm{t}}^{2,1}$	3	2	
$D_{\mathrm{t}}^{2,2}$	1	1	

As a result GUSEK says that there are variables out of domain.

D.3.2. Results

The four different extreme conditions that are used during this test are explained in the table below, together with the results GUSEK gave.

Table 77: Results Extended Model Extreme Condition Test

Input	GUSEK output
Total capacity in the ROW lower than the total capacity needed to revise all bogies.	No optimal solution found
No ready-for-use bogies in inventory when the planning horizon starts, while there is demand in the first period.	No optimal solution found
No bogies that need revision in inventory when the planning horizon starts, while revision in necessary to meet future demand.	No optimal solution found
Period that one of the bogie types is taken out of the field is outside the planning horizon.	Variable out of domain

As can be seen in the table above, the model does not give output when the input parameters are not correct or not all conditions can be met.

Appendix E: Model Input

This appendix contains the input parameters used for the basic model.

Table 78: Bogie Type Input Parameters

Bogie type	Train type	# NedTrain	Description	# of Bogies	# built in	# in stock (b^i)
1	SLT	D130	Kopmotordraaistel	212	202	10
2		D131	Jacobs-motordraaistel (MB)	158	152	6
3		D135	Jacobs-loopdraaistel (LP, type 3a/b)	160	152	8
4		D136	Jacobs-loopdraaistel (LR, type 4)	106	101	5
5	SGM / SGMm	D030	Motordraaistel (SGM-0 II, EMLA-0)	7	4	3
6		D035	Motordraaistel (SGM-1/-2 II/III, EMLA-1n)	229	222	7
7		D036	Motordraaistel (SGM-1/-2 II/III, EMLA-2n)	79	76	3
8		D037	Midden- motordraaistel (EMLA-0)	63	52	11
9		D063	Loopdraaistel (LG, SGM-2/-3 III)	128	120	8
10	ICM / ICMm	D064	Loopdraaistel (ICM-1/-2 III + I, LH-1/-2)	365	350	15
11		D065	Loopdraaistel (ICM-3/-4 IV, LH-3/-4)	110	98	12
12		D066	Loopdraaistel met magneetrem (LH-3/-4M)	158	150	8
13		D079	Motordraaistel (ICM-1/-2 III + IV, MU-1/-2)	193	172	21
14		D080	Motordraaistel (ICM-3/-4 IV, MU-3/-4)	158	151	7
15	VIRM	D040	Loopdraaistel (LN)	302	274	28
16		D042	Motordraaistel (MY)	299	275	24
17		D044	Loopdraaistel (LM)	666	611	55
18		D068	Loopdraaistel (DD-IRM, LJ)	278	256	22
19		D069	Koploopdraaistel (DD-IRM, LK)	178	161	17
20		D082	Motordraaistel (DD-IRM, MW)	175	161	14
21	DDZ	D104	Loopdraaistel (DDM-2/-3, RD)	89	76	13
22		D105	Loopdraaistel magneetrem (DDM-2/-3, RD-M)	272	257	15
23		D106	Loopdraaistel met blokkenrem (RD-B)	192	178	14
24		D083	Motorkopdraaistel (mDDM, MX-K)	55	49	6
25		D084	Motorvouwbalgdraaistel (mDDM, MX-V)	56	49	7
26		D085	Motortussendraaistel (mDDM, MX-T)	55	49	6
27	ICRm	D098	Loopdraaistel (RA-1/-2)	298	286	12
28		D099	Loopdraaistel (RA-3)	78	60	18
29		D100	Loopdraaistel (RA-4)	35	31	4
30		D103	Kopdraaistel (RC)	37	32	5
31	Replacing SGM / SGMm		Motordraaistel	7	4	3
32			Motordraaistel	229	222	7
33			Motordraaistel	79	76	3
34			Midden- motordraaistel	63	52	11
35			Loopdraaistel	128	120	8
36	Replacing ICM /		Loopdraaistel	365	350	15
37			Loopdraaistel	110	98	12

38	ICMm		Loopdraaistel met magneetrem	158	150	8
39			Motordraaistel	193	172	21
40			Motordraaistel	158	151	7
41	Replacing VIRM		Loopdraaistel	302	274	28
42			Motordraaistel	299	275	24
43			Loopdraaistel	666	611	55
44			Loopdraaistel	278	256	22
45			Koploopdraaistel	178	161	17
46			Motordraaistel	175	161	14
47	Replacing DDZ		Loopdraaistel	89	76	13
48			Loopdraaistel magneetrem	272	257	15
49			Loopdraaistel met blokkenrem	192	178	14
50			Motorkopdraaistel	55	49	6
51			Motorvouwbalgdraaistel	56	49	7
52			Motortussendraaistel	55	49	6
53	Replacing ICRm		Loopdraaistel	298	286	12
54			Loopdraaistel	78	60	18
55			Loopdraaistel	35	31	4
56			Kopdraaistel	37	32	5

Table 79: Bogie Lifetime Input Parameters

Bogie type	Start period (a^i)	End period (p^i)	Inter-revision deadline (q^i)
1	1	360	72
2	1	360	72
3	1	360	72
4	1	360	72
5	1	168	180
6	1	168	180
7	1	168	120
8	1	168	180
9	1	168	180
10	1	144	180
11	1	228	240
12	1	228	240
13	1	144	180
14	1	228	240
15	1	336	90
16	1	336	90
17	1	336	90
18	1	240	180
19	1	240	90
20	1	240	132
21	1	216	216

22	1	216	216
23	1	216	216
24	1	216	216
25	1	216	216
26	1	216	216
27	1	180	84
28	1	180	84
29	1	180	84
30	1	180	84
31	169	360	180
32	169	360	180
33	169	360	120
34	169	360	180
35	169	360	180
36	145	360	180
37	229	360	240
38	229	360	240
39	145	360	180
40	229	360	240
41	337	360	90
42	337	360	90
43	337	360	90
44	241	360	180
45	241	360	90
46	241	360	132
47	217	360	216
48	217	360	216
49	217	360	216
50	217	360	216
51	217	360	216
52	217	360	216
53	181	360	84
54	181	360	84
55	181	360	84
56	181	360	84

Table 80: Cost Input Parameters

Bogie type	Purchasing cost (c_c^i)	Holding cost (c_h^i)	Material cost (c_m^i)	Transport cost (MD-ROW) (c_{w1})	Transport cost (ROW-MD) (c_{w2})
1	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
2	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
3	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
4	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-

5	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
6	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
7	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
8	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
9	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
10	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
11	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
12	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
13	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
14	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
15	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
16	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
17	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
18	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
19	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
20	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
21	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
22	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
23	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
24	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
25	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
26	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
27	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
28	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
29	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
30	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
31	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
32	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
33	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
34	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
35	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
36	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
37	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
38	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
39	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
40	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
41	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
42	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
43	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
44	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
45	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
46	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
47	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-

48	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
49	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
50	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
51	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
52	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
53	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
54	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
55	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-
56	€200,000.-	€40.-	€10,000.-	€1,000.-	€1,000,-

Table 81: Labor Capacity Input Parameters

Bogie type	Labor hours MD (z^{i})	Labor hours ROW (r^i)
1	2	200
2	2	200
3	2	200
4	2	200
5	1	200
6	1	200
7	1	200
8	1	200
9	1	200
10	1	200
11	1	200
12	1	200
13	1	200
14	1	200
15	1	200
16	1	200
17	1	200
18	1	200
19	1	200
20	1	200
21	1	200
22	1	200
23	1	200
24	1	200
25	1	200
26	1	200
27	1	200
28	1	200
29	1	200
30	1	200
31	1	200

32	1	200
33	1	200
34	1	200
35	1	200
36	1	200
37	1	200
38	1	200
39	1	200
40	1	200
41	1	200
42	1	200
43	1	200
44	1	200
45	1	200
46	1	200
47	1	200
48	1	200
49	1	200
50	1	200
51	1	200
52	1	200
53	1	200
54	1	200
55	1	200
56	1	200

Table 82: Demand Input Parameters

Bogie type	Period	Demand (D_t^i)	Start Demand	End Demand
1	60	212	1	72
2	60	158	1	72
3	60	160	1	72
4	60	106	1	72
5			1	180
6			1	180
7	60	79	1	120
8			1	180
9			1	180
10	84	365	1	180
11	180	110	1	240
12	180	158	1	240
13	84	193	1	180
14	180	158	1	240
15	24	302	1	90

16	24	299	1	90
17	36	666	1	90
18	48	278	1	180
19	48	178	1	90
20	72	175	1	132
21	48	89	1	216
22	48	272	1	216
23	48	192	1	216
24	48	55	1	216
25	72	56	1	216
26	72	55	1	216
27	84	298	1	84
28	48	78	1	84
29	72	35	1	84
30	72	37	1	84
31	349	7	169	349
32	349	229	169	349
33	289	79	169	289
34	349	63	169	349
35	349	128	169	349
36	325	365	145	325
37			229	360
38			229	360
39	325	193	145	325
40			229	360
41			337	360
42			337	360
43			337	360
44			241	360
45	331	178	241	331
46			241	360
47			217	360
48			217	360
49			217	360
50			217	360
51			217	360
52			217	360
53	265	298	181	265
54	265	78	181	265
55	265	35	181	265
56	265	37	181	265

Appendix F: Results; Planning of Revisions and Replacements

Table 83: Planning Revisions (Part 1)

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Type 1	10	0	6.8	0	3.2	10	0	0	0	0	0	10	3.1	0	0	0
Type 2	0	0	6	6	0	0	6	2.8	3.2	3.1	6	6	0	0	0	6
Type 3	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	8
Type 4	0	0	0	0	0	0	0	0	0	5	0	0	0	5	0	0
Type 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 7	0	0	3	0	0	0	3	0	0	0	0	0	0	0	0	0
Type 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 10	0	0	0	0	0	0	0	15	2.9	0	0	0	15	15	6.9	8.1
Type 11	9.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 15	28	28	28	17.1	10.2	28	0	0	0	0	6.3	21.1	0	0	0	0
Type 16	0	0	0	9	24	0	0	22.2	0	24	24	24	24	0	24	24
Type 17	0	0	0	0	9.7	0	40.1	0	55	0	0	0	7	25.1	13.3	0
Type 18	0	18.1	0	0	0	22	0	0	0	0	0	0	0	0	0	0
Type 19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 22	0	15	0	15	0	0.9	0	13.1	0	15	15	0	0	15	15	15
Type 23	14	0	14	14	14	0.2	0	0	0	14	9.8	0	0	0	0	0
Type 24	0	0	0	0	0	0	6	0	0	0	0	0	0	1	0	0
Type 25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 26	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0
Type 27	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0
Type 28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.9	0
Type 31																
Type 32																
Type 33																
Type 34																
Type 35																
Type 36																
Type 37																
Type 38																
Type 39																
Type 40																
Type 41																
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Type 48																
Type 49																
Type 50																
Type 51																
Type 52																
Type 53																
Type 54																
Type 55																
Type 56																

Table 84: Planning Revisions (Part 2)

Period	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Type 1	0	0	0	10	0	7.3	0	1.4	8.6	0	0	0	0	0	0	0
Type 2	6	0	0	0	0	6	0	0	6	0	0	0	0	0	0	0
Type 3	0	0	0	8	2.9	0	8	8	0	8	8	0	0	0	0	0
Type 4	5	0	5	5	0	0	0	0	0	0	5	0	0	0	0	0
Type 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 7	1	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0
Type 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 10	15	15	15	2.1	15	0	0	15	15	15	0	0	15	0	0	15
Type 11	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0
Type 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 13	14.4	0	0	0	0	0	0	0	4.5	0	0	0	0	0	0	0
Type 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 15	0	0	0	28	23.3	28	0	0	0	0	0	0	0	0	0	0
Type 16	0	0	0	8	0	19.8	24	0	0	0	0	0	0	0	0	0
Type 17	19.7	21.2	41.1	0	19.9	0	0	7.2	0	0	48.1	44.3	0	55	30.2	9.1
Type 18	0	22	0	0	0	0	0	0	0	6.1	0	1.8	22	0	22	22
Type 19	0	0	0	0	0	0	0	0	17	17	0	0	17	0	0	0
Type 20	0	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.9	0
Type 22	0	0	0	0	0	0	0	15	6.6	15	0	15	0	6.1	0	15
Type 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 24	0	0	0	0	0	0	0	6	0	0	0	0	6	0	0	0
Type 25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 26	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0
Type 27	0	0	0	0	0	0	0	0	2.5	0	0	0	0	0	0	0
Type 28	0	0	0	0	0	0	0	5.5	0	0	0	0	0	0	0	0
Type 29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 31																
Type 32																
Type 33																
Type 34																
Type 35																
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Type 49																
Type 50																
Type 51																
Type 52																
Type 53																
Type 54																
Type 55																
Type 56																

Table 85: Planning Revisions (Part 3)

Period	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Type 1	0	0	0	0	10	0	3.5	5.1	10	10	0	0	0	0	0	10
Type 2	6	0	6	6	0	0	5.6	6	6	0	0	6	6	0	0	1.2
Type 3	0	0	0	0	8	0	0	0	0	8	8	0	0	8	0	8
Type 4	0	0	0	0	5	0	0	5	0	5	0	5	0	5	5	0
Type 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 7	0	3	0	3	0	0	3	3	3	3	0	3	0	3	0	3
Type 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 10	0	0	0	0	0	0	0	15	0	0	15	0	0	0	15	15
Type 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0
Type 13	17.1	0	0	0	0	10	0	0	21	0	0	0	0	0	0	0
Type 14	7	3.1	0	0	4.1	0	7	0	7	7	7	0	0	0	0	4.9
Type 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 17	0	55	55	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 18	13	0	0	20.1	0	0	0	0	0	0	20.9	22	22	0	0	0
Type 19	0	0	0	17	0	5.1	17	0	2.1	0.8	0	0	17	17	17	0
Type 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 21	0	0	0	0	13	0	13	0	0	0	0	13	2.1	13	0	0
Type 22	0	0	0	15	0	15	0	15	0	0	4.2	0	0	1.1	0	0
Type 23	0	0	0	0	14	14	0	0	0	14	0	0	14	14	14	0
Type 24	0	0	0	0	0	0	6	0	6	0	6	0	0	0	6	0
Type 25	0	0	0	0	7	7	0	0	0	0	0	7	0	0	0	7
Type 26	0	0	0	0	0	6	6	0	6	0	0	0	0	0	0	0
Type 27	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	12
Type 28	18	0	0.1	0	0	0	0	0	0	13.3	0	5.1	0	0	0	0
Type 29	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
Type 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 31																
Type 32																
Type 33																
Type 34																
Type 35																
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Type 50																
Type 51																
Type 52																
Type 53																
Type 54																
Type 55																
Type 56																

Table 86: Planning Replacements (Part 1)

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Type 1	10	0	6.8	0	3.2	10	0	0	0	0	0	10	3.1	0	0	0
Type 2	0	0	6	6	0	0	6	6	0	6	3.1	6	0	0	6	0
Type 3	0	0	0	0	0	0	5.8	2.2	0	0	0	0	0	0	0	8
Type 4	0	0	0	0	0	0	0	5	0	0	0	0	0	5	0	0
Type 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 7	3	0	0	3	0	0	0	3	0	0	0	0	0	0	0	0
Type 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 10	15	0	0	0	0	0	0	0	2.9	0	15	0	0	15	15	0
Type 11	12	9.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 12	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 13	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 14	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 15	28	28	28	17.1	15.1	23.1	0	0	0	0	6.3	21.1	0	0	0	0
Type 16	0	0	0	9	24	0	0	22.2	0	24	24	24	24	0	24	24
Type 17	0	0	0	0	9.7	0	40.1	0	55	0	0	0	7	25.1	13.3	0
Type 18	0	18.1	0	0	0	22	0	0	0	0	0	0	0	0	0	0
Type 19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 21	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 22	15	0	15	0	15	0	0.9	0	13.1	0	15	15	0	0	15	15
Type 23	14	14	0	14	14	14	0.2	0	0	0	14	0	9.8	0	0	0
Type 24	6	0	0	0	0	0	0	6	0	0	0	0	0	0	1	0
Type 25	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0
Type 26	6	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0
Type 27	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0
Type 28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.9	0
Type 31																
Type 32																
Type 33																
Type 34																
Type 35																
Type 36																
Type 37																
Type 38																
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Type 40																
Type 41																
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Type 50																
Type 51																
Type 52																
Type 53																
Type 54																
Type 55																
Type 56																

Table 87: Planning Replacements (Part 2)

Period	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Type 1	0	0	0	10	0	7.3	0	10	0	0	0	0	0	0	0	0
Type 2	6	0	0	0	0	6	6	0	0	0	0	0	0	0	0	0
Type 3	0	0	2.9	5.1	2.9	0	8	8	8	0	8	0	0	0	0	0
Type 4	5	0	5	5	0	0	0	0	0	0	5	0	0	0	0	0
Type 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 7	0	1	0	0	0	0	0	3	3	0	0	0	0	0	0	0
Type 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 10	15	15	15	15	2.1	15	0	0	15	15	15	0	0	0	15	0
Type 11	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0
Type 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 13	0	14.4	0	0	0	0	0	0	0	4.5	0	0	0	0	0	0
Type 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 15	0	0	0	28	23.3	28	0	28	0	0	0	0	0	0	0	0
Type 16	0	0	0	8	0	19.8	24	24	0	0	0	0	0	0	0	0
Type 17	19.7	21.2	41.1	13.9	6	0	0	7.2	0	0	48.1	44.3	16.5	38.5	39.3	0
Type 18	0	22	0	0	0	0	0	0	0	6.1	1.8	0	22	0	22	22
Type 19	0	0	0	0	0	0	0	0	17	17	0	0	17	0	0	0
Type 20	0	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.9
Type 22	15	0	0	0	0	0	0	0	15	6.6	15	0	15	0	6.1	0
Type 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 24	0	0	0	0	0	0	0	0	6	0	0	0	0	6	0	0
Type 25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 26	0	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0
Type 27	0	0	0	0	0	0	0	0	2.5	0	0	0	0	0	0	0
Type 28	0	0	0	0	0	0	0	5.5	0	0	0	0	0	0	0	0
Type 29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 31																
Type 32																
Type 33																
Type 34																
Type 35																
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Type 49																
Type 50																
Type 51																
Type 52																
Type 53																
Type 54																
Type 55																
Type 56																

Table 88: Planning Replacements (Part 3)

Period	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Type 1	0	0	0	0	10	0	10	0	8.6	10	0	0	0	0	0	10
Type 2	6	0	6	6	0	0	5.6	6	6	0	1.2	4.8	6	0	1.2	0
Type 3	0	0	0	0	8	0	0	0	0	8	8	8	0	0	0	8
Type 4	0	0	0	0	5	0	0	5	0	5	0	5	0	5	5	0
Type 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 7	0	0	0	3	0	0	3	3	3	3	3	0	3	0	0	3
Type 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 10	15	0	0	0	0	0	0	0	15	0	0	15	0	0	0	15
Type 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9
Type 13	0	17.1	0	0	0	0	10	0	0	21	0	0	0	0	0	0
Type 14	0	3.1	7	0	0	4.1	0	0	7	7	7	0	0	7	0	0
Type 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 17	0	55	55	55	0	0	0	0	0	0	0	0	0	0	0	0
Type 18	13	0	0	20.1	0	0	0	0	0	0	20.9	22	22	0	0	22
Type 19	0	0	0	17	0	5.1	17	0	2.9	0	0	17	0	17	17	17
Type 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Type 21	0	0	0	0	0	13	0	13	0	0	0	0	2.1	13	13	0
Type 22	15	0	0	0	15	0	15	0	15	0	0	4.2	0	0	1.1	0
Type 23	0	0	0	0	0	14	14	0	0	0	14	0	0	14	14	14
Type 24	0	0	0	0	0	0	0	6	0	6	0	6	0	0	0	6
Type 25	0	0	0	0	0	7	7	0	0	0	0	0	7	0	0	0
Type 26	0	0	0	0	0	0	6	6	0	6	0	0	0	0	0	0
Type 27	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	12
Type 28	18	0	0.1	0	0	0	0	0	0	13.3	0	5.1	0	0	0	18
Type 29	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
Type 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1
Type 31																
Type 32																
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Appendix G: Possible Extensions Basic Model

G.1. Differentiation Revisions

Sets:

I : Set of all different types of bogies considered in the model, $i \in \{1,2,3,\dots,i_e\}$.

K : Set of all different types of revisions considered in the model, $k \in \{1,2,3,\dots,k_e\}$.

T : Set of all periods considered in the planning horizon, $t \in \{1,2,3,\dots,t_e\}$.

I_t : Set of all types of bogies that are in the field in period t.

Parameters:

a^i : For all bogie types that are already in use before the first period of the planning horizon this parameter is set 1. For all bogie types that are not in use before the first period of the planning horizon this parameter is set to the period in the planning horizon that bogie type i goes into the field.

b^i : For all bogie types that are in use before the first period of the planning horizon this parameter indicates the number of ready-for-use bogies type i in inventory at the beginning of the first period of the planning horizon. For all bogie types that are not in use before the first period of the planning horizon this parameter is the number of spare bogies of type i that are purchased and are ready-for-use in the first period that bogie type i comes into the field.

c_c^i : The cost for purchasing one bogie type i in the period on the planning horizon that bogie type i goes into the field.

c_h^i : The cost of holding one bogie type i in inventory for one period.

c_f : The cost of one mechanic when working on the replacement of a bogie for one hour in the MD.

c_l : The cost of one mechanic for one hour in the ROW, independent on whether the mechanic is working on the revision of a bogie or not.

$c_m^{i,k}$: The cost of materials required for the k$^{\text{th}}$ revision of one bogie type i in the ROW.

c_{w1} : The cost of transporting one bogie from the MD to the ROW.

c_{w2} : The cost of transporting one bogie from the ROW to the MD.

$d_{\mathrm{t}}^{i,k}$: The demand for the replacement of bogie type i before the k$^{\text{th}}$ revision in period t, $t \in \left\{\mathrm{a}^{\mathrm{i}},\dots,\min\left(\mathrm{p}^{\mathrm{i}},\left(a^i+q^{i,k}-1\right)\right)\right\}$.

g^i : This parameter shows whether or not bogie type i was already in the field before the planning horizon. This parameter is zero if bogie type i was already in the field before the planning horizon and one if the type or bogie comes into the field during the planning horizon.

$h^{i,k}$: For all bogie types that are already in use before the first period of the planning horizon this parameter indicates the number of bogies type i waiting for the k$^{\text{th}}$ revision in inventory at the beginning of the first period of the planning horizon. For all bogie types that are not in use before the first period of the planning horizon this parameter is set zero.

i_e : The last type of bogie considered in the model.

k_e : The last type of revision considered in the model.

p^i : For all bogie types that go out of the field before the last period of the planning horizon, this parameter indicates the period on the planning horizon that bogie type i is taken out of the field. For all bogie types that don't go out of the field before the last period of the planning horizon the value of this parameter is set the last period in the planning horizon.

$q^{i,k}$: The inter-revision deadline, i.e. the maximum number of periods allowed between the k-1th revision and the kth revision of bogie type i (in periods).

$r^{i,k}$: The number of labor hours necessary for the kth revision of one bogie type i in the ROW.

R_t : The number of hours of labor capacity available for preventive maintenance in the ROW in period t.

t_e : The last period in the planning horizon.

z^{i} : The number of labor hours necessary for replacing one bogie of type i in the MD.

Decision variables:

$n_t^{i,k}: t \geq a^i, t \leq p^i$: The number of bogies of type i that will undergo their kth revision in the ROW in period t, for all types of bogies that are in the field in period t.

$x_t^{i,k}: t \geq a^i, t \leq p^i$: The number of bogies of type i that are ready for their kth revision and will be replaced in the MD in period t, for all types of bogies that are in the field in period t.

Variables:

$B_t^i: t \geq a^i, t \leq p^i$: The number of ready-for-use bogies of type i in inventory at the beginning of period t.

$H_t^{i,k}: t \geq a^i, t \leq p^i$: The number of bogies of type i that need their kth revision before they can be used for replacement in inventory at the beginning of period t.

$W_t^{i,k}: \mathrm{k} \in \{2, \dots, \mathrm{K}\},\ \forall i \in I: (a^i + q^{i,k}) \leq p^i, \forall t \in \{(\mathrm{a^i} + \mathrm{q}^{\mathrm{i,k}}), \dots, \mathrm{p^i}\}$: The number of replacements for their kth revision of bogies type i that must been executed in period t.

Objective:

$$Minimize\ \sum_{i\in \mathrm{I}} g^i(b^i * \mathrm{c_c^i}) + \sum_{\mathrm{t\in T}}(R_t * c_l) + \sum_{i\in I} \sum_{t'=a^i}^{p^i} \Big(c_h^i\ (b^i + \sum_{k\in K}(h^{i,k}))\Big) +$$

$$\sum_{i\in I} \sum_{\mathrm{k\in K}} \sum_{t'=a^i}^{p^i} \Big((x_{t'}^{i,k} * \mathrm{z^i} * c_f) + (\, n_{t'}^{i,k} * c_m^{i,k}) + (n_{t'}^{i,k} * c_{w1} + x_{t'}^{i,k} * c_{w2})\Big) \tag{14}$$

(14) Objective function; being the sum of the purchase cost of all the new bogies that will be bought within the planning horizon, the labor cost in the ROW, the holding cost, the labor cost in the MD, the material cost in the ROW and the transport cost from the ROW to the MD and from the MD to the ROW.

Constraints:

$$H_t^{i,k} = H_{t-1}^{i,k} + x_{t-1}^{i,k} - n_{t-1}^{i,k}, \qquad \forall \mathrm{k} \in \mathrm{K}, \forall i \in I: p^i \geq a^i + 1, \forall t \in \{a^i + 1, \dots, p^i\} \tag{15}$$

$$H_{a^i}^{i,k} = h^{i,k}, \qquad \forall \mathrm{i} \in \mathrm{I}, \forall \mathrm{k} \in \mathrm{K} \tag{16}$$

$$B_t^i = B_{t-1}^i + \sum_{k\in K} n_{t-1}^{i,k} - \sum_{k\in K} x_{t-1}^{i,k}, \qquad \forall i \in I: p^i \geq a^i + 1, \forall t \in \{a^i + 1, \dots, p^i\} \tag{17}$$

$$B_{a^i}^i = b^i, \qquad \forall \mathrm{i} \in \mathrm{I} \tag{18}$$

$$\sum_{\mathrm{i\in I}} \sum_{k\in K}(n_t^{i,k} * r^{i,k}) \leq R_t, \qquad \forall t \in \{1, \dots, t_e\} \tag{19}$$

$$n_t^{i,k} \leq H_t^{i,k} + x_t^{i,k}, \qquad \mathrm{k} \in \mathrm{K}, \forall i \in I, \forall, \forall t \in \{a^i, \dots, p^i\} \tag{20}$$

$$\sum_{k\in K} x_t^{i,k} \le B_t^i, \qquad \forall i \in I, \forall t \in \{a^i, \dots, p^i\} \tag{21}$$

$$\sum_{t'=\mathrm{a}^\mathrm{i}}^{\mathrm{t}} d_{t'}^{i,k} \le \sum_{t'=\mathrm{a}^\mathrm{i}}^{\mathrm{t}} x_{t'}^{i,k}\ , \qquad \forall \mathrm{k} \in \mathrm{K}, \forall i \in I, \forall t \in \{\mathrm{a}^\mathrm{i}, \dots, \min(\mathrm{p}^\mathrm{i}, \mathrm{a}^\mathrm{i} + \mathrm{q}^{\mathrm{i,k}} - 1)\} \tag{22}$$

$$W_t^{i,k} = x_{t-q^{i,k}}^{i,k-1}, \qquad \mathrm{k} \in \{2, \dots, k_e^i\},\ \forall i \in I\colon (a^i + q^{i,k}) \le p^i, \forall t \in \{(\mathrm{a}^\mathrm{i} + \mathrm{q}^{\,\mathrm{i,k}}), \dots, \mathrm{p}^\mathrm{i}\} \tag{23}$$

$$\sum_{t'=\mathrm{a}^\mathrm{i}}^{\mathrm{a}^\mathrm{i}+\mathrm{q}^{\mathrm{i,k}}-1} d_{t'}^{i,k} + \sum_{t'=\mathrm{a}^\mathrm{i}+\mathrm{q}^{\mathrm{i,k}}}^{\mathrm{t}} W_{t'}^{i,k} \le \sum_{t'=\mathrm{a}^\mathrm{i}}^{\mathrm{t}} x_{t'}^{i,k}, \qquad \forall \mathrm{k} \in \{2, \dots, k_e^i\}, \forall i \in I\colon \mathrm{p}^\mathrm{i} \ge \mathrm{a}^\mathrm{i} + \mathrm{q}^{\mathrm{i,k}}, \forall t \in \{(\mathrm{a}^\mathrm{i} + \mathrm{q}^{\mathrm{i,k}}), \dots, \mathrm{p}^\mathrm{i}\} \tag{24}$$

$$n_t^{i,k} \ge 0, x_t^{i,k} \ge 0, H_t^{i,k} \ge 0, B_t^i \ge 0, \qquad \forall \mathrm{k} \in \mathrm{K}, \forall i \in I, \forall t \in \{a^i, \dots, p^i\} \tag{25}$$

(15) The number of bogies of type i in stock at the beginning of period t that need their k^{th} revision equals the number of bogies of type i in stock at the beginning of period t-1 that need their k^{th} revision, plus the number of replacements of bogies type i that has been done in period t-1, minus the number of revisions of bogies type i that has been bone in period t-1. This constraint holds for all i where the second period that the bogie is in the field is lower or equal then the period that the bogie goes out of the field. This constraint holds for all k. This constraint holds for all t from the second period that the bogie is in the field to the last period that the bogie is in the field during the planning horizon.

(16) The number of bogies of type i that need their k^{th} revision in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of spare bogies of type i that need their k^{th} revision that are in inventory in the first period that the type or bogies goes into the field. This constraint holds for all i and all k.

(17) The number of ready-for-use bogies of type i in stock at the beginning of period t equals the number of ready-for-use bogies of type i in stock at the beginning of period t-1, plus the number of bogies type i that had their k^{th} revisions in period t-1, minus the number of replacements of bogies type I that need their k^{th} revision that has been bone in period t-1. This constraint holds for all i where the second period that the bogie is in the field is lower or equal then the period that the bogie goes out of the field. This constraint holds for all t from the second period that the bogie is in the field to the last period that the bogie is in the field during the planning horizon.

(18) The number of ready-for-use bogies of type i in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of extra ready-for-use bogies of type i that are in inventory in the first period that the type or bogies goes into the field. This constraint holds for all i.

(19) For every period, the total amount of time to do all the planned revisions can never be more than the total available revision time in the ROW, for every period.

(20) There can never be more k^{th} revisions of bogies type i in period t then the number of bogies of type i that need their k^{th} revision in stock at the beginning of the period plus the number of replacements of bogies that need their k^{th} revision that is done in period t. This constraint holds for all i between the beginning of the first period that the specific type of bogies comes into the field until the end of the last period that the type of bogie is in the field.

(21) There can never be more replacements of bogies type i in period t then there are revised bogies of type i in stock at the beginning of the period. This constraint holds for all i between the beginning of the first period that the specific type of bogies comes into the field until the end of the last period that the type of bogie is in the field.

(22) If t is less than or equal to the period when the bogie comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be equal to the total demand until the current period, for every period. This constraint holds for all i's and all k's.

(23) The demand for the kth revision of bogie type i in period t is equal to the number of replacements of bogie type I the k-1th revision, τ periods ago. This constraint holds for all i's where the period when the bogie comes into the field plus the inter-revision deadline is less than or equal to the period that the bogie goes out of the field. This constraint holds for all period periods from $\left(\mathrm{a}^{\mathrm{i}}+\mathrm{q}^{\mathrm{i}}\right)$ up to p^{i}.

(24) If t is greater than the period when the bogie comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be the total demand until the current period, for every period. The total demand until the current period equals the sum of the parameter $D_t^{i,k}$ and the variable $W_t^{i,k}$ over the period from a^{i} to t.

(25) Non-negativity constraint.

This model is also put in GUSEK and the validation is shown in appendix D. There are no results from this model jet, because there is currently not enough data available by NedTrain on the different revisions.

G.2. Labor Capacity in the ROW

G.2.1. Flexible Labor Contracts for the ROW

Sets:

I : Set of all different types of bogies considered in the model, $i \in \{1,2,3, \dots, i_e\}$.

I_t : Set of all types of bogies that are in the field in period t.

T : Set of all periods considered in the planning horizon, $t \in \{1,2,3, \dots, t_e\}$.

Y : Set of all years in the planning horizon, $y = \{1,2,3, \dots, y_e = t_e/12\}$.

Parameters:

a^i : For all bogie types that are already in use before the first period of the planning horizon this parameter is set 1. For all bogie types that are not in use before the first period of the planning horizon this parameter is set to the period in the planning horizon that bogie type i goes into the field.

b^i : For all bogie types that are in use before the first period of the planning horizon this parameter indicates the number of ready-for-use bogies type i in inventory at the beginning of the first period of the planning horizon. For all bogie types that are not in use before the first period of the planning horizon this parameter is the number of spare bogies of type i that are purchased and are ready-for-use in the first period that bogie type i comes into the field.

c_c^i : The cost for purchasing one bogie type i in the period in the planning horizon that bogie type i goes into the field.

c_h^i : The cost of holding one bogie type i in inventory for one period.

c_f : The cost of one mechanic when working on the replacement of a bogie for one hour in the MD.

c_l : The cost of one mechanic for one hour in the ROW, independent on whether the mechanic is working on the revision of a bogie or not.

c_m^i : The cost of materials required for the revision of one bogie type i in the ROW.

c_{w1} : The cost of transporting one bogie from the MD to the ROW.

c_{w2} : The cost of transporting one bogie from the ROW to the MD.

d_{t}^i : The demand for the replacement of bogie type i in period t, $t \in \left\{\mathrm{a}^{\mathrm{i}}, \ldots, \min\left(\mathrm{p}^{\mathrm{i}}, (a^i + q^i - 1)\right)\right\}$.

f : The flexibility parameter for the capacity of the ROW.

g^i : This parameter shows whether or not a bogie type i was already in the field before the planning horizon. This parameter is zero if bogie type i was already in the field before the planning horizon and one if the type or bogie comes into the field during the planning horizon.

h^i : For all bogie types that are already in use before the first period of the planning horizon this parameter indicates the number of bogies type i waiting for revision in inventory at the beginning of the first period of the planning horizon. For all bogie types that are not in use before the first period of the planning horizon this parameter is set zero.

i_e : The last type of bogie considered in the model.

p^i : For all bogie types that go out of the field before the last period of the planning horizon, this parameter indicates the period on the planning horizon that bogie type i is taken out of the field. For all bogie types that don't go out of the field before the last period of the planning horizon the value of this parameter is set the last period in the planning horizon.

q^i : The inter-revision deadline, i.e. the maximum number of periods allowed between two consecutive revisions of bogie type i (in periods).

r^i : The number of labor hours necessary for the revision of one bogie type i in the ROW.

t_e : The last period in the planning horizon.

U_y : The maximum number of hours of labor capacity available for preventive and corrective maintenance in the ROW in year y.

v_t : The expected number of hours needed for corrective maintenance in period t.

y_e : The last year in the planning horizon.

z^{i} : The number of labor hours necessary for replacing one bogie of type i in the MD.

Decision variables:

U_t : Number of hours labor capacity used for preventive and corrective maintenance in the ROW in period t.

$n_t^i\!: t \geq a^i, t \leq p^i$: The number of bogies of type i that will undergo revision in the ROW in period t, for all types of bogies that are in the field in period t.

$x_t^i\!: t \geq a^i, t \leq p^i$: The number of bogies of type i that will be replaced in the MD in period t, for all types of bogies that are in the field in period t.

Variables:

$B_t^i\!: t \geq a^i, t \leq p^i$: The number of ready-for-use bogies type i in inventory at the beginning of period t.

$H_t^i\!: t \geq a^i, t \leq p^i$: The number of bogies of type i that need revision before they can be used for replacement in inventory at the beginning of period t.

$W_t^i\!: \forall i \in I\!: (\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}) \leq \mathrm{p}^{\mathrm{i}}, \forall t \in \left\{(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}), \ldots, \mathrm{p}^{\mathrm{i}}\right\}$: The number of replacements of bogies type i that must have been executed in period t.

Objective:

$$Minimize\ \sum_{i\in I} g^i\left(b^i * c_c^i\right) + \sum_{t\in T}(R_t * c_l) + \sum_{i\in I}\sum_{t'=a^i}^{p^i}\left(c_h\left(b^i + h^i\right) + \left(x_{t'}^i * z^i * c_f\right) + \left(n_{t'}^i * c_m^i\right) + \left(n_{t'}^i * c_{w1} + x_{t'}^i * c_{w2}\right)\right) \tag{26}$$

(26) Objective function; being the sum of the purchase cost of all the new bogies that will be bought within the planning horizon, the labor cost in the ROW, the holding cost, the labor cost in the MD, the material cost in the ROW and the transport cost from the ROW to the MD and from the MD to the ROW.

Constraints:

$$H_t^i = H_{t-1}^i + x_{t-1}^i - n_{t-1}^i, \qquad \forall i \in I: p^i \ge a^i + 1, \forall t \in \left\{a^i + 1, \dots, p^i\right\} \tag{27}$$

$$H_{a^i}^i = h^i, \qquad \forall i \in I \tag{28}$$

$$B_t^i = B_{t-1}^i + n_{t-1}^i - x_{t-1}^i, \qquad \forall i \in I: p^i \ge a^i + 1, \forall t \in \left\{a^i + 1, \dots, p^i\right\} \tag{29}$$

$$B_{a^i}^i = b^i, \qquad \forall i \in I \tag{30}$$

$$\sum_{i\in I_t}\left(n_t^i * r^i\right) \le U_t - v_t, \qquad \forall t \in \{1, \dots, t_e\} \tag{31}$$

$$(1-f)\frac{U_y}{12} \le U_t \le (1+f)\frac{U_y}{12}, \qquad \forall t \in \{12(y-1)+1, \dots, 12(y-1)+12\} \tag{32}$$

$$\sum_{t'=(12y-12+1)}^{12y} U_{t'} \le U_y, \qquad \forall y \in Y \tag{33}$$

$$n_t^i \le H_t^i + x_t^i, \qquad \forall i \in I, \forall t \in a^i, \dots, p^i \tag{34}$$

$$x_t^i \le B_t^i, \qquad \forall i \in I, \forall t \in \left\{a^i, \dots, p^i\right\} \tag{35}$$

$$\sum_{t'=a^i}^{t} d_{t'}^i \le \sum_{t'=a^i}^{t} x_{t'}^i, \qquad \forall i \in I, \forall t \in \left\{a^i, \dots, \min\left(p^i, a^i + q^i - 1\right)\right\} \tag{36}$$

$$W_t^i = x_{t-q^i}^i, \qquad \forall i \in I: \left(a^i + q^i\right) \le p^i, \forall t \in \left\{\left(a^i + q^i\right), \dots, p^i\right\} \tag{37}$$

$$\sum_{t'=a^i}^{a^i+q^i-1} d_{t'}^i + \sum_{t'=a^i+q^i}^{t} W_{t'}^i \le \sum_{t'=a^i}^{t} x_{t'}^i, \qquad \forall i \in I: a^i + q^i \le p^i, \forall t \in \left\{\left(a^i + q^i\right), \dots, p^i\right\} \tag{38}$$

$$n_t^i \ge 0,\ x_t^i \ge 0, B_t^i \ge 0, H_t^i \ge 0, \qquad \forall i \in I, \forall t \in \left\{a^i, \dots, p^i\right\} \tag{39}$$

$$R_t \ge 0 \qquad \forall t \in T \tag{40}$$

(27) The number of bogies of type i in stock at the beginning of period t that need a revision equals the number of bogies of type i in stock at the beginning of period t-1 that need a revision, plus the number of replacements of bogies type i that has been done in period t-1, minus the number of revisions of bogies type i that has been bone in period t-1. This constraint holds for all i where the second period that the bogie is in the field is lower or equal then the period that the bogie goes out of the field. This constraint holds for all t from the second period that the bogie is in the field to the last period that the bogie is in the field during the planning horizon.

(28) The number of bogies of type i that need revision in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of spare bogies of type i that need

revision that are in inventory in the first period that the type or bogies goes into the field. This constraint holds for all i.

(29) The number of ready-for-use bogies of type i in stock at the beginning of period t equals the number of ready-for-use bogies of type i in stock at the beginning of period t-1, plus the number of revisions of bogies type i that has been done in period t-1, minus the number of replacements of bogies type i that has been bone in period t-1. This constraint holds for all i where the second period that the bogie is in the field is lower or equal then the period that the bogie goes out of the field. This constraint holds for all t from the second period that the bogie is in the field to the last period that the bogie is in the field during the planning horizon.

(30) The number of ready-for-use bogies of type i in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of extra ready-for-use bogies of type i that are in inventory in the first period that the type or bogies goes into the field. This constraint holds for all i.

(31) For every period, the total amount of time to do all the planned revisions can never be more than the total available revision time in the ROW minus the time for corrective maintenance, for every period.

(32) For every period, the time available for preventive and corrective maintenance in the ROW has to be between $(1-f)$ and $(1+f)$ times the average capacity per period.

(33) For every year, the sum of the capacity available per month has to be less than or equal to the capacity available per year.

(34) There can never be more revisions of bogies type i in period t then the number of bogies of type i that need revision in stock at the beginning of the period plus the number of replacements that is done in period t. This constraint holds for all i between the beginning of the first period that the specific type of bogies comes into the field until the end of the last period that the type of bogie is in the field.

(35) There can never be more replacements of bogies type i in period t then there are revised bogies of type i in stock at the beginning of the period. This constraint holds for all i between the beginning of the first period that the specific type of bogies comes into the field until the end of the last period that the type of bogie is in the field.

(36) If t is less than or equal to the period when the bogie comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be equal to the total demand until the current period, for every period. This constraint holds for all i's.

(37) The demand for bogie type i in period t is equal to the number of replacements of bogie type i, τ periods ago. This constraint holds for all i's where the period when the bogie comes into the field plus the inter-revision deadline is less than or equal to the period that the bogie goes out of the field. This constraint holds for all period periods from $\left(\mathrm{a}^{\mathrm{i}}+\mathrm{q}^{\mathrm{i}}\right)$ up to p^{i}.

(38) If t is greater than the period when the bogie comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be the total demand until the current period, for every period. The total demand until the current period equals the sum of the parameter D_t^i and the variable W_t^i over the period from a^{i} to t.

(39) Non-negativity constraint.

(40) Non-negativity constraint.

G.2.2. Variable Labor Cost for the ROW

Sets:

I : Set of all different types of bogies considered in the model, $i \in \{1,2,3, \dots, i_e\}$.

T : Set of all periods considered in the planning horizon, $t \in \{1,2,3, \dots, t_e\}$.

I_t : Set of all types of bogies that are in the field in period t.

Parameters:

a^i : For all bogie types that are already in use before the first period of the planning horizon this parameter is set 1. For all bogie types that are not in use before the first period of the planning horizon this parameter is set to the period in the planning horizon that bogie type i goes into the field.

b^i : For all bogie types that are in use before the first period of the planning horizon this parameter indicates the number of ready-for-use bogies type i in inventory at the beginning of the first period of the planning horizon. For all bogie types that are not in use before the first period of the planning horizon this parameter is the number of spare bogies of type i that are purchased and are ready-for-use in the first period that bogie type i comes into the field.

c_c^i : The cost for purchasing one bogie type i in the period in the planning horizon that bogie type i goes into the field.

c_h^i : The cost of holding one bogie type i in inventory for one period.

c_f : The cost of one mechanic when working on the replacement of a bogie for one hour in the MD.

c_l : The cost of one mechanic for one hour in the ROW.

c_m^i : The cost of materials required for the revision of one bogie type i in the ROW.

$c_{\mathrm{w}1}$: The cost of transporting one bogie from the MD to the ROW.

$c_{\mathrm{w}2}$: The cost of transporting one bogie from the ROW to the MD.

d_{t}^i : The demand for the replacement of bogie type i in period t, $t \in \left\{\mathrm{a}^{\mathrm{i}}, \dots, \min\left(\mathrm{p}^{\mathrm{i}}, \left(a^i + q^i - 1\right)\right)\right\}$.

g^i : This parameter shows whether or not a bogie type i was already in the field before the planning horizon. This parameter is zero if bogie type i was already in the field before the planning horizon and one if the type or bogie comes into the field during the planning horizon.

h^i : For all bogie types that are already in use before the first period of the planning horizon this parameter indicates the number of bogies type i waiting for revision in inventory at the beginning of the first period of the planning horizon. For all bogie types that are not in use before the first period of the planning horizon this parameter is set zero.

i_e : The last type of bogie considered in the model.

p^i : For all bogie types that go out of the field before the last period of the planning horizon, this parameter indicates the period on the planning horizon that bogie type i is taken out of the field. For all bogie types that don't go out of the field before the last period of the planning horizon the value of this parameter is set the last period in the planning horizon.

q^i : The inter-revision deadline, i.e. the maximum number of periods allowed between two consecutive revisions of bogie type i (in periods).

r^i : The number of labor hours necessary for the revision of one bogie type i in the ROW.

R_t : The number of hours of labor capacity available for preventive maintenance in the ROW in period t.

t_e : The last period in the planning horizon.

z^{i} : The number of labor hours necessary for replacing one bogie of type i in the MD.

Decision variables:

$n_t^i: t \geq a^i, t \leq p^i$: The number of bogies of type i that will undergo revision in the ROW in period t, for all types of bogies that are in the field in period t.

$x_t^i: t \geq a^i, t \leq p^i$: The number of bogies of type i that will be replaced in the MD in period t, for all types of bogies that are in the field in period t.

Variables:

$B_t^i: t \geq a^i, t \leq p^i$: The number of ready-for-use bogies type i in inventory at the beginning of period t.

$H_t^i: t \geq a^i, t \leq p^i$: The number of bogies of type i that need revision before they can be used for replacement in inventory at the beginning of period t.

$W_t^i: \forall i \in I: (\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}) \leq \mathrm{p}^{\mathrm{i}}, \forall t \in \{(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}), \ldots, \mathrm{p}^{\mathrm{i}}\}$: The number of replacements of bogies type i that must have been executed in period t.

Objective:

$$Minimize\ \sum_{i \in \mathrm{I}} g^i(b^i * \mathrm{c}_{\mathrm{c}}^{\mathrm{i}}) + \sum_{i \in I} \sum_{t'=a^i}^{p^i} \Big(\mathrm{c}_{\mathrm{h}}(b^i + h^i) + (x_{t'}^i * z^{\mathrm{i}} * c_f) + (n_{t'}^i * r^i * c_l) + (n_{t'}^i * c_m^i) + (n_{t'}^i * c_{w1} + x_{t'}^i * c_{w2})\Big) \qquad (41)$$

(41) Objective function; being the sum of the purchase cost of all the new bogies that will be bought within the planning horizon, the labor cost in the ROW, the holding cost, the labor cost in the MD, the material cost in the ROW and the transport cost from the ROW to the MD and from the MD to the ROW.

Constraints:

$$H_t^i = H_{t-1}^i + x_{t-1}^i - n_{t-1}^i, \qquad \forall i \in I: p^i \geq a^i + 1, \forall t \in \{a^i + 1, \ldots, p^i\} \qquad (42)$$

$$H_{a^i}^i = h^i, \qquad \forall i \in I \qquad (43)$$

$$B_t^i = B_{t-1}^i + n_{t-1}^i - x_{t-1}^i, \qquad \forall i \in I: p^i \geq a^i + 1, \forall t \in \{a^i + 1, \ldots, p^i\} \qquad (44)$$

$$B_{a^i}^i = b^i, \qquad \forall i \in I \qquad (45)$$

$$\sum_{i \in I_t} (n_t^i * r^i) \leq R_t, \qquad \forall t \in \{1, \ldots, t_e\} \qquad (46)$$

$$n_t^i \leq H_t^i + x_t^i, \qquad \forall i \in I, \forall t \in a^i, \ldots, p^i \qquad (47)$$

$$x_t^i \leq B_t^i, \qquad \forall i \in I, \forall t \in \{a^i, \ldots, p^i\} \qquad (48)$$

$$\sum_{t'=\mathrm{a}^{\mathrm{i}}}^{\mathrm{t}} d_{t'}^i \leq \sum_{t'=\mathrm{a}^{\mathrm{i}}}^{\mathrm{t}} x_{t'}^i, \qquad \forall i \in I, \forall t \in \{\mathrm{a}^{\mathrm{i}}, \ldots, \min(\mathrm{p}^{\mathrm{i}}, \mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}} - 1)\} \qquad (49)$$

$$W_t^i = x_{t-q^i}^i, \qquad \forall i \in I: (\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}) \leq \mathrm{p}^{\mathrm{i}}, \forall t \in \{(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}), \ldots, \mathrm{p}^{\mathrm{i}}\} \qquad (50)$$

$$\sum_{t'=\mathrm{a}^{\mathrm{i}}}^{\mathrm{a}^{\mathrm{i}}+\mathrm{q}^{\mathrm{i}}-1} d_{t'}^i + \sum_{t'=\mathrm{a}^{\mathrm{i}}+\mathrm{q}^{\mathrm{i}}}^{\mathrm{t}} W_{t'}^i \leq \sum_{t'=\mathrm{a}^{\mathrm{i}}}^{\mathrm{t}} x_{t'}^i, \qquad \forall i \in I: a^i + q^i \leq p^i, \forall t \in \{(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}), \ldots, \mathrm{p}^{\mathrm{i}}\} \qquad (51)$$

$$n_t^i \geq 0,\ x_t^i \geq 0, B_t^i \geq 0, H_t^i \geq 0, \qquad \forall i \in I, \forall t \in \{a^i, \dots, p^i\} \tag{52}$$

(42) The number of bogies of type i in stock at the beginning of period t that need a revision equals the number of bogies of type i in stock at the beginning of period t-1 that need a revision, plus the number of replacements of bogies type i that has been done in period t-1, minus the number of revisions of bogies type i that has been bone in period t-1. This constraint holds for all i where the second period that the bogie is in the field is lower or equal then the period that the bogie goes out of the field. This constraint holds for all t from the second period that the bogie is in the field to the last period that the bogie is in the field during the planning horizon.

(43) The number of bogies of type i that need revision in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of spare bogies of type i that need revision that are in inventory in the first period that the type or bogies goes into the field. This constraint holds for all i.

(44) The number of ready-for-use bogies of type i in stock at the beginning of period t equals the number of ready-for-use bogies of type i in stock at the beginning of period t-1, plus the number of revisions of bogies type i that has been done in period t-1, minus the number of replacements of bogies type i that has been bone in period t-1. This constraint holds for all i where the second period that the bogie is in the field is lower or equal then the period that the bogie goes out of the field. This constraint holds for all t from the second period that the bogie is in the field to the last period that the bogie is in the field during the planning horizon.

(45) The number of ready-for-use bogies of type i in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of extra ready-for-use bogies of type i that are in inventory in the first period that the type or bogies goes into the field. This constraint holds for all i.

(46) For every period, the total amount of time to do all the planned revisions can never be more than the total available revision time in the ROW, for every period.

(47) There can never be more revisions of bogies type i in period t then the number of bogies of type i that need revision in stock at the beginning of the period plus the number of replacements that is done in period t. This constraint holds for all i between the beginning of the first period that the specific type of bogies comes into the field until the end of the last period that the type of bogie is in the field.

(48) There can never be more replacements of bogies type i in period t then there are revised bogies of type i in stock at the beginning of the period. This constraint holds for all i between the beginning of the first period that the specific type of bogies comes into the field until the end of the last period that the type of bogie is in the field.

(49) If t is less than or equal to the period when the bogie comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be equal to the total demand until the current period, for every period. This constraint holds for all i's.

(50) The demand for bogie type i in period t is equal to the number of replacements of bogie type i, τ periods ago. This constraint holds for all i's where the period when the bogie comes into the field plus the inter-revision deadline is less than or equal to the period that the bogie goes out of the field. This constraint holds for all period periods from $(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}})$ up to p^{i}.

(51) If t is greater than the period when the bogie comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be the total

demand until the current period, for every period. The total demand until the current period equals the sum of the parameter D_t^i and the variable W_t^i over the period from a^i to t.

(52) Non-negativity constraint.

G.3. Cost Differentiation by MD's

Sets:

I : Set of all different types of bogies considered in the model, $i \in \{1,2,3,\dots,i_e\}$.

T : Set of all periods considered in the planning horizon, $t \in \{1,2,3,\dots,t_e\}$.

I_t : Set of all types of bogies that are in the field in period t.

J : Set of all different MD's, $j \in \{1,\dots,j_e\}$.

Parameters:

a^i : For all bogie types that are already in use before the first period of the planning horizon this parameter is set 1. For all bogie types that are not in use before the first period of the planning horizon this parameter is set to the period in the planning horizon that bogie type i goes into the field.

b^i : For all bogie types that are in use before the first period of the planning horizon this parameter indicates the number of ready-for-use bogies type i in inventory at the beginning of the first period of the planning horizon. For all bogie types that are not in use before the first period of the planning horizon this parameter is the number of spare bogies of type i that are purchased and are ready-for-use in the first period that bogie type i comes into the field.

c_c^i : The cost for purchasing one bogie type i in the period in the planning horizon that bogie type i goes into the field.

c_h^i : The cost of holding one bogie type i in inventory for one period.

c_f^j : The cost of one mechanic when working on the replacement of a bogie for one hour in MD j.

c_l : The cost of one mechanic for one hour in the ROW.

c_m^i : The cost of materials required for the revision of one bogie type i in the ROW.

c_{w1} : The cost of transporting one bogie from MD's to the ROW.

c_{w2} : The cost of transporting one bogie from the ROW to MD's .

d_t^i : The demand for the replacement of bogie type i in period t, $t \in \left\{a^i, \dots, \min\left(p^i, (a^i + q^i - 1)\right)\right\}$.

g^i : This parameter shows whether or not a bogie type i was already in the field before the planning horizon. This parameter is zero if bogie type i was already in the field before the planning horizon and one if the type or bogie comes into the field during the planning horizon.

h^i : For all bogie types that are already in use before the first period of the planning horizon this parameter indicates the number of bogies type i waiting for revision in inventory at the beginning of the first period of the planning horizon. For all bogie types that are not in use before the first period of the planning horizon this parameter is set zero.

i_e : The last type of bogie considered in the model.

j_e : Number of MD's that replace bogies.

p^i : For all bogie types that go out of the field before the last period of the planning horizon, this parameter indicates the period on the planning horizon that bogie type i is taken out of the field. For all bogie types that don't go out of the field before the last period of the planning horizon the value of this parameter is set the last period in the planning horizon.
q^i : The inter-revision deadline, i.e. the maximum number of periods allowed between two consecutive revisions of bogie type i (in periods).
r^i : The number of labor hours necessary for the revision of one bogie type i in the ROW.
R_t : The number of hours of labor capacity available for preventive maintenance in the ROW in period t.
t_e : The last period in the planning horizon.
z^{i} : The number of labor hours necessary for replacing one bogie of type i in the MD.

Decision variables:

$n_t^i: t \geq a^i, t \leq p^i$: The number of bogies of type i that will undergo revision in the ROW in period t, for all types of bogies that are in the field in period t.
$x_t^{i,j}: t \geq a^i, t \leq p^i$: The number of bogies of type i that will be replaced in MD j in period t, for all types of bogies that are in the field in period t.

Variables:

$B_t^i: t \geq a^i, t \leq p^i$: The number of ready-for-use bogies type i in inventory at the beginning of period t.
$H_t^i: t \geq a^i, t \leq p^i$: The number of bogies of type i that need revision before they can be used for replacement in inventory at the beginning of period t.
$W_t^i: \forall i \in I: (\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}) \leq \mathrm{p}^{\mathrm{i}}, \forall t \in \{(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}), \dots, \mathrm{p}^{\mathrm{i}}\}$: The number of replacements of bogies type i that must have been executed in period t.

Objective:

$$Minimize\ \sum_{i\in \mathrm{I}} g^i\left(b^i * \mathrm{c}_{\mathrm{c}}^{\mathrm{i}}\right) + \sum_{\mathrm{t}\in\mathrm{T}}\left(R_t * c_l\right) + \sum_{i\in I}\sum_{t'=a^i}^{p^i}\Big(\mathrm{c}_{\mathrm{h}}\left(b^i + h^i\right) + \Big(\sum_{j\in J}\left(x_{t'}^{i,j} * c_f^j\right) * z^{\mathrm{i}}\Big) + \left(n_{t'}^i * c_m^i\right) + \Big(n_{t'}^i * c_{w1} + \sum_{j\in J}\left(x_{t'}^{i,j}\right) * c_{w2}\Big)\Big) \quad (53)$$

(53) Objective function; being the sum of the purchase cost of all the new bogies that will be bought within the planning horizon, the labor cost in the ROW, the holding cost, the labor cost in the MD, the material cost in the ROW and the transport cost from the ROW to the MD's and from the MD's to the ROW.

Constraints:

$$H_t^i = H_{t-1}^i + \sum_{j\in J}\left(x_{t-1}^{i,j}\right) - n_{t-1}^i, \qquad \forall i \in I: p^i \geq a^i + 1, \forall t \in \{a^i + 1, \dots, p^i\} \quad (54)$$

$$H_{a^i}^i = h^i, \qquad \forall i \in I \quad (55)$$

$$B_t^i = B_{t-1}^i + n_{t-1}^i - \sum_{j\in J}\left(x_{t-1}^{i,j}\right), \qquad \forall i \in I: p^i \geq a^i + 1, \forall t \in \{a^i + 1, \dots, p^i\} \quad (56)$$

$$B_{a^i}^i = b^i, \qquad \forall i \in I \quad (57)$$

$$\sum_{i\in I_t}\left(n_t^i * r^i\right) \leq R_t, \qquad \forall t \in \{1, \dots, t_e\} \quad (58)$$

$$n_t^i \le H_t^i + x_t^i, \qquad \forall i \in I, \forall t \in a^i, \dots, p^i \tag{59}$$

$$\sum_{j \in J}\left(x_t^{i,j}\right) \le B_t^i, \qquad \forall i \in I, \forall t \in \left\{a^i, \dots, p^i\right\} \tag{60}$$

$$\sum_{t'=\mathrm{a}^{\mathrm{i}}}^{\mathrm{t}} d_{t'}^i \le \sum_{t'=\mathrm{a}^{\mathrm{i}}}^{\mathrm{t}}\left(\sum_{j \in J}\left(x_{t'}^{i,j}\right)\right), \qquad \forall i \in I, \forall t \in \left\{\mathrm{a}^{\mathrm{i}}, \dots, \min\left(\mathrm{p}^{\mathrm{i}}, \mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}} - 1\right)\right\} \tag{61}$$

$$W_t^i = \sum_{j \in J}\left(x_{t-q^i}^{i,j}\right), \qquad \forall i \in I: \left(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}\right) \le \mathrm{p}^{\mathrm{i}}, \forall t \in \left\{\left(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}\right), \dots, \mathrm{p}^{\mathrm{i}}\right\} \tag{62}$$

$$\sum_{t'=\mathrm{a}^{\mathrm{i}}}^{\mathrm{a}^{\mathrm{i}}+\mathrm{q}^{\mathrm{i}}-1} d_{t'}^i + \sum_{t'=\mathrm{a}^{\mathrm{i}}+\mathrm{q}^{\mathrm{i}}}^{\mathrm{t}} W_{t'}^i \le \sum_{t'=\mathrm{a}^{\mathrm{i}}}^{\mathrm{t}}\left(\sum_{j \in J}\left(x_{t'}^{i,j}\right)\right), \qquad \forall i \in I: a^i + q^i \le p^i, \forall t \in \left\{\left(\mathrm{a}^{\mathrm{i}} + \mathrm{q}^{\mathrm{i}}\right), \dots, \mathrm{p}^{\mathrm{i}}\right\} \tag{63}$$

$$n_t^i \ge 0,\ x_t^{i,j} \ge 0, B_t^i \ge 0, H_t^i \ge 0, \qquad \forall i \in I, \forall t \in \left\{a^i, \dots, p^i\right\} \tag{64}$$

(54) The number of bogies of type i in stock at the beginning of period t that need a revision equals the number of bogies of type i in stock at the beginning of period t-1 that need a revision, plus the number of replacements of bogies type i that has been done in period t-1, minus the number of revisions of bogies type i that has been bone in period t-1. This constraint holds for all i where the second period that the bogie is in the field is lower or equal then the period that the bogie goes out of the field. This constraint holds for all t from the second period that the bogie is in the field to the last period that the bogie is in the field during the planning horizon.

(55) The number of bogies of type i that need revision in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of spare bogies of type i that need revision that are in inventory in the first period that the type or bogies goes into the field. This constraint holds for all i.

(56) The number of ready-for-use bogies of type i in stock at the beginning of period t equals the number of ready-for-use bogies of type i in stock at the beginning of period t-1, plus the number of revisions of bogies type i that has been done in period t-1, minus the number of replacements of bogies type i that has been bone in period t-1. This constraint holds for all i where the second period that the bogie is in the field is lower or equal then the period that the bogie goes out of the field. This constraint holds for all t from the second period that the bogie is in the field to the last period that the bogie is in the field during the planning horizon.

(57) The number of ready-for-use bogies of type i in stock at the beginning of the period that the type of rolling stock comes into the field equals the number of extra ready-for-use bogies of type i that are in inventory in the first period that the type or bogies goes into the field. This constraint holds for all i.

(58) For every period, the total amount of time to do all the planned revisions can never be more than the total available revision time in the ROW, for every period.

(59) There can never be more revisions of bogies type i in period t then the number of bogies of type i that need revision in stock at the beginning of the period plus the number of replacements that is done in period t. This constraint holds for all i between the beginning of the first period that the specific type of bogies comes into the field until the end of the last period that the type of bogie is in the field.

(60) There can never be more replacements of bogies type i in period t then there are revised bogies of type i in stock at the beginning of the period. This constraint holds for all i between the beginning of the first period that the specific type of bogies comes into the field until the end of the last period that the type of bogie is in the field.

(61) If t is less than or equal to the period when the bogie comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be equal to the total demand until the current period, for every period. This constraint holds for all i's.

(62) The demand for bogie type i in period t is equal to the number of replacements of bogie type i, τ periods ago. This constraint holds for all i's where the period when the bogie comes into the field plus the inter-revision deadline is less than or equal to the period that the bogie goes out of the field. This constraint holds for all period periods from $\left(\mathrm{a}^{\mathrm{i}}+\mathrm{q}^{\mathrm{i}}\right)$ up to p^{i}.

(63) If t is greater than the period when the bogie comes into the field plus the inter-revision deadline, the total number of replacements until the current period should at least be the total demand until the current period, for every period. The total demand until the current period equals the sum of the parameter D_t^i and the variable W_t^i over the period from a^{i} to t.

(64) Non-negativity constraint.