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The facility location problem applied to a train maintenance environment

de Jonge, T.M.

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The Facility Location Problem Applied to a Train Maintenance Environment

T.M. de Jonge

School of Industrial Engineering
Eindhoven University of Technology

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T.M. (Tim) de Jonge
Student no. 0659435

Supervisors Eindhoven University of Technology:
prof.dr.ir. G.J.J.A.N. (Geert-Jan) van Houtum
dr.ir. J.J. (Joachim) Arts

Supervisor NedTrain:
ir. B. (Bob) Huisman
Abstract

This master thesis makes an application of the facility location problems to the train maintenance environment. During the last decades a vast amount of literature has been published around facility location problems. However, only a few of them discuss facility location problems in a maintenance environment. This thesis adds a new business case, conducted at NedTrain B.V., to the literature and it is the first that applies this problem to this unique environment where demand can move through the network. In our work, we designed a simple, but comprehensive model which determines the optimal number, size, and location of train maintenance facilities, which works well in gathering first insights. The MIP (Mixed Integer Programming) model is implemented in a solver and sensitivity analyses are performed.

The main conclusion is that the optimal solution is restricted by the number of maintenance paths available. The transport cost only comprises a small portion of the total cost and thus has no detectable influence on the optimal solution. As the number of trains changes, the optimal solution changes, but this can be explained by the effect of the other factors. Changes in fixed facility cost and resource cost do not cause any changes in the optimal solution.

Two extensions have been made and separately added to the model, providing extra insights in the behaviour of input parameters on the optimal solution. Both extensions make the solution more sensitive to changes in input parameters. Therefore, the transport cost and the fixed facility cost become more important. Therefore, both extensions should be added in further research.

Keywords: Facility Location Problem, Plant Location Problem, Maintenance, Decision Support Model, Strategic Level, Mixed Integer Programming.
Preface

The thesis you started reading is the concluding work of my master Operations Management and Logistics at the Eindhoven University of Technology. With this work an end has come to my student life and I have to say farewell to the nice time I had at the university.

In the past five and a half years I studied to become an engineer, but sometimes my study was more a side issue than the main issue. I enjoyed the projects I did and the people I met, inside as well as outside the university. The people with whom I worked and the projects I did challenged me every day again, letting me grow on a professional as well as on a social level. I especially want to thank my best friends, who always supported me and who were there when I needed them. Together we worked hard in project groups and committees, but above all we had a lot of fun. Thanks for the great time!

For my master and this thesis in particular, I would like to thank some people explicitly. First of all my mentor for the past two years, Geert-Jan van Houtum. He always offered me opportunities to develop myself such as letting me choose my thesis project. I am very grateful for this and for the discussions we had in order to improve my thesis. Furthermore, he brought me in contact with Will Bertrand who accepted me for the Design Honors Track. Although I decided not to continue with the Logistics Management Systems post-master, I learned a lot from the courses I took during this track.

During my thesis two other people supported me in conducting my research. First, I would like to thank Bob Huisman. He provided me with his knowledge and insights about NedTrain. In addition he challenged me by using his own experiences as a consultant to let me think as the consultant I want to become. Moreover, he provided me with the freedom with which I could get the most out of myself, while keep doing committees. Second, I would like to thank Joachim Arts, who provided me with his sharp remarks and who was very interested in my project directly from the start. Furthermore, I would like to thank all the people within NedTrain who were always very helpful and willing to provide me with the data and insights I needed for my thesis. Finally, I would like to thank the friends who helped me with the design decisions and who reviewed my work.

Last, but most important, I would like to thank my parents and my sister. They always supported me in the decisions I made. Due to their support I could do the activities I wanted to do and I developed myself to the person I wanted to be.

Thanks all and let's go for new challenges!

Tim de Jonge
Executive Summary

Problem Description
NedTrain has started a new research project in cooperation with the Eindhoven University of Technology to gather insight in facility location models in a train maintenance environment. At this moment NedTrain does not have not enough insight in which factors are important and how these factors influence the optimal situation. The main goal of this research is to gather insight in the effects and sensitivity of input parameters on the optimal number, size, and locations of facilities, i.e. the optimal solution. We identified the following parameters for which we tested what the effect is on the optimal solution: the number of trains existing, the fixed facility cost, the transport cost, the number of maintenance paths available, and the resource cost. The final goal is to minimise the total cost which is a sum of the cost parameters multiplied by the three decision variables, depicted in Table 1.

Table 1. The cost parameters with the corresponding decision variables.

<table>
<thead>
<tr>
<th>Cost parameter</th>
<th>Decision variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>The fixed facility cost</td>
<td>Whether a facility is open</td>
</tr>
<tr>
<td>The resource cost</td>
<td>The number of resources of each type located at each facility</td>
</tr>
<tr>
<td>The transport cost</td>
<td>The routings of trains</td>
</tr>
</tbody>
</table>

In order to investigate the problem on hand, we used the Operations Research Process formulated by Sagasti & Mitroff (1973). The process consists of four steps which are:

1. Conceptualisation, starting from the Reality and ending in a Conceptual Model;
2. Modelling, starting form the Conceptual Model and ending in a Scientific Model;
3. Model Solving, starting from the Scientific Model and ending in a Solution;
4. Implementation, starting from the Solution and ending in the Reality.

The first three steps are conducted in this research. The fourth step is not performed because this research is intended to be a theoretical work to create first insights and form merely the basis for a decision support model.

Conclusions
The model we develop in this research proves to be a good model to create the first insights in the large facility location research for train maintenance. It takes into account the most important factors and the results show to which factors extra attention have to be paid and which factors are of less influence. Although the model has no direct stochastic parameters, it does take into account stochastics by a parameter which creates slack for operational variability. Also the two extensions (the time penalty for transport and the EBKs, which are extra unplanned maintenance visits) added, provide more and other insights in changes on input parameters on the optimal solution.

In our research we found that only for two of the input parameters defined the optimal solution might change due to changes in the input parameter. First we have the number of maintenance paths, which determines the optimal number of facilities. This parameter provides a lower bound for the number of facilities, which is also due to the fact that the total fixed facility cost are four times as high as the total transport cost. If the number of maintenance paths is varied, consequently also the optimal solution might change. Second, if the number of trains changes, subsequently the optimal solution changes. However, the change in the optimal solution is due to the effect of other
parameters. For example if the number of trains increases and the number of maintenance paths per facility remains equal, more facilities are necessary to maintain all trains. Changes in the resource cost, transport cost or fixed facility cost do not lead to any change in the optimal solution.

A time penalty for transport cost is added to penalise the total trains cannot be used. As the throughput time does not change in our model due to change in the optimal solution, the transport time is the only thing we could penalise. The effect is that the transport cost are around six times as high and now the transport cost are twice as high as the fixed facility cost. The consequence is that still the number of maintenance paths plays in important role, but less important as before. The optimal number of locations now also depends on the transport cost, while this was not the case in the original model. Moreover, the optimal solution become sensitive for changes in the fixed facility cost and the transport cost. The solution still remains sensitive for changes in the resource cost.

The addition of EBKs to our basic model does not lead to large differences. The parameters for which the optimal solution was insensitive, still do not influence the solution. However, new insights are developed in the sense that it is better to optimally use a resource and increase by doing this the transport cost than to increase the number of resources; this makes the size of facilities more stable for changes in the number of maintenance paths.

Finally, we reflected on our conceptualisation phase by providing “feedback in the wider sense”, as it was named by Sagasti & Mitroff (1973), on our model. We remarked that is important to gather more information about the fixed facility cost. Which part is completely insensitive for the size of facilities and which part still depends on the size of facilities although not directly related to the number of resources in a facility. Furthermore, the distribution of trains over the network that need an EBK needs to be improved. The addition of train types is only useful if one also wants to gather insight in the number of trains of each type maintained at each facility or if one wants to include expertise, otherwise it the model will not provide a different solution. Finally the inventory of spare parts could be included. However, one should be aware that this is a complicated problem for which one has to decide whether to integrate this or to handle the problem separately. Finally, the two extension could be improved. First, the time penalty for transport time can be changed in a constraint in availability, if desirable. When one wants to include such a constraint, one should also consider to include stochastics in the model. Second, the number of EBKs to a facility is not limited at this moment. However, the model would be more realistic to somehow include a constraint on the number of trains that can visit a facility for EBKs.
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CHAPTER 1

Research Introduction

In this chapter, we introduce the research that we conducted at NedTrain regarding facility location problems applied to a railway maintenance environment. In Section 1.1 we describe the company and the department for which we conducted the research. In Section 1.2, an overview of the literature about facility location problems is provided. After that, in Section 1.3 the actual research assignment is provided together with the main decision variables of the model to be developed in the next chapter. Further, we included an explanation about the complete operations research process developed by Sagasti & Mitroff (1973) in Section 1.4. In the same section, we indicate which steps of the cycle we have taken. Finally, in Section 1.5 we provide the outline of the thesis.

1.1 NedTrain

In this section we provide background information about NedTrain in general and in Section 1.1.1 we introduce the department for which the research is conducted. NedTrain is a fully-fledged subsidiary company to the NS business group. The NS Group, founded in 1837, has an annual turnover of €4.6 billion and has as core business the transport of passengers by trains and buses in The Netherlands, Germany, and The United Kingdom. NedTrain provides maintenance and modernisation activities for NS Reizigers (mainly national transport) and NS HiSpeed (mainly international transport at higher speeds) within the NS group as can be seen in Figure 1.1, but it also conducts maintenance for some smaller parties within the Netherlands such as Arriva. The annual turnover of NedTrain is around €500 million and just over 3,000 people work at NedTrain. (Dutch Railways, 2014)

![Organisational chart of NS. (Dutch Railways, 2013)](image)

Figure 1.1. Organisational chart of NS. (Dutch Railways, 2013)

Due to their 165 years of experience in maintaining the NS and regional carrier trains, NedTrain is expert in the fields of delivering components, optimising maintenance, and modernising trains. NedTrain performs three types of maintenance for the NS. First, they perform the daily maintenance in terms of safety checks and cleaning activities. Second, short term maintenance is performed on a three monthly basis where the train gets an extensive safety check and necessary replacements of components are conducted. Third, every fifteen to twenty years trains are overhauled by converting
the train or by modernising the interior. Currently, NedTrain has 35 locations along the railway network in the Netherlands where they perform their maintenance activities. These locations can be distinguished in four types:

- **Service Companies (SBs)** in which the daily maintenance and cleaning activities are performed;
- **OBs** in which the short term (three monthly) maintenance activities are performed;
- **Refurbishment and Overhaul Workshop** in which the trains are completely overhauled;
- **Components Company** in which parts are refurbished and repaired.

Our main focus is on the activities performed in the OBs. The current OBs of NedTrain are located in Onnen, Leidschendam, Maastricht, and Amsterdam. Where the last OB is focussed on maintenance activities for NS HiSpeed. Next to the aforementioned types, NedTrain is currently building a new type of facility on four locations in the Netherlands called TCs. These TCs can be described as smaller types of OBs or upgraded SBs. Because of the design of our research, in which we also take into account the capacity of facilities, it is possible to create new types of facilities regarding the size, disassociated form the current types and names of facilities.

1.1.1 Maintenance Development

NedTrain currently consists of four business units as depicted in Figure 1.2. The research that we conduct, is under the responsibility of the business unit Fleet Services. Within Fleet Services, the department of Maintenance Development continuously tries to improve current methods and processes within NedTrain. This department can be seen as the research department for operational processes within NedTrain. The department currently consists of three employees and a number of master thesis and PhD students from the technical universities in the Netherlands which try to improve NedTrain while simultaneously extending the literature.

1.2 Previous Research

In this section, we review the current literature and explain the context of this research from an academic perspective. Reviewing the literature provides us with useful information and insights. Moreover, by reviewing the current literature we are able to identify gaps which the current research can fill. The literature review presented here is a summarised version of the work of De Jonge (2013). We refer the interested reader to his complete work. In Section 1.2.1 we discuss the general
facility location problems. Next, we want to highlight the only three articles to our knowledge which simultaneously optimise the number and location of facilities, the inventory, and the capacity of the facilities in a repair environment. First, in Section 1.2.2 a model is discussed in which the three aforementioned factors are optimised for a stochastic environment. Next, a model is discussed in which the three factors are optimised in a multi-echelon environment in Section 1.2.3. Finally, in Section 1.2.4 we provide a very recent article in which a model is presented in which also a decision can be made to exchange or repair a part.

1.2.1 Facility Location Problems in General

Facility location problems (or plant location problems) are described since 1909 by Weber. After this first publication a substantial amount of literature has been published, especially in the last twenty years. In this section, we summarise the literature discussed in the literature review (De Jonge, 2013) by highlighting the most important findings and indicating gaps in the literature.

Due to the vast amount of literature, researchers tried to classify the existing models in a classification position model. One attempt was to make a position model after the example of Kendall (1951) who made such a position model for queueing models. However, the researchers who made this attempt were not successful, probably because the literature is to extensive and the amount of variations possible on the models is too large. Other researchers also tried to classify the literature, but without proposing a position classification. This was more successful and there are a number of good literature reviews. (See for example the reviews of Aikens, 1985; Brandeau & Chiu, 1989; Current, Hokey, & Schilling, 1990; Francis, McGinnis, & White, 1983; Hamacher & Nickel, 1998; Klose & Drexl, 2005; Melo, Nickel, & Saldanha-da-Gama, 2009; ReVelle, Eiselt, & Daskin, 2008) The most important concepts by which facility location models can be distinguished are by topography (analytical, planar/continuous, warehouse, network, discrete), by objective (cost, demand, profit, environment), by capacity, by echelon, by commodity, by period, and by parameter uncertainty. Most research conducted, is based on production companies who want to distribute their goods in the most cost efficient way and on institutions that deliver a service, such as fire brigades, who want to locate their facilities in such a way that they cover a certain area.

The facility location problem of NedTrain can be characterised by two factors: the determination of the number and locations of the facilities and the capacity of its facilities. Aikens (1985) discussed two models which provide a good insight in the capacitated (models constrained by a capacity) facility location models. These models could be used as a start, but missing in these models is the determination of the capacity; the capacity of the facilities is an input variable instead of a decision variable in this article. ReVelle & Laporte (1996) describe two models in which also the capacity is determined, but in these models the capacity of only one resource is determined while the problem of NedTrain deals with multiple resources. To our knowledge there are no articles with models optimising more than one resource. So, this is a gap in the literature which can be filled by our research.

1.2.2 Locating repair shops in a stochastic environment - Van Ommeren, Bumb, & Sleptchenko (2006)

The article by Van Ommeren, Bumb, & Sleptchenko (2006) discusses the facility location problem for repair shops in a stochastic environment. In the problem described by the authors, broken buses go by design choice to the nearest local repair shop where the bus is repaired. If repairing a bus is not possible, it is directed to the central repair shop, where the bus can always be fixed. The article simultaneously optimises the number and location of the local repair shops (the location of the central repair shop is predefined), the inventory held at each of the repair shops, and the number of servers at each repair shop. The performance of the system is measured by the fill rate, i.e. the probability that a bus does not have to wait to be repaired. The final model of Van Ommeren et al. (2006) is a capacitated facility location problem with non-linear capacity constraints.

We identified a number of differences with the current situation of NedTrain. First, in the article there is a central repair shop where buses have to go when they cannot be repaired at the
local repair shop, in the situation of NedTrain there is only one echelon (the maintenance facility) where trains are repaired. Second, the authors penalise only the use of servers, while the number of servers is not penalised. In other words, they only take into account the use of a server, while some server (or resource) types at NedTrain have to be bought. Third, there is another performance measure than NedTrain has; NedTrain wants to maximise the availability of the number of train instead of maximising the fill rate.

1.2.3 Designing multi-echelon service parts networks with finite repair capacity - Rappold & Van Roo (2009)

The problem described by Rappold & Van Roo (2009) is based on the situation of the United States Air Force which takes a strategic decision about their repair network. Aeroplanes of the USAF are located at field stock locations (FSL) where they can fail. When a plane fails, the failed subsystem, the engine or another complex system, is sent to the central repair facility and at the same time a replacement unit, if available, is sent to the FSL. The authors make the design choice that each FSL can only be linked to one facility.

Different from the situation of NedTrain is that the model of Rappold & Van Roo (2009) is a single item model, where NedTrain has multiple items in a train that have to be maintained. However, the model is designed with a multi-item and multi-indenture application in mind, which could be useful when modelling the case of NedTrain. Another assumption of the model is that a single resource is necessary for repairs, while repairs within NedTrain require most of the time at least two resources (tools and people).

While Van Ommeren et al. (2006) optimises all decisions in one go, Rappold & Van Roo (2009) choose to use a two-step approach for their non-linear integer program, which first minimises opening cost of facilities, transportation cost, and the minimum cost of capacity at each facility. In the second step, incremental capacity gains are balanced together with the allocation of the network inventory.

1.2.4 Optimization of a stochastic remanufacturing network with an exchange option - Lieckens, Colen, & Lambrecht (2013)

Lieckens, Colen, & Lambrecht (2013) describe the situation of a manufacturer in the compressed air and generator industry who wants to redesign its remanufacturing network. The company wants to make a decision between two strategies that can be used to provide the customers with certain spare parts. In the exchange strategy, the worn-out part are immediately replaced at the customers site for a new one (completely new or revised), while with the refurbishment strategy the part is taken to the repair shop, refurbished, and installed at the customers site again. The authors make the design choice that the model determines which parts are linked to each of the routings. The final model of the authors is a Mixed Integer Non-Linear Programming model. Finding a solution for such a model is hard and therefore the authors use a Differential Evolution heuristic to solve the problem.

A difference with the previous two articles is that in this case parts can also completely replaced by new parts if necessary, while in the other two cases the number of parts remains fixed. Similar to the case described in Van Ommeren et al. (2006), the inventory network is multi-echelon. In addition to the other articles, the authors investigated also whether their network design would be different in case of fast or slow moving parts. Also different is that Lieckens, Colen, & Lambrecht (2013) choose for a profit maximisation instead of a cost minimisation objective. This is not applicable for the NedTrain case because NedTrain is a subsidiary of the NS which means that the best objective if to minimise the cost. New compared to the other two articles is that in this model, more than one item can be handled which is an advantage for building the model of NedTrain. However, capacity is solely determined by the number of operators in a repair facility.

1.2.5 Concluding Remarks

None of the articles found, describes a case in which the facility location problem is applied to a planned maintenance environment (all articles described unplanned repair environments), solving
simultaneously the facility location problem as well as the capacity problem. This is a gap in literature to be filled. The reasoning is that the lower uncertainty in a planned environment can be approached by a simpler model than the described uncertain repair environments.

1.3 Research Assignment

In this section, we describe in short the goal of this research and in Section 1.3.1 we describe the decision variables. The main goal of this research is to gather insight in the effects and sensitivity of input parameters on the outcome of decisions variables regarding facility locations. First, a conceptual and scientific model is developed. With the model, we can test the influence of a number of parameters by performing a sensitivity analysis. The influence of following parameters on the optimal solution are tested: the number of trains existing, the fixed facility cost, the transport cost, the number of maintenance paths available, and the resource cost. The results of these sensitivity analyses are used to get a feeling and understanding for the effect of changes of input parameters on the number, size, and locations of facilities.

This research is a success when the effect of the formulated parameters can be shown, such that new insights can be developed and such that we can contribute our modelling experience to science by this exploratory research. Eventually, the NedTrain wants to make and use a decision support model based on insights gathered on this initial research to make assessments for the investment in new facilities to be built. Our research makes a start by building a rather simple, but comprehensive model.

1.3.1 Decision Variables

The field of facility location is very extensive and many variables can be added to models. Therefore we make clear in this section which decision variables we have included in our model. Our model makes a decision regarding the following variables:

- **Location**, for each of the candidate locations it is decided whether a facility is built or not. By making this decision, it is also decided how many facilities are built in total.
- **Capacity**, the model provides the number of resources for each type available in each facility.
- **Routes**, for each location in the network from which trains can be transported to facilities, the model indicates to which facility the trains are directed.

1.4 The Operations Research Process

This thesis is the first in the new research field in which NedTrain wants to gather more insights. It is therefore important to decide upon the scope of this thesis because there is simply too much that can be investigated and too little time for us to investigate everything. Therefore in this thesis directions for further research are identified.

Besides scoping, one also has to realise that there is no existing framework that can be used in making this first step in this research field. There are no existing models that directly can be used and implemented within NedTrain because the situation is unique with respect to the maintenance aspect. Already existing facility location models are focussed on the production environment and only a few of them are focussed on the maintenance environment such as exist within NedTrain. What is different in the situation of NedTrain is that demand can move across the predefined space, whereas in other known models, demand occurs and “stays” at predefined places.

In literature there exist a framework made by Sagasti & Mitroff (1973) and later developed by Mitroff, Betz, Pondy, & Sagasti (1974), depicted in Figure 1.3, which shows the operations research process. What the authors in both articles bring to the attention is that in many articles in literature one or more of the phases in the operations research process are omitted. However, they state that it is crucial in conducting good research that all phases in the circle are executed. In Section 1.4.1 we discuss the operation research process of the aforementioned authors and second in Section 1.4.2 the steps which are executed in this research are explained.
1.4.1 The Operations Research Process in Literature

First the reality with the situation or problem on hand exists in the left circle of Figure 1.3. The first step is not to build a complete model of the reality or problem, what is often done in literature, but to think about the problem and to truly understand the problem. Questions such as “What is exactly the problem?”, “Is this problem the real problem?”, and “What are important factors in this problem?” have to be addressed first. Based on this check with reality the real problem and its design parameters can be identified, which leads to an conceptual model, the upper circle in the figure. Identifying the real design space and parameters is a time consuming and hard step. The difficulty in this step is that the researchers have to make sure that they develop a “mental model”, i.e. the conceptual model, which is consistent with the reality. Because putting this in words can quickly lead to ambiguity, this step can be seen as the hardest step in the model.

The next step is to create a scientific model, the right circle in Figure 1.3, from the conceptual model. The main difference between these two steps is that in the conceptual model it is decided which rules are used and which assumptions are made. This is done primarily in words, while the scientific model consists of formulas and numbers. In this modelling step between these two models the correct representation in formulas is determined for the problem described in the conceptual model. Modelling the conceptual design in a scientific model is not the most difficult part if a sound conceptual design has been made. The difficult part in the modelling is ensuring that each part of the conceptual model is also included in the scientific model. During the transformation of the conceptual model to the scientific model, one has to constantly check with the reality whether the scientific model is still consistent with the reality. This check is named the validation of the scientific model.

After the model has been validated with the reality, the third step has to been conducted. This step ends in a solution, which is the circle at the bottom in Figure 1.3. In this step the scientific model is solved and a solution is obtained. The difficulty of this step heavily depends on the scientific model made. Some models can easily be solved in spreadsheet programs or by hand, while others can only be approached by using a heuristic. Based on the solution one can decide to adjust the conceptual model. However, one has to be aware not to lose sight of the reality and the reasons on
Chapter 1. Research Introduction

why the conceptual model has been made as it has been made.

The last step is to implement the solution found back in the reality, which is the left circle in Figure 1.3. This last step can be very complex, but differs from situation to situation. The implementation of the optimal inventory levels for example is less drastic than implementing the solution of a facility location problem. Moreover, one can experience problems with implementation on different levels. For example on the level of cost, information systems, and people have to be convinced. In short, the implementation of an operations research process includes more than solely implementing the quantitative solution.

1.4.2 The Operations Research Process in the Current Research

In our research we have also followed the cycle of Sagasti & Mitroff (1973). First, we performed a number of interviews to gather insight in the problem and the company. Which can be identified as the first stage (Reality, Problem Situation) in the cycle. Next, we tried to go directly to the third stage (Scientific Model). However, by implicitly doing the first step (Conceptualisation) and thereby not making a precise the conceptual model, we faced a number of problems. One of the problems was that our understanding of the first stage (Reality, Problem Situation) grew during the process and thereby validating our scientific model with the reality. The consequence was that we had to perform a large number of iterations of the second and third stage before reaching a final state of the third stage. As aforementioned, we did the first step implicitly and thus we iterated the second step (modelling) a large number of times. However, this does not mean that we did not know how to model the scientific model, but this meant that we did not have a clear understanding of the conceptual model, which had to be created in the first step. Although, after the iterations we did, we are confident that we have a good understanding of the reality and that we thus have a sound conceptual model. Therefore, it was also relatively simple to build the scientific model.

After building the scientific model, we performed the third step in the process (Model Solving), which was the easiest step because this was done by a solver which provided us with the solution for every instance. With the solutions the solver provided we received the narrow feedback on our conceptual model. A solution for only one set of parameter settings provides us with only very few feedback. Therefore a sensitively analysis is performed for a set of parameters as can be read in Chapter 5. With the outcome of these sensitivity analyses, the model can be placed in perspective and the goal of this research is reached: gathering insights in the model.

The fourth step (implementation) is thus not performed. As one can understand, implementing the solution of a facility location model can be very expensive. Especially in the case of NedTrain which works with special facilities and infrastructure to these facilities are extremely costly; changing the current situation is not easy. Moreover, this is the first research in a row of research projects for NedTrain with this theme. Therefore a number of simplifications has been made in this thesis which first need thorough research. Moreover, this work provides research directions for the other research projects such that these projects can be more focussed on specific parts of the larger whole.

1.5 Structure of the Thesis

In the remainder of the thesis we follow the structure of the operations research process as proposed by Sagasti & Mitroff (1973). This leads to the following structure of the thesis:

Chapter 2, Conceptualisation and Conceptual Model
First we model the reality as we experience and see it in a conceptual model. In this conceptualisation phase we decide what we think is important and we underpin why certain aspects are taken into account and why others are not. By doing this we determine the domain of the problem and the design parameters are chosen. We conclude the chapter with our conceptual model and with extension which could be added to the basic conceptual model.
Chapter 3, Modelling and Scientific Model
The conceptual model made in the previous chapter is the starting point of this chapter. All aspects of the conceptual model are modelled in scientific notation. The final result of this chapter is the scientific model. Also for the extensions scientific notation is introduced in this chapter.

Chapter 4, Model Solving
In this fourth chapter we solve the model by implementing it in software and by gathering data for all parameters modelled in the scientific model. After all data has been gathered a verification and validation is executed. Finally, we provide the optimal result for the basic parameter setting as well as for the extensions.

Chapter 5, Sensitivity Analysis
After a optimal solution has been found for the given parameter setting, we perform a sensitivity analysis for a number of parameters. The analyses show how robust the optimal solution is for changes in the parameters. This chapter concludes with the sensitivity analyses for the extensions and the most important findings are summarised.

Chapter 6, Conclusions, Recommendations, and Feedback
Finally the managerial insights are provided and it is indicated which implications this has on future decision making processes regarding facility location problems within and outside NedTrain. Furthermore, feedback in the wider sense is provided on the current model in order to indicate the weaknesses of the current model and help future researchers, which might want to use the model.
CHAPTER 2

Conceptualisation and Conceptual Model

The first step in the operations research process of Sagasti & Mitroff (1973) is the conceptualisation of the reality, which results in the conceptual model or design. The conceptual design we made in this chapter comprises the most important factors which play a role in the decision making of the number, size, and location of facilities. However, it is not a one-to-one copy of the reality, which is nearly impossible. Therefore we made Design Choices and Assumptions, which are indicated accordingly in this report. The difference between an assumption and a design choice is the following. A design choice is an explicit decision that has been made regarding the development of the model (the reality is "made"), while an assumption is a decision made because the reality is unknown and it is approached as best as possible (the reality is "estimated"). For example, a design choice is which parameters are included in the model. While deciding to use a maximum utilisation level for a resource type to ensure a smooth process is an assumption because the real behaviour of throughput times for different utilisation levels is unknown. In addition to design choices and assumptions we made remarks in our report indicated as Practical Point. These aspects are too minor or too complex to model, but can explain a deviation between the model and the reality. Furthermore, practical points are also aspects which a decision maker have to take into account, but which cannot be modelled, such as laws.

The remainder of this chapter is structured as follows. First we define three aspects which are out of scope for this report in Section 2.1. Second, in Section 2.2, we explain the layout of the network. On this network, a number of trains travel to transport people, the trains are described in Section 2.3. Each train has to undergo a number of maintenance jobs, which are described in Section 2.4. To conduct the maintenance jobs resources are necessary, which are explained in Section 2.5. These jobs are executed in facilities in which also the resources are located. These facilities and their cost are described in Section 2.6. Next, in Section 2.7 we define the locations at which “demand” occurs and subsequently in Section 2.8 it is explained how we decide which trains go to which facilities and what the transport cost are. In Section 2.9, we conclude our conceptualisation phase with the conceptual model. Next, in Section 2.10 we introduce three extensions which are described in more detail.

Design Choice: One full year is taken into account
We decided to design the model for one full year, this means that all costs have to be calculated for one year. With the term “full" in our definition, we mean that within the company 24 hours a day, 365 days a year maintenance can be conducted. This has the implication that all parameters must be scaled to this full year. For example the availability of operators must be a scaled such that the model is valid and correct.

2.1 Out of Scope
Facility location problems can be very extensive as we saw during the literature review. Therefore, we scope the problem in this section to make clear which parts of the problem are included in the model and which parts are left out. What follows is an explanation why inventory (Section 2.1.1), uncertainty(Section 2.1.2), and non-short cyclic maintenance (Section 2.1.3) are out of scope in this research. Furthermore, we also excluded a time penalty for transport time, unplanned short cyclic maintenance, and job classes, but these are added in extension in Sections 2.10.1 to 2.10.3.
2.1.1 Inventory
The inventory of the facilities is excluded from this research because the primary focus is on the location and the capacity of the facilities. Inventory is defined as the spare parts and the general inventory of parts which are consumed in the maintenance process. When the inventory would be included, it is probably harder to model the problem and subsequently draw conclusions and gather insights in the sensitivity of the other factors. Moreover, there is not one single strategy how to position the inventory in the supply chain. For example every facility can hold the same inventory or there can be a central warehouse that supplies the facilities with goods. As this is almost a separate problem, one has to decide whether it is preferred to include this in the facility location problem or to solve this problem after the facility location problem has been solved.

2.1.2 Uncertainty
A deterministic approach is taken by us to ensure a focus on the core of the problem: the effect of the factors playing a role in this research. Moreover, the focus in this research is on the strategic level, leaving detailed calculations of queues for a tactical level. On this strategic level it is important to have a simple, but correct model with which we can gather insights in the influence factors have on the optimal solution.

We are aware that in reality due to stochastic behaviour of arrivals of trains, the probability of execution of jobs, and the duration of jobs it is possible that work has to be queued. Therefore, we take this into account in our conceptualisation and modelling. We have to ensure that there is slack available, which enables a smooth operation, but the amount of slack is an estimate rather than an exact calculation. Moreover, it means that the number of trains arriving at a facility, the number of arrivals per job type per facility, and the duration per job type are made deterministic by aggregating and averaging the numbers for the concerning parameters.

2.1.3 Non-Short Cyclic Maintenance
We take into account only one maintenance echelon. This means that we do not take into account component repair shops or overhaul companies. We furthermore do not take into account any inventory facilities or facilities that could be classified as central repair shop. Connected with the echelons, we only take into account the maintenance activities that are performed at the current OBs, which are the three-monthly (short cyclic) activities and some long term cyclic maintenance activities. In an OB also a number of (simple) construction changes are performed and sometimes parts are revised because of a practical point of view. These last activities are out of scope of this research because these only occur once or on an irregular basis.

2.2 Network Layout
A network consists of lines, with a line being a connection between two places in the network which are connected directly by a railway, for example Utrecht and ‘s-. It is important that all lines are connected by intersections, such that all lines together comprise only one network, a so called connected graph. It is thus not possible that a line exists which cannot be reached from another line. An example of a network is depicted in Figure 2.1 on the next page.

2.3 Trains
On the network, only one type of train exists. A train type can be for example the double decks train, which is officially named Verlengd InterRegio Materieel (Dutch for: Extended InterRegio Equipment, VIRM). In reality probably different types of trains exist and also of the same type, different variants may exist. At this moment it is not our intention to gather insights in changes for each train type or to investigate the influence of each train type. Moreover, the maintenance programs of different trains can differ extensively and thus the use of one train type suffices for our goal to create initial insights.
Assumption: Demand is stable over time
The number of trains in the network are assumed to be stable, this means that no trains are added or withdrawn from the network. This is reasonable because in the long term trains are only replaced when they are obsolete. So it is not plausible that the number of trains will change. Because the model calculates everything on an annual level, it cannot take into account changes in number of trains over years. So, the optimal solution could be different if the number of trains would not been stable.

2.4 Maintenance Jobs
A train has to be maintained regularly which is done by the execution of a set of job types. A job type could be regular maintenance or the exchange of a bogie (a bogie is the set of wheels assembled in a frame, located at the end of a carriage, which provides the train flexibility in making curves). Each job type has a certain workload in the number of hours it takes to execute the job. Note the difference between lead time (time between start and end of the job type) and workload (the number of hours it takes to execute the job). If for example two operators can work simultaneously on a job type, the lead time can be twice as short as the lead time when one operator would execute the complete job type, while the total workload remains the same.

Next to this, for every job type it is defined how often it must be executed. This can be decided based on the number of kilometres driven by the train or the time passed since the last execution of a job type. Such a number can be translated to a number of times a year the job type has to be executed.

2.5 Resources
For every job type one or more resource types are necessary to execute the job such as a bogie drop table (a tool with which bogies can be replaced easily) and electro technical skilled engineers. Moreover, one or more resources of one type can be necessary to execute the job. For example changing a bogie takes three people at the same time. For each resource it has to be determined what the annual price is, either by depreciating the cost over a period (e.g. for a bogie drop table) or by taking the annual cost (i.e. for wages).

In this problem it is very difficult to analyse the flow of jobs that are executed within a maintenance facility because resources types can be used for multiple jobs and there is no predetermined order in which the jobs are executed. Moreover, jobs can be created and subsequently have to be planned while doing other jobs. For example, when during an inspection a part is indicated for maintenance, this is planned directly and executed subsequently. Due to these facts, it is difficult to
analyse what the utilisation level will be for each resource type. Therefore we introduce a parameter in our conceptual model which indicates the maximum utilisation level for each resource type that ensures a smooth, robust, and feasible “production”. By setting a maximum utilisation level, the time that the resource is not utilised (i.e. waiting and idle time), is set as slack for the stochastic nature of the jobs.

Note that introducing this parameter is just one method to ensure that with the result of this model also a feasible operational plan could be made. Another method could be for example to increase the duration of all job types with a certain factor, but this has the drawback that the effect on the utilisation of the resource type is not directly visible.

**Design Choice:** The same number of resources of a type is necessary during the complete execution of the job

For simplicity we decided that each job type needs the same (number of) resource types every time it is executed and that the resource types are needed during the complete execution of the job type. Otherwise we would have to define for each unit of resource that is needed for a job how long it is needed during the execution of that job. This would make the analysis more complicated and furthermore the overestimation of the number of resources available of a certain type in a facility in case resources are not necessary the complete execution of a job is thought to be negligible.

**Assumption:** Price of resources is location independent

It is assumed that a railway carriages maintenance company operates from one country and is organised in such a way that it purchases its (non-human) resources centrally. Moreover, it is assumed that human resources are paid the same salary in all facilities because these are located in the same country. This assumption makes the cost of resources location and thus facility independent.

**Practical Point:** Right personnel is not always available

In one of our interviews it was mentioned that in a large number of cases not the right personnel is available to perform the job. This can be caused by two things: one, the personnel schedule is not made in consultation with the production schedule. Two, the uncertainty in the jobs to be executed and the trains to be arrived that it is very hard to ensure that the right people are available. Because the investigation of the real cause is beyond scope of this thesis, this should be investigated further such that it could be included in the right way in a tactical model. In our model we could adjust the $\beta_r$ in such a way that for example inspection sheds have a lower maximum utilisation level because trains have to wait for personnel to perform the job and thus they block the resource while no progress is made.

### 2.6 Facilities

Essential in facility location problems are the facilities. A facility is defined as a building along a railway in which maintenance jobs can be executed. An example of a maintenance facility can be found in Figure B.1 on page 64. This is an artist impression of the maintenance facility for hi-speed trains, built in Amsterdam Watergraafsmeer. In creating a set of candidate facility locations, a green field approach is used. This means that we do not include current facilities as given in our model. An example of a network with candidate facilities locations is depicted in Figure 2.2 on the next page.

Whether a facility has to be opened or not, is one of the decision variables in our model. The model makes two decisions regarding candidate facility locations with this single decision variable. First it determines the locations of the facilities and at the same time it determines the total number of facilities is. Furthermore, the model decides with another decision variable the capacity of a facility, i.e. how many resources of each resource type are available in a facility and thus how many trains can be maintained.

The upper bound on the number of facilities that can be opened is the number of candidate facility locations. The associated cost driver is the fixed facility cost, i.e. the cost for building an
empty facility without any job type related resources. The price of the facility can differ for each candidate facility location because for example due to the price of the land. Furthermore included in this fixed facility cost are:

- **Side buildings**, such as the company’s restaurant, bathrooms, changing rooms, offices;
- **Waste storage facility**, for the recycling of waste;
- **Warehouse**, filled with parts needed on a short term, note that we only include the space and not the parts itself;
- **Infrastructure**, all railways needed around the facility, which are in direct relation to the facility.

**Design Choice: Discrete set of candidate facility locations**

We restrict the locations where facilities can be located by providing a set of candidate facility locations. This design choice is made because it would be irrational to provide a space in which the model could select any point in that space. It would be very expensive to build the complete infrastructure towards locations which are not located along a railway. Leaving aside whether it is even possible to build a railway towards such a location, for example because of governmental rules or because of existing buildings. Even if it is possible, it would be difficult to estimate the transport distance and cost of transporting the trains to such a facility location. A restriction for items in the set of candidate facility locations is therefore that their physical location is located along a railway which already exists.

**Design Choice: All facilities can execute all job types**

Deciding that all job types can be executed at facilities makes the outcome of the model more robust in two ways. One, trains can be sent to any facility and are ensured that all job types can be executed, preventing operational problems which can occur when resource types needed for a job type are not available in the facility where the problem has been observed. Two, the influence of the other parameters is not disturbed by the inequality in resources types available in facilities.

**Practical Point: Considerations in selecting candidate facility locations**

When one wants to expand this form the set of candidate facility locations, one has to take into account a number of factors. First, the ground of the candidate location must be in possession or can be acquired. Next, in selecting a location, one has to take into account all regulations and laws, which can be very restricting in the number of possibilities left nowadays. Also one has to
communicate properly to all people and organisations involved such as pressure groups, to prevent unwanted costs and delays. Finally, one has to consider the space around the facility to be built in order to be able to locate trains which are awaiting maintenance or service.

**Practical Point: Facility accessibility and surroundings design**

Once a facility has been established, it cannot be changed easily. Especially the infrastructure in and outside a facility is very costly (more than € 10 million) to establish. This means that one has to take into account the layout of a facility when building it. Moreover, the layout of a facility can influence the utilisation of resources. An expert we interviewed stressed that facilities must be built flexible and future proof. We explain this with a small example. In case a facility can only be accessed from one side it can occur that one train blocks another train and thus keeps resources unnecessarily utilised. If two trains are positioned at the same inspection shed and the train most far from the door is ready, but the one closest to the door is not, the train at the door causes two effects. One, the resources are utilised unnecessary and two, the availability of the train for passenger transport is less than it could be. A train which can be accessed at two sides does not contain this problem. However, it can be more costly in building the infrastructure. The effects of the accessibility of a facility are neglected in this research, but should be investigated in new research.

Next to the accessibility, another important point is the layout of the surrounding of the facility. How many tracks are available to park trains that are not currently maintained? Also the shunting yard and the traffic control play an important role. NedTrain employees indicated that it can depend on the staff of traffic control and the shunters whether a planning can be met or not. Besides this dependency, the layout of the shunting yard can influence the order in which jobs are executed. This is not included in our model, but it might be possible to focus on this in an analysis.

**Practical Point: Overhead personnel not taken into account**

At this moment we did not include any overhead personnel. However, employees of NedTrain indicated that the total cost per operator (including overhead personnel necessary) at different facilities can be different. This means that also for the overhead personnel a certain degree of economies of scale is applicable. When our analysis indicates that the economies of scale is important, a factor should be incorporated which is dependent on the size of facility, but which is not directly related to the total amount of work to be executed in the facility.

**2.7 End Stations**

One of the key factors in facility location problems is the demand that has to be satisfied. Here, the demand is the maintenance jobs that has to be executed. We made the design choice (explained below) to let the demand occur at certain fixed locations in the network which are defined as end stations. End stations are closely located to passenger stations and consist of a number of railways on which trains can be located if they are not used according to the timetable, for example overnight, in off-peak periods, and awaiting maintenance. The total number of trains in the network are distributed over all the end stations in the network. An example of a network with end stations is depicted in Figure 2.3 on the next page.

**Design Choice: Demand can only occur at a discrete set of end stations**

Trains travel across the network and at a certain moment in time, it is indicated that these trains has to be maintained. This moment is known in advance because we observe planned maintenance. When trains have to be maintained, they are taken out of service at logical places. For example when the train has reached a last station during service and all passenger exit the train. These places are the end stations defined earlier. Therefore, the design choice is made to predetermine a number of locations in the network from which demand, trains that have to undergo maintenance, could occur. We decided to select a number of locations on beforehand because this simplifies the analysis and it is line with reality.
2.8 Routing of Trains

The third and last cost driver in this problem is the transport cost. To calculate this cost the total number and length of travels have to be determined because we made the decision that the cost of transportation depends on the number of railway kilometres to be covered. A travel from an end station to a facility is defined as a maintenance visit. Because we recalculate everything to an annual number, the number of maintenance visits per year has to be determined.

What is left, is the number of trains transported from a certain end station to a certain facility. This number is decided on by the model and thus a decision variable. Note that in our model we do not link trains to facilities, but end stations to facilities. This simplifies the calculation of the transport cost, i.e. it is not necessary to know the exact locations of trains, but it is assumed that a stable number of trains are located at each end station. Which specific trains are located at the end stations does not matter for the model. However, it has to be assured that all trains at an end station that need maintenance, also receive maintenance. Figure 2.4 on the next page explains our modelling in pictures. The sets of end stations and candidate facility locations are input to the model. Also the total number of trains and the distribution over the end stations is an input. The model decides on which facilities are open and the fraction of trains of the total (and thus also from the end stations) is maintained in which facility.

2.8.1 Maintenance Paths

The number of trains that can use a track, a piece of railway, is restricted by regulations. Every year, an authority allocates the capacity of the tracks among all rail transport companies. This is done by providing every company a number of paths. At a path, a combination of time, date and a track, a company is allowed to drive a train over this specific track. We include these paths because they are essential in the capacity determination of the facilities. Note that we only take into account maintenance paths, these are paths that lead to a maintenance facility. For every facility it is determined how many maintenance paths are available per year. The use of maintenance paths in our model decouples the capacity available on the tracks for maintenance transports and for other transports as passenger and freight transport.

2.9 The Conceptual Model

Now all aspects of our conceptual model have been introduced, we summarise the conceptual model in this section. Please note that this conceptual model is our vision on the reality. Each Operation Research scholar makes his own conceptual model based on what the scholar thinks are the aspects
Chapter 2. Conceptualisation and Conceptual Model

The total number of trains
End station
Candidate facility location

100%

15%
4%
30%
12%
8%
5%
37%
32%

Figure 2.4. The trains divided over end stations and next over facilities.

*1 = 3% of total, 20% of end station
*2 = 12% of total, 80% of end station
*3 = 3% of total, 55% of end station
*4 = 5% of total, 47% of end station

Table 2.1. The cost parameters with the corresponding decision variables.

<table>
<thead>
<tr>
<th>Cost parameter</th>
<th>Decision variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>The fixed facility cost</td>
<td>Whether a facility is open</td>
</tr>
<tr>
<td>The resource cost</td>
<td>The number of resources of each type located at each facility</td>
</tr>
<tr>
<td>The transport cost</td>
<td>The routings of trains from end stations to facilities</td>
</tr>
</tbody>
</table>
2.10 Extensions

The conceptual model only covers a basic situation to gather the most important insights in the problem. During our research we identified three extensions which could be implemented in the model. These extensions are based on the data gathered or on the interests of NedTrain. However it is attempted to make each extension universal and also applicable for other situations.

In each of the following sections we introduce one extension at a time because we only want to investigate the effect of the extension on the basic model. For each extension we first explain the reason why the extension has been made. First in Section 2.10.1 an extra constraint is added to ensure a certain level of availability. The second extension to the basic model is the addition of EBKs. This is done in Section 2.10.2. Third, different job classes are introduced in Section 2.10.3. Finally we mention two extensions in Section 2.10.4 which also could have been added in future research, but on which is not elaborated here.

2.10.1 Extension I: Penalty for Transport Time

An important measure in contracts between a maintenance company and the rail carrier can be the availability of trains for passenger transport. This parameter is not included earlier because if we would have done so, the effect of the transport cost itself and the effect of the time penalty on top of it would be hard to distinguish and identify. By adding the time penalty in this extension, we can investigate the effect of changes of input parameters on the outcomes and gather new insights.

The original thought is to add a penalty for every hour the train cannot be used (due to transport, waiting time, or maintenance), but as the total duration of work stays the same and the waiting time is not taken into account directly, only the transport time can make a difference in the outcome of the model.

2.10.2 Extension II: EBK

Trains have planned and unplanned maintenance visits, the latter is also named EBK within NedTrain, which is a Dutch abbreviation for an extra entry or visit. This means that the train has to visit the facility in addition to the regular, planned maintenance visits. We excluded this from the basic model because these visits are irregular and the amount of time spent during each EBK was thought to be little by a NedTrain expert. During the data collection we discovered that the influence of EBK was larger than expected; the time spent on maintenance jobs during an EBK is about one-third of the total maintenance conducted during planned and unplanned maintenance visits. Moreover, the data showed that EBKs occur on average more often than regular maintenance is conducted. This means that the transport cost will be doubled under the same conditions of the basic optimal solution. Therefore, we decided to make an extension on the basic model to investigate the influence of adding these maintenance jobs and visits on top of the amount of regular maintenance.

EBK Jobs

In Section 2.4 we modelled a set of job types. For the EBKs we decided to define a separate set of EBK job types. Another option was to add these jobs to the set earlier created. However, we prefer to clearly distinguish the two sets of job types because the characteristics are considerably different. For example the number of times a job type is expected to be executed during an EBK and the duration of a job type during an EBK differs from regular maintenance for the same job type. All resource types necessary for the EBK job types are the same as for the planned jobs. So, no new resource types has to be added in this extension.

The Distribution and Routing of EBKs

For the regular maintenance visits we determined that demand always occurs at end stations where trains are located when they are not in service because of for example overnight stays. As for planned maintenance it is known at which moment maintenance is needed, this is not or less known for EBKs. Trains which need an EBK could have broken down during service or can still be used in service till they reach an end station. In all cases we assume that these trains are driven to an end station. Due
to this assumption demand for EBKs occurs only at end stations. We are aware that we simplify the process when trains are broken down and cannot drive by itself any more.

Every train that has to be transported from an end station to a facility and back bring a certain amount of cost. The method how we calculate the transport cost for EBKs is the same as for planned maintenance visits. However, we use a different parameter to express the transport cost for EBKs because it is possible that an EBK would be more expensive that regular transportation for example due to its uncertainty of occurrence. In addition we add a fourth decision variables which decides on the fraction of trains that are transported from a certain end station to a certain facility to execute an EBK. Finally, it is chosen to introduce a separate parameter that expresses the number of EBKs per train per year above working with a total number of EBKs per year because in this way the structure of the model with the extension is as close as possible to the basic model. Moreover, by introducing this parameter the amount of EBKs is still linked to the number of trains existing.

2.10.3 Extension III: Job Classes

The last extension is comparable to the EBK extension. However, the difference is that we do not add an extra set of jobs, but that we classify the current set of jobs in a number of classes. By this extension it is possible for the model to make unequal facilities in the sense of the resource types available at a facility. It is thus possible that facilities cannot execute all jobs any more. One reason to add this extension is that NedTrain is interested whether unequal facilities would lead to a decrease in cost and an increase in service to the NS. The reasoning is that there is a set of job types that occurs more often than others, while only using a minimal set of (simple) resource types is used for this set of job types. When facilities are built which only contain this minimal set of resource types, it might be optimal to built a relatively high number of these type of facilities, which in its turn leads to lower transport cost and lead time. For jobs types that occur less often and need special and expensive resource types, trains can be transported to better equipped facilities of which a relatively low number exist. The reason why we did not include this extension in our basic model is because we first wanted to gather insight in this basic model. Creating unequal facilities would make it harder to thoroughly understand the working of the model and the influences of the parameters. In the remainder of the section, we introduce the concept of job classes in more detail.

Job Classes

Each class consists of one or more job types. These job types preferably share a certain set of resource types which are not used by jobs types in other classes. By this method, unequal facilities can be designed which may lead to a higher service level (percentage of trains that is operational) against the same or lower cost. We do not provide the exact criteria how to divide the different job types in the different classes, but we want to indicate that it only makes sense to divide the job types in classes if the resource types needed for each class differ because otherwise distinctive facilities are not created. Note that a job type can be classified in more than one class.

2.10.4 Other Extensions

In the previous we included indicated a large amount of factors which are included in our model or which are not included but of which we are aware that these factors exist and which influence they could have. In this section we want to add two more factors that could have been included in the model:

Cost Free Transports

In our current model we penalise every transport of a train from an end station to a facility by a transport cost per kilometre. However, this is not completely fair if we look at the reality because it might be that facilities can be reached while being in service. Therefore it should be investigated what the number of trains are that can drive from an end station to a facility while being in service. These numbers should then be implemented in our model such that for these transports, no transport cost is paid because the train are not transported empty for maintenance. Next the effect should be
investigated on the optimal solution.

**Hard Constraint On Availability**

In this chapter we introduced a soft constraint on the availability of trains. As we have seen, the influence of this constraint on the optimal solution was that the optimal solution remained the same. Moreover, it is not ensure by this constraint that a certain service level is met. Therefore, it would be interesting to extent the model with a hard constraint on the availability of trains and investigate the effect on the optimal solution.
Modelling and Scientific Model

The previous chapter concluded with the conceptual model. In this chapter we conduct the modelling step defined in the operations research process defined by Sagasti & Mitroff (1973). For each aspects defined in the conceptual model, we model this in formal notation, ending this chapter with the scientific model. In each section necessary assumptions are underpinned, we explain the parameters and variables, and we explain how they are used in the model (a complete list of parameters and variables can be found in Appendix A). The structure of this chapter is the same as for Chapter 2.

In the first six sections we define notation for the aspects introduced in Sections 2.2 to 2.8. Next, we explain in Section 3.8 a number of constraints on the number of resources available in a facility. Thereafter, the scientific model is presented in Section 3.9 and finally in Section 3.10 we define the notation for the extensions.

### 3.1 Network Layout

The network itself or the lines are not used directly in the model, but they form a basis to understand the situation and thereby the model. We want to emphasise that the lines in our network are not the same as the lines defined normally in railway jargon. The actual shape of the model does not matter, which is explained in Section 3.7.

### 3.2 Trains

The total number of trains in the network that exist is denoted by $N$. Note that this $N$ is not directly used in the model, but that it is used later to determine the number of maintenance visits (see Section 3.6). The scientific notation becomes:

$$N := \text{the total number of trains existing in the network.}$$

### 3.3 Maintenance Jobs

$J$ is the set of job types. The average duration (the time between start and end of the job) for the execution for job type $j \in J$, expressed in years, is assumed to be deterministic and indicated by $\mu_j$.

Because we defined a maintenance visit, we have to determine the occurrence of a job type during a maintenance visit. Note that a job type can be executed more than once per maintenance visit because for example more than one bogie of a train has to undergo a job type. The number of times per maintenance visit that job type $j \in J$ is executed is expressed in the parameter $\chi_j$, which is an expected number of execution of job type $j \in J$ instead of a probability; the number can thus also be higher than 1. The scientific notation becomes:

$$J = \text{the set of job types;}$$

$$\chi_j = \text{the number of times that job type } j \in J \text{ has to be executed per maintenance visit;}$$

$$\mu_j = \text{the expected duration for the execution of job type } j \in J \text{ in years.}$$

### 3.4 Resources

The set of resource types is denoted by $R$. For every job type the number of resource type $r \in R$ necessary to execute job type $j \in J$ is indicated by $z_{jr}^n$. The annual resource cost per unit of resource type $r \in R$ are denoted by the parameter $c_r^i$. As explained in the conceptual model, we introduce a
parameter that expresses the maximum utilisation level for resource type. This parameter is denoted by $\beta_r$, which is the maximum utilisation level for resource type $r \in R$ and expressed in a number between 0 and 1. The scientific notation becomes:

$$
R = \text{the set of resource types};
$$

$$
c_r^t = \text{the resource cost per year per unit of resource type } r \in R;
$$

$$
\beta_r = \text{the maximum utilisation level for resource } r \in R;
$$

$$
z_{jr}^n = \text{the number of resources of type } r \in R \text{ necessary for job type } j \in J.
$$

**Practical Point:** Economies of scale for resources are not taken into account

At this moment we have defined the utilisation level for each resource type by $\beta_r$. In our model this parameter is independent of the size of a facility. In reality it is probably the case that when the size of a facility is increased more work has to be performed. In case a facility is larger, it has an economies of scale advantage. For example in the case described in the previous point it is more likely that the resources can be used to perform other tasks when the train has not yet arrived in a large facility in comparison to a small facility. On a tactical level one should include this effect.

### 3.5 Facilities

$F$ is the set of these candidate facility locations. Whether a facility is open is denoted by the decision variable $y_f$, which has the value 1 if a facility $f \in F$ is open and 0 if the facility $f \in F$ is closed. The annual cost per facility (taking into account the total sum of cost and the depreciation period) is denoted by $c_f^i$ for facility $f \in F$, which can be different for each candidate facility as explained in the conceptual model. Another decision variable is $z_{fr}^a$, which expresses the number of resource type $r \in R$ which are available at candidate facility $f \in F$. This number must be a non-negative integer, as explained in the Design Choice below. The scientific notation becomes:

$$
F = \text{the set of candidate facility locations};
$$

$$
c_f^i = \text{the fixed facility cost per year for facility } f \in F;
$$

$$
y_f = \begin{cases} 
1 & \text{if facility } f \in F \text{ is open} \\
0 & \text{if facility } f \in F \text{ is closed} 
\end{cases} \quad \forall f \in F \quad \text{(decision variable)};
$$

$$
z_{fr}^a = \text{the number of resources of type } r \in R \text{ available at facility } f \in F \quad \text{(decision variable)};
$$

$$
z_{fr}^a \in \mathbb{N}_0.
$$

**Design Choice:** Only an integer number of resources is possible

In our model we decided that only integer numbers of resources are possible. We made this design choice because for many resources it holds that non-integer numbers are not possible, as for example for inspection sheds. We realise that the model overestimates the number of resources necessary for which it is possible to have a non-integer number, for example for the number of FTE of operators. However, this overestimation is small because the cost per resource is relatively low.

### 3.6 End Stations

The set of predetermined end stations is denoted by $E$. As explained earlier, we have a fixed number of trains $N$ in the network. This total number of trains in the network is divided over all the end stations in the network. The parameter $N_e$ expresses the average number of trains at an end station $e \in E$ at the end of a day and is deterministic (see Design Choice below). Note that this is a number and not a fraction because we are interested in the total number of maintenance visits per year. By definition the sum over $N_e$ for all end stations $e \in E$ is equal to $N$. The scientific notation becomes:

$$
E = \text{the set of end stations};
$$

$$
N_e = \text{the average number of trains at end station } e \in E \text{ at the end of a day}.
$$
Design Choice: The number of trains at an end station is deterministic
We decided to set a deterministic number for the number of trains at an end station because as on the strategic level we model, it does not matter how many trains are exactly located at an end station at a given day. In reality, it is known in advance for every end station how many trains stay overnight. The number is based on the overnight stay table, which is made by the carrier and depicts for every end station the number of trains that stay overnight, after being used according to the timetable. We assume that the number of every end station is stable over time for every end station (i.e. there is a balance in the number, for every train that leaves the station, another train will return and the other way around).

3.7 Routing of Trains
First, we introduce the decision variable that indicates the number of trains that drive from end station \( e \in E \) to facility \( f \in F \) for maintenance visits. This variable is denoted by \( x_{ef} \), which is a fraction of \( N_e \) expressed as absolute number. By logic, this number must be equal or greater than zero. Note that \( x_{ef} \) has no dimension regarding the time. Therefore we introduce the parameter \( \lambda \), the number of maintenance visits per year. Second, we denote \( p_f \) which is the maximum number of maintenance paths available per year to reach facility \( f \in F \).

This parameter only depends on the facility and not on the end station because it is unknown which paths are actually selected. If we want to make the maintenance paths also dependent on the end stations, we would have to determine for each piece of railway what the capacity is and check whether the capacity is not violated because more than one path could go through the same piece of railway. First it would be very difficult to determine this information for each piece of railway and second it would be very complicated to model. Furthermore, the last piece of railway to a facility has the most increase in volume because all routings come together at this point and so we think it is sufficient to model only the path to the facility.

Each train that travels from an end station \( e \in E \) to a facility \( f \in F \) costs a certain amount. The cost of transporting a train for a single maintenance visit from an end station \( e \in E \) to a facility \( f \in F \) and back is denoted by \( c_{tf} \). Note that \( c_{tf} \) is in input parameter and can have an underlying cost structure which is however decoupled and not influenced by the model, therefore the shape of the actual model does not influence the results. The scientific notation becomes:

\[
x_{ef} = \text{the number of trains located at end station } e \in E \text{ assigned to facility } f \in F \text{ for maintenance (decision variable)};
\]

\[
x_{ef} \geq 0; \quad \lambda = \text{the number of maintenance visits per train per year};
\]

\[
p_f = \text{the number of maintenance paths available to access facility } f \in F \text{ per year};
\]

\[
c_{tf} = \text{the cost of transporting a train from end station } e \in E \text{ to facility } f \in F \text{ and back}.
\]

Regarding the routing of trains, we have to pose two constraints. First, we have to ensure that all demand at all end stations in the set \( E \) is routed to a facility. This constraint is made by summing the total number of trains routed from an end station \( e \in E \) to a facility \( f \in F \) for every facility in the set \( F \). For every end station in the set \( E \), this summation must be equal to the average number of trains at an end station \( e \in E \) at the end of the day, resulting in Constraint 3.1. Second, for all facilities in the set \( F \), it must hold that the total number of maintenance visits to a facility \( f \) in \( F \) must be equal or less than the maximum number of maintenance paths available to access facility \( f \in F \), resulting in Constraint 3.2.

\[
\sum_{f \in F} x_{ef} = N_e \quad \forall e \in E; \quad (3.1)
\]

\[
\lambda \sum_{e \in E} x_{ef} \leq p_f \quad \forall f \in F. \quad (3.2)
\]
Practical Point: Disturbances
Both in our model as in reality the trains have to travel across the network before arriving at a maintenance facility. Due to disturbances, such as suicides, the weather, or technical disturbances, it might be possible that a train will not reach its facility on time. In such a case the reserved time for the train cannot be used at this moment and the resources are not utilised. In our model this should be included in the parameter $\beta_r$, which is maximum utilisation of resources. In a tactical model the reliability of the delivery of trains at the right time should be included in the model.

3.8 Constraints on the Availability of Resources
With the variables introduced in the previous sections we can pose constraints on $z_{f,r}^a$, the number of resources of type $r \in R$ available in facility $f \in F$. First we explain a constraint that forces that there are enough resources to perform all the work to be executed of one year, which is done in a number of steps. We start with the calculation of the total time that resource type $r \in R$ is used during job type $j \in J$ per maintenance visit. This is done by multiplying the number of times a job type has to be executed during a maintenance visit (denoted by $\chi_j$) by the duration of that job type (denoted by $\mu_j$) and by the number of resources necessary to execute the job, which is $z_{jr}^n$. The second step is to calculate this number for every job type $j \in J$ and to sum up these numbers. The last step is to multiply this result by the total number of maintenance visits per year, given by the sum of the trains that make use of the specific facility $f \in F$ for their maintenance visit (sum of all $x_{ef}$ over all $e \in E$), multiplied by the number of maintenance visits per year, which has been denoted by $\lambda$. The resulting number is rounded upwards to an integer as explained earlier. Finally, the resulting number is multiplied by $\beta_r$ to ensure a maximum utilisation level, which lead to Constraint 3.3.

An extra constraint is needed to ensure that a certain number of resources of a type is available, when they are needed simultaneously for the executing of a job type. For example, in case a facility receives only a relatively small number of maintenance visits per year, it can be that the total demand can be covered by one unit of a certain resource type, e.g. an operator. The result is that if a job type needs two operators to work on the job type simultaneously, the job type cannot be executed because there are too little resources available. Therefore a constraint is added which ensures that the minimum number of resources of a type $r \in R$ available in a facility $f \in F$ (denoted by $z_{jr}^n$) is equal or greater to the maximum number of resources of a type $r \in R$ needed simultaneously for each of the jobs in the set $J$ (denoted by $z_{jr}^a$) if the facility $f \in F$ is open (denoted by $y_f$), resulting in Constraint 3.4.

Finally we pose a constraint that the number of resources of type $r \in R$ in a facility $f \in F$ can only be positive if the facility $f \in F$ is open. To ensure this, $y_f$ is multiplied by a large number $M$, such that if the facility is closed no resources of any type can be available in facility $f \in F$, resulting in Constraint 3.6 However, $M$ is chosen such that it does not limit in any way the number of resources of all types available in facility (denoted by $z_{f,r}^a$) when a facility is open.

$$\lambda \sum_{e \in E} x_{ef} \sum_{j \in J} \chi_j \mu_j z_{jr}^n \leq \beta_r z_{f,r}^a \quad \forall f \in F, \forall r \in R;$$  \hspace{1cm} (3.3)

$$z_{jr}^n y_f \leq z_{f,r}^a \quad \forall f \in F, \forall r \in R;$$  \hspace{1cm} (3.4)

$$M = \text{a large number};$$  \hspace{1cm} (3.5)

$$z_{f,r}^a \leq M y_f \quad \forall f \in F, \forall r \in R.$$  \hspace{1cm} (3.6)
3.9 The Scientific Model

In this section we present the complete model including the constraints. Note that the objective is a summation over all cost factors (fixed facility cost, resource cost, and transport cost). Based on the variables, parameters, and constraints introduced in the previous sections, we can present the following scientific model:

\[
\begin{align*}
\text{Minimise} & \quad \sum_{f \in F} c_f y_f + \sum_{f \in F} \sum_{r \in R} c^r_j z^a_{jfr} + \lambda \sum_{e \in E} \sum_{f \in F} c^t_{ef} x_{ef} \\
\text{subject to} & \quad \sum_{f \in F} x_{ef} = N_e \quad \forall e \in E; \\
& \quad \lambda \sum_{e \in E} x_{ef} \leq p_f \quad \forall f \in F; \\
& \quad \lambda \sum_{e \in E} x_{ef} \sum_{j \in J} \chi_j \mu_j z^n_{jfr} \leq \beta_r z^a_{jfr} \quad \forall f \in F, \forall r \in R; \\
& \quad z^n_{jfr} \leq \frac{z^a_{jfr}}{y_f} \quad \forall f \in F, \forall j \in J, \forall r \in R; \\
& \quad z^a_{jfr} \leq M y_f \quad \forall f \in F, \forall r \in R; \\
& \quad y_f \in \{0, 1\} \quad \forall f \in F; \\
& \quad x_{ef} \geq 0; \\
& \quad z^a_{jfr} \in \mathbb{N}_0.
\end{align*}
\]

Input parameters

- \( F \) = the set of candidate facility locations;
- \( R \) = the set of resource types;
- \( E \) = the set of end stations;
- \( J \) = the set of job types;
- \( N_e \) = the average number of trains at end station \( e \in E \) at the end of a day;
- \( c_f \) = the fixed facility cost per year of facility \( f \in F \);
- \( c^r_j \) = the resource cost per year per unit of resource type \( r \in R \);
- \( c^t_{ef} \) = the cost of transporting a train from end station \( e \in E \) to facility \( f \in F \) and back;
- \( p_f \) = the number of maintenance paths available to access facility \( f \in F \) per year;
- \( \lambda \) = the number of maintenance visits per train per year;
- \( \chi_j \) = the number of times that job type \( j \in J \) has to be executed per maintenance visit;
- \( z^n_{jfr} \) = the number of resources of type \( r \in R \) necessary for job type \( j \in J \);
- \( \mu_j \) = the expected duration for the execution of job type \( j \in J \) in years;
- \( \beta_r \) = the maximum utilisation level for resource \( r \in R \);
- \( M \) = a large number;
- \( \mathbb{N}_0 := \mathbb{N} \cup \{0\} \).

Decision variables

- \( y_f \) = \( \begin{cases} 1 & \text{if facility } f \in F \text{ is opened} \\ 0 & \text{if facility } f \in F \text{ is closed} \end{cases} \);
- \( z^a_{jfr} \) = the number of resources of type \( r \in R \) available at facility \( f \in F \);
- \( x_{ef} \) = the number of trains located at end station \( e \in E \) assigned to facility \( f \in F \) for maintenance.
3.10 Extensions

In this section we introduce the scientific notation for the three extensions proposed in Section 2.10. First we model the transport time penalty in Section 3.10.1, next the extension for the EBKs is modelled in Section 3.10.2 and finally we model the job classes extension in Section 3.10.3.

3.10.1 Extension I: Penalty for Transport Time

In our model we included the cost parameter $c_{et}$, as explained earlier, the cost structure behind this parameter is not included in the model, which provides freedom to the users of the model. Therefore, we decided to add the availability constraint as a soft constraint instead of a hard constraint, this means that the availability is maximised instead of being set at a minimum level. By changing the underlying cost structure of the transport cost $c_{et}$, we include the transport cost. The basic model however remains unchanged.

3.10.2 Extension II: EBK

In the following three subsections we explain the scientific notation for the EBK jobs, the distribution of EBK over the end stations and the routing to the facilities and the extra constraints needed for the availability of resources. The extended scientific model with the newly introduced parameters and variables can be found in Section H.1.

EBK Jobs

The the set of EBK job types, which is denoted by $U$. Each EBK job type $u \in U$ has a duration expressed in years denoted by $\mu_u$ and a number of times it is executed during an EBK, which is denoted by $\chi_u$. All numbers are aggregated over all trains types and it are expected numbers which are a deterministic input in our model. For each job type in the set $U$ we have to model the number of resources of type $r \in R$ necessary for the execution of EBK job type $u \in U$, which is denoted by $z_{ur}^n$. The scientific notation becomes:

- $U =$ the set of EBK job types;
- $\chi_u =$ the number of times that EBK job type $u \in U$ has to be executed per EBK;
- $\mu_u =$ the expected duration for the execution of EBK job type $u \in U$ in years;
- $z_{ur}^n =$ the number of resources of type $r \in R$ necessary for EBK job type $u \in U$.

The Distribution and Routing of EBKs

The absolute number of trains at each end station that need an EBK is modelled by $u_e$ which is the total number of trains that depart from end station $e \in E$ for and EBK. The transport cost for an EBK is modelled by the parameter $c_{ef}^u$. Note that this parameter can have an underlying cost structure which is not part of the model.

The next part needed is how many trains are actually being transported from a certain end station $e \in E$ to a certain facility $f \in F$. As with $x_{ef}$, the number of $u_{ef}$ is a fraction of $u_e$, however because we are interested in the number of EBKs and not in fraction, we expressed it in an absolute number. In addition we introduce the expected number of EBKs per train per year, which is denoted by $\lambda_u$. The scientific notation becomes:

- $u_e =$ the number of trains that need EBK that depart from end station $e \in E$;
- $u_{ef} \geq 0$;
- $c_{ef}^u =$ the cost of transporting a train from end station $e \in E$ to facility $f \in F$ and back for an EBK;
- $u_{ef} =$ the number of trains located at end station $e \in E$ assigned to facility $f \in F$ for EBKs (decision variable);
- $\lambda_u =$ the number of EBKs per train per year.
We pose the constraint on the decision variable that for all end stations in the set \( E \), all trains with an EBK occurring at an end station \( e \in E \) must be maintained, similar to Constraint 3.8. The sum of all \( u_{ef} \) over all facilities \( f \in F \) must be equal to \( u_e \) for every end station leading to Constraint 3.16. The number of maintenance paths do not restrict the number of trains that can be directed to a facility because the maintenance paths are only created for planned maintenance.

\[
\sum_{f \in F} u_{ef} = u_e \quad \forall e \in E.
\] (3.16)

**Constraints to Resources**

There are two constraints posed on the number of resources available at a facility. The idea of Constraint 3.11 must also be applied to this setting; the number of resources for each resource type must be at least the number of resources needed for each EBK job type, resulting in constraint 3.17. Constraint 3.10 determines the number of resources of each type at each facility. As with the normal jobs, also for the EBK jobs it is calculated how much work has to be executed, leading to Constraint 3.18. This is done by a summation of all trains that are transported from the end stations in set \( E \) to facility \( f \in F \), which is multiplied by the expected number of times a train has an EBK per year, which was denoted by \( \lambda_u \). This provides the total number of EBKs to be conducted at this facility. This number is then multiplied by the sum of all work from EBK jobs that must be executed during an EBK. This is a multiplication for all job types \( u \in U \) of the number of times an job type \( u \in U \) has to be conducted during an EBK (denoted by \( \chi_u \)), the duration of that job type \( u \in U \) (denoted by \( \mu_u \)), and the number of resources of type \( r \in R \) necessary (denoted by \( z_{ur}^n \)). The final number provides the total amount of work per year to be conducted on EBKs and is summed to the total amount of work per year to be conducted on planned maintenance. The total sum must be less than the total number of resources available for each type in a facility multiplied by the maximum utilisation level \( \beta_r \) for each resource type.

\[
\sum_{e \in E} \sum_{j \in J} \chi_{j} u_{e} \mu_{u} z_{ur}^n + \sum_{e \in E} \sum_{u \in U} \chi_{u} u_{e} \mu_{u} z_{ur}^n \leq \beta_r \sum_{f \in F} z_{af r} \quad \forall f \in F, \forall r \in R.
\] (3.18)

**3.10.3 Extension III: Job Classes**

In the previous chapter we introduced the job classes extensions. The decision which job type is classified in which class can be made by a user, but also by the model itself. A classification made by the model while also considering the other decision variables probably leads to a better solution than classifying the jobs by hand. Therefore in this section a model has been made where the job classes are an input parameter. The extended model with the new introduced parameters and variables can be found in Section H.2.

**Job Classes**

We define \( S \) as the set of the job classes. For every job type it has to be indicated whether it is included in a certain set of jobs or not. This is modelled by the parameter \( w_{js} \), which is 1 if the job type \( j \in J \) is included in class \( s \in S \) and 0 if the job type is not included in the class. We want to stress that the user has to ensure that all jobs types are classified in at least one class. The scientific notation becomes:

\[
S = \text{the set of job classes};
\]

\[
w_{js} = \begin{cases} 
1 & \text{if job } j \in J \text{ belongs to class } s \in S \\
0 & \text{otherwise}
\end{cases}
\]

**Routings**

In the basic model we only had one job class. Now that we have more job classes, for every job class it has to be determined how often it must be executed. This is modelled by the parameter \( \lambda_s \), which
indicates the number of maintenance visits per year for class \( s \in S \). The model decides for all trains at a certain end station \( e \in E \) for each class of jobs \( s \in S \) at which facility \( f \in F \) this class is executed. This decision variable is modelled by \( x_{ef} \). The scientific notation becomes:

\[
\begin{align*}
\lambda_s &= \text{the number of maintenance visits per train per year for class } s \in S; \\
x_{ef} &= \text{the number of trains located at end station } e \in E \text{ assigned to facility } f \in F \text{ for maintenance of class } s \quad \text{(decision variable).}
\end{align*}
\]

**Adjusted Constraints**

Due to the change of \( x_{ef} \) in \( x_{efs} \) and the change of \( \lambda \) in \( \lambda_s \), also four constraints change. Note that we had to drop Constraint 3.11 because otherwise each facility would still have all resource types available. First, Constraint 3.8 must be changed such that all job classes for all trains at an end station are executed and thus the summation over all \( x_{efs} \) must be equal to the number of trains at an end station, \( N_e \), for each class \( s \in S \) resulting in Constraint 3.19. Second, Constraint 3.9 has been changed. Because each class has its own frequency per year and every time it is executed, a train has to be transported the total sum over all end stations \( e \in E \) and over all classes \( e \in E \) has to be taken to calculate the number of maintenance paths used, resulting in Constraint 3.20. Third, the total sum of work at each facility changes, which influence the number of resources of each type necessary and also Constraint 3.10. Therefore a multiplication has been made six terms which can be divided in two parts. The first three terms describe the total number of maintenance visits per year, the last three terms describe the total amount of work in years for each combination of facility \( f \in F \) and resource \( r \). The multiplication is summed over the set of classes \( S \), the set of jobs \( J \), and the set of end stations \( E \). This leads to the total number of resources of type \( r \in R \) needed in facility \( f \in F \), resulting in Constraint 3.21. The final and fourth constraint is a simple adjustment of the non-zero constraint of \( x_{ef} \) to \( x_{efs} \), resulting in Constraint 3.22.

\[
\begin{align*}
\sum_{f \in F} x_{efs} &= N_e \quad \forall e \in E, \forall s \in S; \quad (3.19) \\
\sum_{e \in E} \sum_{s \in S} \lambda_s x_{efs} &\leq p_f \quad \forall f \in F; \quad (3.20) \\
\sum_{e \in E} \sum_{j \in J} \sum_{s \in S} w_{js} \lambda_s x_{efs} \mu_j \mu_{js} &\leq \beta_r \gamma_{fr} \quad \forall f \in F, \forall r \in R; \quad (3.21) \\
x_{efs} &\geq 0. \quad (3.22)
\end{align*}
\]
In the previous chapter we introduced the scientific notation for the decision support model. In this chapter we introduce the data we gathered at NedTrain to fill the model with. The structure of this chapter is as follows. First in Section 4.1, it is explained which software is used to solve the model. In Sections 4.2 to 4.7 NedTrain data is gathered for the aspects introduced in Chapter 2. Next, the implementation of the model in the software is validated and a verification has been conducted in Section 4.8. Thereafter, the model is run and the optimal solution is presented in Section 4.9. Last, the data is presented which has been gathered from NedTrain to use with the extensions in Section 4.10.

### 4.1 Selected Software

The scientific model introduced in Chapter 3 can be characterised as an Mixed Integer Programming (MIP) model. This means that this is a linear programming model, where the word "mixed" means that next to integer decision variables, also continuous decision variables are used in the model. The model is implemented in the software package Advanced Interactive Multidimensional Modeling System (AIMMS), which can solve a wide range of models, by using commercial solvers such as CPLEX and Gurobi.

There are a number of reasons why AIMMS is chosen to solve the problem. First, AIMMS is widely used and accepted in industry (it is also used by the NS), which increases the chance of acceptance. Moreover, AIMMS has the ability to easily make and use a Graphical User Interface. Besides, AIMMS makes use of the fastest and best (commercial) solvers which are currently available, which are CPLEX and Gurobi (Koch et al., 2011; Hvattum, Løkketangen, & Glover, 2012; Meindl & Templ, 2013; Mittelmann, 2014).

We have chosen to use the Gurobi-solver for our problem because AIMMS only uses one core of our two core processor computer when using CPLEX and it uses the power of both processors when choosing Gurobi. This implies that Gurobi computes a result faster than CPLEX will do, the performance in terms of result of the calculation is about the same for both solvers (Koch et al., 2011; Hvattum et al., 2012; Meindl & Templ, 2013; Mittelmann, 2014).

Besides using AIMMS with the Gurobi solver, we also used Microsoft Excel. Excel is not used for any solving calculations and thus not strictly necessary, but it is used for the preprocessing of input data. The necessary preprocessing actions are executed with the help of short pieces of code written in Visual Basic for Applications (VBA). The programming language VBA is included in Excel and is able to automate simple actions. To be able to use the data in Excel, we have written a piece of code in AIMMS which imports the data from Excel and another piece which writes information back to AIMMS. We have chosen to use Excel because it is widely used in industry and also used within NedTrain. Moreover, it has more data processing functions than AIMMS has, which enables us to easily do a number of data preprocessing actions and it is easier to compare multiple runs of AIMMS.

The procedure for one run (which is one set of input parameters) is as follows. First, in Excel the necessary preprocessing steps are executed. Next, the main procedure in AIMMS is started which calls a procedure to read the data from Excel. Subsequent, the model is solved by AIMMS and finally the results are written to Excel. The run times of the model are short, under one minute. This solver is stopped after five minutes, but the optimal solution was always found by then. The solver was stopped in less than 1% of the runs because of exceeding the time limit. All steps are performed on
a 2.5-GHz Intel Core2Duo T9300 processor with 6-MB L2 cache and 4,096MB (2*2GB) memory. All versions of the software can be found in Table 4.1.

Table 4.1. The used software packages with their versions.

<table>
<thead>
<tr>
<th>Software package</th>
<th>Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microsoft Windows</td>
<td>7 Enterprise, Service Pack 1 (32-bit)</td>
</tr>
<tr>
<td>Microsoft Excel</td>
<td>2010, Version 14.0</td>
</tr>
<tr>
<td>AIMMS</td>
<td>3.13, Software Update 3</td>
</tr>
<tr>
<td>Gurobi</td>
<td>5.6</td>
</tr>
</tbody>
</table>

4.2 Network and Trains

In this business case we use the current network of railways in the Netherlands (depicted in Figure D.1) and we restrict us to the trains maintained by NedTrain and owned by the NS, which is the biggest customer. We decided not to take one of the existing train types of the NS, but we defined our own type. This type is an aggregated version of all current trains maintained by NedTrain which are used for national transportation and owned by NS. We think that more insights are created when this aggregated version is used, than to use one of the real train types as an example for all other train types because in our way a real number of trains can be chosen with the right amount of maintenance to be conducted.

The train we model has on average 3.97 railway carriages and a total number of 675 trains travel through the network, so \( N = 675 \). The number of railway carriages per train are determined by summing the total number of railway carriages that are currently maintained by NedTrain, divided by the total number of trains. This number is not used directly, but for the sake of completeness it is provided.

4.3 Maintenance Jobs

The complete description how the maintenance program of NedTrain is structured can be read in Appendix C. The set of job types \( j \in J \), the number of executions per maintenance visit and the duration (in hours and years) for each of the job types are provided in Table 4.2. The numbers are deduced from the most recent production budgets of the current OBs, currently located in Leidschendam, Maastricht, and Onnen. In these budgets, for every train type, the number of executions
per year for every job type is specified. This has been translated to a number of executions per main-
tenance visit. These numbers are recalculated, such that for each job type an aggregated number for
all trains resulted, by taking a weighted average of the numbers per train type. In case the number
of executions per job type of a certain train type was not stable over the time of the year, it was
calculated, whether the number would have been stable.

Next, the duration per job type is calculated. Because taking the same approach as for the
number of executions per maintenance visit per job type gives incorrect results, a different approach
is chosen. First the total duration in hours per job type is calculated over all train types for a year.
This number is then divided by the number trains, next divided by the number of executions of a
job type per maintenance visit per job type, and finally divided by the number of maintenance visits
of our train per year. The numbers in this table are 100% efficient hours and do not include waiting
time or any other bias.

Last, based on the production budgets we also calculated the number of maintenance visits
per year per train. This number is determined by counting for each train type the number of tasks
named “maintenance” per year, which is the regular maintenance and considered to be executed
every maintenance visit because the number of “shunting” tasks were equal to this number plus
the number of EBKs. This number of maintenance visits per year per train type are divided by the
number of that trains type. Next the weighted average over all trains types is calculated which
resulted in 4.13 maintenance visits per year for our train.

4.4 Resources
A complete overview of the set of all resource types and for each type the cost per year and the
maximum utilisation level can be found in Table 4.3. Furthermore we made Figure B.2 on page 65
and B.3 on page 66 in which most of the resources are depicted in an exploded view of a maintenance
facility.

Table 4.3. The set of resources types with the characteristics per resources type.

<table>
<thead>
<tr>
<th>Nb</th>
<th>Resource Type</th>
<th>Cost per year (in euros)</th>
<th>Maximum utilisation level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bogie drop table</td>
<td>20,000</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>Underfloor wheel lathe</td>
<td>180,000</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>Inspection shed</td>
<td>192,000</td>
<td>0.7</td>
</tr>
<tr>
<td>4</td>
<td>Operator regular maintenance</td>
<td>51,672</td>
<td>0.114</td>
</tr>
<tr>
<td>5</td>
<td>Operator failure based maintenance</td>
<td>51,672</td>
<td>0.114</td>
</tr>
<tr>
<td>6</td>
<td>Operator wheel lathe</td>
<td>47,880</td>
<td>0.114</td>
</tr>
<tr>
<td>7</td>
<td>Operator TAE</td>
<td>56,620</td>
<td>0.114</td>
</tr>
<tr>
<td>8</td>
<td>Shunter</td>
<td>47,880</td>
<td>0.114</td>
</tr>
</tbody>
</table>

The cost for the resource types are derived from interviews with NedTrain employees. One of the
interviewees was a project manager, who was involved in the construction of all maintenance facili-
ties built in the past 15 years and thus with an excellent overview of the cost of large resources such
as the cost of an (underfloor) wheel lathe. Furthermore, he gave an indication for the depreciation
period of these resources. For each resource type we calculated the cost per year by dividing the
cost of the type by its depreciation period.

TA controller with insight in the salaries of OB personnel provided us information for the
human resource types. The cost depicted in Table 4.3 consists of three types of cost: the gross
salary, the National Insurance contributions, and the cost for fringe benefits, which are respectively
represent 65.8%, 19.1% and 15.1% of the total cost. The controller indicated that it is not possible to
link the functions of the operators one to one to salaries because operators are divided in different
salary scales based on their qualifications. Therefore, the numbers for regular and failure based
maintenance operators are averages of the different salary scales. Note that the salary scales also depend on other aspects as age and years of experience and that the numbers for each salary scale provided to us is already an average for that scale. For the other three types of operators, the controller indicated that these are often classified in a certain scale. This salary scale is then taken as the scale for all operators of the certain type.

Last in Table 4.3 on the facing page, the maximum utilisation levels are provided. For the non-human resources types the maximum utilisation level is estimated by NedTrain employees at around 0.7 and checked based on the current utilisation of these resource types found in the production schedule of a current maintenance facility. The maximum utilisation level for the human resource types (or employees) is calculated by dividing the total number of effective hours an employee can work per year (1,000 hours) by the total number of hours NedTrain is open in a year (8,760 hours). The total number of effective hours per employee is taken from the production budgets of the OBs. The gross number of hours per employee is 1,872 per year, which equals 1 Full-Time Equivalent (FTE). From this number 872 hours are subtracted for illness, leave (such as holidays, vacation), education, communication, start-up, finishing, breaks, committees, cleaning, and other. The maximum utilisation level for an employee is thus 0.114. It is not possible to set one unit of a human resource type to 8.76 FTE and thereby setting the maximum utilisation level to one because we have chosen to use integer numbers of resources available at facilities. For human resource types of which only a few FTE are necessary, this would mean that at least 8.76 FTE are necessary which leads to an overestimation of the cost for this resource type.

For all job types, it is also determined how many resources of each type are necessary to execute the job type. This is based on a production schedule for one week of a current OB. In this schedule, it is depicted which train types are maintained that week, the maintenance paths that are used, on which specific track (for example inspection shed number 4 or the wheel lathe track) the maintenance is done, which job types have to be executed, and the planned duration for each job type. For the non-human resources it is easy to determine how much resources are necessary per job type because they can either be necessary (1) or not (0); a train can only use one track at a time. For the number of operators this is less trivial. Unfortunately, this information was not provided in the production schedule and therefore these numbers are based on a mix of interviews, intuition, and calculations based on the production schedule and the information about the job types discussed earlier. The number of resources necessary for each job type is depicted in Table 4.4.

<table>
<thead>
<tr>
<th>Job Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular maintenance</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Underfloor wheel lathe</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Intermediate check (A-type)</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measuring work</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Periodic work</td>
<td></td>
<td>1</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changing bogies, planned</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changing set of wheels, planned</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changing other main parts, planned</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repair during maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Shunting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

4.5 Facilities
Currently NedTrain has four OBs in the Netherlands, which are located in Amsterdam (Watergraafsmeer), Leidschendam, Maastricht, and Onnen (see Figure E.1). These OBs are comparable to the
facilities in our research. In addition, NedTrain has two TCs which are small maintenance facilities with a limited number of resources, which are located in Eindhoven and Hengelo. Currently, NedTrain is expanding the number of TCs in the Netherlands with new centres in Den Haag, Nijmegen, Utrecht, and Zwolle (see Figure E.2 for all TCs). The set of current and future OBs and TCs locations forms our initial set of candidate facility locations. The list of all candidate facility locations with the fixed cost per location and the maximum number of maintenance paths per year is provided in Table 4.5.

Table 4.5. The set of candidate facility locations with the characteristics per location.

<table>
<thead>
<tr>
<th>Location</th>
<th>Cost per year (in euros)</th>
<th>Maximum number of maintenance paths per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Den Haag Binckhorst</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Eindhoven</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Hengelo</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Leidschendam</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Maastricht</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Nijmegen</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Onnen</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Utrecht Cartesiusweg</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Watergraafsmeer</td>
<td>800,000</td>
<td>1,286</td>
</tr>
<tr>
<td>Zwolle</td>
<td>800,000</td>
<td>1,286</td>
</tr>
</tbody>
</table>

The fixed location cost are determined in an interview with a NedTrain employee who was involved in the construction of facilities in the past 15 years. Based on this interview a rough estimate is used and divided by the depreciation period, which is 25 years. For all locations in our set, we initially use the same value of €20,000,000 or €800,000 per year for the fixed facility cost.

The number of maintenance paths differ per current maintenance facility dependent on factors such as the size of the maintenance facility. However, upfront the size of a maintenance facility is unknown and thus the maximum number of maintenance paths is fixed for each location. The current number of maintenance paths per week for the current OBs and TCs are provided in Table 4.6. It is chosen to average the weekly number of maintenance paths of the current OBs and recalculate this to a number of paths available per year, which is 1,286 paths per year. Note that the number of paths per year is relatively sensitive to the number of paths per week and that this number is more an indication than a hard number. Therefore it is important to analyse the sensitivity of this input parameter on the optimal solution.

Table 4.6. The maximum number of maintenance paths per week for the current facilities.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Paths per week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eindhoven</td>
<td>9</td>
</tr>
<tr>
<td>Hengelo</td>
<td>2</td>
</tr>
<tr>
<td>Leidschendam</td>
<td>25</td>
</tr>
<tr>
<td>Maastricht</td>
<td>26</td>
</tr>
<tr>
<td>Onnen</td>
<td>23</td>
</tr>
</tbody>
</table>

4.6 End Stations
The end stations are based on the current overnight stay locations for trains. The distribution of trains over these end stations cannot be based on the current number of trains located at each end
station awaiting maintenance because a relative high number of trains are located after service at end stations closely located to facilities. If we would use this distribution, this would bias our green field approach because the number of trains is high at end stations closely located to current facilities. We do not want to bias the analysis by the current situation and we thus have to use a different distribution for the trains awaiting maintenance over the end stations. Therefore we decided to use the number of trains that are stationed at an end station for overnight stay.

For every day in the week it is known how many trains stay overnight at each location. Currently 43 locations in the Netherlands are used, which are depicted on the map in Figure E.3. The number of trains per end station is known for each train type and day of the week. First the number of trains per end stations are summed over all train types. Next, the average per end station is taken over all train stations. This is the actual number of trains located at each end station. However, we want to know the total demand occurring at each end station; not all existing trains overnight at these places, a proportion is in maintenance and stays overnight at these locations. Therefore, we used the proportion of trains at each end station and scaled it in such a way that the total number of trains are equal to the total number of trains that need maintenance, which is 675. The total overview of all end stations, with the fraction of the total number of trains and with the initial number of trains based on a total of 675 is provided in Table F.1.

4.7 Routing Of Trains

In our model we included the transport cost of transporting a train from an end station to a facility and we included a variable by which the model chooses how many trains or maintenance visits are directed to each facility. This approach deviates in two ways from the current way of working of NedTrain because currently NedTrain determines beforehand which train types visit which facility. Moreover, each train always visits the same facility. We differ in approach because we use a green field approach in which we assume no facilities have been located yet. This approach leads to an important difference that distinguish our model from NedTrain’s current situation.

NedTrain is responsible for the execution of maintenance and becomes responsible for the train from the moment the train is delivered at a facility. In order to transport the train to the facility, the NS tries to optimally use the train until the moment of handing it over to NedTrain. This means that the NS uses the train in their service till the location of the facility is reached. By doing this the NS minimises the transport cost (of driving an empty train) to a facility and maximises the availability of the train. If we would implement this in our model, i.e. a transport cost of zero, the optimal solution would be to build one large facility where the sum of fixed and variable cost is the lowest. This, however, could lead to more difficulties for the NS to optimally use the trains. This situation is unwanted because NedTrain is a 100% subsidiary of the NS as explained before which means that the solution of the problem must be the best for the NS group as a whole. The approach that we use is to let trains be transported from an end station where it would normally end to the facility. Moreover, we respect the constraint which also consists in reality: the number of paths to a facility are limited due to the capacity of the railways.

For the transport cost we make use of a matrix which contains the distances rounded to kilometres between 399 positions in the network (all stations). This matrix was found on the internet (Geert, 2014) and was used because NedTrain could not provide such a matrix. Unfortunately, not all locations of candidate facility locations and end stations where included in the database. In case a location was not found in the matrix, the closest station was chosen based on the network information found on the internet (Positions of Locations in the Network, 2014).

Another problem with the matrix is that all distances are direct distances using electrified and non-electrified railways. However, (almost) all trains used by NedTrain are electrified, this means that these trains cannot drive on the non-electrified railways and thus have to take a detour. In Figure D.2 it is indicated which railways are electrified and which are not. Two solutions exist for this problem. One solution is to check for every value in the matrix whether the distance may include a railway which is non-electrified and if so, recalculate the distance without using the non-electrified
railways. A second solution would be to search for all distances in the matrix that use non-electrified railways and calculate a penalty per kilometre of non-electrified railway (for example because the train is towed by a diesel locomotive). Both solutions are hard to implement in our situation because we do not know which railways are used for the calculation of the distances in the matrix, the exact positions of non-electrified railways are unknown, and it would cost a considerable amount of time to recalculate all distances. We accept this flaw and use the current, non-adapted distance matrix.

With this matrix and the cost per kilometre per train type, obtained the NS, we can calculate the cost per kilometre per train. Again the weighted average is taken over all trains types to obtain the cost per kilometre for our train, which is € 1.87 per kilometre, per train. This cost include the infrastructure tax, cleaning, power, the engine driver, and the maintenance for the kilometres that the train drives empty. Because the train has to travel there and back, the cost per kilometre is doubled (see Assumption below) and set to € 3.75 per kilometre per train (deviation due to rounding). Next, the cost are calculated for all distances necessary by multiplying the distance by the cost per kilometre.

**Assumption: The return route is the same as the there route**

When a train is transported to a facility, it follows a certain route. After maintenance, it is assumed that the train is transported back to the end station it came from following the same route because there is no reason to assume another route is taken.

### 4.8 Verification and Validation

Now all input data has been defined for the model, we have to perform a verification check (Section 4.8.1), a general validation check (Section 4.8.2) and an assumption validation (Section 4.8.3) before we can use the model. These checks ensure us that the model provides us with the right results. Verification is checking whether the model performs as it has to. Whereas validation is the check whether the model provides an output that is reasonable with respect to the reality.

#### 4.8.1 Verification

First we performed a number of verification checks by providing infeasible input parameter settings and extreme parameter settings. For the infeasible parameter setting one test was to set the number of maintenance paths in such a way that the total sum of paths available at all facilities was not enough to accept all demand. The model responded that the model was infeasible, as expected. For the extreme parameter setting, we tested the model with a very high and a zero transport cost. With a high transport cost, the model indeed returned the highest number of facilities possible and with zero transport cost the model provided us with random routings to facilities. Also we checked if just enough maintenance paths in total was available, which resulted in all facilities open which were all equally sized.

#### 4.8.2 General Validation

For the validation check less options were available to test the model. In two ways we tested whether the output of the model could also occur in reality. First we checked the number of operators that the model provided as an output with the number of operators that were needed according to the production budgets of the current facilities and the number was about the same. Second, we plotted the facilities and the routings that were selected by the model on a map. The facilities were located on logical places and the routings were as expected.

#### 4.8.3 Assumption Validation

In Chapters 2 and 3 we made two assumptions, which are validated for the NedTrain situation in this section.

- **Demand is stable over time**
  
  As the number, size and location of maintenance facilities is a long term decision, so is the
purchase of trains. Trains are depreciated over 20 years, which means that also these are bought to use for a long term as facilities are depreciated in 25 years. The number of trains remain relatively stable over the years.

- **Price of resources is location independent**
  The current facilities of NedTrain are all located in the Netherlands and thus all human resources are paid the same wage across the country if people have the same qualifications and experience and the work has the same characteristics. Moreover, non-human resources are bought centrally and thus the cost are location independent.

### 4.9 The Optimal Solution

The parameters set in the previous sections are now used to determine the optimal number, size, and location of the facilities. First, we provide Table 4.7 which contains the values for all parameters. Note that we have set $M$ to 1,000. This is based on the total number of regular maintenance operators currently working in OBs as depicted in the production budgets rounded upwards to thousands. The model solved optimally in 13.4 seconds and the solution can be seen in Figure 4.1 on the next page. The optimal number of facilities are three and these locations are located in Den Haag, Binckhorst, Eindhoven, and Zwolle. The sizes of the locations are respectively 45.8%, 20.8%, and 33.5% expressed in a percentage of the total demand of trains (due to rounding the sum exceeds 100%). The total flow of all trains is depicted in Figure 4.1. One can see that the three locations form a triangle in the centre of the country, which looks logical based on the fact that one of the goals is to minimise the transport cost. As minimising the facility cost is part of the objective three facilities is the lowest number possible because of Constraint 3.9 describing the maximum number of maintenance paths. In total there are 2,788 number of maintenance visits a year and each facility can handle at maximum 1,268 maintenance visits. So, it is easy to calculate that at least three facilities are necessary to be able to execute all maintenance visits.

The cost of the (optimal) solution consists of three factors: the fixed facility cost, the cost of all resources, and the transportation cost. The proportion of each cost as part of the whole is respectively 12.0%, 85.1%, and 3.0% (due to rounding the sum exceeds 100%) of the total of €20,078,954.67. As one can see, the resource cost comprise the main part of the cost, while the transportation cost are only a small fraction of the whole. However, these numbers only hold for the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of trains</td>
<td>$N$</td>
<td>675</td>
</tr>
<tr>
<td>Set of job types</td>
<td>$J$</td>
<td>Table 4.2</td>
</tr>
<tr>
<td>Number of executions of job type per maintenance visit</td>
<td>$\chi_j$</td>
<td>Table 4.2</td>
</tr>
<tr>
<td>Expected duration of a job type in years</td>
<td>$\mu_j$</td>
<td>Table 4.2</td>
</tr>
<tr>
<td>Number of maintenance visits per year</td>
<td>$\lambda$</td>
<td>4.13</td>
</tr>
<tr>
<td>Set of resources</td>
<td>$R$</td>
<td>Table 4.3</td>
</tr>
<tr>
<td>Variable facility cost per resource, per year</td>
<td>$c_r^f$</td>
<td>Table 4.3</td>
</tr>
<tr>
<td>The maximum utilisation level per resource</td>
<td>$\beta_r$</td>
<td>Table 4.3</td>
</tr>
<tr>
<td>Number of resource necessary per job type</td>
<td>$z^r_{je}$</td>
<td>Table 4.4</td>
</tr>
<tr>
<td>Set of candidate facility locations</td>
<td>$F$</td>
<td>Table 4.5</td>
</tr>
<tr>
<td>Fixed cost per facility per year</td>
<td>$c_f^c$</td>
<td>€800,000</td>
</tr>
<tr>
<td>Number of maintenance paths per facility</td>
<td>$p_f$</td>
<td>1,268</td>
</tr>
<tr>
<td>Set of end stations</td>
<td>$E$</td>
<td>Table E1</td>
</tr>
<tr>
<td>Number of trains that need maintenance per end station</td>
<td>$N_e$</td>
<td>Table E1</td>
</tr>
<tr>
<td>Transport cost per train per kilometre</td>
<td></td>
<td>€3.75</td>
</tr>
<tr>
<td>A large number</td>
<td>$M$</td>
<td>1,000</td>
</tr>
</tbody>
</table>
Chapter 4. Model Solving

Figure 4.1. The optimal solution map.

parameter setting based on the current values. The current values however are subject to change, so it is interesting to investigate what the behaviour of each cost type is on changes. These sensitivity of these parameters are investigated in the next section.

**Conclusion:** The optimal number of facilities is three. The optimal locations are Den Haag (Binckhorst), Eindhoven, and Zwolle which respectively maintain 45.8%, 20.8%, and 33.5% of the trains.

4.10 Extensions

In this section we introduce the data gathered for the three extensions proposed in Section 2.10. First we provide the data for the transport time penalty in Section 4.10.1, next the data for the EBKs extension is provided in Section 4.10.2 and finally we provide the data for the job classes extension in Section 4.10.3.

4.10.1 Extension I: Penalty for Transport Time

The current transport cost structure is as follows: the distance from an end station to a facility is multiplied by two times the cost per kilometre which is €1.87, so each kilometre distance costs €3.75. Now we add a cost factor for every hour it takes that a train is transported. The cost per hour of transport are €164.07 per hour per railway carriage and are provided by an expert within NedTrain. Because these cost are provided by hour, we have to convert this number to a number per kilometre. The average transport speed per hour is estimated on 70 kilometres per hour by NedTrain experts. This would lead to a time penalty of €2.34 per kilometre, which must also be doubled because of the there and back transportation, which leads to a final cost of €4.69 per distance kilometre per railway carriage. Multiplying this number by the average number of railways carriages per train, which is €3.97, results in a time penalty of €18.59 per kilometre per train, leading to a total cost of €22.54 per kilometre per train.

**Optimal Solution**

For the calculation of the optimal solution, all parameters are set as in Table 4.7 except the transport cost per kilometre. The model solved optimal in 1.9 seconds and the solution is depicted in
Chapter 4. Model Solving

Figure 4.2. The optimal solution map with and without the time penalty extension.

Figure 4.2a on the next page. The solution is exactly the same as the solution for basic parameter settings (Figure 4.2b) in terms of the optimal number, size, and locations of facilities and the routings to the facilities. The total cost of the solution is €23,022,835.11, consisting of 10.4% fixed facility cost, 74.2% resources cost, and 15.4% transportation cost. The resource cost still comprise the main part of the cost, while the transportation cost are now comprise a large fraction of the whole, even larger than the fixed facility cost. Where the ratio transportation cost to fixed facility cost for the basic parameter setting was 4:1, the ratio for the time penalty is 2:3. However, these numbers only hold for the current parameter setting and thus also for this extension a sensitivity analysis is conducted.

Conclusion: The addition of the time penalty does not influence the optimal number, size, and location of the facilities. However, the transport cost comprise a greater part of the total cost than the fixed facility cost.

4.10.2 Extension II: EBK

All data for the jobs (and how many resources are necessary for each type) is gathered from the same sources and calculated in the same way as explained in Sections 4.3 and 4.4. The data can be found in Tables 4.8 and 4.9 (see for the resource types Table 4.3 on page 30). The value for $\lambda_u$ is not mentioned in these tables. We calculated that a train has an expected number of 5.20 EBKs per year, where the expected number of regular maintenance visits are 4.13 per year. The ratio of planned to unplanned maintenance visits is around 4:5 and we saw for some train types two unplanned maintenance visits for every regular maintenance visit. However out of scope of our research, we want to stress that the reason of this high number must be investigated further to make the work in OBs better to plan and control.

The Distribution and Transport of EBKs

Also data for $u_e$ has been gathered. For the time being, as no better data is available at this point, we assume the same distribution of trains over all end stations as we did the planned maintenance visits. This distribution can be found in Table F.1. The cost per kilometre for EBKs is set the same as
for maintenance visits as indicated by the expert of the NS, which is € 3.75. So the same cost matrix is used as introduced in Section 4.7. A penalty cost for transportation of trains that need an EBK could be included in later research.

### Optimal Solution

For the calculation of the optimal solution, all parameters are set as in Tables 4.7 on page 35 and 4.10. The model solved optimal in 22.1 seconds and the solution is depicted in Figure 4.3 on the next page, with the routings for the planned maintenance visits on top in red in Figure 4.3a and the routings for EBK on top in blue in Figure 4.3b. The solution for the extension with EBKs is the same as the solution for basic parameter settings in terms of the optimal number and locations of the facilities. However, the routings to the facilities slightly differ; trains from Arnhem, Nijmegen, Roosendaal, and Utrecht are now directed to another facility. The difference between the routings

<table>
<thead>
<tr>
<th>Job Type</th>
<th>Number of executions per EBK</th>
<th>Duration (in hours)</th>
<th>Duration (in years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underfloor wheel lathe work</td>
<td>0.59</td>
<td>1.95</td>
<td>0.00022</td>
</tr>
<tr>
<td>Intermediate check (A-type)</td>
<td>0.39</td>
<td>0.91</td>
<td>0.00010</td>
</tr>
<tr>
<td>Measuring work</td>
<td>0.39</td>
<td>2.05</td>
<td>0.00023</td>
</tr>
<tr>
<td>Changing bogies, unplanned</td>
<td>0.41</td>
<td>1.65</td>
<td>0.00019</td>
</tr>
<tr>
<td>Changing set of wheels, unplanned</td>
<td>1.02</td>
<td>1.09</td>
<td>0.00012</td>
</tr>
<tr>
<td>Changing other main parts, unplanned</td>
<td>0.43</td>
<td>0.85</td>
<td>0.00010</td>
</tr>
<tr>
<td>Repair during EBK</td>
<td>1.00</td>
<td>2.28</td>
<td>0.00026</td>
</tr>
</tbody>
</table>
| Shunting                  | 1.00                        | 3.77                | 0.00043             

**Table 4.8.** The set of EBK job types with the characteristics per job type.

<table>
<thead>
<tr>
<th>Job Type</th>
<th>Resource type (number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underfloor wheel lathe work</td>
<td>1</td>
</tr>
<tr>
<td>Intermediate check (A-type)</td>
<td>2</td>
</tr>
<tr>
<td>Measuring work</td>
<td>3</td>
</tr>
<tr>
<td>Changing bogies, unplanned</td>
<td>4</td>
</tr>
<tr>
<td>Changing set of wheels, unplanned</td>
<td>5</td>
</tr>
<tr>
<td>Changing other main parts, unplanned</td>
<td>6</td>
</tr>
<tr>
<td>Repair during EBK</td>
<td>7</td>
</tr>
<tr>
<td>Shunting</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table 4.9.** The number of resources necessary for each resource type.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set of EBK job types</td>
<td>U</td>
<td>Table 4.8</td>
</tr>
<tr>
<td>Number of executions of job type per EBK</td>
<td>( \chi_u )</td>
<td>Table 4.8</td>
</tr>
<tr>
<td>Expected duration of an EBK job type in years</td>
<td>( \mu_u )</td>
<td>Table 4.8</td>
</tr>
<tr>
<td>Number of maintenance visits per year</td>
<td>( \lambda_u )</td>
<td>5.20</td>
</tr>
<tr>
<td>Number of resource necessary per EBK job type</td>
<td>( z_{ur} )</td>
<td>Table 4.9</td>
</tr>
<tr>
<td>Number of trains that need an EBK per end station</td>
<td>( u_e )</td>
<td>Table F.1</td>
</tr>
<tr>
<td>Transport cost per train per kilometre for EBK</td>
<td>€</td>
<td>3.75</td>
</tr>
</tbody>
</table>
for the maintenance visits and the EBKs in this extension is only for three end stations: Arnhem, Roosendaal and Utrecht. Where the routings of the maintenance visits are probably determined by the maintenance paths constraint in combination with the transport cost, the routings for EBKs are determined by the resources available and optimally using these in combination with the transport cost. Because the aforementioned three end stations are almost equally close to two facilities, that with the routings of from these end stations the resource utilisation in the facilities is balanced. The total cost of the solution is €27,469,328.71, consisting of 8.7% fixed facility cost, 86.4% resources cost, and 4.8% transportation cost (due to rounding the sum is not 100%). The resource cost still comprise the main part of the cost, while the ratio transportation cost are to fixed facility is now 1:2 instead of 1:4, which is not surprisingly as the number of transports is more than doubled. However, these numbers only hold for the current parameter setting and thus also for this extension a sensitivity analysis is conducted.

Conclusion: The addition of EBKs does not influence the optimal number and location of the facilities. The routings are changed slightly to optimise the resource utilisations and the sizes of the facilities are increased due to the increase work.

4.10.3 Extension III: Job Classes

In Section 3.10.3 we introduced the scientific model for the job classes extension. At this moment there is not enough insight how to divide the job types in classes within NedTrain. Among other things because it is unknown what the influence of the frequency and duration of job types is on each other. For example if a job type is executed twice as often, it is unknown what the duration of the job type will be. Therefore the model with extension is not tested in our research.
Sensitivity Analysis

The optimal number, size, and location (in the following referred to as the optimal solution) has been determined Section 4.9. This is valuable information, but it is more important to know how sensitive this solution is for changes in the input of parameters. The decision to build a new facility is taken for at least 25 years. It is thus preferred to choose a solution which is robust for changes over time. In each of the following sections we investigate the sensitivity of one parameter at a time. All other parameters are set as defined in Table 4.7 on page 35. Note that in the sensitivity analysis the number of executions of each job type, the duration of each job type, and the number of maintenance visits per year are not changed because it is unknown how these three factors influence each other and this is beyond the scope of this research. The following parameters are investigated: the number of trains (Section 5.1), the fixed facility cost (Section 5.2), the transport cost (Section 5.3), the number of maintenance paths (Section 5.4), and the resource cost (Section 5.5). Also for the extensions a sensitivity analysis is performed in Section 5.6.

5.1 Number of Trains

The fleet of the NS is constantly changing due to the overhaul, purchase, sale, and scrapping of trains. Moreover, NedTrain can decide to accept maintenance work for other companies besides the NS. Consequently, the number of trains to be maintained changes over time, which can have an impact on the optimal solution. In this sensitivity analysis we varied the total number of trains. Our starting point is the number of 675 trains which are distributed over the end stations as provided in Table F.1, Appendix F. For each station the number of trains is multiplied by a fraction between 0.50 and 1.50 (respectively between 337.5 and 1012.5 trains in total).

For each percent increase or decrease in the total number of trains, we calculated the optimal solution. This graph is depicted in Figure 5.1. Within a range of 7% decrease and a 38% increase (respectively between 627.8 and 931.5 trains), the number and location of the facilities stays the same. The size of the facilities increases as the number of trains is increased. The number of trains

![Figure 5.1. The influence of the number of trains on the optimal solution.](image-url)
directed to the facility in Den Haag stay relatively stable because the number of trains is limited by the maintenance paths constraint. Furthermore, it can be seen that Eindhoven is the preferred location after Den Haag has been filled because the number of trains going to Zwolle remains relatively stable.

If the decrease in the number of trains is more than 7%, only two facilities are selected, which are Nijmegen and Watergraafsmeer (Amsterdam). The choice for these two facilities is not surprising, as the facilities are located on a central axis in the network. The change in locations is due to the combination of transport cost and the maintenance paths constraint. As the number of trains decreases below 623, the total demand can be handled by two facilities based on the number of maintenance paths available per facility. As the cost per facility are high compared to the transport cost, it is preferred to open less facilities. Watergraafsmeer is preferred above Nijmegen as the trains maintained in Watergraafsmeer remains stable while the total number of trains decreases. This is because Watergraafsmeer is closer located to a number of end stations. However, due to the maintenance paths constraint, it is not possible for Watergraafsmeer to maintain more trains.

**Conclusion:** As the number of trains decreases with more than 7%, two facilities are preferred which are Watergraafsmeer and Nijmegen, with a preference of Watergraafsmeer above Nijmegen. Between a 7% decrease and a 41% increase in the number of trains, three facilities are preferred, which are in order of preference Den Haag, Eindhoven, and Zwolle.

Next, we investigated what the influence on the cost. Therefore we made Figure 5.2, which depicts the percentage increase or decrease of the three types of cost and the total cost against the percentage change in the number of trains. In the figure, twice a sudden and large decrease of the transport cost and an increase of the facility cost occurs, this is due to the fact that at these points an extra facility is necessary because of the maintenance paths constraint. Furthermore, one can see that the resource and transport cost increase relatively slower than the total cost. The facility cost remain stable over time because these cost only change with the change in the number of facilities. What also attracts the attention is that the total cost increases at a slightly lower rate than the increase of the number of trains. This can be due to the fact of economies of scale; as the number of trains increase, resources and facilities can be used better because always integer number of resources and facilities are used.

**Conclusion:** The increase of total cost goes at a lower rate than of the number of trains.

![Figure 5.2. The influence of the number of trains on the cost types.](image-url)
5.2 Fixed Facility Cost

The fixed cost for a new facility is currently set at €20 million. However, this price can vary over time because of regulations, subsidies or cost changes in other factors that influence the fixed facility cost. It is therefore interesting to see what the change in fixed facility cost is on the optimal solution. Note that increasing or decreasing the depreciation period with the same percentage has the same effect as respectively decrease or increasing the fixed facility cost. We analysed the effect for a range between an 50% decrease and a 50% increase of the fixed facility cost. The result is provided in Figure 5.3. This figure shows a clear message: the optimal solution does not change with a change in the fixed facility cost within the defined range. Lowering the fixed facility cost does not outweigh the transportation cost, which is due to the fact that when a new facility is built, also the resources for that facility have to be purchased. The cost for the smallest set of non-human resources to be bought equals around €0.4 million, which is equal to two-third of the total transport cost in the optimal situation. In other words, only if the transport cost drops by more than €0.4 million, it would be interesting to build a new facility, leaving aside the fixed facility cost. As mentioned in Section 4.9 the number of facilities cannot be less than three due to maintenance paths constraint; an increase in the fixed facility cost thus never leads to less facilities. Furthermore, the size remains unchanged because the fixed facility cost does not influence the routing of the trains. The location of the facilities does not change because all facilities are equally expensive. This leads to the following conclusion:

Conclusion: Changing the fixed facility cost between a 50% decrease and an 50% increase, respectively 50% increase and 50% decrease of the depreciation period, has no effect on the optimal solution.

When we focus on the cost changes of the three types of cost, we can conclude that the cost of the resources and the transport do not change by a change of the fixed facility cost, which is confirmed in Figure 5.4 on the next page. Furthermore it can be seen that the total cost only change slightly by changing the fixed facility cost. With a change of the fixed facility cost of 50%, the total cost changes in the same direction with only 5.98%. This is due to the fact that the fixed facility cost constitute only 12% of the total cost.

Conclusion: A change in the fixed facility cost of 50%, leads to a change in the total cost of 6% in the same direction. The resource and transport cost are insensitive for changes in the fixed facility cost.
5.3 Transport Cost

In this analysis we varied the transport cost per kilometre between € 0.01 and € 7.50 per kilometre, so between a 99.7% increase and a 100% increase, which is a wide range. In the basic setting this was € 3.75 per kilometre. In Figure 5.5, the influence of the transport cost per kilometre is depicted. The graph makes clear that there is no influence of the transportation cost for the investigated range. Logically, the number of facilities will never be lower than three due to the maintenance paths constraint. Also this analysis confirms the findings in the previous analysis: the increase in transport cost does not outweigh the cost of the fixed facility cost due to the large difference between two cost types. Recall that in the optimal solution the fixed facility cost are around four times as high as the transport cost.

**Conclusion:** There is no influence of the transport cost per kilometre on the optimal solution for a range between a 99.7% decrease and a 100% increase in the transport cost.

Again we made a cost graph, see Figure 5.6. As one can see the fixed facility and the resource cost remain stable because there is not change in the demand or in the number of facilities. The growth in absolute numbers of the total cost and the transport cost is the same, but the percentage change
is different. The total cost increases with 2.96% when the transport cost per kilometre are increased by 100%, making the change in total cost marginal and thus the influence of the transport cost very small. This can be explained by the fact that the transport cost only comprise a small fraction of the total cost.

**Conclusion:** Changes in the transport cost per kilometre have a very small effect on the total cost.

### 5.4 Number of Maintenance Paths

The total number of maintenance paths per year is set to 1,286 per facility and is the same for all facilities. We varied the number of maintenance paths from 730 to 2,800 in this analysis. The lower bound is set to 730 maintenance paths per year which is 14 paths per week. Whereas 2,800 is chosen such that it is the first multiply of hundred which allows the model to direct all trains to one facility.

In the following we discuss the findings we can retrieve from Figure 5.7, which depicts the influence of the maximum number of maintenance paths per facility.

The first finding is that the number of maintenance paths are very restricting. The changes in the optimal number of facilities is directly caused by the maximum number of maintenance paths. The optimal number of facilities increases at an 21.8% decrease in the number of maintenance paths per facility.

**Figure 5.7.** The influence of the number of maintenance paths per facility on the optimal solution.
Chapter 5. Sensitivity Analysis

(to 929 paths per year, 17.9 per week). It decreases to respectively two and one with a 8.5% and a 117.0% increase in the number of paths (1,395 and 2,790 paths per year, 26.7 and 53.5 per week). Note that all maintenance paths are per facility.

Most important in the figure is the change in optimal locations for facilities. A decrease in the number of maintenance paths leads to an optimal number of four facilities, where an extra location has to be added to the previous three optimal locations, except for some exceptions for some small series of maintenance paths. So the existing three locations can still be used. However, when the number of maintenance paths is increased, none of the locations which where optimal to use for at maximum 1,394 maintenance paths per year are optimal any more. It is therefore very important to make a good estimation of the number of maintenance paths available for each of the candidate facility locations as this heavily influences the optimal location.

Furthermore, we noticed that the optimal size for the facilities remains stable to a certain degree for an increase or decrease of the number of maintenance paths. However, the lower the number of maintenance paths is, the more sensitive the optimal size of the facilities becomes because the maintenance paths are more restricting.

**Conclusion:** The optimal number and locations for the facilities heavily depends on the number of maintenance paths available for each facility. The size of the facilities is relatively stable, but becomes more sensitive when less maintenance paths per facility are available.

If we investigate the cost changes, provided in Figure 5.8, we see that all cost types react to changes in the number of maintenance paths, which can easily be explained by the fact that a difference in facilities affect directly the fixed facility cost and the resource cost. In general adding an extra facility due to the maintenance paths constraint increases the total cost, but at the same time the distances to each facility are shorter, decreasing the transport cost. In this graph also the effect of economies of scale is visible. As the number of maintenance paths increase, and thus the number of facilities decrease, the size of each facility increases and thereby less resources are necessary in total. For example, a wheel lathe is necessary in each location because all trains have to undergo the same jobs. This resource is however not often used to its full capacity. In other words, the total sum of wheel lathes decreases if less facilities are used.

The total cost remains relatively stable as the number of maintenance paths change. When the number of maintenance paths decrease, the total cost becomes more sensitive to changes. When the number of facilities change, the change in total cost is around 4%. Based on the current situation,
the total cost can be decreased by 3.4% if the number of maintenance paths are increased with 8.5% to 1,395 paths per year or 26.75 per week. The disadvantage of this increase in maintenance paths is that the optimal solution changes drastically as discussed.

**Conclusion:** The total cost are relatively insensitive for changes in the maximum number of maintenance paths per facility per year unless the number of facilities changes. Then the total cost changes with around 4% due to a relatively large change in the facility and transport cost, while the resources cost changes relatively stable.

### 5.5 Resource Cost

Last, we analysed the resource cost which we split in human and non-human resources. We made this division because the human resources because these are better utilised than the non-human resources. The reason that we varied the cost for these resources is that in the sensitivity analysis of the fixed facility cost, we discovered that the number of facilities was heavily dependent on the non-human resource cost, i.e. the cost for non-human resources when building an extra facility is €0.4 million. Lowering the non-human resource cost may lead to a change in the optimal solution.

First we changed the non-human resource cost with a percentage between 50% and 150%. The result can be seen in Figure 5.9. The non-human resource cost has no effect on the optimal solution because the increase in cost is the same for all facilities and three is lowest number possible due to the maintenance paths constraint. Also a decrease of non-human resource cost has no influence on the optimal solution. The reason is that besides the non-human resource cost of €0.4 million, also an investment of €0.8 million for the fixed facility cost have to be made. As explained earlier, the total transport cost are only €0.6 million. So the total sum of fixed facility and non-human resource cost, does not outweigh the decrease in transport cost that can be obtained. Only in the case of a simultaneous extreme decrease in fixed facility and resource cost, it would be possible that extra facilities outweigh the transport cost.

**Conclusion:** The non-human resource cost have no detectable influence the optimal solution.

If we look at the cost changes in Figure 5.10 on the next page, we see a similar graph as with the fixed facility cost; facility and transport cost remain the same. Total cost decrease with the same absolute amount as the resource cost, but as a percentage less steep. Still, if the cost of fixed resources are decreased with 50%, the total cost only decrease by 5.8%.

![Figure 5.9. The influence of the non-human resource cost on the optimal solution.](image-url)
Chapter 5. Sensitivity Analysis

Conclusion: Changing the fixed resource cost between a 50% decrease and an 50% increase, leads to respectively a relatively small decrease and increase of the total cost. The resource and transport cost are insensitive for changes in the fixed facility cost.

Note: The same analysis has been conducted for the human resources. The results for this resources are exactly the same as for the fixed resources and thus results are not discussed. The interested reader can see the result in Figures G.1 and G.2. As expected the total cost is much more sensitive to changes in the human resources because it comprises a large part in the total cost (85.1% for the current parameter setting).

5.6 Extensions

Also for each of the extensions proposed in Section 2.10 a sensitivity analysis is executed. In this section we refer to the basic setting as the parameter setting we used to test the initial model as done in Section 4.9. First, we discuss the sensitivity analysis for the transport time penalty in Section 4.10.1 and next we provide the analysis for the EBKs extension is provided in Section 4.10.2.

5.6.1 Extension I: Penalty for Transport Time

The transport cost per kilometre are increase from €3.75 per kilometre to €22.34 per kilometre due to the time penalty for transport, in the following denoted as time penalty. We performed all sensitivity analyses performed for the basic setting again for this extension with the same ranges and all other parameters set as depicted in Table 4.7. We only discuss the differences in detail in this section. Therefore, the influence of changes in the resource cost are not discussed; the optimal solution does not change due to changes in the (non-)human resource cost.

Number of Trains

First the number of trains is varied, which results in Figure 5.11 on the next page. If the number of trains is decreased, the graph for the time penalty extension is comparable to the basic setting (See Figure 5.1 on page 40). However, if the number of trains is increased with 16.8% to 803.3 trains, the optimal solution changes to four facilities, where Utrecht and Maastricht are selected instead of Eindhoven. As a consequence also the size of the other facilities changes considerably. In comparison, for the basic setting, the optimal number of facilities changed after an increase of 38% to 931.5 trains. Due to the increase in trains also the absolute transport cost increase. With the time penalty, it is not the maintenance paths constraint causing more facilities to be opened, but the transport cost itself. This is also visible in Figure 5.12. The transport cost are higher than the fixed facility cost and at clear points in graph an increase in the number of facilities outweighs the
Current Number of trains

<table>
<thead>
<tr>
<th>Number of trains</th>
<th>Watergraafsmeer</th>
<th>Hengelo</th>
<th>Onnen</th>
<th>Utrecht</th>
<th>Leidschendam</th>
<th>Maasbracht</th>
<th>Zwolle</th>
<th>Nijmegen</th>
</tr>
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<td>400</td>
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<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 5.11. The influence of the number of trains on the optimal solution for the time penalty extension.

\[
\text{Number of trains (100\% = 675)}
\]

<table>
<thead>
<tr>
<th>Number of trains</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
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<td>Cost</td>
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<td>(\times 10^6)</td>
<td>(\times 10^6)</td>
<td>(\times 10^6)</td>
<td>(\times 10^6)</td>
<td>(\times 10^6)</td>
<td>(\times 10^6)</td>
<td>(\times 10^6)</td>
<td>(\times 10^6)</td>
<td>(\times 10^6)</td>
</tr>
<tr>
<td>€0</td>
<td>€10</td>
<td>€20</td>
<td>€30</td>
<td>€40</td>
<td>€50</td>
<td>€60</td>
<td>€70</td>
<td>€80</td>
<td>€90</td>
<td>€100</td>
<td>€110</td>
</tr>
</tbody>
</table>

\[
\text{Figure 5.12. The influence of the number of trains on the cost types for the time penalty extension.}
\]

increase in transport cost. Finally, we can see that the total cost increase at a relatively stable rate, which can be explained by the fact that extra facilities are now added due to optimality and not due to the maintenance paths constraint.

**Conclusion:** The optimal number of facilities increases at a lower number of trains due to the time penalty. Moreover, the transport cost have a stronger influence on the optimal solution.

**Fixed Facility Cost**

Second, the fixed facility cost are changed, resulting in Figure 5.13 on the next page. Where in the basic setting the optimal solution did not change because of a decrease in the fixed facility cost, here the optimal number of facilities increases with one if the fixed facility cost are decreased by 31.5% to an annual amount of €13.4 million against the current €20 million. As the optimal solution is now more sensitive to changes in the fixed facility cost, these cost have to be determined in more detail because at this moment they are roughly estimated. The graph of the cost types is depicted in Figure G.3 and is not discussed in further detail because it provides no new information.
Chapter 5. Sensitivity Analysis

Conclusion: The optimal solution is more sensitive to a decrease in the fixed facility cost than in the basic setting; at a decrease of 31.5% of the cost, another facility is added.

Transport Cost

Third, the transport cost are changed. Because a 100% would now lead to a larger absolute change, the transport cost are changed by 50%. This results in Figure 5.14. Note that the transport cost now consist of the time penalty part and the transport cost per kilometre, where the time penalty part is also dependent on the average transport speed. When the current transport cost factor is increased by 29.8% a four facilities is optimal instead of three facilities. In absolute terms, this is an increase of € 6.65 per kilometre. As one can see, such an increase is unlike to occur from the transport cost by itself. However, if the average transport speed drops from 70 kilometre per hour to below 52 kilometre per hour, the same cost increase happens. This means that it must be investigated further what the exact transport speed is because the numbers are now estimated by experts instead of calculated. The graph of the cost types is depicted in Figure G.4 and is not discussed in further detail because it provides no new information.

Figure 5.13. The influence of the fixed facility cost per facility in million euros on the optimal solution for the time penalty extension.

Figure 5.14. The influence of the transport cost per kilometre on the optimal solution for the time penalty extension.
**Conclusion:** The optimal solution is not likely to change due to changes in the transport cost per kilometre. However, the average transport speed component in the time penalty has to be investigated in more detail as this can have an impact on the optimal solution.

**Number of Maintenance Paths**

Last, the number of maintenance paths are changed, resulting in Figure 5.15. At first sight the new graph that depicts the influence of the number of maintenance paths looks the same as the graph for the basic setting. However, at closer inspection one can see that major changes in the size or number of facilities now occur at different number of maintenance paths. In general, the change in the optimal number of locations is no longer due to the maintenance path constraint, but due to the sum of all transport cost, the decrease in total transport cost outweighs opening an extra facility. If we look at the cost, depicted in Figure 5.16, it can be seen that the total cost slowly decrease as the number of maintenance paths increase. This is logical because less facilities can be selected and thus the total fixed facility decrease each time a facility less is selected, but the transport cost increase because on average the transport distance will be greater till the facility. Note that for the basic settings we remarked that an increase in the number of maintenance paths with 8.5% to 1,395

![Figure 5.15](image-url)  
*Figure 5.15. The influence of the number of maintenance paths per facility on the optimal solution for the time penalty extension.*

![Figure 5.16](image-url)  
*Figure 5.16. The influence of the number of maintenance paths per facility on the cost types for the time penalty extension.*
paths per year, or 26.75 per week, would lead to a the total cost decrease of 3.4%. In the new situation the number of maintenance paths has to be increased with 17.4% to decrease the number of facilities. However, this now lead to a cost decrease of only 0.2% because the maintenance paths are no longer crucial in the determination of the number of facilities.

**Conclusion:** The constraint on the number of maintenance paths still influences the number of facilities to be selected, but less sensitive as before. The cost decrease to be obtained with an increase in maintenance paths is now very marginal.

### 5.6.2 Extension II: EBK

For the EBK extension, we performed all sensitivity analyses as we performed for the basic setting with the same ranges and all parameters set as depicted in Tables 4.7 and 4.10. We only discuss the differences in detail in this section. Therefore, the influence of changes in the transport cost, the fixed facility cost, and the (non-)human resource cost are not discussed; the optimal solution stays the same for changes in these parameters within the set ranges which were respectively 99% to 100%, -50% to 50%, and -50% to 50%.

#### Number of Trains

First the number of trains is varied, which results in Figure 5.17. Overall the graph has similarities with the graph for the basic setting which can be found in Figure 5.1. The optimal solution is not stable for changes in the number of trains. Note that the optimal number of facilities is the same as for the basic setting, and is dependent on the number of maintenance paths available, the increase in transport cost is not enough to make opening extra facilities attractive. Of course, the size of facilities differs due to the varying demand (number of trains), but also the optimal locations for the facilities is less stable for changes in the number of trains. However, the same sets of facilities come back several times. This would indicate that the difference between the optimal solution and the sub-optimal solution in terms of different locations is probably not very large. I.e. if a set of facilities is finally chosen and the number of trains changes to a number for which the optimal locations are different than the chosen set, the difference in cost between the chosen solution and the optimal solution is probably not very large. Still this is an expectation and we want to stress that it is important when making a selection of locations to investigate what the probability is for changes in the total number of trains and what the impact would be on the cost. The graph of the

![Figure 5.17. The influence of the number of trains on the optimal solution for the EBK extension.](image-url)
cost types is depicted in Figure G.5 and is not discussed in further detail because it provides no new information.

**Conclusion:** The optimal number of locations, when EBKs are added, is dependent on the number of trains due to the maintenance constraint. The optimal locations for facilities is quite dependent on the number of trains; in selecting the locations, research must be conducted about the probabilities of changes in the number of trains.

**Number of Maintenance Paths**

Second, the number of maintenance paths is varied, which results in Figure 5.18. The conspicuous difference with Figure 5.7 is that Watergraafsmeer en Nijmegen are the optimal locations for a much smaller range of maintenance paths. Furthermore, interesting to see is that if the sizes of the facilities remain the same for large ranges. If we look at the sizes of the facilities, the sizes remain relatively stable for the range from around 1,000 to 2,789 maintenance paths per facility, although the number of maintenance paths is decreasing. When the number of paths decreases, less planned maintenance visits can be routed to a facility, but this decrease is counterbalanced with EBKs in order to optimally use the resources, leading to a stable size of a facility. Also interesting is that the optimal locations for the facilities are less stable for changes in the number of maintenance paths. One has to investigate what the cost difference is between the optimal solution and solutions with the use of other locations which are optimal for different number of maintenance paths. For example if Den Haag, Eindhoven, and Zwolle are selected, what is then the cost difference between this solution and the optimal solution for the range between 1,290 to 1,310 maintenance paths per facility. Still, the number of maintenance paths determines the optimal number of locations because every switch in the number of locations is directly caused by a change in the number of maintenance paths. This is also confirmed in Figure 5.19 on the next page, where small sudden changes are visible in the total cost line if the number of locations changes.

![Figure 5.18. The influence of the number of maintenance paths per facility on the optimal solution for the EBK extension.](image)
Conclusion: The number of maintenance paths is crucial for the optimal number of locations and this on its turn influences the optimal locations. For an optimal number of locations, the sizes of locations remain constant; the decrease in maintenance paths is counterbalanced by EBKs.

Figure 5.19. The influence of the number of maintenance paths per facility on the cost types for the EBK extension.
Conclusions, Recommendations, and Feedback

In this final chapter we provide an answer on the research assignment as stated in Section 1.3 by drawing the most important conclusions and recommendations in Section 6.1. Finally we conclude with Section 6.2 in which we describe how we would improve our model in further research, i.e. what changes we would make in the conceptualisation phase.

6.1 Conclusions and Recommendations

During our research the main question was what the optimal number, size, and location of facilities would be under changing input parameters. Therefore, we built a model and tested it with real data. Based on the data we performed a number of sensitivity analyses. The most important findings and insights are provided in this section per model and per input parameter changed. Note: if there is a change in the number of facilities, as a consequence the size and locations of the optimal solution change. As this is trivial, it is not mentioned below in case of changes in the optimal number of facilities.

Model Performance

The model used in this research proves to be a good model to create the first insights in the large facility location research for train maintenance. It takes into account the most important factors and the results show to which factors extra attention have to be paid and which factors are of less influence. Moreover, the runtime of the model is very short, under the minute, which makes it very practical to calculate many different parameter settings. Although the model has no direct stochastic parameters, it does take into account stochasticity by a parameter which creates slack for operational variability.

The two extensions (the time penalty and the EBKs) added, provide more and other insights in changes on input parameters on the optimal solution. Because both extensions are modelled in a very similar way as the original model, it is justified to compare the results of the basic model to the results of the model with extensions. Note that the time penalty extension could have been modelled in other ways, which is discussed later on. Nevertheless, we are confident that the extension modelled in this way also leads to a model that includes the aimed effect in a correct way as it penalises the time trains cannot be use in service.

Conclusion: The basic model is very useful in creating first insights in the problem on hand. The extensions show that influences of the input parameters on the optimal solution change and it is recommended to include both extensions in future models as they make the model more complete.

Number of Trains

The number of trains has an influence on the optimal solution. However, it is not the number of trains itself which influence the optimal solution, but other factors such as the number of maintenance paths. As the number of trains increases while the number of maintenance paths per facility remains constant, more facilities are necessary to handle all maintenance visits. For the situation under the two extensions holds the same conclusion.

Conclusion: The number of trains influences the optimal solution as a consequence of other restricting factors.
Fixed Facility Cost
The fixed facility cost directly influences the optimal solution: less facilities means a lower total cost. When the total number of maintenance paths is such that the number of facilities can be lowered, the number of facilities is lowered due to the fixed facility cost. Changes in the fixed facility cost have no detectable influence on the optimal solution for the basic setting and the extension with EBKs. However, with the time penalty extension, the optimal solution becomes sensitive, in terms of the number of facilities, for a decrease in the fixed facility cost. Although a decrease of 31.5% in the fixed facility cost seems large, one has to keep in mind that half of the fixed facility cost are cost for infrastructure. If infrastructure is (partially) available, the fixed facility cost can be decreased with a large percentage, which might influence the optimal solution.

**Conclusion:** The fixed facility cost strongly influences the optimal solution, the less facilities, the better. Changes in the fixed facility cost only influence the optimal solution if the time penalty extension is taken into account. Because this cost parameter is now roughly estimated, it is recommended to investigate the cost in more detail.

Transport Cost
It is trivial that the transport cost influences the optimal location of the facilities as the total transport cost are minimised. Note that it is also the only factor that influences the locations as all other parameters for the facilities are equal for all locations. However, for the basic setting, the transport cost comprises a very small part of the total cost. As the EBKs are added, the part roughly doubles as the ratio planned maintenance visit to EBK is about 4:5, still the transport cost does not influence the optimal number of facilities. When the time penalty is added to the model, the solution becomes more sensitive to changes in the transport cost. The number of maintenance paths is no longer the only factor that influences the number of facilities.

**Conclusion:** The transport cost does not influence the optimal solution for the basic setting and the EBK setting, but the number of facilities becomes sensitive to changes in the transport cost if the time penalty extension is added.

Maintenance Paths
The influence of the number of maintenance paths per facility is crucial for the optimal number of facilities for the basic setting and the EBK extension. The number of maintenance paths provides a minimum for the number of facilities as all trains must be maintained. With the time penalty extension it still provides a lower bound. Although, other factors also influence the solution also, i.e. the transport cost causes a higher number of facilities than is necessary based on the number of maintenance paths.

**Conclusion:** The number of maintenance paths has a large influence on the optimal solution as it provides a lower bound for the optimal number of facilities. The time penalty extension weakens the effect, but it is still recommended to investigate the real number of maintenance paths available at each facility.

Resource Cost
The resource cost itself directly influences the optimal solution: the less resources, the lower the total cost. Moreover, resources are used as optimal as possible. Once a resource has to be located to a facility, it is better to route trains to this facility than to place another resource of the same type at a different facility. Besides, changes in the resource cost never led to a change in the optimal solution for all models.

**Conclusion:** The resource cost only influences the optimal size of a facility, in terms that resources are used as optimal as possible. Changes in the resource cost, the human as well as the non-human resource cost, never influence the optimal solution.
6.2 Feedback
Throughout our research we followed the operations research process as described by Sagasti & Mitroff (1973). In this last section we provide a reflection on our conceptualisation phase based on the insights gathered by performing the sensitivity analyses. Sagasti & Mitroff (1973) have named this reflection step “feedback in a wider sense”. This feedback can help future researchers with their work to improve the model. We provide feedback on the basic model in Section 6.2.1 and on the extensions in Section 6.2.2. Finally we conclude this chapter with a discussion about the applicability of the current model for countries and industries in Section 6.2.3.

6.2.1 Basic Setting
Fixed Facility Cost
In our basic model we included one parameter which comprised all fixed facility cost, excluding the overhead personnel. First we would advice to better investigate which costs are included in the fixed facility cost and which of them are (partial) dependent on the size of the facility because now we set the fixed facility cost to €20 million, while NedTrain recently built four TCs (small facility with only one inspection shed) for €2.5 million each. We can imagine that both depend (partially) on the size of a facility, e.g. 50 operators need a smaller restaurant, changing and washing facility than 200 operators. Second, we also advice to include the cost for overhead personnel in the model as this is not proportional to the number of operators although it is related to the size of the facility. This would lead to two parameters: one for fixed facility cost and one for facility cost dependent on the size, but not directly related to the number of resources in a facility. The expectation is that smaller facilities become less costly and as a consequence the optimal number and locations of facilities may change.

Routing of Trains
Trains are routed from end stations to facilities. The current distance matrix has a flaw in terms of the use of non-electrified railways. A new distance matrix has to be made which takes this into account. There is a chance that using this new matrix leads to different optimal locations. Furthermore, the model currently determines the number of trains at each end stations that is routed to a facility.

One could argue that it would have been more logical to route a number of maintenance visits as this is the smallest unity possible because each trains makes 4.13 maintenance visits per year. The implication for the model is that the $x_{ef}$ has to be defined as the number of maintenance visits from an end station to a facility. The $\lambda$ should be removed at all current places in the model and added at the right side of Constraint 3.8. There is no effect on the optimal solution because the number of trains routed is a continuous variable.

Train Types
We used only one type of trains. Extending the model with train types does not lead to a different solution than the solutions found here because the train type used is an aggregation over all train types. Only when one is interested in which train types are routed to which facilities or when one want to influence the train types that could be maintained at a facility, it makes sense to include different train types. Note that it is also interesting to model train types if one decides to model expertise in maintaining specific train types, influencing the duration of job types or the number of resources necessary. The model then assesses whether an decrease in the number of resources available (due to the expertise) compensates the increase in transport cost.

Inventory
The inventory is not included in the current research. However, inventory can influence the cost of a facility and the availability of spare parts can influence the maintenance process and the availability of trains. It should be investigated how the inventory should be included: integrated with the current model and thus a simultaneous determination or a subsequent determination of facilities and inventory. After that an analysis must be performed what the influences is on the optimal
solution. As known from theory, having inventory at two locations is more costly than placing it at one location. So, when inventory is included in the model this may influence the optimal solution in the way that a lower number of locations is preferred or that more central locations are preferred (when a central warehouse is used).

6.2.2 Extensions

Penalty for Transport Time

In the contracts between NedTrain and the NS penalties are included if the availability of trains drops below certain levels. In our research we did not include this in the basic model, but in our first extension we did an attempt to include this by adding a penalty for the transport time. If one wants to add a hard constraint on the availability (for example 92% of the trains must be available), one also has to consider whether one wants to include variability and in which way. The current parameter $\beta_r$ may have to be replaced by a structure where the size of facility is taken into account; i.e. within a large facility one can better deal with the variability of processes because of economies of scale and thus resources might have a higher maximum utilisation level.

EBKs

The current approach used for EBKs is very similar to the approach used for planned maintenance. However, two aspects could be improved. First, it is now chosen to route trains that need an EBK from end stations and to use the same distribution of trains over end stations as is done for planned maintenance visits. However, this might not be correct because there is also a probability that a train breaks down at any point in the network. Therefore it should be investigated what a better way is to model the “demand” that occurs when an EBK is needed, although it could be useful to continue with the end stations approach. Second, maintenance paths are used to limit the number of planned maintenance visits. At this moment there is no limit on the number of EBKs a facility can accept per year based on the available capacity on the railways. As there are more EBKs than planned maintenance visits, it has to be investigated whether there should be included a limit in the model on the number of EBKs to be routed to a facility.

6.2.3 Applicability to Other Countries and Industries

The current research is conducted at NedTrain, which mainly operates in the Netherlands. The main passenger transport carrier, the NS, strives to optimise the trip of the passenger, which means to let the passenger have as less changeovers as possible. The result is that trains drive across the country. We think that the model also works for countries, for example France, where the trains drive from one city to another and back. However, the applicability of our model to the networks in these countries should be investigated in more detail.

Moreover, it should be investigated whether the model could be used in a different industry. Now it is focussed on train maintenance. However, it might be that the model can also used for aeroplane maintenance as this industry has the same characteristics as the train maintenance: expensive equipment and thus high service level demand, demand can only occur at certain points, there is a limited number of paths to an airport available, specialised and expensive resources are necessary to conduct maintenance, and facilities can only be built close to airports.
References


## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AIMMS</td>
<td>Advanced Interactive Multidimensional Modeling System</td>
</tr>
<tr>
<td>DAO</td>
<td>Defect Based Maintenance (Dutch: DefectAfhankelijk Onderhoud)</td>
</tr>
<tr>
<td>EBK</td>
<td>Extra Entry (Dutch: Extra BinnenKomst)</td>
</tr>
<tr>
<td>FTE</td>
<td>Full-Time Equivalent</td>
</tr>
<tr>
<td>G.O.I.D.S.</td>
<td>No Maintenance In Rush Hour (Dutch: Geen Onderhoud In De Spits, G.O.I.D.S.)</td>
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<td>GAO</td>
<td>Use Based Maintenance (Dutch: GebruiksAfhankelijk Onderhoud)</td>
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<td>IV-list</td>
<td>List of contents (Dutch: Inventarisatielijst)</td>
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<td>KCO</td>
<td>Short Cyclic Maintenance (Dutch: Kort Cyclistisch Onderhoud)</td>
</tr>
<tr>
<td>LCO</td>
<td>Long Cyclic Maintenance (Dutch: Lang Cyclistisch Onderhoud)</td>
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<tr>
<td>LRU</td>
<td>Line-Replaceable Unit</td>
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<td>MIP</td>
<td>Mixed Integer Programming</td>
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<tr>
<td>MSI</td>
<td>Maintenance Specific Item</td>
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<tr>
<td>MTE</td>
<td>Material Technical Requirement (Dutch: Materiaal Technische Eis)</td>
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<tr>
<td>NS</td>
<td>Dutch Railways (Dutch: Nederlandse Spoorwegen)</td>
</tr>
<tr>
<td>OB</td>
<td>Maintenance Depot (Dutch: OnderhoudsBedrijf)</td>
</tr>
<tr>
<td>SB</td>
<td>Service Company (Dutch: ServiceBedrijf)</td>
</tr>
<tr>
<td>STG</td>
<td>System Technical Limit (Dutch: Systeem Technische Grens)</td>
</tr>
<tr>
<td>TAO</td>
<td>Condition Based Maintenance (Dutch: ToestandsAfhankelijk Onderhoud)</td>
</tr>
<tr>
<td>TC</td>
<td>Technical Centre (Dutch: Technisch Centrum)</td>
</tr>
<tr>
<td>VBA</td>
<td>Visual Basic for Applications</td>
</tr>
<tr>
<td>VIRM</td>
<td>Extended InterRegio Equipment (Dutch: Verlengd InterRegio Materieel)</td>
</tr>
</tbody>
</table>
List of Definitions

(underfloor) wheel lathe
a tool with which the wheels of a train can be ground

bogie
a bogie is the set of wheels assembled in a frame, located at the end of a carriage, which provides the train flexibility in making curves

end station
position in the network from which trains can depart for maintenance visits

facility
a building located along a railway in which maintenance is conducted

inspection shed
a railway such that operator can inspect and conduct maintenance from under the train

job
a maintenance operation

line
a railway that connects two geographical positions with each other

location
a geographic place in the network

maintenance
work that is conducted to ensure trains remain operational

maintenance visit
a single ride there and back to a facility

network
a number of lines which are connected with each other

resource
a human or material that is necessary for the maintenance process, but which is not consumed in the maintenance process

train
a number of railway carriages that are able to transport people
List of Parameters and Variables

In this Appendix an alphabetical list is provided of all parameters and variables used in this thesis.

- $\beta_r$ = the maximum utilisation level for resource $r \in R$;
- $c^f$ = the fixed facility cost per year for facility $f \in F$;
- $c^e$ = the cost of transporting a train from end station $e \in E$ to facility $f \in F$ and back;
- $c^u$ = the cost of transporting a train from end station $e \in E$ to facility $f \in F$ and back for an EBK;
- $c^r$ = the resource cost per year per unit of resource type $r \in R$;
- $E$ = the set of end stations;
- $F$ = the set of candidate facility locations;
- $J$ = the set of job types;
- $\lambda$ = the number of maintenance visits per train per year;
- $\lambda_s$ = the number of maintenance visits per train per year for class $s \in S$;
- $\lambda_u$ = the number of EBKs per train per year;
- $M$ = a large number;
- $\mu_j$ = the expected duration for the execution of job type $j \in J$ in years;
- $\mu_u$ = the expected duration for the execution of EBK job type $u \in U$ in years;
- $N : = \text{the average number of trains at end station } e \in E \text{ at the end of a day};$
- $N_0 : = N \cup 0;$
- $N_e$ = the number of trains ending at end station $e \in E$;
- $p_f$ = the number of maintenance paths available to access facility $f \in F$ per year;
- $R$ = the set of resource types;
- $S$ = the set of job classes;
- $U$ = the set of EBK job types;
- $u_e$ = the number of trains that need EBK that depart from end station $e \in E$;
- $u_e f$ = the number of trains located at end station $e \in E$ assigned to facility $f \in F$ for EBKs;
- $w_{js}$ = \begin{align*}
1 & \text{ if job } j \in J \text{ belongs to class } s \in S; \\
0 & \text{ otherwise};
\end{align*}
- $x_e f$ = the number of trains located at end station $e \in E$ assigned to facility $f \in F$ for maintenance;
- $x_e f s$ = the number of trains located at end station $e \in E$ assigned to facility $f \in F$ for maintenance of class $s$;
- $\chi_j$ = the number of times that job type $j \in J$ has to be executed per maintenance visit;
- $\chi_u$ = the number of times that EBK job type $u \in U$ has to be executed per EBK;
- $y_f$ = \begin{align*}
1 & \text{ if facility } f \in F \text{ is opened}; \\
0 & \text{ if facility } f \in F \text{ is closed};
\end{align*}
- $z^a_{fr}$ = the number of resources of type $r \in R$ available at facility $f \in F$;
- $z^n_{fr}$ = the number of resources of type $r \in R$ necessary for job type $j \in J$;
- $z^n_{ur}$ = the number of resources of type $r \in R$ necessary for EBK job type $u \in U$. 
An Exploded View on a Maintenance Facility

The exploded views can be found on the next three pages.
Figure B.1. An exploded view on a maintenance facility (Copyright: Project development HSA OB Watergraafsmeer).
Figure B.2. An exploded view on a maintenance facility (Copyright: project development HSA OB Watergraafsmeer).
Figure B.3. An exploded view on a maintenance facility (Copyright: project development HSA OB Watergraafsmeer).
The Structure of NedTrain’s Maintenance Program

A train consists of many parts ranging from screws to bogies. This level of detail is not very useful for NedTrain. NedTrain is only interested in the items that it can maintain, where maintenance is defined as repairing, replacing, cleaning or setting items. In order to distinguish these items, NedTrain made an List of contents (Dutch: Inventarisatielijst, IV-list) of all Maintenance Specific Items (MSIs), which will interchangeably be used with jobs in this report. These items can consist of different components which can be seen in Figure C.1a. Components as well as MSIs can be replaced individually. However, if one of the underlying components of an MSI fails, the whole item will fail. So, inspecting only the MSIs is sufficiently in depth for the conduction of maintenance, which can also be seen in Figure C.1b. Note that the MSI is different than the Line-Replaceable Unit (LRU) level because an MSI is not necessarily easy to replace or an LRU can consist of different MSIs or the other way around.

\[ \text{(a) The structure of an MSI.} \]

\[ \text{(b) A defective component in an MSI.} \]

Figure C.1. MSI.

All the MSIs can be divided in Short Cyclic Maintenance (Dutch: Kort Cyclistisch Onderhoud, KCO) and Long Cyclic Maintenance (Dutch: Lang Cyclistisch Onderhoud, LCO). The former consists of MSIs which will be checked every time period (for VIRM this is 1 month because of the No Maintenance In Rush Hour (Dutch: Geen Onderhoud In De Spits, G.O.I.D.S.) project at this moment, however for all other types of trains this is normally three months) or a multiple of this time period. The latter consists of MSIs which will be checked every five years or less often. All MSIs have a maintenance rule which can be divided in one of the following three categories:

- Defect Based Maintenance (Dutch: DefectAfhankelijk Onderhoud, DAO). Maintenance will only be conducted when an item is defect;
- Condition Based Maintenance (Dutch: ToestandsAfhankelijk Onderhoud, TAO). Maintenance will be conducted when the condition of an item is below a certain lower limit;
- Use Based Maintenance (Dutch: GebruiksAfhankelijk Onderhoud, GAO). Maintenance will be done based on the number of years and/or the number of kilometres a train has driven.

Furthermore, for each MSI a System Technical Limit (Dutch: Systeem Technische Grens, STG) is determined. The STG, which is the rule on which will be decided whether maintenance will be conducted or not, can be determined in three ways:
Appendix C. The Structure of NedTrain’s Maintenance Program

- Making use of the Material Technical Requirement (Dutch: Materiaal Technische Eis, MTE). This is a lower limit for the MSI. For example, a brake cannot be thinner than a certain number of millimetres;
- Using a functional requirement, for example whether the train is free of all non-NS signs as graffiti;
- The maintenance rule is directly copied from the manufacturer.

All MSIs which have to be inspected at the same moment in time comprise a work package (in Dutch: beurt). A work package contains all MSIs that have their inspection based on the KCO, but it can be extended with MSIs that need its LCO. We will explain this in more detail in the following and it is depicted in Figure C.2. When a train enters an OB for its KCO, it is unknown which MSIs need maintenance. However, it is clear which MSIs will be inspected. So, all MSIs which have their inspection moment will be inspected and based on the STG engineers determine whether maintenance has to be conducted, which will be conducted immediately in the current situation. This implies that the inspection frequency for an MSI is not equal to its maintenance frequency. There are also MSIs which need LCO such as compressors, traction motors, and bogies, which are called main parts (in Dutch: hoofddelen). The approach for these MSIs is different because they will be replaced by another item, where the actual maintenance will be done in a different facility. All LCO items have their own maintenance program and thus their own STG value. So the LCO of such an MSI is not dependent or linked to the train, but to the MSI itself. Therefore, it is known before entering the OB whether these MSIs need maintenance or not. A work package thus consist of three parts: inspections (known before a train enters an OB), KCO (not known before a train enters an OB), LCO (if any but known before a train enters an OB). To be complete, the total of all work packages for the complete life time of a train is called the maintenance concept or maintenance program (in Dutch also: instandhoudingsregelement).

![Figure C.2. An example of a maintenance concept.](image-url)
Figure D.1. The map with all railways in the Netherlands (Systems, 2014).
Figure D.2. The maximum speeds and the electrification on railways (Allowed Speed on Railways, 2014).
Current Locations Mapped

Figure E.1. All current OBs of NedTrain.
Figure E.2. All current and future TCs of NedTrain.
Figure E.3. All end stations currently used by the NS.
APPENDIX F

Demand per End Station

The table can be found on the next page.
Appendix F. Demand per End Station

Table F.1. The set of end stations with the characteristics per end station.

<table>
<thead>
<tr>
<th>Location</th>
<th>Percentage</th>
<th>Trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arnhem</td>
<td>2.25%</td>
<td>15.18</td>
</tr>
<tr>
<td>Amersfoort</td>
<td>0.14%</td>
<td>0.95</td>
</tr>
<tr>
<td>Alkmaar</td>
<td>3.02%</td>
<td>20.40</td>
</tr>
<tr>
<td>Amsterdam CS</td>
<td>0.40%</td>
<td>2.69</td>
</tr>
<tr>
<td>Amsterdam Sloterdijk</td>
<td>0.02%</td>
<td>0.16</td>
</tr>
<tr>
<td>Amsterdam Lijnwerkplaats Noord</td>
<td>0.37%</td>
<td>2.53</td>
</tr>
<tr>
<td>Amsterdam Lijnwerkplaats Zuid</td>
<td>1.64%</td>
<td>11.07</td>
</tr>
<tr>
<td>Bokkeduinen</td>
<td>3.87%</td>
<td>26.10</td>
</tr>
<tr>
<td>Den Haag Binckhorst</td>
<td>7.66%</td>
<td>51.72</td>
</tr>
<tr>
<td>Dordrecht</td>
<td>1.10%</td>
<td>7.43</td>
</tr>
<tr>
<td>Eindhoven</td>
<td>4.38%</td>
<td>29.57</td>
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<tr>
<td>Enkhuizen</td>
<td>2.46%</td>
<td>16.61</td>
</tr>
<tr>
<td>Enschede</td>
<td>2.91%</td>
<td>19.61</td>
</tr>
<tr>
<td>Groningen</td>
<td>2.13%</td>
<td>14.39</td>
</tr>
<tr>
<td>Den Haag HS</td>
<td>0.35%</td>
<td>2.37</td>
</tr>
<tr>
<td>Den Haag CS</td>
<td>0.28%</td>
<td>1.90</td>
</tr>
<tr>
<td>Den Helder</td>
<td>1.27%</td>
<td>8.54</td>
</tr>
<tr>
<td>Hoofddorp Opstelterrein</td>
<td>3.66%</td>
<td>24.67</td>
</tr>
<tr>
<td>Hengelo</td>
<td>1.92%</td>
<td>12.97</td>
</tr>
<tr>
<td>Haarlem</td>
<td>1.08%</td>
<td>7.28</td>
</tr>
<tr>
<td>Hoorn</td>
<td>0.89%</td>
<td>6.01</td>
</tr>
<tr>
<td>Hoorn Kersenboogerd</td>
<td>0.05%</td>
<td>0.32</td>
</tr>
<tr>
<td>Heerlen</td>
<td>1.94%</td>
<td>13.13</td>
</tr>
<tr>
<td>Hertogenbosch ('s)</td>
<td>1.01%</td>
<td>6.80</td>
</tr>
<tr>
<td>Heerhugowaard</td>
<td>0.21%</td>
<td>1.42</td>
</tr>
<tr>
<td>Leidschendam</td>
<td>4.48%</td>
<td>30.21</td>
</tr>
<tr>
<td>Leiden</td>
<td>0.09%</td>
<td>0.63</td>
</tr>
<tr>
<td>Lelystad Centrum</td>
<td>0.07%</td>
<td>0.47</td>
</tr>
<tr>
<td>Lelystad Opstelterrein</td>
<td>4.01%</td>
<td>27.04</td>
</tr>
<tr>
<td>Leeuwarden</td>
<td>1.78%</td>
<td>12.02</td>
</tr>
<tr>
<td>Maastricht</td>
<td>6.02%</td>
<td>40.65</td>
</tr>
<tr>
<td>Nijmegen</td>
<td>3.54%</td>
<td>23.88</td>
</tr>
<tr>
<td>Onnen</td>
<td>2.65%</td>
<td>17.87</td>
</tr>
<tr>
<td>Roosendaal</td>
<td>4.19%</td>
<td>28.30</td>
</tr>
<tr>
<td>Rotterdam CS</td>
<td>4.85%</td>
<td>32.74</td>
</tr>
<tr>
<td>Utrecht CS</td>
<td>9.91%</td>
<td>66.90</td>
</tr>
<tr>
<td>Venlo</td>
<td>1.64%</td>
<td>11.07</td>
</tr>
<tr>
<td>Vlissingen</td>
<td>0.84%</td>
<td>5.69</td>
</tr>
<tr>
<td>Watergraafsmeer</td>
<td>3.56%</td>
<td>24.04</td>
</tr>
<tr>
<td>Zwolle</td>
<td>3.54%</td>
<td>23.88</td>
</tr>
<tr>
<td>Zutphen</td>
<td>2.60%</td>
<td>17.56</td>
</tr>
<tr>
<td>Zutphen Goederenemplacement</td>
<td>1.10%</td>
<td>7.43</td>
</tr>
<tr>
<td>Zoetermeer Oost</td>
<td>0.12%</td>
<td>0.79</td>
</tr>
</tbody>
</table>
Graphs

In this appendix you can find the following graphs:

<table>
<thead>
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<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
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<td>The influence of the human resource cost on the optimal solution.</td>
<td>Page 77</td>
</tr>
<tr>
<td>Figure G.2</td>
<td>The influence of the human resource cost on the cost types.</td>
<td>Page 77</td>
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<td>Figure G.3</td>
<td>The influence of the fixed facility cost per facility on the cost types for the time penalty extension.</td>
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<tr>
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<td>The influence of the transport cost per kilometre on the cost types for the time penalty extension.</td>
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<td>Figure G.5</td>
<td>The influence of the number of trains on the cost types.</td>
<td>Page 79</td>
</tr>
</tbody>
</table>
G.1 Human Resource Cost for the Basic Setting

Figure G.1. The influence of the human resource cost on the optimal solution.

Figure G.2. The influence of the human resource cost on the cost types.
G.2 Fixed Facility Cost for the Time Penalty Extension

Figure G.3. The influence of the fixed facility cost per facility on the cost types for the time penalty extension.

G.3 Transport Cost for the Time Penalty Extension

Figure G.4. The influence of the transport cost per kilometre on the cost types for the time penalty extension.
G.4 Number of Trains for the EBK Extension

Figure G.5. The influence of the number of trains on the cost types.
Extended Models

In this chapter the extended models with their variables can be found. The extension are indicated by the blue colour.

H.1 The Model Extended with EBKs

Minimise

\[ \sum_{f \in F} c_f y_f + \sum_{f \in F} \sum_{r \in R} c_f^a z_{fr} + \lambda \sum_{e \in E} \sum_{f \in F} c_{ef} x_{ef} + \lambda_u \sum_{e \in E} \sum_{f \in F} c_{ef}^u u_{ef} \]

subject to

\[ \sum_{f \in F} x_{ef} = N_e \quad \forall e \in E; \]

\[ \sum_{f \in F} u_{ef} = u_e \quad \forall e \in E; \]

\[ \lambda \sum_{e \in E} x_{ef} \leq p_f \quad \forall f \in F; \]

\[ \lambda \sum_{e \in E} x_{ef} \sum_{j \in J} \chi_{j} \mu_{u} z_{jr}^n + \lambda_u \sum_{e \in E} u_{ef} \sum_{u \in U} \chi_u \mu_u z_{u_ir}^n \leq \beta_r z_{fr}^a \quad \forall f \in F, \forall r \in R; \]

\[ z_{jr}^n y_f \leq z_{fr}^a \quad \forall f \in F, \forall j \in J, \forall r \in R; \]

\[ z_{u_ir}^n y_f \leq z_{fr}^a \quad \forall f \in F, \forall u \in U, \forall r \in R; \]

\[ z_{fr}^a \leq M y_f \quad \forall f \in F, \forall r \in R; \]

\[ y_f \in \{0, 1\} \quad \forall f \in F; \]

\[ x_{ef}, u_{ef} \geq 0; \]

\[ z_{fr}^a \in \mathbb{N}_0. \]

Input parameters

- \( U \) = the set of EBK job types;
- \( \chi_u \) = the number of times that EBK job type \( u \in U \) has to be executed per EBK;
- \( \mu_u \) = the expected duration for the execution of EBK job type \( u \in U \) in years;
- \( z_{u_ir}^n \) = the number of resources of type \( r \in R \) necessary for EBK job type \( u \in U \);
- \( \lambda_u \) = the number of EBKs per train per year;
- \( c_{ef}^u \) = the cost of transporting a train from end station \( e \in E \) to facility \( f \in F \) and back for an EBK;
- \( u_e \) = the number of trains that need EBK that depart from end station \( e \in E \).

Decision variable

- \( u_{ef} \) = the number of trains located at end station \( e \in E \) assigned to facility \( f \in F \) for EBKs.
Appendix H. Extended Models

H.2 The Model Extended with Job Classes

Minimise  \[ \sum_{f \in F} c_f y_f + \sum_{f \in F} \sum_{r \in R} c_f^a z_f^r + \sum_{e \in E} \sum_{f \in F} \sum_{s \in S} c_f^f \lambda_s x_{efs} \]

subject to
\[ \sum_{f \in F} x_{efs} = N_e \quad \forall e \in E, \forall s \in S; \]
\[ \sum_{e \in E} \sum_{s \in S} \lambda_s x_{efs} \leq p_f \quad \forall f \in F; \]
\[ \sum_{e \in E} \sum_{j \in J} \sum_{s \in S} w_{js} x_{efs} + \sum_{j \in J} \sum_{s \in S} \mu_j z_{j, s} \leq \beta_r z_{raf} \quad \forall f \in F, \forall r \in R; \]
\[ z_{raf} \leq M y_f \quad \forall f \in F, \forall r \in R; \]
\[ y_f \in \{0, 1\} \quad \forall f \in F; \]
\[ x_{efs} \geq 0; \]
\[ z_{raf} \in \mathbb{N}_0. \]

Input parameters
\( S = \) the set of job classes;
\( w_{js} = \begin{cases} 1 & \text{if job } j \in J \text{ belongs to class } s \in S; \\ 0 & \text{otherwise} \end{cases} \)
\( \lambda_s = \) the number of maintenance visits per year for class \( s \in S. \)

Decision variable
\( x_{efs} = \) the number of trains located at end station \( e \in E \) assigned to facility \( f \in F \) for maintenance of class \( s. \)