MASTER

A rolling horizon approach for integral long-term overhaul and supply chain planning

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A rolling horizon approach for integral long-term overhaul and supply chain planning

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ABSTRACT

In this thesis, we developed a model for the integral long-term overhaul and supply chain planning of rotables. Prior literature showed that the integral long-term overhaul and supply chain planning of overhauls could ensure major costs savings. These models assumed fixed and deterministic maximum inter-overhaul deadlines. In contrast to these researches, we analyze the long-term overhaul planning of rotables under maximum inter-overhaul deadline uncertainties.

This thesis developed a mathematical integral rotable overhaul supply chain planning model (IROSPC), which schedules rotable replacements, overhaul order releases, the required workforce and the turn-around stock for new rotables such that the involved life cycle costs are minimized.

To test the model in a realistic situation and under maximum inter-overhaul deadline uncertainties, a case study at NedTrain is conducted. A rolling horizon simulation is used to compare the results of the IROSPC model with the current NedTrain planning method. The results showed that using the IROSPC model causes a decrease in labor and bogie acquisition costs.
EXECUTIVE SUMMARY

Problem statement

In this thesis, we research the optimal planning method for planning bogie overhauls at NedTrain. During an overhaul, the state of a part is restored to a specified level due to maintenance activities. After an overhaul, the part is considered as a ready-for-use rotable. The bogie supply chain of NedTrain is characterized as a two-level closed-loop supply chain. Bogies are replaced before they reach their maximum inter-overhaul deadline (MIOT) with ready-for-use bogies in one of the four maintenance depots. The replaced bogies are subsequently overhauled in the refurbishment & overhaul (R&O) workshop.

NedTrain faces a very deviating workload in the R&O workshop. This deviating workload is caused by a combination of the use of maximum-inter overhaul deadlines and overhaul schedules per bogie type. The MIOTs cause peaks and dips in demand for overhaul capacity because trains enter the field approximately on the same time, and operate approximately the same number of kilometers per year. Since NedTrain schedules all the overhauls per bogie type and does not consider the overall workload for the R&O workshop, the workload deviates significantly. A deviating workload causes high overhaul costs since additional temporary employees need to be hired in order to cope with the workload. Extra hired temporary employees can be prevented when workload is reallocated to earlier periods in which the workload was not sufficient for all employees in the R&O workshop with a fixed contract.

An aggregated overhaul and supply chain planning model already has been developed by Arts & Flapper (2015) in order to deal with the planning problems NedTrain faces. However, their model assumes that each MIOT between overhauls is the same. Because this assumption almost never holds in practice, our mathematical model distinguishes different overhauls which enables us to model overhaul specific MIOTs. The main research question of this research is:

| How can the number of employees with a temporary contract, the number of spare rotatables and the overhaul and replacement quantities be determined such that the involved life cycle costs are minimized, taken into account different overhauls? |

Analysis

A mathematical model is developed that schedules the bogie overhaul order releases, the necessary bogie replacements for 30 years, such that the life cycle costs are minimized. Besides that, the model also determines the turn-around stock for bogies that are not in the field yet. The model assumes fixed and deterministic maximum inter-overhaul deadlines. However, in practice the maximum inter-overhaul deadlines can change values depending on events such as maintenance researches. During a maintenance research the deterioration of bogie parts are analyzed and based on this analysis the actual MIOT is set. Before the maintenance research the MIOT value is unknown and is therefore predicted. Because we want to know the long-term effects of the developed mathematical model, we must include the MIOT uncertainties in our analysis.
The rolling horizon concept is used in order to include the MIOT uncertainties in our analysis of the mathematical model. Because the actual MIOTs of future overhauls are not known yet, the MIOT values are simulated based on the data of previous MIOT values of NedTrain. The resulting rolling horizon simulation is an iterative process in which a long-term bogie overhaul planning is made. The first year of the generated bogie overhaul planning is implemented. During the year of which the planning is implemented, more information becomes available of the actual MIOT values of different overhauls. This new information is used to update the input parameters of the mathematical model. After the update of all the parameter values, a new long-term bogie overhaul planning is generated.

The rolling horizon simulation has a horizon length of 30 years of which the first 5 years are part of the warm-up period. The rolling horizon simulation consists of eight replications. The results of the rolling horizon simulation are used to compare the current bogie overhaul planning method with the developed mathematical model.

The current bogie overhaul planning method of NedTrain has a planning horizon of two years. In order to generate a long-term bogie overhaul planning based on the short-term planning method of NedTrain, a heuristic is developed. The planning method of NedTrain minimizes the replacement earliness. The replacement earliness describes the time between the maximum inter-overhaul deadline and the moment of actual replacement. Besides that, the NedTrain planning method also tries to minimize the replacement rate deviations per period. NedTrain prefers a fixed replacement rate per bogie type per period because that would minimize the miscommunication within the R&O workshop. In order to compare the results of the rolling horizon simulation with the current NedTrain planning method, the heuristic is used 8 times with the same simulated actual MIOTs as is used in the rolling horizon simulation.

The two planning methods are compared on the total life cycle costs. The total life cycle costs consists of labor costs, material costs, replacement costs and bogie acquisition costs. The normalized costs of the mathematical model compared to the current NedTrain planning method is shown in figure 0.1.

![Cost savings per costs type](image-url)
As is shown in figure 0.1, the total life cycle costs are decreased with 4% due to the developed mathematical model. The costs savings are caused by the decreased labor and bogie acquisition costs. The labor costs are decreased because the workload became more balanced. The workload of periods in which the workload exceeds the capacity of the employees with a fixed contract is party reallocated to periods in which the workload was not sufficient for the employees with a fixed contract. By reallocating the workload, less temporary employees are needed which causes the decreased labor costs. The bogie acquisition costs decreased with 26% due to including the turn-around determination in the planning model. The model determines the optimal turn-around stock size based on a tradeoff between all the involved cost parameters.

The sensitivity analysis of the number of employees with a fixed contract on the total life cycle costs showed that a 10% change does not have a large influence on the life cycle costs. The sensitivity analysis on the number of labor hours required per overhaul showed that a 10% change causes a 2% change in the same direction in life cycle costs.

**Recommendations**

The most important recommendation for NedTrain is to start using the planning tool developed during this master thesis project. As the rolling horizon simulation shows, the long-term planning of overhauls results in decreased life cycle costs and optimized fixed workforce utilization.

In the developed model developed in chapter 3 we did not schedule replacements and overhauls by a fixed replacement rate per period per bogie type. However, the current NedTrain planning method takes into account this fixed replacement rate in order to minimize miscommunications between MDs and the R&O workshop. In order to let the IROSCP model be a success in practice, NedTrain should develop a communication system that minimizes the miscommunications between the MDs and the R&O workshop without having a fixed replacement rate.

Besides that it might be interesting to look to the possibilities of purchasing a Gurobi license. Gurobi is the solver that is used in this thesis to generate the integral bogie overhaul and supply chain planning. The model is also modeled in an open solver and that model can be used immediately by NedTrain. However, the model is only capable of solving the linear programming problem, which causes non-integer decision variable values. Besides that, the open solver takes around 40 times as long to solve the linear programming problem as Gurobi does. Therefore, it might be interesting for NedTrain to purchase a Gurobi license when multiple situations, that require integer decision variables, have to be calculated.
This report concludes my master thesis project developed at the Eindhoven University of Technology in collaboration with NedTrain. The project is the final stage of the Master’s program in Operations Management & Logistics. Therefore, this project marks the end of a legendary and unforgettable student life in Eindhoven.

I would like to thank several people who were of great help during my thesis project. First of all, Joachim Arts. Joachim, your extensive knowledge of mathematical concepts and the skills to explain those concepts were very valuable for me. Moreover, the support you gave me during the project and your availability for unannounced meetings (even once in the weekend) ensured a great work-relationship. Besides that, I really enjoyed the on- and off-topic chats with you during our meetings. Thank you for everything, it was very pleasant to work with you!

Secondly, I would like to thank Simme Douwe Flapper. The very extensive and detailed feedback you gave me during the project pushed me to my limits, which ensured a high quality research. Thank you very much Simme Douwe!

Next, I would like to thank my supervisor from NedTrain, Sander Smolders. On my first day at NedTrain you cleared your complete schedule in order to give me an introduction into the subject and the company. This warm welcome was the start of a great collaboration on a complex subject. Your great content related knowledge together with your large network within NedTrain ensured that I received the necessary information as quick as possible. Besides that, I really enjoyed the personal and football related talks during our meal-break (despite some club related differences). Thank you Sander for a great time at NedTrain! Furthermore, I would like to thank Erik Dielissen for the opportunity he gave me to conduct my master thesis at NedTrain. During the project, Erik became very sick and passed away unexpectedly. It was a major drive for me to successfully complete the project, which he co-initiated.

I also would like to thank all the students I met last five and a half years at Industria during various committees and activities. Especially I would like to thank the guys of l´Eon Dix for the amazing and legendary weekends, holidays and many other activities during my student life. I also would like to thanks the students of The Villa Crew 2012 and the Race of the Classics 2014 committee. The collaboration on non-study related topics enabled many friendships. Besides that, I am very grateful for the possibility to study a semester in Sweden and participate in the International Research Project 2014 to the USA.

Finally yet importantly, I would like to thank my girlfriend Sophie. Your experience with individual, unstructured projects helped me a lot. Besides, you supported me during difficult moments in this project, but you were also the first one to celebrate milestones. Thanks you for your happiness, support and love!

Maarten Vermeulen

Eindhoven, March 2016
LIST OF CONCEPTS

In this section the basic concepts used in this master thesis are explained briefly. When the concept is followed by NT between parentheses, the concept is NedTrain specific.

Bogies
Frameworks that connect the two wheel sets with the carriage.

Carriages
Pieces of rolling stock, which are designed to carry passengers. Carriages can be combined to form a train. NS Trains consist of at least 2 and at most 6 carriages.

Consumable parts (NT)
Parts that cannot be repaired or reused and are discarded in case of breaking.

Corrective maintenance
Maintenance activities performed to identify, isolate and rectify a fault so that the failed system can be restored to an operational condition.

Fixed workforce utilization
The percentage of time the workload is sufficient for all employees with a fixed contract.

Life cycle cost
The total costs during the entire life of a part. In this thesis, the life cycle costs are defined by rotatable acquisition costs, labor costs, material costs, and replacement costs.

Main parts (NT)
Expensive parts that can be traced individually during their life time and have own maintenance programs that follow the principles of preventive maintenance.

Maintenance depots (NT)
Maintenance depots are locations where trains are inspected, repaired and cleaned once every 3 months on average. Moreover, main parts are replaced for overhaul in one of the 4 maintenance depots (MDs).

Maintenance researches
Researches where a few sample main parts are inspected in order to predict the deterioration process and the next overhaul deadline.

Maintenance programs (NT)
Individual programs that define the size of the maximum inter-overhaul deadline (MIOT) and the overhaul activities that have to be conducted during an overhaul.

Maximum inter-overhaul deadlines
The maximum amount of time / usage (in kilometers) (main) parts are allowed to operate before they need to be overhauled.

Overhauls
Preventive maintenance activities that restore the state of parts to specified levels.

Planning horizon
The number of time periods considered in the planning.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Plantermijn (NT)</td>
<td>Temporary MIOT assumption, which is documented in the information system of NedTrain.</td>
</tr>
<tr>
<td>Population of bogies (NT)</td>
<td>All bogies of a specific bogie type, including the bogies on stock.</td>
</tr>
<tr>
<td>Population of trains (NT)</td>
<td>All trains of a specific train type that are in the field.</td>
</tr>
<tr>
<td>Preventive maintenance</td>
<td>All actions performed in an attempt to retain a part in specified condition providing systematic inspection, detection, and prevention on incipient failures.</td>
</tr>
<tr>
<td>Refurbishment and overhaul workshop (NT)</td>
<td>The workshop in Haarlem that, among other activities, conducts maintenance research and overhauls wheel sets and bogies.</td>
</tr>
<tr>
<td>Repairable parts (NT)</td>
<td>Parts that are repaired or reused in case they are broken.</td>
</tr>
<tr>
<td>Revision</td>
<td>Interchangeable with &quot;overhaul&quot;.</td>
</tr>
<tr>
<td>Rolling horizon</td>
<td>Concept where deterministic planning systems can take into account stochastic parameters.</td>
</tr>
<tr>
<td>Rolling stock</td>
<td>All vehicles that move on a railway, including powered and unpowered vehicles.</td>
</tr>
<tr>
<td>Rotables</td>
<td>Components or inventory items that can repeatedly and economically be restored to a fully serviceable condition.</td>
</tr>
<tr>
<td>Turn-around stock</td>
<td>The number of additional bought rotables which ensures that operational rotables can be replaced.</td>
</tr>
<tr>
<td>Veilige voorlopige termijn (NT)</td>
<td>The number of operational kilometers before a maintenance research has to be conducted.</td>
</tr>
</tbody>
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### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>IROSCP</td>
<td>Integrated rotatable overhaul and supply chain planning</td>
</tr>
<tr>
<td>CM</td>
<td>Corrective maintenance</td>
</tr>
<tr>
<td>LCC</td>
<td>Life cycle costs</td>
</tr>
<tr>
<td>LP</td>
<td>Linear programming</td>
</tr>
<tr>
<td>MD</td>
<td>Maintenance depot</td>
</tr>
<tr>
<td>MIOT</td>
<td>Maximum inter-overhaul deadline</td>
</tr>
<tr>
<td>MIP</td>
<td>Mixed integer programming</td>
</tr>
<tr>
<td>NS</td>
<td>Dutch Railways, “Nederlandse Spoorwegen”</td>
</tr>
<tr>
<td>PM</td>
<td>Preventive maintenance</td>
</tr>
<tr>
<td>PT</td>
<td>“Plantermijn”</td>
</tr>
<tr>
<td>R&amp;O workshop</td>
<td>Refurbishment &amp; Overhaul workshop</td>
</tr>
<tr>
<td>VVT</td>
<td>&quot;Veilige voorlopige termijn&quot;</td>
</tr>
</tbody>
</table>
**LIST OF VARIABLES**

<table>
<thead>
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<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>(a_i)</td>
<td>First period in the planning horizon that rotables of type (i \in I) are in the field ((a_i \in T)).</td>
</tr>
<tr>
<td>(c_i^a)</td>
<td>Acquisition costs of a rotable of type (i \in I\setminus I_1).</td>
</tr>
<tr>
<td>(c_i^m)</td>
<td>Material costs associated with the (e^{th}) overhaul of bogie type (i \in I) in period (t \in T).</td>
</tr>
<tr>
<td>(c_i^r)</td>
<td>Costs of replacing retables of type (i \in I) during period (t \in T^l_i).</td>
</tr>
<tr>
<td>(c_0^w)</td>
<td>The labor hour costs of the predecessor of the first aggregated period in the planning horizon.</td>
</tr>
<tr>
<td>(c_y^w)</td>
<td>Costs per labor hour during aggregated period (y \in Y).</td>
</tr>
<tr>
<td>(c_y^{WR})</td>
<td>Cost difference per year between a temporary employee and an employee with a fixed contract in aggregated period (y \in Y).</td>
</tr>
<tr>
<td>(D_{i,e}^d)</td>
<td>Number of retables of type (i \in I), that have to be replaced in or before period (t \in {a_i, ..., a_i + q_i e - 1}). The substitute rotable must have been subjected to overhaul (e \in E_i).</td>
</tr>
<tr>
<td>(D_{i,e}^t)</td>
<td>Number of retables of type (i \in I), that have to be replaced in or before period (t \in T^l_i). The substitute rotable must have been subjected to overhaul (e \in E_i).</td>
</tr>
<tr>
<td>(E_i)</td>
<td>Set of all overhauls per rotable type (i \in I) considered in the planning horizon. (E = {g_i, ..., k_i}).</td>
</tr>
<tr>
<td>(F_{i,e}^d)</td>
<td>Number of ready-for-use retables of type (i \in I) that have been subjected to overhaul number (e \in E_i) at the beginning of period (a_i).</td>
</tr>
<tr>
<td>(F_{i,t,e})</td>
<td>Number of ready-for-use retables of type (i \in I) at the beginning of period (t \in T^l_i) that have been subjected to overhaul number (e \in E_i).</td>
</tr>
<tr>
<td>(g_i)</td>
<td>The first overhaul number of bogie type (i \in I) considered in the planning horizon.</td>
</tr>
<tr>
<td>(H_{i}^d)</td>
<td>Number of non-ready-for-use retables of type (i \in I) available (on stock) at the beginning of period (a_i).</td>
</tr>
<tr>
<td>(H_{i,t})</td>
<td>Number of non-ready-for-use retables of type (i \in I) available at the beginning of period (t \in T^l_i).</td>
</tr>
<tr>
<td>(I)</td>
<td>Set of all types of retables.</td>
</tr>
<tr>
<td>(I_t)</td>
<td>Set of all rotable types in the field in period (t \in T, I_t = {i \in I \mid a_i \leq t \leq p_i}).</td>
</tr>
<tr>
<td>(k_i)</td>
<td>The last overhaul number of bogie type (i \in I) considered in the planning horizon.</td>
</tr>
<tr>
<td>(L_{i,e})</td>
<td>The overhaul lead time (in periods) for (e^{th}) overhaul, for retables of type (i \in I).</td>
</tr>
<tr>
<td>(m^f)</td>
<td>Number of employees that have a fixed contract during the entire planning horizon.</td>
</tr>
</tbody>
</table>
Number of employees that are hired temporary and don't have a fixed contract in aggregated period \( y \in Y \).

Number of order releases for the \( e^{th} \) overhaul of rotable type \( i \in I \) during period \( t \in \{ a_i - L_i, ..., a_i - 1 \} \).

Number of order releases for the \( e^{th} \) overhaul of rotable type \( i \in I \) during period \( t \in \{ a_i - L_i + 1, ..., p_i \} \).

Last period in the planning horizon that rotables of type \( i \in I \) are in the field (\( p_i \in T \)).

The inter-overhaul deadline of rotable type \( i \in I \) after being subjected to the \( e^{th} \) overhaul.

Amount of labor hours required to start \( e^{th} \) overhaul of rotable type \( i \in I \).

Turn-around stock of rotables of type \( i \in I \).

Set of all periods considered in the planning horizon (\( T = \{1, ..., |T|\} \)).

Set of periods during which rotable type \( i \in I \) is active in the field (\( T^i = \{ a_i, ..., p_i \} \)).

Set of periods during which deadlines for replacements of rotable type \( i \in I \) that have been subjected to overhaul \( e \in E_i \) are dependent on its previous replacement (\( T_{i,e} = \{ a_i + q_{i,e-1}, p_i \} \)).

Set of periods that are contained in a certain aggregated period \( y \in Y \).

Number of in excess replacements of rotables of type \( i \in I \) that have been subjected to the \( e^{th} \) overhaul, at period \( a_i - 1 \).

Number of excess rotable replacements of rotable type \( i \in I \), at the end of period \( t \in T^i \), with rotables that have been subjected to overhaul \( e \in E_i \).

Initial number of bogie replacements for overhaul number \( e \in E_i \) of type \( i \in I \) during period \( t \in T \).

Number of labor hours available in aggregated period \( y \in Y \).

Number of labor hours for overhaul that are allocated to period \( t \in T \).

Number of rotable replacements of rotable type \( i \in I \) during period \( t \in T^i \). The substitute rotable must have been subjected to overhaul \( e \in E_i \).

Set of aggregated periods (typically years) (\( Y = \{1, ..., |Y|\} \)).

Average number of yearly work hours per employee.

Input factor that takes into account the lost capacity due to corrective overhauls and breaks. \( 0 \leq \beta \leq 1 \).

Lower (upper) bound on available labor hours for rotable overhauls expressed as a fraction of \( W_y / |T^y| \).
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1. INTRODUCTION

This report presents our study on the long term effects of an integral overhaul and supply chain planning at NedTrain. This planning schedules rotatable replacements, overhaul releases, the required workforce and the turn-around stock such that the involved life cycle costs are minimized. In order to minimize the total life cycle costs, the planning horizon should be at least the length of a life cycle (between 25 and 35 years). Because of many uncertainties during the planning horizon, only the first planning period is used in practice (implemented). A rolling horizon simulation is conducted in order to identify the long-term effects of this planning model, considering the maximum inter-overhaul deadline uncertainties.

This project has been specifically initiated in order to improve the aggregated overhaul planning for bogies at NedTrain. NedTrain is in a transition from a short-term bogie overhaul planning method to a long-term bogie planning method. NedTrain decided to change to a long-term bogie overhaul planning method because the current short planning horizon causes a highly deviating workload, which results in high costs due to extra hired employees.

1.1. THESIS COMPOSITION

In order to understand the rest of the thesis, we introduce NedTrain in Chapter 1 together with some basic concepts that are used in the rest of this thesis. The 2nd Chapter describes the problems faced by NedTrain concerning the bogie overhaul processes. The 3rd Chapter introduces a mathematical model that can be used to solve these problems. The 4th Chapter explains the concept of a rolling horizon simulation. This concept is used in order to simulate the long-term performances of the model developed in Chapter 3, considering maximum inter-overhaul deadline uncertainties. Chapter 5 describes the case study conducted at NedTrain together with the current bogie overhaul planning method used by NedTrain. Chapter 6 compares the results of the rolling scheduling simulation of Chapter 4 with the current aggregated overhaul planning process at NedTrain. In the 7th and last Chapter the conclusions and recommendations are stated.

1.2. COMPANY DESCRIPTION

The company involved in the case study of this master thesis is NedTrain, which is part of the Dutch Railways (NS). NedTrain takes care of all maintenance activities for trains in the Netherlands. The activities that NedTrain perform are modernization, damage repair, cleaning, and maintenance & service. The subject of this master thesis project can be categorized within the maintenance & service cluster, because an optimal planning for preventive maintenance is developed. The company is a business-to-business company that mainly serves the Dutch Railways. It has around 3,000 employees and a turnover of around €500 million in 2014 (Dutch Railways, 2015). The headquarter is located in Utrecht and the other locations are spread across the country. The Supply Chain Operations department initiated this project in order to make a transition from a short-term to a long term bogie overhaul planning. They requested a user-friendly planning tool that is easy to use by the responsible planner.
NedTrain distinguishes three types of parts: consumable-parts, repairable-parts and main-parts. Consumable-parts are train parts that are discarded if they break down. Repairable-parts are train parts that are repaired if they break down. Main-parts are expensive train components that have their own maintenance program and are overhauled preventively. The maintenance program determines the maximum amount of time/usage a main-part is allowed to be operational before it requires to be overhauled. This period is defined as the maximum inter-overhaul deadline (MIOT). Examples of main parts are wheelsets, bogies and air-conditioning units.

The NedTrain locations involved in this master thesis are split up into two categories:

- **Maintenance depots (MD)**. MDs are responsible for semi-large maintenance activities that cannot be executed in the short stops in the SD’s. Moreover, MDs replace main-parts. The four MDs are located in Maastricht, Onnen, Watergraafsmeer and Leidschendam.

- **Refurbishment & Overhaul (R&O) workshop**. At the R&O workshop, complete trains are refurbished and wheelsets and bogies are overhauled. The R&O plant is located in Haarlem.

1.3. INTRODUCTION TO ROLLING STOCK AND ROTABLES

Each train or rolling stock contains more than thousand parts and components. This project focusses on one of these parts: bogies. Bogies are frameworks that connect two wheelsets with the carriage. An example of a bogie is shown in Figure 1.1. Bogies can be categorized as rotables, which are components that can be repeatedly economically restored to a fully serviceable condition. During an overhaul the state of a rotable is economically restored to a serviceable condition. Note that NedTrain uses the term main-part to describe rotables. In order to minimize the down-time of the entire rolling stock (e.g. a train), each rotable is replaced by a ready-for-use rotable. Such a system is called a maintenance-by-replacement system. Each rotable becomes a ready-for-use rotable after having been overhauled.

Bogies differ per train series, which results in a wide variety of operational bogies at NedTrain. Moreover, bogies optionally contain an engine or (magnetic) brakes. Figure 1.2 shows the interdependencies between the concepts train type, train series, train series population, bogie types and bogie type population.
The top row in Figure 1.2 describes the different train types. For example, VIRM and SGM are two different train types that NedTrain maintains. VIRM are double-decker trains that are used for long distances, whereas SGM trains are so called "stop-treinen" (stop-trains) that mainly transport travelers on short trajectories with many stops in between.

Each train type can have multiple train series, which is shown on the second row in Figure 1.2. For example, the VIRM train type consists of 5 different train series. The difference between trains series within one train type can be the length of the train, the number of yearly operational kilometers or the moment of entering the field. A train series population represent all the trains of one train series.

Every train series uses different bogies. The third row in Figure 1.2 shows that each train of a specific series can contain multiple bogie types. All the bogies of a specific type together are called the bogie type population, which is shown at the last row in Figure 1.2.
### 1.4. NedTrain Bogie Overhaul Process

In this section, we explain the NedTrain bogie overhaul processes. The bogie overhaul processes are interrelated with two other processes: the preventive maintenance process and the maintenance research process. An overview of these processes and their interrelation are shown in Figure 1.3.

#### 1.4.1. Preventive Maintenance (PM)

NedTrain executes preventive maintenance in one of the four maintenance depots (MD). Each train type has a specific maintenance depot, where preventive maintenance is executed. Preventive maintenance for a train is executed every 3 months on average. The activities performed during PM are planned maintenance activities. Moreover, corrective maintenance activities that cannot be performed at smaller maintenance stops are added to the planned PM activities.

When trains visit the maintenance depot for PM, time is reserved to replace bogies when necessary. The decision whether to replace the bogie depends on the MIOT (t(overhaul)) in Figure 1.3. When the MIOT of a bogie is earlier than the next visit to the MD (t(Next PM) in Figure 1.3), that specific bogie is replaced with a ready-for-use bogie.

Figure 1.3 does not show the inventory location at Lage Weide to increase the readability. Figure 1.4 describes the inventory processes and its decisions in more detail. This Figure shows that the bogie that will be built into a train can come from the inventory location or directly from the R&O plant. The origin of the bogie depends on the inventory level of ready-for-use parts and the need for ready-for-use bogies. If there is no inventory and a bogie needs to be replaced, the ready-for-use bogie is sent directly to the MD. In every other situation, the bogie is sent to the inventory location and it stays there until an MD needs it.
1.4.2. **OVERHAULS**

Overhauls have the purpose of restoring the state of a component to a specified level by executing maintenance activities. These maintenance activities are repairs, replacements and cleaning activities. The result of the maintenance research describes the set of activities that the mechanics in the R&O workshop execute during an overhaul.

1.4.3. **MAINTENANCE RESEARCH (MR)**

The maintenance research is an investigation where the deterioration processes of the bogie are analyzed. Based on these findings, the MIOT is set and the set of activities is defined which have to be carried out during the upcoming overhaul. The maintenance research is important for the overhaul planning and the activities performed during the overhaul. For the upcoming overhaul a so-called PT ("plantermijn" in Dutch) is known. The PT defines the number of operational periods the bogie is expected to travel before it requires an overhaul. The temporary maximum inter-overhaul deadline (MIOT) is equal to the PT, if the maintenance research has not been executed yet. After the MR, the actual MIOT is set based on the deterioration processes of the bogie. The VVT ("veilige voorlopige termijn" in Dutch) is the number of operational periods before bogies of that bogie type are subjected to a maintenance research. Maintenance research is carried out before the number of operational periods exceeds the VVT.

The 4 or 5 bogies with the highest number of operational kilometers are subject to the maintenance research. Mechanics in the R&O workshop inspect every part of the selected bogie extensively and reports the deterioration of each part to the maintenance engineer. Based on the deterioration results, the maintenance engineer determines the actual MIOT level, with three possible results:

1. The maximum inter-overhaul deadline stays equal to the PT because the deterioration process elapses as expected.
2. The maximum inter-overhaul deadline is set lower than the PT because the deterioration process elapses faster than expected.
3. The maximum inter-overhaul deadline is set higher than the PT because the deterioration process elapses slower than expected.
This decision immediately affects the planning of overhauls at the R&O plant. If, for example, the actual MIOT is set smaller than the PT, the bogies will be overhauled earlier than initially expected. The maintenance engineer can also decide to conduct another maintenance research if the deterioration of parts cannot be predicted with precision. An additional MR can be done in combination with number 1 or 3. According to the maintenance engineers within NedTrain, it rarely occurs that the MIOT is set lower than the PT.

Besides the final determination of the maximum-inter overhaul deadline, the maintenance engineer also decides which maintenance actions are executed during the overhaul. This is based on the deterioration of all parts of the component. Because this decision influences the overhaul itself, a dependency between the results of an MR and the overhaul process can be seen in Figure 1.3.

1.5. REFURBISHMENT & OVERHAUL WORKSHOP

All bogies that are overhauled by NedTrain are overhauled at the refurbishment & overhaul workshop in Haarlem. The workshop is divided in two parts, a production environment for: (1) bogies, and (2) wheel sets. Note that wheel sets are out of the scope of this research. We use the term R&O workshop to refer to the bogies production environment of the workshop.

The maintenance activities during an overhaul are labor intensive. Therefore, the capacity of the R&O workshop is expressed in labor hours. All bogies are overhauled in the same production workshop; thus, all bogies demand for the same labor capacity. The number of available labor hours in the R&O workshop is divided in labor hours of employees with a fixed contract and employees with a temporary (year) contract. These temporary workers are hired in order to cope with high peaks in workload. High peaks in workload occur when a major number of bogies require an overhaul. Temporary employees are more expensive for NedTrain than employees with a fixed contract. Before the beginning of 2016 the number of available labor hours have always been the restricting factor in the R&O workshop. However, when an excessive number of employees are hired, the space in the workshop will become the restricting factor. However, according to the long-term planner of the R&O workshop, this excessive number of hired employees will probably never be reached. Therefore, we assume no restriction on the number of hired employees.

Each overhaul requires a number of labor hours in order to restore the condition of that bogie to a specified state. NedTrain uses two types of overhauls: large and small. Large overhauls require conservation of the bogie frames, which costs many labor hours and is expensive. During the conservation of a bogie frame, the condition of the frame is restored to a specified state. Small overhauls do not require conservation of the bogie frames and are therefore cheaper and require less labor hours. Next to costs and the number of labor hours, the MIOT after the conducted overhaul depends as well on the overhaul type of the last overhaul. The MIOT after a large overhaul is on average 60% larger than after a small overhaul (Vermeulen, 2015).
2. PROBLEM DESCRIPTION AND PROJECT DEFINITION

In the first part of this Chapter, we describe the problems related to the NedTrain bogie overhaul processes. In section 2.2, we discuss comparable problems in literature. Based on the problem statement and the available related literature, we define the research questions in section 2.3.

2.1. PROBLEM DEFINITION

In previous Chapter, an introduction to the bogie overhaul processes at NedTrain has been given. From these processes, we derive four problems, which are elaborated in this section.

Strict MIOT deadline

The first problem occurs due to strict maximum-inter-overhaul deadline (MIOT). Bogies can never be overhauled later than the MIOT. Peaks and dips occur in the workload of the R&O workshop, since trains of the same train series enter the field approximately on the same time and operate approximately the same number of kilometers per year. During workload dips, the workload is not sufficient for all employees with fixed contracts. The workload during peaks exceeds the capacity of the employees with fixed contracts. More expensive personnel must be hired temporarily in order to satisfy the overhaul demand.

Overhaul scheduling per bogie type

NedTrain schedules all the overhauls per bogie type, which causes the second problem. By scheduling the overhauls per bogie type, NedTrain does not consider the overall workload in the R&O workshop. For example, if multiple bogie types are overhauled at the same moment, a demand peak for overhaul capacity occurs. Scheduling overhauls per bogie type does not only result in peaks but also in dips in the R&O workshop workload. During a workload dip not every employee with a fixed contract is needed. However, every employee with a fixed contract needs to be paid, which causes unnecessary high costs per conducted overhaul. The workload during peaks could be distributed to periods, where the workload is insufficient for every employee with a fixed contract.

Short planning horizon

The third problem is caused by the short planning horizon that NedTrain currently uses. NedTrain schedules the overhauls of each bogie type for the upcoming two years. Therefore, NedTrain is not able to see the effects that these schedules have on the remaining life cycle. For example, assume that a bogie is overhauled once every 5 years and leaves the field in 2027. The first situation in Table 2.1 describes the overhaul schedule when the overhauls are executed at the same moment as the MIOT. If more bogies demand overhaul capacity in 2017, a peak occurs in 2017. NedTrain can decide to overhaul the bogie in 2016. However, this decision causes an extra overhaul in 2026. This extra overhaul causes a major increase in labor and material costs and is due to the current two-year planning horizon, not considered. Therefore, the current short planning horizon of NedTrain can cause an extra unnecessary overhaul at the end of the life cycle by reallocating previous overhauls to earlier periods. Therefore, the planning horizon should be at least the length of a rotatable lifecycle to overcome the inefficient planned schedules.
Table 2.1: Short planning horizon example

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<tbody>
<tr>
<td>Situation 1</td>
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<tr>
<td>Situation 2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
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</table>

Overhaul costs not included

The last problem is caused by the fact that bogie overhaul costs are not included in current NedTrain bogie overhaul planning processes. The goal of the current bogie overhaul process is to overhaul bogies as close as possible to its MIOT, in order to minimize thrown away useful life. Overhauling bogies as close as possible to their MIOTs lead to peaks and dips in demand for overhaul capacity and unnecessarily high labor costs. However, minimizing peaks in demand by distributing overhauls to other periods could cause extra costs due to additional overhauls at the end of the life cycle. Thus, a tradeoff should be considered between minimizing the variation of demand for overhaul capacity and minimizing the lost useful life. This tradeoff can be expressed in costs during the life cycle. Therefore, these life cycle costs must be included in the bogie overhaul planning processes. The involved life cycle costs are labor costs, material costs, replacement costs and bogie acquisition costs.

The four problems can be combined into the problem statement, which is stated below.

The combination of the use maximum-inter-overhaul deadlines and an overhaul planning per bogie type causes a strongly deviating workload at the R&O workshop, which may lead to unnecessarily high life cycle costs.

2.2. LITERATURE REVIEW

One of the first articles that addresses the joint problem of preventive maintenance and capacity planning is the article of Wagner et al. (1964). The models in that article allocate work force under capacity constraints in order to execute overhauls of a major functional element or group of elements on time. However, no general conclusion could be drawn, because the size of the tests was too small. The model of Charest & Ferland (1993) includes inter-maintenance intervals in the planning of preventive maintenance for power generating units. These inter-maintenance intervals are included into patterns; these patterns are matched with each maintenance task. When such a pattern is matched with each maintenance activity, then no possibility exists to execute the maintenance activity before its due date. The model of Go et al (2013) distinguishes due dates with the actual starting time and minimizes the total sum of earliness and tardiness under capacity, operational schedule and work force constraints.

Öner et al. (2007) show that the costs due to maintenance activities and down time over the lifecycle of a capital good can be 3 to 4 times the acquisition price. Arts & Flapper (2015) developed a model for the aggregate overhaul planning of rotables at Nedtrain, which minimizes the total life cycle costs. The model determines the number of replacements and overhauls per period, the number of spare rotables, and the workforce required in order to meet the number of overhauls. The model takes the whole life cycle of rotables into consideration and Arts & Flapper (2015) argue that the decision to execute overhauls in advance of the due date can cause additional overhauls at the end of their life cycles, which increases total costs. The objective function contains all relevant costs (rotables acquisition
costs, labor costs, material costs, and replacement costs). Besides that, the model of Arts & Flapper (2015) considers, just as the model of Joo (2009), the inventory position of parts, which is necessary to replace or overhaul rotables.

The model of Arts & Flapper (2015) models the same environment as described in Chapter 1. However, the model of Arts & Flapper (2015) assumes that every overhaul is similar and that each maximum-inter-overhaul deadline is similar. This assumption does not hold in practice in the NedTrain case. As discussed in Section 1.4, NedTrain makes use of two overhaul types: large and small overhauls. No model is developed yet to plan the aggregate overhaul planning in which different overhaul types are modeled for the complete life cycle. Therefore, this master thesis considers the aggregate overhaul planning of rotables with different overhaul types.

2.3. PROJECT DEFINITION AND RESEARCH QUESTIONS

We stated that the problem that has to be solved is the deviating workload, which is caused by the use of MIOTs and overhaul schedules per bogie type. The deviating workload causes high costs, which may be solved by redistributing the overhauls to previous periods. Because in practice not all overhauls are similar, different overhauls should be distinguished. The importance of distinguishing overhauls in the aggregate overhaul planning model for rotables is explained with help of Table 2.2.

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
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<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Situation 1</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Situation 2</td>
<td>X1</td>
<td>X2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X1</td>
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<td>X1</td>
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</tbody>
</table>

Situation 1 in Table 2.2 is the situation where each overhaul is assumed to be similar, which means that all MIOTs are the same. As is shown, the rotable is overhauled once every 4 years. Let us assume that in year 10 multiple rotable types are planned to be subjected to an overhaul, which result in a high peak in demand for overhaul capacity. The model of Arts & Flapper (2015) can decide to redistribute the third overhaul from year 10 to year 9 (and fourth overhaul from year 14 to year 13) because of leftover useful life after the fourth overhaul. Situation 2 in Table 2.2, describes the situation in which a distinction between overhauls is made. Each overhaul can be a small or a large overhaul. The MIOT is 3 years after a small overhaul (X1) and 6 years after a large overhaul (X2). The second situation shown in Table 2.2 does not need to redistribute the third overhaul, because the third overhaul is not located in year 10 due to the distinction between overhaul types. Hence, distinguishing overhauls could result in a more accurate planning model.

The main research question for this master thesis project is stated below.

How can the number of employees with an temporary contract, the number of spare rotables and the overhaul and replacement quantities be determined such that the involved life cycle costs are minimized, taken into account different overhauls?

In order to answer the main research question, one design goal and two sub-research questions are stated.
1. Design a mathematical model that plans the aggregate rotable overhaul processes such that the life cycle costs of rotables are minimized, taking into account different overhauls and the following constraints:
   a. Labor capacity constraints in the R&O workshop
   b. Workforce flexibility constraints
   c. (Non-)Ready-for-use rotable availability constraints
   d. Maximum-inter-overhaul deadline constraints

Case study:

2. How does NedTrain determine the number of employees with a temporary contract, the number of spare rotables and the overhaul and replacement quantities?

3. What are the costs savings generated by the model in the NedTrain case for the upcoming 30 years?

In Chapter 3, we develop a mathematical model for the planning of aggregate rotable overhaul processes, which minimizes the total life cycle costs (design goal). The model takes into account different overhauls, which increases the accuracy of the model results compared to the results obtained by the model of Arts & Flapper (2015). Because NedTrain requested an operational usable planning model, the mathematical model is implemented in a solver.

In Chapter 4, the rolling horizon concept is explained in order to help to answer research question 2. This concept is used to develop a long-term bogie overhaul planning using the developed mathematical model described in Chapter 3, under MIOT uncertainties. This long-term bogie overhaul planning is used to compare the mathematical model developed in Chapter 3 with the current NedTrain bogie overhaul planning method.

In the first part of Chapter 5, the case study conducted at NedTrain is discussed, while in the second part of Chapter 5, the current bogie overhaul planning method used by NedTrain is evaluated. The second part of Chapter 5 answers the first sub-research question. The goal of the first sub-research question is to gain insights in the current aggregate bogie overhaul planning method of NedTrain. These insights are used in order to compare the model that is presented in Chapter 3 with the current situation of NedTrain. We have developed a heuristic that can be used to generate a long-term bogie overhaul planning, taking into account the current NedTrain planning method which has a 2-year planning horizon.

In order to compare the current bogie overhaul planning method with the mathematical model developed in Chapter 3, a rolling horizon simulation is conducted. The results of this simulation are described in Chapter 6 and answer the last research question. Both planning methods are compared on the following costs: labor costs, rotable acquisition costs, material costs, and replacement costs. Note that life cycle inventory costs can be included with the acquisition costs of a rotable.
3. Mathematical Model

The mathematical model in this Chapter describes a system, where rotables are overhauled according to the maintenance-by-replacement policy. As described in Section 1.2, a maintenance-by-replacement policy replaces rotables when they require an overhaul. These rotables are replaced with ready-for-use rotables. A replaced rotable becomes a ready-for-use rotable after it is overhauled. Rotables of different types are overhauled at the same overhaul workshop. Rotables are parts of a larger asset such as trains or airplanes and each asset can contain multiple rotable types. The number of rotables of a specific type per asset is called the rotable population. Each rotable in the population of a type requires to be overhauled before the rotable has been in the field for MIOT periods. The time indicator in this model is modeled by the use of periods and aggregated periods. The set of periods considered in the planning horizon is denoted by $T = \{1, ..., |T|\}$. Each period describes for example a 4-week period. The length of the planning horizon must be at least equal to the length of the life cycle of the asset in which rotables are used in order to capture the entire life cycle costs. Life cycles for rolling stock and airplanes are between 25 and 35 years (Arts & Flapper, 2015).

The set of considered rotable types is denoted by $I$. The parameters $a_i$ and $p_i$ denote the first and last period during which rotables of type $i \in I$ are in the field, $a_i < p_i$. When rotable types are already in the field at the moment of generating a plan, then $a_i = 1$. When $a_i > 1$, the company involved plans to start using a new asset that contains rotable type $i \in I$ at $a_i$. If $p_i < |T|$, then the company plans to stop using the asset that contains rotable type $i \in I$. The company does not plan to stop using the asset that contains rotable type $i \in I$, when $p_i = |T|$. The set of periods in the planning horizon during which rotables of type $i \in I$ are active in the field is denoted by $T^i = \{a_i, ..., p_i\}$. Furthermore, the set of rotable types that are active in the field during period $t \in T$ is denoted by $I_t = \{i \in I | a_i \leq t \leq p_i\}$. So, the set $I_1$ denotes the rotable types that are active in the field in period 1.

The set of aggregated periods considered in the planning horizon is denoted by $Y = \{1, ..., |Y|\}$. Typically, aggregated periods are quarters of a year or years. The set of periods that are contained in the corresponding aggregated period $y \in Y$ is denoted by $T^y$. The relations between both types of periods are shown in Figure 3.1. The example contains 3 aggregated periods (quarters of a year) and 9 periods (months). $T^y$ denotes the set of periods that are contained in the first aggregated period and as Table 3.1 shows: $T^1 = \{1, 2, 3\}$.

<table>
<thead>
<tr>
<th>Time in aggregated periods ($Y$)</th>
<th>$T^1$</th>
<th>$T^2$</th>
<th>$T^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in periods ($T$)</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1 2 3</td>
<td>4 5 6</td>
<td>7 8 9</td>
</tr>
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</table>

In the planning horizon each rotable will be subject to multiple overhauls. These overhauls considered in the planning horizon for rotable type $i \in I$ is denoted by set $E_i = \{g_i, ..., k_i\}$. Parameters $g_i$ and $k_i$ denote the first and last overhaul that is considered in the planning horizon for rotable type $i \in I$. Each rotable is subjected to overhaul number $e \in E_i$ if it has previously been subjected to overhaul number $e - 1$. 
3.1. SUPPLY CHAIN DYNAMICS

The supply chain of this rotable overhaul system is described by a two-level closed-loop supply chain, which is shown in Figure 3.1. The supply chain consists of a maintenance depot, two types of stock points and an overhaul workshop. The number of non-ready-for-use rotables of type \( i \in I \) at the beginning of period \( t \in T_i^l \) is denoted by \( H_{i,t} \). Furthermore, the number of ready-for-use rotables at the beginning of period \( t \in T_i^l \) of rotable type \( i \in I \), that have been subjected to overhaul number \( e \in E_i \) is denoted by \( F_{i,t,e} \).

Figure 3.1: Rotable supply chain overview

Rotables are replaced in the maintenance depot with ready-for-use rotables of the same type. The number of replacements of rotable type \( i \in I \) in period \( t \in T_i^l \) with a ready-for-use rotable that has been subjected to overhaul \( e \in E_i \) is denoted by \( x_{i,t,e} \). The number of order releases for the \( e^{th} \) overhaul of rotable \( i \in I \) at period \( t \in T_i^l \) is denoted by \( n_{i,t,e} \). All rotables are overhauled at the same overhaul workshop and the overhaul lead time per rotable type \( i \in I \) and per overhaul number \( e \in E_i \) is denoted by \( L_{i,e} \). As shown in Figure 3.1, the number of rotables that started their overhaul in period \( t - L_{i,e} \) become available for the ready-for-use stock point in period \( t \). The replacement lead time at the maintenance depot is negligible compared to the length of a period and is therefore equal to zero in the model. The inventory balance equations are described in equations (3.1) and (3.2).

\[
F_{i,t,e} = F_{i,t-1,e} - x_{i,t-1,e} + n_{i,t-L_{i,e}-1,e} \quad \forall i \in I, \forall t \in T_i^l \setminus \{a_i\}, \forall e \in E_i 
\]

\[
H_{i,t} = H_{i,t-1} + \sum_{e \in E_i} x_{i,t-1,e} - \sum_{e \in E_i} n_{i,t-1,e} \quad \forall i \in I, \forall t \in T_i^l \setminus \{a_i\} 
\]

Equations (3.1) and (3.2) require initial conditions. Input parameter \( H_{i,t}^d \) denotes the initial non-ready-for-use stock levels for rotable type \( i \in I \) that are already in the field at the moment the
planning is made \( (a_i = 1) \). Input parameter \( F_{i,e}^d \) denotes the initial ready-for-use rotatables that have been subjected to overhaul \( e \in E_i \) for rotatable type \( i \in I \) that are in the field on the moment the planning is made \( (a_i = 1) \). So, \( F_{i,a_i,e} = F_{i,e}^d \) and \( H_{i,a_i} = H_{i,e}^d \). Note that the superscript \( d \) is used to indicate input parameters.

Overhaul order releases are triggered by required rotatable replacements. When a rotatable is replaced, it is not known which overhaul it will be subjected to, because that depends on the future required rotatable replacements. Thus, non-ready-for-use rotatables are assumed to be identical because it is not yet planned to which overhaul \( e \in E_i \) they will be subjected. By contrast to non-ready-for-use rotatables, ready-for-use rotatables are not assumed to be identical. That is because each replacement requires a rotatable that has been subjected to a specific overhaul \( e \in E_i \).

For rotatables that are not yet in the field \( (a_i > 1) \), the number of ready-for-use rotatables at \( t = a_i \) which have been subjected to the first overhaul \( (e = g_i) \) equals the entire turn-around stock \( S_{i} \in \mathbb{N}^+ \). Therefore, the number of non-ready-for-use rotatables at \( t = a_i \), and the number of ready-for-use rotatables at \( t = a_i \) that have not been subjected to the first overhaul \( (e \in E_i \setminus \{g_i\}) \) equals 0. Thus, \( F_{i,a_i,g_i} = S_{i} \), \( H_{i,a_i} = 0 \) and \( F_{i,a_i,e} = 0 \) \( (\text{for } e \in E_i \setminus \{g_i\}) \) for rotatables that are not yet in the field \( (a_i > 1) \). The turn-around stock levels for rotatable types that are not yet in the field \( (a_i > 1) \) are decision variables. Decision variable \( n_{i,t,e} \) also has initial conditions for \( t \in \{a_i - L_i + 1, ..., a_i - 1\} \) and is denoted by input parameter \( n_{i,t,e}^d \). For rotatables that are already in the field the values for input parameter \( n_{i,t,e}^d \) are known, for rotatables that are not yet in the field the value of \( n_{i,t,e}^d \) is set to 0. Thus \( n_{i,t,e} = n_{i,t,e}^d \) for \( t \in \{a_i - L_i + 1, ..., a_i - 1\} \).

3.2. WORKFORCE CAPACITY IN THE OVERHAUL WORKSHOP

Two types of employees work at the overhaul workshop: (1) employees with fixed contracts and (2) employees with temporary contracts for one aggregated period. The number of employees with a fixed contract is denoted by \( m^f \). The number of employees with a temporary contract in aggregated period \( y \in Y \) is a decision variable and is denoted by \( m^t_y \). Both types of employees are assumed to work \( z \) hours per aggregated period. Moreover, the parameter \( \beta \) denotes the fraction of time employees work on the overhaul processes for rotatables. The total available capacity expressed in labor hours per aggregated period \( y \in Y \) is denoted by \( W_y \). Equation (3.3) describes the relationship between the number of employees and the number of labor hours.

\[
W_y = (m^f + m^t_y) \ast z \ast \beta \quad \forall y \in Y
\]  

(3.3)

The number of labor hours available per regular period \( t \in T \) is denoted by \( w_t \). The number of labor hours per regular period should be flexible in order to cope with varying overhaul order releases per period. The relationship between the labor capacity per regular- and aggregated period is described in equation (3.4).

\[
W_y = \sum_{t \in T^y} w_t \quad \forall y \in Y
\]  

(3.4)

The average number of labor hours during any period \( t \in T^y \) is \( W_y / |T^y| \). The labor hours flexibility per period is restricted by the input parameters \( \delta^l(\delta^u) \), which denotes the lower (upper) bound on workforce flexibility. The constrained workforce flexibility per period is
described in equation (3.5). Equation (3.5) is added to the model in order to reflect the flexibility of the workforce in the R&O workshop due to the possibility of overtime or sickness.

$$\delta^l \cdot \frac{W_y}{T_y^l} \leq w_t \leq \delta^u \cdot \frac{W_y}{T_y^u} \quad \forall y \in Y, \forall t \in T_y^l \quad (3.5)$$

The number of labor hours required, depends on the number of overhaul order releases. Parameter $r_{i,e}$ denotes the required number of labor hours in order to conduct an overhaul of type $e \in E_i$ for rotatables of type $i \in I$. The relationship between the number of order releases and the available workforce is described in equation (3.6).

$$\sum_i \sum_e r_{i,e} \cdot n_{i,t,e} \leq w_t \quad \forall t \in T \quad (3.6)$$

### 3.3. Rotable Availability

The time a capital asset stays in the maintenance depot should be minimized in order to minimize capital asset down time. Therefore, there should always be sufficient ready-for-use rotatables that were subjected to overhaul $e \in E_i$ in stock, in order to meet the number of replacements per overhaul number $e \in E_i$ in period $t \in T_i^l$. The same holds for overhaul order releases; in order to meet the number of overhaul order releases per period $t \in T_i^l$, there must be enough non-ready-for-use rotatables in stock. Note that non-ready-for-use rotatables are assumed to be similar and are subjected to the overhaul number $e \in E_i$ that has a ready-for-use rotable shortage. These rotable availability constraints are described in equation (3.7) and (3.8).

$$\sum_{e \in E_i} n_{i,t,e} \leq H_{i,t} + \sum_{e \in E_i} x_{i,t,e} \quad \forall i \in I, \forall t \in T_i^l \quad (3.7)$$

$$x_{i,t,e} \leq F_{i,t,e} + n_{i,t-\ell_{i,e},e} \quad \forall i \in I, \forall t \in T_i^l, e \in E_i \quad (3.8)$$

### 3.4. Overhaul Deadlines Propagation

Any rotatable has a deadline at which it should be replaced. These deadlines ensure that rotatables rarely break down during usage in the field, which is not allowed due to safety reasons. The number of operational periods before each rotatable type $i \in I$ must be replaced is assumed to depend on the last overhaul the rotatable has been subjected to. This concept is shown in Figure 3.2.

![Figure 3.2: Maximum inter-overhaul deadline example](image-url)
Parameter $q_{i,e}$ denotes the maximum number of periods rotatable type $i \in I$ can be operational after being subjected to overhaul $e \in E_i$. Before the number of operational periods exceed $q_{i,e}$, the rotatable must be replaced by a ready-for-use rotatable that has been subjected to overhaul $(e + 1) \in E_i$.

The number of rotatables of type $i \in I$ that have to be replaced before or in period $t \in T^I_i$ by ready-for-use rotatables that have been subjected to overhaul $e \in E_i$ is denoted by auxiliary variable $D_{i,t,e}$. The deadlines for the first overhaul in the planning horizon ($e = g_i$) are known from data for every rotatable type and are given by parameter $D_{i,t,g_i}$. Hence, $D_{i,t,g_i} = D^d_{i,t,g_i}$. Figure 3.2 shows an example of the dependencies between $q_{i,e}$, $D_{i,t,e}$ and $x_{i,t,e}$.

The deadline of the upcoming overhaul for each rotatable is known. When at least one rotatable has already been subjected to overhaul $g_i$, the deadlines for overhaul $g_i + 1$ for those rotatables are known. Note that this only holds when $k_i \geq g_i + 1$. So, for period $a_i$ up to $\min(a_i, \ldots, \min\{a_i + q_{l,g_i} - 1, p_i\})$, $D_{i,t,g_i+1} = D^d_{i,t,g_i+1}$. The remainder of the deadlines depends on the period each rotatable is lastly replaced. Set $T_{i,e}$ denotes the periods where replacement deadlines of rotatable type $i \in I$ with rotatables that have been subjected to overhaul $e \in E_i$, depend on its previous replacement $(T_{i,e} = \{a_i + q_{i,e-1}, p_i\})$. The dependencies between replacements and deadlines is described in equations (3.9) and (3.10).

$$D_{i,t,e} = x_{i,t-q_{i,e-1},e-1} \quad \forall i \in I, \forall t \in T_{i,e}, \forall e \in \{g_i + 1, \ldots, \min(g_i + 1, k_i)\} \quad (3.9)$$

$$D_{i,t,e} = x_{i,t-q_{i,e-1},e-1} \quad \forall i \in I, \forall t \in T_{i,e}, \forall e \in \{g_i + 2, k_i\} \quad (3.10)$$

It is possible to replace rotatables earlier than necessary in order to balance the workload. Auxiliary variable $U_{i,t,e}$ denotes the number of rotatables of type $i \in I$ that have been subjected to overhaul $e \in E_i$ and are replaced earlier than strictly necessary at the end of period $t$. Rotatables that are replaced earlier than strictly necessary are classified as excess replacements in that particular period. Parameter $U^d_{i,e}$ denotes the number of excess replacements at period $a_i - 1$ of rotatable type $i \in I$ that have been subjected to overhaul $e \in E_i$. Thus, $U_{i,a_i-1,e} = U^d_{i,e}$. The excess replacements balance equation is described in equation (3.11). Equation (3.12) describes the lower bound on the number of replacements, which is equal to the demand minus the number of already replaced rotatables.

$$U_{i,t,e} = x_{i,t,e} - D_{i,t,e} + U_{i,t-1,e} \quad \forall i \in I, \forall t \in T^I_i, \forall e \in E_i \quad (3.11)$$

$$x_{i,t,e} \geq D_{i,t,e} - U_{i,t-1,e} \quad \forall i \in I, \forall t \in T^I_i, \forall e \in E_i \quad (3.12)$$
3.5. **OBJECTIVE FUNCTION**

The objective function of this model is to minimize the total life cycle costs over \(|Y|\) aggregated periods. The life cycle costs can be split up into four categories: labor costs, rotable-acquisition costs, material costs, and replacement costs. The labor costs per hour in aggregated period \(y \in Y\) is denoted by \(c^W_y\). The additional costs to hire employees with a temporary contract in aggregated period \(y \in Y\) is denoted by \(c^{wT}_y\). The acquisition costs of new rotables of type \(i \in I \setminus I_1\) that are not yet active in the field are denoted by the parameter \(c^a_i\). Note that the expected inventory holding costs during the life cycle of rotable of type \(i \in I \setminus I_1\) are included in the acquisition costs. The material costs involved with overhaul \(e \in E_i\) of rotable \(i \in I\) at period \(t \in T^i_i\) is denoted by the parameters \(c^m_{i,t,e}\). The costs of replacing a rotable of type \(i \in I \setminus I_1\) at period \(t \in T^i_i\) is denoted by \(c^r_{i,t}\). The total involved costs during the time horizon is described in equation (3.13).

\[
TRC = \sum_{y \in Y} (c^W_y \cdot W_y + c^{wT}_y \cdot m_y) + \sum_{i \in I | a_i > 1} c^a_i \cdot S_i + \sum_{i \in I} \sum_{t \in T^i_i} \sum_{e \in E_i} c^m_{i,t,e} \cdot n_{i,t,e} 
\]

In order to reflect the investment decisions during the planning horizon, all involved cost parameters can be discounted. Equation (3.14) describes, as an example, the formula to discount the labor hours costs per aggregated period \(y \in Y\). Parameter \(c^W_0\) denotes the basic labor hour costs. An example of the basic labor hour costs can be the labor hour costs of the predecessor of the first aggregated period in the planning horizon. All the costs parameters can be discounted in the same way as is described in equation (3.14).

\[
c^W_y = c^W_0 \cdot \left(\frac{1 + yearly\ price\ increase}{1 + discounting\ factor}\right)^y \quad \forall y \in Y 
\]
3.6. MODEL ASSUMPTIONS

3.6.1. NEW ROTABLE TYPE ASSUMPTIONS
1. Rotable types that will stop being used during the time horizon \((p_i < |T|)\) are replaced by a new rotatable type with the same population size, lead time and the same (discounted) acquisition, replacement and material costs.
2. The first period new capital asset is operational is the same period that the turn-around stock of the bogie types of the new capital asset enter the field.
3. Turn-around stock becomes available at the same period in which the rotatable type enters the field.
4. No additional rotables (of one type) can be bought during the life cycle of the rotatable type.
5. Rotables cannot change type during the planning horizon.
6. Rotables are usable until the moment the capital asset that contains rotatable type \(i \in I\), leaves the field. So, no rotables break down without being able to be repaired during the periods its type is in the field.

3.6.2. INTER OVERHAUL DEADLINES
1. All MIOTs are fixed deterministic time deadlines.
2. All MIOTs depend on the last replacement and the usage in the field.

3.6.3. MAINTENANCE DEPOT
1. The maintenance depots have no capacity restrictions.
2. Rotable replacement times are assumed to be negligible in comparison to the period length.
3. Transportation activities between maintenance depots, inventory stock points and the R&O workshop are included into the overhaul lead times.

3.6.4. OVERHAUL WORKSHOP
1. The efficiency of employees with fixed or temporary contracts are equal.
2. The number of labor hours is the restricting factor in the overhaul workshop. There are always sufficient places to overhaul rotables if there are enough labor hours available.
3. The learning curve of employees is not considered.
4. The contract of employees with a temporary contract starts at the beginning of each aggregated period. There is no maximum on the number of hired employees with a temporary contract.
5. Each rotatable overhaul requires a fixed amount of resources, i.e. labor hours of mechanics and materials.
6. The number of employees with a fixed contract does not change during the planning horizon.

3.6.5. STOCK POINTS
1. Life cycle inventory costs are included in the acquisition costs of the rotables.
2. The inventory location has no capacity restriction.

3.6.6. WITHDRAWN ROTABLE TYPES
1. All rotatable types have a fixed deterministic lifetime.
3.7. Mixed Integer Programming Formulation

The integer variables are restricted to be only integer in the first aggregated period due to the large size of the mixed integer programming model and the corresponding large computational times of the entire MIP model. Restricting the variables to be integer in only the first aggregated period causes no problems, because only the first aggregated period is implemented by the company due to parameter uncertainties.

Sets

- $E_i$: Set of all overhauls per rotable type $i \in I$ considered in the planning horizon.
  \[ E_i = \{ g_i, ..., k_i \} \]
- $I$: Set of all types of rotables.
- $I_t$: Set of all rotable types in the field in period $t \in T$, $I_t = \{ i \in I | a_i \leq t \leq p_i \}$.
- $T$: Set of all periods considered in the planning horizon ($T = \{ 1, ..., |T| \}$).
- $T_i^I$: Set of periods during which rotable type $i \in I$ is active in the field ($T_i^I = \{ a_i, ..., p_i \}$).
- $T_{le}$: Set of periods during which deadlines for replacements of rotable type $i \in I$ that have been subjected to overhaul $e \in E_i \setminus \{ g_i \}$, are dependent on its previous replacement that has been conducted during the planning horizon ($T_{le} = \{ a_i + q_{l,e-1}, p_i \}$).
- $Y$: Set of periods that are contained in an aggregated period $y \in Y$.
- $Y$: Set of aggregated periods ($Y = \{ 1, ..., |Y| \}$).

Input parameters

- $a_i$: First period in the planning horizon that rotables of type $i \in I$ are in the field ($a_i \in T$).
- $H_i^d$: Number of non-ready-for-use rotables of type $i \in I$ available (on stock) at the beginning of period $a_i$.
- $c_i^a$: Acquisition costs of a rotable of type $i \in I \setminus I_1$.
- $c_i^{m,le}$: Material costs associated with the $e^{th}$ overhaul of bogie type $i \in I$ in period $t \in T$.
- $c_i^{le}$: Costs of replacing rotables of type $i \in I$ during period $t \in T_i^I$.
- $c_y^{w}$: Cost per labor hour during aggregated period $y \in Y$.
- $c_y^{c}$: Cost difference per year between a temporary employee and an employee with a fixed contract in aggregated period $y \in Y$.
- $D_{lt,e}^d$: Number of rotables of type $i \in I$, in or before period $t \in \{ a_i, ..., a_i + q_{l,e-1} \}$, that have to be replaced with rotables that have been subjected to the $e^{th}$ overhaul.
- $F_{lt,e}^d$: Number of ready-for-use rotables of type $i \in I$ that have been subjected to overhaul number $e \in E_i$ at the beginning of period $a_i$.
- $g_i$: The first overhaul number of bogie type $i \in I$ considered in the planning horizon.
- $k_i$: The last overhaul number of bogie type $i \in I$ considered in the planning horizon.
- $L_{le}$: The overhaul lead time (in periods) for $e^{th}$ overhaul, for rotables of type $i \in I$.
- $m^f$: Number of employees that have a fixed contract during the entire planning horizon.
- $n_{lt,e}^d$: Number of order releases for the $e^{th}$ overhaul of rotable type $i \in I$ during period $t \in \{ a_i - L_{le}, ..., a_i - 1 \}$.
- $p_i$: Last period in the planning horizon that rotables of type $i \in I$ are in the field ($p_i \in T$).
- $q_{l,e}$: The inter-overhaul deadline of rotable type $i \in I$ after being subjected to the $e^{th}$ overhaul.
- $r_{l,e}$: Amount of labor hours required to start $e^{th}$ overhaul of rotable type $i \in I$. 
\[ U_{i,e} \] Number of in excess replacements of rotables of type \( i \in I \) that have been subjected to the \( e^{th} \) overhaul, at period \( a_i - 1 \).

\( z \) Average number of yearly work hours per employee.

\( \beta \) Input factor that takes into account the lost capacity due to corrective overhauls and breaks. \( 0 \leq \beta \leq 1 \).

\( \delta^l (\delta^u) \) Lower (upper) bound on available labor hours for rotable overhauls expressed as a fraction of \( W_y/|T_y^r| \).

**Auxiliary variables**

- \( H_{i,t} \) Number of non-ready-for-use rotables of type \( i \in I \) available at the beginning of period \( t \in T_i^l \).
- \( D_{i,t,e} \) Number of rotables of type \( i \in I \), in or before period \( t \in T_i^l \), that have to be replaced with rotables that have been subjected to the \( e^{th} \) overhaul.
- \( F_{i,t,e} \) Number of ready-for-use rotables of type \( i \in I \) at the beginning of period \( t \in T_i^l \) that have been subjected to overhaul number \( e \in E_i \).
- \( U_{i,t,e} \) Number of excess rotable replacements of rotable type \( i \in I \), at the end of period \( t \in T_i^l \), with rotables that have been subjected to overhaul \( e \in E_i \).

\[ i.e. \ U_{i,t,e} = \sum_{t'=a_i}^{t} x_{i,t,e} - \sum_{t'=a_i}^{t} D_{i,t,e}. \]

- \( W_y \) Number of labor hours available in aggregated period \( y \in Y \).

**Decision variables**

- \( m_y^\xi \) Number of employees that are hired temporary and do not have a fixed contract in aggregated period \( y \in Y \).
- \( n_{i,t,e} \) Number of order releases for the \( e^{th} \) overhaul of rotable type \( i \in I \) during period \( t \in \{a_i - L_i + 1, ..., p_i\} \).
- \( S_i \) Turn-around stock of rotables of type \( i \in I \).
- \( w_t \) Number of labor hours for overhaul that are allocated to period \( t \in T \).
- \( x_{i,t,e} \) Number of rotable replacements of rotable type \( i \in I \) during period \( t \in T_i^l \), with rotables that have been subjected to overhaul \( e \in E_i \).
minimize \[ TRC = \sum_{y \in Y} (c^w_y * W_y + c^w_T * m^w_T) + \sum_{i \in I \mid a_i > 1} c^a_i * S_i + \sum_{i \in I} \sum_{t \in T^i} \sum_{e \in E_i} c^m_{i,t,e} * n_{i,t,e} \]

\[ + \sum_{i \in I} \sum_{t \in T^i} \sum_{e \in E_i} c^r_{i,t,e} * x_{i,t,e} \]

Subject to

\[ F_{i,t,e} = F_{i,t-1,e} - x_{i,t-1,e} + n_{i,t-l_{i,e}-1,e} \quad \forall t \in I, \forall t \subseteq T^i \setminus \{a_i\}, \forall e \subseteq E_i \quad (3.16) \]

\[ H_{i,t} = H_{i,t-1} + \sum_{e \in E_i} x_{i,t-1,e} - \sum_{e \in E_i} n_{i,t-1,e} \quad \forall t \in I, \forall t \subseteq T^i \setminus \{a_i\} \quad (3.17) \]

\[ F_{i,a_i,e} = F^d_{i,e} \quad \forall i \subseteq I \setminus \{a_i\} \quad (3.18) \]

\[ F_{i,a_i, \emptyset} = S_i \quad \forall i \subseteq I \setminus \{a_i\} \quad (3.19) \]

\[ F_{i,a_i,e} = 0 \quad \forall i \subseteq \{a_i, I_i\}, \forall e \subseteq E_i \setminus \{g_i\} \quad (3.20) \]

\[ H_{i,a_i} = 0 \quad \forall i \subseteq \{a_i, I_i\} \quad (3.21) \]

\[ H_{i,a_i} = H^d_i \quad \forall i \subseteq \{a_i, I_i\} \quad (3.22) \]

\[ n_{i,t,e} = n^d_{i,t,e} \quad \forall i \subseteq I, \forall t \subseteq \{a_i - L_i, ..., a_i - 1\}, \forall e \subseteq E_i \quad (3.23) \]

\[ W_y = \sum_{t \in T^y_y} \quad \forall y \subseteq Y \quad (3.24) \]

\[ \delta^l \times \frac{W_y}{|T^y_y|} \leq w_t \leq \delta^u \times \frac{W_y}{|T^y_y|} \quad \forall y \subseteq Y, \forall t \subseteq T^y \quad (3.25) \]

\[ W_y = (m^l + m^u) * z * \beta \quad \forall y \subseteq Y \quad (3.26) \]

\[ \sum_{i \subseteq I} \sum_{t \subseteq T^i} r_{i,t,e} * n_{i,t,e} \leq w_t \quad \forall t \subseteq T \quad (3.27) \]

\[ \sum_{e \subseteq E_i} n_{i,t,e} \leq H_{i,t} + \sum_{e \subseteq E_i} x_{i,t,e} \quad \forall i \subseteq I, \forall t \subseteq T^i \quad (3.28) \]

\[ x_{i,t,e} \leq F_{i,t,e} + n_{i,t-L_i,e} \quad \forall i \subseteq I, \forall t \subseteq T^i, \forall e \subseteq E_i \quad (3.29) \]

\[ x_{i,t,e} \geq D_{i,t,e} - U_{i,t-1,e} \quad \forall i \subseteq I, \forall t \subseteq T^i, \forall e \subseteq E_i \quad (3.30) \]

\[ U_{i,t,e} = x_{i,t,e} - D_{i,t,e} + U_{i,t-1,e} \quad \forall i \subseteq I, \forall t \subseteq T^i, \forall e \subseteq E_i \quad (3.31) \]

\[ U_{i,a_i-1,e} = U^d_i \quad \forall i \subseteq I, \forall e \subseteq E_i \quad (3.32) \]

\[ D_{i,t,e} = D^d_{i,e} \quad \forall i \subseteq I, \forall t \subseteq T^i, \forall e \subseteq \{g_i\} \quad (3.33) \]

\[ D_{i,t,e} = D^d_{i,t,e} \quad \forall i \subseteq I, \forall t \subseteq T^i \setminus T_{i,e} \quad (3.34) \]

\[ e \subseteq \{g_i + 1, ..., \min(g_i + 1, g_i)\} \quad \forall i \subseteq I, \forall t \subseteq T_{i,e} \quad (3.35) \]

\[ D_{i,t,e} = x_{i,t-g_i-1,e-1} \quad \forall e \subseteq \{g_i + 1, ..., \min(g_i + 1, k_i)\} \quad \forall i \subseteq I, \forall t \subseteq T_{i,e}, \forall e \subseteq \{g_i + 2, k_i\} \quad (3.36) \]

\[ D_{i,t,e} = x_{i,t-g_i-1,e-1} \quad \forall e \subseteq \{g_i + 1, ..., \min(g_i + 1, k_i)\} \quad \forall i \subseteq I, \forall t \subseteq T_{i,e}, \forall e \subseteq \{g_i + 2, k_i\} \quad (3.36) \]

\[ x_{i,t,e} \in N_0 \quad \forall i \subseteq I, \forall t \subseteq \{1, ..., 13\}, \forall e \subseteq E_i \quad (3.37) \]

\[ m^w_T \in N_0 \quad \forall e \subseteq \{1\} \quad (3.38) \]

\[ S_i \in N_0 \quad \forall i \subseteq \{i \mid a_i > 1\} \quad (3.39) \]

\[ 0 \leq U_{i,t,e}, F_{i,t,e} \quad \forall i \subseteq I, \forall t \subseteq T, \forall e \subseteq E_i \quad (3.40) \]

\[ 0 \leq H_{i,t}, H_{t,e} \quad \forall i \subseteq I, \forall t \subseteq T \quad (3.41) \]

\[ 0 \leq W_y \quad \forall y \subseteq Y \quad (3.42) \]

\[ 0 \leq w_t \quad \forall t \subseteq T \quad (3.43) \]
4. ROLLING HORIZON SIMULATION

The model presented in Chapter 3 assumes fixed, deterministic parameter values. In practice, these assumptions never hold because of various uncertainties. One such uncertainty is the maximum inter-overhaul deadlines uncertainty. Maximum inter-overhaul deadlines can change for example due to the results of maintenance researches. The maximum inter-overhaul deadlines influence the replacement deadlines and therefore have a direct and major impact on the aggregated rotable overhaul planning. In this chapter, the maximum inter-overhaul deadline uncertainties are explained, after which the rolling horizon concept is explained. The rolling horizon concept can help to include parameter uncertainties into deterministic mixed integer programming problems.

4.1. MAXIMUM INTER-OVERHAUL DEADLINE UNCERTAINTIES

Maximum inter-overhaul deadlines (MIOTs) are the maximum number of periods a rotable can be operational before it requires to be subjected to an overhaul. Due to major uncertainties related to deterioration processes of a rotable, only the MIOT between overhaul $g_i$ and $g_{i+1}$ described by $q_{i,gi}$ is known in practice. The rest of the maximum inter-overhaul deadlines are uncertain. However, in the planning horizon of the model described in Chapter 3, the real MIOT becomes known at a certain moment. Figure 4.1 shows an example of the different maximum inter-overhaul deadlines over time for the same overhaul.

The example in Figure 4.1 shows that the parameter $q_{i,1}$ can have three possible values for the same overhaul. What value $q_{i,1}$ has, is dependent on the time the planning is made. Assume that the rotable of the example in Figure 4.1 is the first rotable of its population that is replaced at number 1. The bogie is replaced with a rotable that has already been subjected to overhaul $e = 1$. Before this replacement, no information is known on the replacement deadlines of the next overhaul ($e = 2$). This is because no rotable has been replaced yet with an rotable that has been subjected to overhaul $e = 1$. So, before the replacement at number 1 in Figure 4.1, an assumption is made on the length of $q_{i,1}$, called the MIOT assumption. The MIOT assumption can be for example an average of the past MIOT lengths which corresponds with the overhaul type of overhaul $e \in E_i$. 
After the first replacement with a rotatable that has been subjected to overhaul \( e = 1 \), a better prediction on the inter-maintenance deadline can be made. This better prediction is based on the analyzed deterioration processes during overhaul \( e = 1 \). So, after number 1 in Figure 4.1, the replacement deadlines for overhaul \( e = 2 \) can be scheduled with more precision. In the NedTrain case such a better prediction is called the "Plantermijn" as discussed in section 1.3. So in the NedTrain case, after number 1 in Figure 4.1 the MIOT is equal to the PT value \( q_{l,1} = PT \) value.

However, the PT is still a prediction for the actual MIOT. In practice, a maintenance research is conducted in order to research whether the prediction is accurate or not. The maintenance research in the example in Figure 4.1, is scheduled two years before the predicted replacement deadlines. After the maintenance research, the actual MIOT is known. So after number 3 in Figure 4.1, the maximum inter-maintenance deadline is known: \( q_{l,1} = \text{actual MIOT} \).

The example shows that the maximum inter-overhaul deadline of each overhaul is very dependent on the moment at which the planning is made. Because the model developed in Chapter 3 has a planning horizon of the length of a life cycle, not every maximum inter-overhaul deadline is known on the moment of planning. However, during the planning horizon a better prediction and the actual MIOT value become known. Therefore, the rolling horizon concept is used in order to research the long-term cost savings of the model developed in Chapter 3, in the NedTrain case, under MIOT uncertainties.

4.2. ROLLING HORIZON INTRODUCTION

Spitter (2005) researched different planning methods for a supply chain planning problem under demand uncertainty. Solving this problem is highly complex and optimal control is, according to Spitter (2005), even beyond mathematical traceability. Therefore, Spitter (2005) used a rolling horizon simulation in order to compare different methods. The problem that we face in this thesis is very similar to the problem solved by Spitter (2005). In this section, the rolling horizon concept of Spitter (2005) is translated to the problem of this thesis. The visualization of the rolling horizon concept is shown in Figure 4.2.
As is shown in Figure 4.2, the first step of the rolling horizon concept is the determination of the aggregated rotable overhaul planning for the planning horizon \((y, |\mathcal{Y}|)\). In step 2, only the planning for the first aggregated period is implemented. During the first aggregated period, more information about the inter-maintenance deadlines become available due to maintenance researches or the first replacement with a rotable that was subjected to overhaul number \(e \in E_i\). This new information on MIOT values becomes available in step 3 of the rolling horizon concept. The MIOTs and corresponding replacement deadlines are updated in step 4. With the updated parameter values, a new planning is developed. By using the rolling horizon concept, the uncertainties in the maximum inter-maintenance deadlines can be taken into account.

Important to note is that in the 5th and last step, all the other parameter values must be updated. So for example, all initial inventory parameters \((F_{i,e}^d, H_{i}^d)\) in the new planning must become equal to the inventory levels of the last period within the implemented aggregated period. So for example if each aggregated period contains 13 periods, equations (4.1) and (4.2) describe the parameter update for the next planning horizon within the rolling horizon concept.

\[
\begin{align*}
F_{i,e}^d &= F_{i,13,e} & \forall i \in I, \forall e \in E_i \\
H_{i}^d &= H_{i,13} & \forall i \in I
\end{align*}
\] (4.1) (4.2)

All other parameters not involved with the maximum inter-overhaul deadline have to be updated in similar ways as described by equations (4.1) and (4.2). Besides that, new rotables with all corresponding parameters need to be added in the planning whenever a rotable leaves the field during the planning horizon.

In this thesis, we use the rolling horizon concept in order to generate a 30-year planning horizon. This enables us to generate long-term results with the model described in Chapter 3.

The MIOT values should be simulated since not all MIOT values for the upcoming 30-years are known at the moment of conducting the rolling horizon simulation. This can be performed by analyzing the distribution of the past maximum inter-overhaul deadlines. After the determination of the distribution of past MIOTs, MIOTs can be simulated by generating random numbers according to those estimated distributions.
5. CASE STUDY AT NedTrain

This Chapter consists of three parts. The first part describes all the sets, parameter values and decision variables involved with the overhaul processes of bogies at NedTrain. The sets, parameter values and decision variables described in section 5.1 are appropriate for generating a planning between 2016 and 2045, based on the model described in Chapter 3. Section 5.2 describes the simulation of the maximum inter-overhaul deadlines. The MIOTs are simulated in order to compare the long-term effects of the model described in Chapter 3 and the current NedTrain planning method. In section 5.3, we discuss the current bogie overhaul planning method of NedTrain and the developed heuristic that is used in order to generate a 30-year planning based on the NedTrain planning method.

5.1. SETS AND PARAMETER INTRODUCTION NedTrain

The case study involves the overhaul planning of bogies at NedTrain. Bogies are frameworks that connect two wheel sets with the carriage of a train. NedTrain bogies are operational for 30 years. The planning horizon is set to 30 years since the planning horizon of the model of Chapter 3 should be at least one life cycle. An aggregated period is equal to a year and thus the set of aggregated periods is denoted by \( Y = \{1, \ldots, 30\} \). The first aggregated period is 2016 and the last aggregated period in the planning horizon is 2045. Each year is divided in 13 periods with a length of 4-weeks, thus \( T_y = 13 \). Periods with a length of 4-weeks are used because NedTrain plans its replacement and overhaul quantities per 4 weeks. The set of periods considered in the planning horizon is denoted by \( T = \{1, \ldots, 390\} \).

NedTrain is responsible for the maintenance of 52 bogie types at the start of 2016, which corresponds with around 6,000 bogies. In the upcoming 30 years, 19 bogie types will enter the field in order to replace the bogies that leave the field. The set of 19 bogies that enter the field in the upcoming 30 years consist of bogies that are part of new trains. However, only information about the trains that will enter the field in the upcoming 5 years is known. For the remainder of the horizon, each bogie type is replaced with a similar bogie type when it leaves the field. Some comparable bogie types per train series are combined in order to generate a smaller MIP model. The set of all bogie types that are active in the field in the upcoming 30 years is denoted by \( I = \{1, \ldots, 71\} \).

5.1.1. ROTABLE TYPE PARAMETERS

The first and last period that bogie types are in the field is denoted by parameters \( a_i \) and \( p_i \). Table A.1 in appendix A shows the first and last period that each bogie type is in the field. The number of overhauls considered in the planning horizon per bogie is dependent on the time between \( a_i \) and \( p_i \). Based on information of maintenance engineers who are responsible for the determination of the maximum inter-overhaul deadline for specific bogie types, the parameter values \( g_i \) and \( k_i \) have been determined. These values for the first and the last overhaul considered in the upcoming 30 years, per bogie type are shown in Table A.1 in appendix A.

The number of non-ready-for-use rotatables per rotatable type \( i \in I \) at the beginning of the planning horizon is denoted by parameter \( H_{i}^{\text{r}} \). For all rotatables, the number of non-ready-for-use bogies at the beginning of 2016 is equal to 0. The number of ready-for-use bogies at the beginning of 2016 that have been subjected to the first overhaul \( (g_i) \) is set to be equal to the
number of turn-around bogies. This is done because NedTrain does not keep track of the number of non-ready-for-use bogies during the current overhaul planning method and assumes therefore that each bogie in inventory is a ready-for-use bogie. The number of ready-for-use bogies that have been subjected to any other overhaul than \( e = g_i \) is set to 0, since the first overhaul requires the turn-around stock in the beginning of the planning period. The turn-around stock levels per overhaul type is shown in Table A.1 in appendix A.

### 5.1.2. Overhaul Parameters

NedTrain distinguishes large and small overhauls. Each overhaul number \( e \in E_i \) can be either a large or a small overhaul. Which type of overhaul, overhaul number \( e \in E_i \) is, is decided by the maintenance engineer responsible for bogie type \( i \in I \). This decision is made on the rule of thumb that each bogie must be subjected to a large overhaul once every 18 years. The MIOT, the number of labor hours required, and the lead time per bogie type \( i \in I \) and overhaul \( e \in E_i \) are dependent on the decision which overhaul type overhaul \( e \in E_i \) is given. Based on the knowledge of the maintenance engineers, each overhaul number \( e \in E_i \) is either indicated as a small or a large overhaul. The overhaul numbers that are classified as a large overhaul are shown in the 9th column in Table A.1 in Appendix A.

Based on the overhaul type, the number of labor hours required per overhaul and the overhaul lead time is allocated to each overhaul number \( e \in E_i \). Vermeulen (2015) describes that the number of labor hours required per overhaul type differs. Large overhauls require on average 88 labor hours in the R&O workshop, while small overhauls require on average 55 labor hours in the R&O workshop. Besides that, Vermeulen (2015) describes that the average overhaul lead time of a large overhaul is 15 days, while for small overhaul it is only 5 days. The transportation lead time was not included in these numbers. Nevertheless, NedTrain accounts one day for each transportation activity between MDs, inventory locations and the R&O workshop. Therefore, the average overhaul lead time for large and small overhauls are on average 17 and 7 days respectively. However, in the planning method of NedTrain a lead time of one 4-week period is used for both overhaul types. NedTrain uses these general lead times of 4-week because of simplicity reasons during their planning processes. Hence, the lead time for all bogie types \( i \in I \) and overhaul numbers \( e \in E_i \) can be denoted as \( L_{i,e} = 1 \).

\( D^d_{i,t,e} \) denotes the replacement deadlines per bogie type \( i \in I \), per overhaul \( e \in \{ g_i, ..., g_i + 1 \} \), per period in which the replacement deadlines are given by the NedTrain information system. Figure 5.1 elaborates an example in which replacement deadlines with different ready-for-use bogies are known for a bogie type with a population of 100 bogies.

![Figure 5.1: Example of stored replacement deadlines by the NedTrain information system](image-url)

Before the planning is made, 50 bogies have already been subjected to overhaul \( e = g_i \). For those 50 bogies, the replacement deadlines for the next overhaul \( (e = g_i + 1) \) is known. The remainder of the bogies that require a replacement with a bogie that has been subjected to
overhaul \( e = g_i + 1 \), depends on the replacement quantities of the prior overhaul \( (e = g_i) \), which are not yet executed at the moment of planning. The set \( T_{i,e} = \{ a_i + q_{i,e-1}, p_i \} \) denotes the set of periods in which the replacement deadlines are influenced by previous replacements during the planning horizon. Note that \( D_{t,e}^d \) is known for periods \( t \in T_i \setminus \{ t_{i,e} \} \).

The replacement deadlines of rotatables that are already in the field are collected with help of the information system of NedTrain. However, rotatables that will enter the field are not yet in NedTrain's information system. The first replacement deadlines for rotatables that will enter the field during the planning horizon are fixed, deterministic deadlines. The replacement deadlines for the first overhaul are fixed and deterministic because the manufacturer advises NedTrain on the first MIOT after new rotatables enter the field. NedTrain always uses this MIOT to plan the first replacement deadlines. The MIOT given by the supplier is not subject to uncertainties, which causes the fixed and deterministic replacement deadlines for overhaul \( e = g_i \).

The information system of NedTrain stores the "plantermijn" of rotatable \( i \in I \) of overhaul \( e = g_i \) when at least one bogie is replaced with a bogie that was subjected to overhaul \( e = g_i \). The information system of NedTrain stores the actual MIOT of rotatable \( i \in I \) of overhaul \( e = g_i \) when the maintenance research for overhaul \( e = g_i + 1 \) already is conducted. The rest of the maximum inter-overhaul deadlines are not yet known by NedTrain. The bogies in train types SLT and RSLT are an exception on this rule \((i = 30, ..., 35 \) and \( i = 68, ..., 71 \)). The SLT and RSLT trains are completely overhauled once every 6 years, so each MIOT is fixed and known for these corresponding bogies. The MIOTs for which the information system of NedTrain stores no data, are estimated with help of the MIOT averages calculated by Vermeulen (2015): the average MIOT after a large and small overhaul is 2,600,000 and 1,600,000 kilometers respectively.

5.1.3. R&O WORKSHOP PARAMETERS

The number of fulltime employees with a fixed contract at the beginning of 2016 is 41. So, \( m^f = 41 \). Each employee in the R&O workshop works on average 1250 hours per year \((z = 1250)\). The parameter \( \beta \) that describes the lost capacity of employees due to corrective maintenance activities and breaks is equal to 0.765. This number is a multiplication of the percentage of preventive overhaul workload in the R&O workshop (90%) and the percentage of time in which employees do not take breaks (85%). NedTrain uses both percentages in order to calculate their available workforce. The upper \((\delta^u)\) and lower \((\delta^l)\) bound on the workforce flexibility per regular period are equal to 1.1 and 0.9 respectively. These bound values are based on an interview with the team chef of the R&O workshop.

5.1.4. COST PARAMETERS

In this section, the values of the cost parameters are given for the year 2016. These parameter values have been obtained after multiple interviews and analysis with a NedTrain controller. The cost parameter values for successor years are discounted with help of formula (3.14). The discounting factor used by NedTrain is 5% and the prices are assumed to increase every year with 2.5%.

Parameter \( c_y^W \) denotes the labor costs per labor hour and is at the beginning of 2016 equal to €104. Parameter \( c_y^{WT} \) denotes the additional costs per year for hiring one employee with a temporary contract and is equal to €9,000 per year per temporary employee. The material costs per overhaul depend on the overhaul type. When overhaul \( e \in E_i \) is a large overhaul, the
material costs in 2016 are €28,196. When overhaul \( e \in E_i \) is a small overhaul, the material costs in 2016 are €14,303. The bogie acquisition costs for rotables that are not yet in the field, denoted by \( c_i^0 \), are shown in Table A.1 in Appendix A. The replacement costs, denoted by \( c_{it}^r \), are dependent on the bogie type. The replacement costs per bogie type in the first year of the planning horizon are shown in Table A.1 in Appendix A.

5.1.5. Decision Variables

In this section, the decision variables are stated. The decision variables of the current NedTrain bogie overhaul planning method and the model developed in chapter 3 are similar.

- The number of order releases per bogie type, per period, per overhaul type \((n_{i,t,e})\).
- The number of replacements per bogie type, per period, per ready-for-use bogie type \((x_{i,t,e})\).
- The number of temporary employees hired per year \((m_i^t)\).
- The turn-around stock size for bogies that will enter the field during the planning horizon \((S_i)\).
- Number of labor hours for overhaul that are allocated to period \( t \in T \) \((w_t)\).

Based on the results of the decision variables, the corresponding life cycle costs can be calculated. The life cycle costs of both planning methods are used in order to compare both methods on a long-term. The life cycle costs are split up in four different cost categories: bogie acquisition costs, labor costs, material costs, and replacement costs.

5.2. Simulation – NedTrain

In this thesis, we investigate the long-term effects of an integral rotable overhaul and supply chain planning (IROSCP) model that minimizes the total involved costs and considers different dissimilar overhauls. A simulation is conducted in order to compare the IROSCP model with the current NedTrain planning method on a long-term (30 years), under MIOT uncertainty. In section 5.2.1, we explain how the MIOT values are generated. We discuss in section 5.2.2 the simulation set-up and in Section 5.2.3, we explain which software has been used in order to generate the rolling horizon simulation of the IROSCP model. We discuss in section 5.2.4 the verification and validation of the developed simulation tool. Note that the explanation of the NedTrain planning method is discussed in section 5.3.

5.2.1. Maximum Inter-overhaul Deadline Simulation

In order to compare the current NedTrain planning method with the IROSCP model, MIOTs are simulated for 30 upcoming years. The MIOTs are simulated since most MIOTs are unknown. Section 4.1 revealed that the value of the MIOT depends on the moment of generating the planning. The simulation, performed in this thesis, assumes that a MIOT can have three different values dependent on the time at which the planning is generated. These three values are: the MIOT assumption, the PT and the actual MIOT. For example: the maximum inter-overhaul deadline for overhaul \( e \in E_i \) has the value of the MIOT assumption when no bogie has been replaced by a bogie that has been subjected to overhaul \( e \in E_i \). After the period, in which the first replacement by a bogie that was subjected to overhaul \( e \in E_i \) is executed, the MIOT is equal to the PT. The actual MIOT is known after the period in which the maintenance research is conducted. The maintenance research at NedTrain is conducted 2 years before the first rotable reaches its PT.
The actual MIOTs are simulated based on historical data of MIOTs. Vermeulen (2015) shows a difference in actual MIOT values after being subjected to a small or a large overhaul. Figure 5.1 shows the MIOT distributions after being subjected to a small and a large overhaul. These MIOTs per overhaul type are tested with help of the statistical software MINITAB to analyze whether the data follows existing distributions. Both overhaul types tested negative on all tested distributions (normal, lognormal, exponential, Weibull, gamma and logistic). The simulated actual MIOTs that are used in the rolling horizon simulations are assumed to follow a uniform distribution because:

1. The researched sample size is relatively small and clustered. The set of MIOTs after a small overhaul contains 47 data points, while the set after a large overhaul consists of 57 data points. Some of the bogies contain the same MIOT value since the bogies are very related and their deterioration processes are similar. Due to this clustering, the data points are not independent. The dependent data points combined with the small sample size makes it rather difficult to show that the MIOT data follows a distribution.

2. According to the interviews with the Maintenance Engineers, who set the actual MIOT, the level is determined based on the maintenance research and a specific MIOT level has no higher probability of being used than another MIOT level.

3. The researched sample size does not follow any distribution tested. Tested distributions are the normal, lognormal, exponential, Weibull, gamma and logistic distribution.

The sample size could have been tested for more distributions such as the Beta distribution. However, due to the small and clustered sample sizes it is unlikely to test positive on any distribution. In combination with the fact that MIOT levels are randomly picked based on the bogie deterioration processes, the uniform distribution is used to simulate the actual MIOT values.

The densities for simulated actual MIOTs after a small and large overhaul are described in equation (5.2) and (5.3).

\[
 f_{\text{Small}}(x) = \begin{cases} 
 1 & \text{for } 700,000 < x < 2,500,000 \\ 
 \frac{1}{2,500,000 - 700,000} & \text{for } x < 700,000 \text{ and } x > 2,500,000 
\end{cases} 
\] (5.2)

\[
 f_{\text{Large}}(x) = \begin{cases} 
 1 & \text{for } 1,600,000 < x < 3,500,000 \\ 
 \frac{1}{3,500,000 - 1,600,000} & \text{for } x < 1,600,000 \text{ and } x > 3,500,000 
\end{cases} 
\] (5.3)
The PT values are generated from the simulated actual MIOT values since NedTrain does not register historical PT values. The maintenance engineers explained that in practice the PT is between 0% and 30% smaller than the value of the actual MIOT. For the simulation, the PT is dependent on the simulated actual MIOT and can have a value between 70-100% of the actual (simulated) MIOT value.

5.2.2. Computational Problems

For small actual MIOTs, the simulated actual MIOTs cause computational problems. When the actual MIOT during the planning horizon for a specific bogie type appears to be so small that two overhaul types are conducted at the same time, a turn-around stock shortage occurs. This turn-around stock shortage occurs since both overhaul types demand bogies of the same turn-around stock. Both the IROSCP model and the NedTrain bogie overhaul planning method are not capable of coping with these problems, which causes infeasibility. In order to cope with this infeasibility, additional safety stock for both planning methods is added to the determined turn-around stock. Equation (5.4a) describes the formula that is used in order to calculate that safety stock.

\[
SS_i = \left\lceil z_\alpha * \sigma_i * \left( \max_{e \in E_i} \left( L_{i,e} \right) \right)^{\frac{1}{2}} \right\rceil \quad \forall i \in I \backslash I_1 \tag{5.4a}
\]

Parameter \(z_\alpha\) denotes the inverse distribution function of a standard normal distribution with cumulative probability \(\alpha\). In other words, Parameter \(z_\alpha\) denotes a multiplier that corresponds to a chosen confidence level. For both simulations a confidence level of \(\alpha = 0.90\) is used, since it is sufficient to solve the infeasibility problems. Parameter \(\sigma\) denotes the standard deviation of the demand for ready-for-use rotables for some specific rotable type. The demand for ready-for-use rotables is assumed to be Poisson distributed. According to Ramaekers & Janssens (2008), the Poisson distribution provides a reasonable fit in case of low demand rates. Since the variance is equal to the average demand for Poisson-distributed data, the standard deviation is denoted as the square root of the average demand. The average demand is equal to the determined turn-around stock because both bogie overhaul planning methods calculate the turn-around stock by multiplying the average demand times the lead time \((L_{i,e} = 1)\). With this average demand, the safety stock can be calculated:

\[
SS_i = \left\lceil 1.645 * \sqrt{S_i} * \sqrt{\bar{T}} \right\rceil \quad \forall i \in I \backslash I_1 \tag{5.4b}
\]

Note that the safety stock calculated by formula (5.4b) is added to both simulations as ready-for-use stock.
5.2.3. Simulation Set-Up

In this section, the simulation set-up is explained. The simulation set-up consists of the warm-up length determination, the simulation length determination and the determination of the number of replications.

**Warm-up period determination**

The warm-up period is the amount of time that a model needs to run before statistical data collection begins according to Mehta (2000). He describes a method to determine the warm-up period based on the steady state of the system and when that steady state is reached. In our situation the steady state is reached after period 1, because the R&O workshop is fully operational after 1 period.

However, the first replacement deadlines are collected with help of the information system of NedTrain and these deadlines are assumed to be fixed and deterministic. In this thesis, we explore the long-term effects of an aggregate bogie overhaul planning model under MIOT uncertainties. These uncertainties have no influence on the first 5 years because the replacement deadlines are assumed to be fixed and deterministic. Therefore, a 5-year warm-up period is used.

**Run length determination**

Mehta (2000) provides a rule of thumb to determine the run length of any simulation. The author states that a minimum of 15 to 20 random numbers from each random number stream should occur during the planning horizon of the simulation. In our simulation, the only random number stream is the change of the MIOT values. Because we initially wanted to test the long-term effects of the aggregate bogie overhaul planning method under MIOT uncertainties, the run length was set to 30 years (warm-up period included). During this run length, the MIOT values change more than 140 times. Therefore, the simulation run length of 25 years (excluding warm-up period) is long enough according to Mehta (2000).

**Number of replications**

The number of replications have been calculated with the relative precision method of Chung (2004). The relative precision method answers the question: How many replications are needed to reduce the chance of making a wrong recommendation? Before the relative precision methods can be used, an initial number of replications are required to start the analysis. Chung (2004) states that 10 replications is a reasonable number of replications to start the analysis. We used an initial number of 8 replications because of the large simulation computation time (10 hours per replication).

After the 8 initial replications, the relative precision is calculated with help of equation (5.5). The author states that a relative precision of 0.09 is acceptable.

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>Confidence level {0,...,1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>Number of replications used to calculate relative precision</td>
</tr>
<tr>
<td>( s_n )</td>
<td>Standard deviation of replication means with ( n ) replications</td>
</tr>
<tr>
<td>( t_{1-\alpha/2,n-1} )</td>
<td>Probability ( t ) distribution for a double sided confidence interval with confidence interval ( \alpha ) and ( n - 1 ) degrees of freedom</td>
</tr>
<tr>
<td>( \bar{X}_n )</td>
<td>Mean of the ( n ) replication means</td>
</tr>
</tbody>
</table>
Relative Precision = \frac{t_{1-\alpha} \sqrt{n} * s_n}{\bar{X}_n} \quad (5.5)

In our simulation study, we compare both models based on the undiscounted total life cycle costs with a planning horizon of 25 years. Undiscounted cost parameters are used in order to weigh each year equally. Thus, the relative precision is calculated for the undiscounted total life cycle costs with a planning horizon of 25 years with 8 initial replications. Table 5.1 shows the relative precision analysis after 8 replications.

Table 5.1: Relative precision analysis

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>(n)</th>
<th>(s_n)</th>
<th>(t_{1-\alpha} \sqrt{n-1})</th>
<th>(\bar{X}_n)</th>
<th>Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>8</td>
<td>21,931,854</td>
<td>2,365</td>
<td>516,709,332</td>
<td>0.035</td>
</tr>
</tbody>
</table>

As can be seen in Table 5.1, the relative precision is lower than the acceptable level stated by Chung (2004), which indicates that the 8 initial replications are sufficient.

5.2.4. ROLLING HORIZON SIMULATION – SOFTWARE

The rolling horizon simulation of the IROSCP model is conducted with help of three software tools. The IROSCP model is modeled in the GNU mathprog language. The GLPK solver is used to compile the MIP model as a MPS format. The Gurobi solver is used to solve this MPS format. We let Gurobi solve the MIP model, because Arts & Flapper (2015) showed that the Gurobi solver solves the aggregate overhaul planning for rotables the quickest with results as good as other solvers. Because solving the complete MIP causes large computation times, the model is solved with help of a partial MIP relaxation. All integer variables are only integer for the first aggregated period, because only the first aggregated period is implemented. Using a partial MIP relaxation reduces the computation times significantly (Arts & Flapper, 2015).

A combination between VBA and GLPK is used to automatically conduct the rolling horizon simulation. The script programmed in VBA ensures that all input parameters are updated after every generated planning. Updating parameter values are step 4 and 5 of the rolling horizon concept. These updated parameter values serve as input parameter values for the next planning horizon. Examples of parameters that require updates are: inventory parameters, overhaul order releases and cost parameters. After the VBA code updates the parameters, Gurobi solves automatically the newly generated problem. After solving the new instance, the results of the first year of the planning horizon is automatically copied and pasted to the Excel workbook containing all implemented yearly schedules.

5.2.5. ROLLING HORIZON SIMULATION – MODEL VERIFICATION AND VALIDATION

Verification is defined as "processes and techniques that the model developer uses to assure that his or her model is correct and matches any agreed-upon specifications and assumptions" (Carson, 2002). In order to verify whether the conceptual model is correctly translated to a simulation model, three verification methods are used: debugging, a consistency check and extreme value checks.
The first method is used during the development of the simulation tool. Each fault or error in the simulation model is solved. Eventually, the simulation model runs without any faults and errors.

The second method checks for outcome differences when the model is used multiple times for the same instances. This check is done for the whole 30 year time span of the rolling horizon simulation and no different output values are found.

The last method tests whether extreme parameter values causes expected simulation results. This test is executed for the following parameters: ready-for-use stock levels, non-ready-for-use stock levels, and replacement deadlines. In case of a ready-for-use stock level of 0 and an extreme high value for the replacement deadlines, the model appeared to be infeasible. Infeasibility in these cases are logical because insufficient resources were available to meet the replacement deadlines. All extreme value checks provided logical results and therefore passed the tests. Besides these three methods, the model assumptions are checked for the NedTrain case. The result of this model assumptions test is shown in Appendix B.

The validity of a simulation model describes its overall accuracy and the ability to meet the project objectives (Mehta, 2000). In order to check the validity of the rolling horizon simulation model, two validation techniques are tested: face validity and internal validity.

Face validity is described by Irobi et al. (2001) by asking people familiar with the system whether the logic that is used in the conceptual model is correct and whether the input-output relationships are reasonable. The two academic supervisors of this project tested the correctness of the logic of the conceptual model (mathematical IROSCP model developed in chapter 3). The long-term bogie overhaul planner of NedTrain tested the reasonability of the input-output relationships. The model passed both face validity tests.

The internal validity of simulation models is tested by researching the variability of the output. According to (Sargent, 2007 ), a large amount of variability (lack of consistency) may cause the model's results to be questionable. We described in Section 5.2.2 the variability of the output of the simulation model after 8 replications. The output variability was small enough to make reliable recommendations.

5.3. NedTrain's Aggregate Bogie Overhaul Planning
In this section, we describe the NedTrain’s bogie overhaul planning method. The bogie overhaul planning at NedTrain has a planning horizon of two years. The planning is made per bogie type which causes a high deviating workload. The current planning method does not take into account the aggregate overhaul workload in the R&O workshop and in the involved life cycle costs. Since NedTrain does not plan the bogie overhaul planning and its supply chain in one process, the processes are divided into two sub processes: turn-around stock determination and overhaul planning processes. We describe the turn-around stock determination in section 5.3.1 and we describe the bogie overhaul planning processes in section 5.3.2. The result of these two processes result in the workload and the resulting costs, which are both not taken into account during both planning processes. In section 5.3.3, we describe how the NedTrain planning method is used in order to simulate a 30-year planning. The software used to develop such simulation is discussed in section 5.3.4 combined with the verification and validation of this simulation tool.
5.3.1. **Turn-around Stock Determination**

The determination of the number of spare bogies or turn-around stock, for bogies that enter the field is not based on the overhaul planning, because on the moment of purchasing the turn-around stock, no replacement deadlines are known. NedTrain determines the number of turn-around stock for new bogie types \( i \in I \setminus I_1 \) based on the implementation density \( \lambda_i \) and the overhaul lead time \( L \). The implementation density describes the average number of bogies that enter the field every period. For example, when a new bogie type enters the field spread over the upcoming two years and the bogie population is equal to 200, the implementation density per 4-week period is equal to \( \frac{200}{26} = 7.69 \). As described in section 5.1.2, the overhaul lead time for every overhaul and bogie type at NedTrain is the same. Therefore, parameter \( L \) does not depend on a specific bogie type \( i \). The turn-around stock is determined with the help of equation (5.6).

\[
S_i = \lceil \lambda_i \cdot L \rceil \quad \forall i \in I \setminus I_1 \tag{5.6}
\]

Note that, in addition to this formula, a safety stock is incorporated in order to make the simulation feasible. Just as the rolling horizon simulation, the safety-stock is determined with help of equation (5.4a).

5.3.2. **NedTrain’s Bogie Overhaul Planning Method**

NedTrain schedules its bogie overhaul activities for the upcoming two years. This two-year schedule allocates overhauls to 4-week periods. The short planning horizon ensures that for all overhauls within the 2-year planning horizon a MR is already conducted. This fact causes that the MIOTs and their corresponding replacement deadlines are fixed and deterministic for the two-year planning horizon. Therefore, the uncertainties in the MIOT values, do not influence the current planning method of NedTrain.

Important to notice is the fact that NedTrain does not distinguish bogie replacements with bogie overhaul order releases. NedTrain assumes in its planning method that replaced bogies are overhauled almost immediately after being replaced. The result of the planning is a replacement schedule that is also used as overhaul order release schedule. The replacement schedule describes the replacement quantities per bogie type, per overhaul, per 4-week period. The planning method used by NedTrain in order to generate such replacement schedule is explained in the remainder of this section.

**Objective function**

The objective of the current bogie overhaul planning method is to minimize the replacement earliness. Replacement earliness in the NedTrain case is described by the time between the replacement due date and the actual replacement. The due dates are given by the information system and are fixed and deterministic.

**Constraint 1 - No replacement shortage**

The most important constraint in NedTrain its planning method is the constraint that no replacement shortage is allowed. A replacement shortage in period \( t \) occurs when the total replaced bogies until period \( t \) is less than the total demand for replacements until period \( t \). By allowing no replacement shortage, each bogie is replaced before its replacement deadline.
Constraint 2 - Maximum number of replacements

The number of replacements per period per bogie type is restricted by the turn-around stock. Moreover, the maximum number of replacements per period per bogie type is calculated by multiplying the turn-around stock with the lead time. NedTrain assumes a 4-week period lead time for all bogies. The lead-time includes (1) the time between replacements and the start of the overhaul, (2) the overhaul lead time itself, and (3) the transportation leadtime after being overhauled. Hence, all replaced bogies in period \( t - 1 \) become available for replacements in period \( t \). Thus, the maximum number of replacements is equal to the turn-around stock of that bogie.

Constraint 3 - Fixed replacement rate

A minimal deviating number of replacements per period per bogie type is preferred because the long-term planner of the R&O plant prefers a yearly fixed production rate per bogie type per period. This fixed production rate minimizes miscommunication within the R&O plant according to the long-term planner.

A minimal deviating replacement rate per year is obtained by allocating replacements to periods in different steps. The first step allocates the rounded down average number of required replacements per 4-week period to each period. This number is also called the initial production rate and is calculated per year. The second step allocates one additional replacement per period to strategic periods in order to prevent for production shortage. Since a fixed production rate with minimal deviations is preferred, the production shortage of periods is divided over the period with the shortage and prior periods within the two-year planning horizon. A shortage after the second step can occur because replacement quantities in some periods already reached their maximum (turn-around stock). In order to prevent shortages, step 2 is iterated until the production shortage is equal to zero.

The process of allocating replacements to periods with help of different steps is executed per overhaul. When all replacements for all bogies are allocated to the periods, the replacement schedule is complete and is implemented for the first year. The workload in the R&O plant and the involved costs are a result of the developed planning and are not considered in the planning method.
5.3.3. **Planning Method Differences**

In this section, we briefly discuss the main differences between the aggregate rotatable overhaul and supply chain planning method developed in chapter 3 and the current NedTrain planning methods.

- **Objective function**

NedTrain minimizes the replacement earliness in order to minimize the discarded useful life time of bogies. However, it is possible that NedTrain discards useful life time at the end of a bogie’s life cycle. This rest life time can be used in order to reallocate replacements and overhauls to earlier periods in order to prevent big peaks in workload later on. However, reallocating replacements and overhauls too much could result in an extra overhaul at the end of the life cycle, which increases the life cycle costs. Thus, a tradeoff exists between minimizing the variation of demand for overhaul capacity and minimizing the lost useful life. This tradeoff can be expressed in costs during the life cycle; therefore, these life cycle costs should be included in the bogie overhaul planning processes.

- **Planning horizon**

The two-year planning horizon of NedTrain’s current bogie overhaul planning method causes a limited possibility of reallocation replacements and overhauls to earlier periods. Possible overhauls can only be reallocated to earlier periods within the two-year planning horizon. Besides that, possible extra replacements at the end of the life cycle are also not considered because of the two-year planning horizon.

- **Yearly replacement rate with minimal deviations**

In the current NedTrain bogie overhaul planning method, a replacement rate with minimal deviation is preferred. The IROSCP model does not consider a minimal deviating replacement rate. Using a minimal deviating replacement rate minimizes communication errors within the R&O plant and the MDs. However, because of the fixed replacement rate, NedTrain is not able to reallocate replacements and overhauls to periods where the workload is insufficient for all employees with a fixed contract.

- **Turn-around stock determination not based on planning**

NedTrain determines the turn-around stock by using implementation densities. Besides that, no cost effects are considered in determining the turn-around stock. The IROSCP model described in Chapter 3 determines the turn-around stock for new bogies, based on a trade-off between bogie acquisition costs and the replacement, labor, and material costs. When too little spare bogies are purchased, the bogie population should be replaced earlier than necessary. Early replacements could increase the material, labor, and replacement costs due to possible additional overhauls at the end of the life cycle. However, buying too many spare bogies results in too high bogie acquisition costs. This life cycle costs trade-off determines the optimal turn-around stock, which probably decreases the acquisition costs.
5.3.4. NedTrain Bogie Overhaul Planning for the Next 30 Years

In this thesis, the long-term (30 years) effects of an aggregate rotatable overhaul planning, which minimizes the life cycle costs, is researched. In order to evaluate the long term effects, a 30 year planning should be developed according to the current NedTrain planning method. A 30 year overhaul schedule can be composed with parts of the rolling horizon concept. Because MIOT uncertainties do not influence the current NedTrain planning method, step 3 and step 4 of the rolling horizon concept in figure 4.2 are never executed. In other words, a 2-year planning is developed for years \( \{y, y + 1\} \) and the first year of the planning is implemented. After the implementation, a new 2-year planning is made for years \( \{y + 1, y + 2\} \). This process is iterated until a 30-year overhaul planning is created. The simulated actual MIOTs from section 5.2.1 are used to generate the 30-year overhaul planning.

The NedTrain bogie overhaul planning processes and the partly rolling horizon concept are combined in a heuristic. This heuristic describes the steps on how a 30-year bogie overhaul planning can be generated considering the 2-year planning horizon of NedTrain. This heuristic is written in pseudo code and is shown in appendix C combined with the used notation and mathematical formulas for calculating the resulting workload and costs. The considered costs are the same as in Chapter 3: bogie acquisition costs, material costs, labor costs, and replacement costs.

5.3.5. Software, Verification and Validation

The heuristic that is introduced in previous section and elaborated in appendix C is programmed in VBA in order to automatically generate the bogie overhaul planning. Resulting from this planning, the simulation automatically generates the workload and costs per period.

The simulation of the current NedTrain planning method is verified and validated based on the same factors as the rolling horizon simulation. The VBA model is again verified with help of three methods, namely: debugging, consistency check and the extreme value check. The extreme value check is conducted on the same variables as the extreme value check of the rolling horizon simulation. None of these methods showed any problems.

The VBA model has been validated with help of two validation techniques, namely: face validity and internal validity. The long-term planner of bogie overhauls checked the correctness of the logic of the conceptual model and the reasonability of the input-output relationship. No problems are detected during both validity checks. The internal validity is checked with help of formula (5.5), which checks the variability of the output. The output variability was small enough to make reliable recommendations.
6. CASE STUDY RESULTS

This chapter describes the results of the case study conducted at NedTrain, which are obtained by using the IROSCP model in a rolling horizon simulation. The results of the rolling horizon simulation are compared with the results of the simulation of the current NedTrain planning method. The key performance indicators that are used to compare both methods are bogie acquisition costs, material costs, labor costs, and replacement costs. The costs in this section are not discounted because no investment decisions are made and the costs of a year should weigh as much as any other year. Section 6.1 describes the case study results. In Section 6.2, the sensitivity analysis that is performed on the IROSCP model is described. We describe in section 6.3 how the developed IROSCP model is implemented within NedTrain.

6.1. CASE STUDY RESULTS

![Workload at the R&O workshop per 4-week period](image)

Table 6.1: Costs savings in optimized situation per costs type

<table>
<thead>
<tr>
<th>Costs Type</th>
<th>Average costs savings in optimized situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor costs savings</td>
<td>7%</td>
</tr>
<tr>
<td>Material costs savings</td>
<td>0%</td>
</tr>
<tr>
<td>Acquisition costs savings</td>
<td>26%</td>
</tr>
<tr>
<td>Replacement costs savings</td>
<td>0%</td>
</tr>
<tr>
<td>Total costs savings</td>
<td>4%</td>
</tr>
</tbody>
</table>

![Box plot of costs savings per costs type](image)
6.1.1. **Workforce Utilization**

Figure 6.1 shows the workload in the R&O workshop for 2021 until 2045. The blue line denotes the workload that results from the simulation with the current NedTrain planning method discussed in section 5.3. The red line denotes the workload that results from the rolling horizon simulation with the model described in Chapter 3.

In Chapter 2, we discussed that the workload in the R&O workshop deviates significantly. The deviating workload causes that the workload in some periods is not sufficient for all the employees with a fixed contract. However, in other periods, the workload exceeds the fixed workforce capacity and temporary employees are required in order to cope with the high workload. The blue line in Figure 6.1 confirms the statement of a deviating workload. The big dips in workload cause an average fixed workforce utilization between 2021 and 2045 of 88%. This utilization denotes the percentage of time the workload is sufficient for all employees with a fixed contract. Currently, NedTrain does not reallocate overhauls to previous periods in order to maximize the fixed workforce utilization because their objective is to minimize the replacement earliness. By reallocating bogies to earlier, non-busy periods, costs for hiring additional employees can be avoided, as can be concluded from the results.

The red line in Figure 6.1 shows the workload of the model that minimizes the total lifecycle costs. Interesting to see is the fact that the model ensures a fixed workforce utilization of approximately 100%. A strongly deviating workload causes high costs due to unnecessary hired employees. Moreover, the IROSCP model reallocates overhauls to periods with less workload in order to minimize the extra hired temporary employees later in the planning horizon. The IROSCP model minimizes the extra hired temporary employees since the model minimizes the total life cycle costs.

Interesting to notice is the fact that, if the fixed workforce utilization is 100% in all periods, the overhauls are not reallocated anymore. Examples of such situations are the years 2031, 2032 and 2044. The model cannot find any possible savings anymore and therefore, the bogies are replaced as close as possible to the replacement deadline. In such situations, bogies are replaced, as close to the replacement deadline as possible, because the cost factors in the IROSCP model are discounted and it is the cheapest to replace the bogie as late as possible.
6.1.2. Bogie Life Cycle Costs

In this section, the results of both simulated planning methods are described per cost factor. The four involved costs factors are: bogie acquisition costs, replacement costs, labor costs, material costs. The composition of the total costs is shown in figure 6.3. As can be seen in figure 6.3, the total costs during the 25-year simulation horizon exist for 67% out of material costs involved with overhauling a bogie. Labor costs account for 25% of the total costs, while the replacement costs in MDs and the turn-around stock acquisition costs account for 3% and 5% respectively.

![Composition of costs during the 25-year simulation horizon](image)

**Figure 6.3: Composition of costs during the 25-year simulation horizon**

**Acquisition costs**

As Figure 6.2 shows, the turn-around stock determination based on the overhaul planning, causes an average decrease of 26% in bogie acquisition costs. NedTrain determines the turn-around stock for new bogies based on the implementation density. The implementation density is the average number of bogies that enter the field per period. The IROSCP model determines the turn-around stock for new bogies, based on a trade-off between bogie acquisition costs and the replacement, labor and material costs. When the turn-around stock is equal to one bogie, the bogie population should be replaced earlier than necessary because of the small turn-around stock. This earlier replacements increase the labor, material and replacement costs due to the discounted costs factors. Besides that, possible additional overhauls require to be conducted at the end of the bogie life cycle, due to the early replacements. On the other hand, a turn-around stock as large as the bogie population causes high bogie acquisition costs, but relatively low labor-, replacement- and material costs. Hence, this contradiction causes a costs trade-off; the IROSCP model finds the optimal number of turn-around stock bogies based on this trade-off. Note that for both methods a safety stock is added in order to cope with the possibility of a small, simulated actual MIOT value. Figure 6.3 shows that the bogie acquisition costs savings per simulation replication do not vary much. Thus, the IROSCP model ensures an optimal replacement schedule which corresponds to an optimal turn-around stock level.
Replacement costs

Bogies are replaced with ready-for-use bogies in one of the 4 maintenance depots of NedTrain. With these replacements, replacement costs are involved. Table 6.1 shows that the IROSCP model causes no decrease or increase in replacement costs. This result is intuitively explainable because the IROSCP model replaces as many bogies during the 25-year simulation horizon as the NedTrain planning method. In some cases, extra overhauls are required at the end of a bogie’s lifecycle. These extra overhauls can occur when replacements during the planning horizon are reallocated to earlier periods than necessary and the MIOT after these replacements appeared to be smaller than expected. However, these cases occur rarely and do not have a significant effect on the total replacement costs, as can be concluded from Table 6.1.

Labor costs

The labor costs at the R&O workshop are dependent on the total required labor hours per period and the number of hired temporary employees per year. These cost factors together describe the total labor costs at the R&O workshop. The labor costs of the IROSCP model described in chapter 3 causes a 7% cost reduction in comparison to the current NedTrain planning method. The IROSCP model reallocates workload from periods with a high workload to periods in which the workload is less than the fixed workforce capacity. By reallocating overhauls to earlier periods, the number of temporary employees that are needed to be hired decreases. This decrease consequently causes a decrease in labor costs. Figure 6.2 shows that the bogie acquisition costs savings per simulation replication varies slightly. This variation is caused by the workload reallocation possibilities: a low fixed workforce utilization provides more opportunities to the IROSCP model to reallocate workload to earlier periods, compared to a high fixed workforce utilization. The more the workload is reallocated to earlier periods in which the workload is insufficient for employees with a fixed contract, the less the labor costs becomes. Thus, the 7% decrease in labor costs is intuitively explainable because the workload is reallocated to periods in which the workload is insufficient which results in less labor costs due to less required temporary employees.

Material costs

The total material costs at the R&O workshop of the IROSCP model does not increase or decrease in comparison to the current NedTrain planning method. This result is intuitively explainable since both models conduct approximately the same number of overhauls. In some rare cases, extra bogie overhauls occur at the end of a bogie life cycle. These extra overhauls can occur when replacements during the planning horizon are reallocated to earlier periods than necessary and the MIOT after these replacements appeared to be smaller than expected. However, these cases occur rarely and do not have a significant effect on the total material costs.

6.2. Sensitivity Analysis Mathematical Model

In this section, a sensitivity analysis is conducted on the mathematical IROSCP model developed in chapter 3. The sensitivity analysis is conducted by adjusting three parameter values: the number of employees with a fixed contract \(m_f\), the number of labor hours required to start the \(e^{th}\) overhaul of bogie type \(i \in I\left(r_{i,e}\right)\), and the overhaul lead time for overhaul \(e \in E_i\) of bogie
type \( i \in I (L_{i,e}) \). The effect of the number of employees with a fixed contract is analyzed because we expect that an increase could cause a more balanced workload and consequently, a decrease in life cycle costs. We expect the same effect when the number of labor hours required per overhaul decreases. The effect of the overhaul lead time is researched because we want to know whether the system can manage a sudden increase. In order to generate the results of the sensitivity analysis, a planning is created with increased and decreased parameters values. Besides, a rolling horizon simulation in all cases is conducted in order to research the parameter effects under MIOT uncertainties. Because of time limitations and high computational times (10 hours), the effects per changed parameter value are evaluated based on 1 planning and 1 simulation replication. This should not cause major problems because the various simulation replications showed that there is not much variation in results. However, some caution is required when evaluating the results.

The effects of the first two parameters \((m_f & r_i,e)\) are examined by increasing and decreasing the parameter values with 10%. We study the effect of the last parameter \((L_{i,e})\) by increasing the lead time with one 4-week period. The effect of a decreased lead time is not considered because the lead-time value should be a multiple of the length of a regular period, which is thus 1 period at minimum. A summary of the parameter values during this sensitivity analysis is shown in table 6.1.

**Table 6.1: Sensitivity analysis set-up**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Decreased situation</th>
<th>Normal situation</th>
<th>Increased situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_f)</td>
<td>37 employees</td>
<td>41 employees</td>
<td>45 employees</td>
</tr>
<tr>
<td>(r_i,e)</td>
<td>50 hours (small overhaul)</td>
<td>55 hours (small overhaul)</td>
<td>60 hours (small overhaul)</td>
</tr>
<tr>
<td>(L_{i,e})</td>
<td>79 hours (large overhaul)</td>
<td>88 hours (large overhaul)</td>
<td>97 hours (large overhaul)</td>
</tr>
</tbody>
</table>

6.2.1. **PARAMETER 1 – NUMBER OF EMPLOYEES WITH A FIXED CONTRACT**

As shown in figure 6.1, the fixed workforce is for most periods not sufficient to cope with the high workload. We expected that by hiring more employees with a fixed contract, the workload become more balanced. A more balanced workload results in decreased life cycle costs because less temporary employees need to be hired. Figure 6.3 shows the normalized total life cycle costs for the original instance with \(m_f = 41\).
As can be seen in figure 6.3, the number of employees with a fixed contract does have a negative relationship with the total life cycle costs according to the planning instance. A negative relationship is intuitively explainable since more workload can be reallocated to periods in which the workload is not sufficient for all employees with a fixed contract. However, the rolling horizon simulation showed contrary results. In the rolling horizon instance, the number of employees with a fixed contract has a positive relationship with the total life cycle costs. This positive relationship is caused by cases in which extra overhauls must be executed at the end of the life cycle. Extra overhauls at the end of the life cycle are caused by reallocating replacements to earlier periods during the planning horizon. After these replacements, the actual MIOT appeared to be smaller than expected, which can causes extra overhauls at the end of the life cycle.

However, as is shown in figure 6.3, the number of employees with a fixed contract does not have a major influence on the total life cycle costs. No major effect is found because the money saved by replacing temporary employees with employees with a fixed contract saves only €9,000 per employee, which is insignificant for the total life cycle costs.

### 6.2.2. Parameter 2 – Required Labor Hours per Overhaul

In the rolling horizon simulation, we assumed that each large overhaul requires 88 labor hours and a small overhaul requires 55 labor hours. In this section, the effect of varying the required number of labor hours per overhaul type on the total life cycle costs is analyzed. In practice, this variation can be caused by a changed labor efficiency level, a change in corrective workload at the R&O workshop or a wrong prediction. Figure 6.4 shows the normalized total life cycle costs for the original instance with $r_{i,e} = 55/88$.

Figure 6.4 shows the effects of a 10% change in the number of required labor hours. A 10% decrease in required labor hours per overhaul causes a 2% decrease in total life cycle costs. The case in which the required labor hours per overhaul increase with 10% results in increased total life cycle costs of approximately 2%. A 10% change in required labor hours logically causes approximately a 10% change in labor costs in the same direction. When the labor costs change with approximately 10%, the total life cycle costs change in the same direction with approximately 2%, which is logical since the labor costs account for approximately 25% of the total life cycle. As shown in figure 6.4, the sensitivity analysis provides no significant differences between the planning instance and the rolling horizon instance.
6.2.3. Parameter 3 – Overhaul lead times

In order to investigate how the model would react to a sudden increase of the overhaul lead time, the overhaul lead time is raised to two 4-week periods. When the planning was developed with the adjusted lead time parameter value, the model appeared to be infeasible. The infeasibility of the model is logical since the increased lead time causes that the demand during two regular 4-week periods can never exceed the turn-around stock. However, the turn-around stock of rotables in the field was determined based on a one 4-week period lead time. So, too less turn-around bogies are available in order to cope with an increased lead time.

6.3.4 Importance of other parameter values

In the previous three sections, a sensitivity analysis is described on three different input parameters. However, these parameters are not the only parameters with an influence on the planning. The input replacement deadlines \( (D_{it,e}^d) \), the past overhaul order releases \( (n_{it,e}^d) \), the ready and non-ready-for-use stock levels \( (F_{it,e}^d, H_{it}^d) \) and the cumulated number of earlier than necessary replaced bogies \( (U_{it,e}^d) \) are of major importance for the results of the mathematical IROSCP model. The GLPK sensitivity analysis report shows that an increase or decrease does not have a major impact on the total life cycle costs (<0.01%), when the model is feasible. However, an increase or decrease could ensure that the model becomes infeasible. For example, if four bogies are required to be overhauled in the first period of the planning horizon and only three ready-for-use bogies are available, the model is infeasible. Such an example can occur when the parameter values are not collected at the same moment. Therefore, it is of a major importance that NedTrain collects the data for the parameters at the same moment.

6.3. Model implementation

As shown in previous sections, the IROSCP model causes a decrease of 4% in life cycle costs. In order to decrease the life cycle costs in practice, the model should be easy accessible and easy in use for the long-term main-parts planner of NedTrain. Therefore, we modeled a data input tool that reformat the data of the information system to the MIP input format. The input tool guides the user systematically through the process of collecting and implementing the right data in the input tool. After collecting the necessary data, the tool controls the data on completeness. Furthermore, it enables the user to adjust parameters in order to conduct the sensitivity analysis. After collecting data and setting all parameter values, the input tool reformats the data in matrices, which is subsequently used as the input for the MIP model.

The input tool is able to run the GUROBI solver automatically and to report the output of the MIP model to the operational users. However, NedTrain does not have a Gurobi license. The IROSCP model is also programmed in the open GLPK solver that can be used directly by NedTrain. Since the GLPK solver is approximately 40 times as slow as the Gurobi solver, the partial MIP model is transformed to a linear programming (LP) model. By transforming the model to a LP model, NedTrain is able to gain optimal results in approximately 10 hours.

Besides generating the necessary input for the IROSCP model, the input tool also shows the results of the solver. The output of the solver is automatically updated in the input tool. However, the results are not integer, which causes implementation problems. This problem is fixed by rounding up the decision variables in a smart way. If for example in each period, the replacement rate is 0.5 bogies, the input tool schedules a replacements once every 2 periods. By managing the non-integer decision variables in this way, the optimal solution can still be used.
The data input tool is still under construction and will be completed in the weeks after graduation. Nevertheless, Appendix D shows some intermediate example screenshots of the data input model that guides the user in generating and formatting the necessary data.
7. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this master thesis project was twofold. On one hand, NedTrain initiated this project to support the change from a short-term bogie overhaul planning to a long term bogie overhaul planning. NedTrain requested a planning tool that can be used to schedule bogie overhauls such that the bogie overhaul costs during the life cycle are minimized. On the other hand, the aim was to fill the gap in literature concerning the situation where different dissimilar overhauls are conducted in the R&O workshop and the corresponding MIOTs depend on the last conducted overhaul. In section 7.1, the conclusions of the master thesis project are described. The conclusions are split up in conclusions for academics and conclusions for NedTrain. We describe the recommendations in section 7.2. The recommendations are split up in recommendations for academics and for NedTrain.

7.1. CONCLUSIONS

7.1.1. CONCLUSIONS FOR ACADEMICS
As described in section 2.2, Arts & Flapper (2015) developed a model for the aggregate overhaul planning of rotables that minimizes the total life cycle costs. They assumed that all overhauls are similar and the maximum inter-overhaul deadline between two overhauls are fixed and the same per bogie type. This assumption does not hold in practice and in current literature, no model schedules rotatable overhauls considering different dissimilar overhauls. This literature gap is filled in this master thesis. In Chapter 3, we developed the IROSCP model that schedules the aggregate rotatable overhaul planning distinguishing different types of overhauls, which makes the planning more accurate. The distinction between different overhauls enables companies to model different overhaul types and to model the dependency of the MIOT on the last conducted overhaul. The distinction between different overhaul types has not yet been modelled in the literature.

Since even the fastest MIP solver was not able to solve the full MIP model, the model is changed to a partial MIP model. For that mode, the decision variables are only required to be integer in the first aggregated period, since only that period is actually implemented.

The IROSCP model schedules bogie overhauls such that the total involved lifecycle costs are minimized. The total life cycle costs in 25 years decreases on average with 4% by using the IROSCP model compared to the current NedTrain bogie overhaul planning method. The main cause of this cost reduction is a result of the reallocation of overhauls to earlier periods in order to fill up the fixed workforce utilization.

We also tested the sensitivity of the IROSCP model in the NedTrain case. The sensitivity analysis was conducted for only one planning instance and one rolling horizon instance, which implies that the results of this analysis are only an indication of the real effects. The sensitivity analysis showed that a 10% change in number of employees, does not influence the total life cycle costs much. A 10% change in the required number of labor hours per overhaul corresponded with a change of approximately 10% in labor costs in the same direction. Because the labor costs account for approximately 25% of the total life cycle costs, the total life cycle costs changed with only 2%.
7.1.2. **Conclusions for NedTrain**

NedTrain demanded that this master thesis project resulted, among other things, in an operational usable planning tool, which schedules bogie overhauls on a long term (30 years). The developed IROSCP model in chapter 3 accomplishes this goal of NedTrain.

In this thesis, we showed that the developed planning tool results in a more balanced workload over the years. The workload of periods where the workload exceeds the fixed workforce is reallocated to earlier periods that are not fully utilizing the fixed workforce. This shift results in less required temporary employees, which decreases the involved costs. The reallocation of workload results on average in a decrease in labor costs of 7%. Important to note is that the model only reallocates overhauls to earlier periods if that does not result in additional overhauls at the end of the life cycle. However, when the actual MIOT after implementing the planning appeared to be smaller than expected, extra overhauls at the end of the life cycle can occur. Nevertheless, these extra overhauls occur rarely and the corresponding extra costs are insignificant compared to the labor costs savings due to workload reallocation.

The developed model also decreases the purchased number of turn-around rotables on average with 26%. This reduction is caused due to another method for determining the number of required turn-around stock. While NedTrain determines the turn-around stock for new bogies based on the implementation density, the IROSCP model determines the turn-around stock for new bogies based on a trade-off between bogie acquisition costs and increased replacement, labor, and material costs. For this trade-off, it is necessary to include the turn-around stock decision in the planning model.

The sensitivity analysis showed that a change in the number of employees with a fixed contract and the number of labor hours required per overhaul do not have large influence on the total life cycle costs. This finding is mainly caused by the fact that the labor costs only account for 25% of the total life cycle costs. Besides that, we showed that NedTrain is not able to cope with an 8-week lead-time because of too less available turn-around stock. However, managing a lead time of 8 weeks is very unlikely because the current overhaul lead times are between 1 and 3 weeks. Besides showing the effects of various parameters on the total life cycle costs, we showed as well that five other input parameters are of major importance for the feasibility of the system.
7.2. **RECOMMENDATIONS**

7.2.1. **RECOMMENDATIONS FOR ACADEMICS**
An interesting subject for further research is to increase the number of uncertainties in the rolling horizon simulation. Uncertainties that can be included into the rolling horizon simulation are for example uncertainties in the operational number of kilometers per period, or in the length of the lifetime of a rolling stock type. Basten (2013) developed an algorithm that takes into consideration uncertainties due to the usage of rolling stock in the field. The output of the algorithm is used in her thesis as input for a mathematical model similar as the model developed in this thesis. Including multiple uncertainties could result in a better prediction of the long-term costs for the optimized model. Therefore, it is an interesting area for further research.

Besides that, it can be interesting to research the influence of the length of the planning horizon. Decreasing the length of the planning horizon of the IROSCP model implies lower computational times, which makes the model more flexible and usable for NedTrain. However, not taking into account the complete life cycle could imply additional overhauls at the end of the life cycle. These extra overhauls are caused by the fact that only the effects of reallocating replacements on part of the life cycle are considered.

For reliability reasons, the sensitivity analysis should be extended with at least 7 more replications. In this thesis, the sensitivity analysis is based on only one planning instance and one rolling horizon simulation replication. Therefore, the results of the sensitivity analysis are only indications for the effects of the parameters. Besides that, it would also be interesting to see the effect of a reduced the lead-time. In order to research the effect of smaller lead times, the number of regular periods per aggregated period should be increased because the lead times must be an integer multiple of the length of one regular period and the current lead time is already minimal (i.e. one 4-week period).

Furthermore, a capacity restriction on the number of hired temporary employees could be interesting to research. In this thesis, we assumed that as many temporary employees can be hired as needed. However, it would be intuitively explainable to set a max on the number of hired temporary employees since each temporary employee has to become familiar with the conducted activities in the R&O workshop. By adding a restriction on the number of temporary hired employees, the model becomes more practical.
7.2.2. **RECOMMENDATIONS FOR NEDTRAIN**

The case study conducted at NedTrain leads to some additional, more specific recommendations for NedTrain than the ones described in section 7.2.1.

The most important recommendation for NedTrain is the recommendation to start using the planning tool developed during this master thesis project. As the rolling horizon simulation shows, the long-term planning of overhauls results in decreased costs and an optimized fixed workforce utilization.

In the sensitivity analysis, we showed that it is important to collect all the necessary data at the same moment in order to prevent for model infeasibility. Thus, the required data for the MIP model should be collected at the same moment.

We used a combination of the GLPK solver and the Gurobi solver in this thesis to solve the MIP model described in Chapter 3. NedTrain does not have a license for Gurobi. However, the aggregate bogie overhaul and supply chain planning model can also be solved by the GLPK solver. The GLPK solver is an open solver, which is significantly slower than Gurobi. Because the GLPK solver is significantly slower, the IROSCP model is solved as a linear programming problem. By solving the model as a linear programming (LP) problem, the model creates a planning within 12 hours. We did not research the difference between the partial MIP model and the rounded up results of the LP model. We expect that the rounded up results still give better results as the current planning method. However, we recommend to investigate the optimality gap between the rounded up results of the LP model and the partial MIP model. When the optimality gap is quite large, we recommend that NedTrain should consider purchasing a Gurobi license.

In the IROSCP model we did not schedule replacements and overhauls by a fixed replacement rate per period per bogie type. However, the current NedTrain planning method takes into account this fixed replacement rate in order to minimize miscommunications between MDs and the R&O workshop. In order to let the IROSCP model be a success in practice, NedTrain should develop a communication system that minimizes the miscommunications between the MDs and the R&O workshop without having a fixed replacement rate.

During the search for parameter values, one of the many information systems of NedTrain was used. The data collection that describes the replacement deadlines per individual bogie was unstructured and unorganized. Multiple nametags are used for the same maintenance activity and some due dates from the past are still in the system. It would be valuable to standardize the input that each NedTrain employee enters in the information system to make the information system more usable for other employees within NedTrain.

We gave proof in this thesis for decreased lifetime costs by using the IROSCP model. It would be interesting for NedTrain to research the possibilities for extending this model to multiple main-parts, such as air-conditioning units and wheelsets.
BIBLIOGRAPHY


## Appendix A – Bogie Types Specification

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APPENDIX B – MODEL ASSUMPTIONS CHECK

B.1. NEW ROTABLE TYPE ASSUMPTIONS

1. Rotable types that will stop being used during the time horizon \( (p_i < |T|) \) are replaced by a new rotable type with the same population size, lead time and the same (discounted) acquisition, replacement and material costs.

   Bogies are in practice within a year replaced with rotables of a new train type. This train type has most of the time the same usage purpose (long or short distances as the old train type). Because the usage purpose of the new trains is similar, the bogie types are quite comparable, which makes the assumption valid.

2. The first period new capital asset is operational is the same period that the turn-around stock of the bogie types of the new capital asset enter the field.

   Because spare bogies are needed for possible corrective replacements during the complete life cycle of the bogies, the spare bogies are purchased together with the operational bogies. Therefore this assumption is valid.

3. Turn-around stock becomes available at the same period in which the rotable type enters the field.

   All the bogies are purchased before the new train type enters the field, which makes this assumption valid.

4. No additional rotables (of one type) can be bought during the life cycle of the rotable type.

   NedTrain is able to buy additional bogies during their life cycles. However, additional spare bogies are never purchased because the lead times are way too long.

5. Rotables cannot change type during the planning horizon.

   In order to cope with unexpected demand for international travel activities, NedTrain did transform bogies of type in order to cope with this demand. However, a change of bogie type is very exceptional and happens hardly ever, which makes this a valid assumption.

6. Rotables are usable until the moment the capital asset that contains that rotable type leaves the field. So, no rotables break down without being able to be repaired during the periods its type is in the field.

   Bogies can become not repairable after events such as a crash or a fire. However, because these events hardly ever occur, this assumption is valid.
B.2. INTER OVERHAUL DEADLINES
1. All MIOTs are fixed deterministic time deadlines.

   The MIOTs are fixed deterministic time deadlines for the time being. NedTrain uses mileage deadlines as well. However, together with the average mileage per regular period, the MIOT is translated into a time deadline.

2. All MIOTs depend on the last replacement and the usage in the field.

   Vermeulen (2015) gave proof for this assumption, which makes this a valid assumption.

B.3. MAINTENANCE DEPOT
1. There are no capacity restrictions in the maintenance depots.

   In practice, the MDs have a capacity restriction on the train track at which bogies are replaced. However, according to the planners of the MDs, the workload will never become so high that it will exceed the capacity. Therefore, the assumption of no capacity restrictions for the MDs is valid.

2. Rotable replacement times are assumed to be negligible in comparison to the period length.

   One bogie replacement takes around 3 or 4 hours which is around 0.5% of a 4-week period. Therefore, this assumption is valid.

3. Transportation activities between maintenance depots, inventory stock points and the R&O workshop are included into the overhaul lead times.

   The actual overhaul lead times have a maximal value of 17 days and the transportation lead times per transportation activity is one day. The total overhaul plus transportation lead time will always be less than the assumed one 4-week lead time. Therefore, it is reasonable to assume that the transportation times are included into the overhaul lead times of one 4-week period.

B.4. OVERHAUL WORKSHOP
1. The efficiency of employees with fixed or temporary contracts are equal.

   After the training period of temporary employees, the efficiency of employees with a fixed and temporary contract is similar. Because during the training period the temporary employees are not scheduled to specific overhaul activities, the assumption is valid.

2. The number of labor hours is the restricting factor in the overhaul workshop. There are always sufficient places to overhaul rotatables if there are enough labor hours available.

   The number of labor hours is the restricting factor for NedTrain.

3. The learning curve of employees is not taken into account.

   NedTrain does not take into account the learning curve of employees in the bogie overhaul planning, which makes this assumption valid.
4. The contract of employees with a temporary contract starts at the beginning of each aggregated period. There is no maximum on the number of hired employees with a temporary contract.

Temporary employees start their first shift in the beginning of the year and according to the long-term planner of the R&O workshop, the R&O workshop did never use a maximum number of hired employees. The required number of temporary employees is hired every year in order to meet the demand for bogie overhauls, which makes this assumption valid.

5. Each rotable overhaul requires a fixed amount of resources, i.e. labor hours of mechanics, materials.

Each individual overhaul of the same overhaul type uses the same number of labor hours and materials because all the activities conducted during an overhaul are the same for that overhaul type.

6. The number of employees with a fixed contract does not change during the planning horizon.

No plans are made in order to increase or decrease the number employees with a fixed contract, which makes this a valid assumption.

B.5. STOCK POINTS
1. Life cycle inventory costs are included in the acquisition costs of the rotables.

The holding costs for rotables on stock that are ready-for-use and the ones that need overhaul are equal. This is a fixed amount per period over the planning horizon. Therefore it is valid to incorporate this in the procurement costs.

2. There is no restriction on the inventory capacity.

The inventory capacity is relatively large compared to the number of rotables in stock, which makes this a valid assumption.

B.6. WITHDRAWN ROTABLE TYPES
1. All rotable types have a fixed deterministic lifetime.

At the moment of entering the field, the moment that the bogie leaves the field is known. The moment that a bogie leaves the field can change, but this rarely happens. Therefore, this assumption is valid.
C.1. Notation

Sets

- $E_i$: Set of all overhauls per bogie type $i \in I$ considered in the planning horizon. $E = \{g_{i_1}, ..., g_{i_k}\}$.
- $I$: Set of all types of bogies in the planning horizon.
- $I_t$: Set of all bogie types in the field in period $t \in T$, $I_t = \{i \in I | a_i \leq t \leq p_i\}$.
- $T$: Set of all periods considered in the planning horizon ($T = \{1, ..., |T|\}$).
- $T_i^t$: Set of periods during which bogie type $i \in I$ is active in the field ($T_i^t = \{a_i, ..., p_i\}$).
- $Y$: Set of aggregated periods (typically years) ($Y = \{1, ..., |Y|\}$).

Input parameters

- $a_i$: First period in the planning horizon that bogies of type $i \in I$ are in the field ($a_i \in T$).
- $c_t^a$: Acquisition costs of a bogie of type $i \in I \setminus I_1$.
- $c_t^{m,e}$: Material costs associated with the $e^{th}$ overhaul of bogie type $i \in I$ in period $t \in T$.
- $c_t^c$: Costs of replacing retables of type $i \in I$ during period $t \in T_i^t$.
- $c_y^{\tau}$: Cost per labor hour during aggregated period $y \in Y$.
- $c_y^r$: Cost difference per year between a temporary employee and an employee with a fixed contract in aggregated period $y \in Y$.
- $D_{t,e}^d$: Number of bogies of type $i \in I$, in or before period $t \in \{a_i, ..., a_i + q_{l,e-1}\}$, that have to be replaced with bogies that have been subjected to the $e^{th}$ overhaul.
- $g_i$: The first overhaul number of bogie type $i \in I$ considered in the planning horizon.
- $k_i$: The last overhaul number of bogie type $i \in I$ considered in the planning horizon.
- $L_{i,e}$: The overhaul lead time (in periods) for $e^{th}$ overhaul, for bogies of type $i \in I$.
- $m^f$: Number of employees that have a fixed contract during the entire planning horizon.
- $p_i$: Last period in the planning horizon that bogies of type $i \in I$ are in the field ($p_i \in T$).
- $q_{l,e}$: The maximum inter-overhaul deadline of bogie type $i \in I$ after being subjected to the $e^{th}$ overhaul.
- $r_{l,e}$: Amount of labor hours required to start $e^{th}$ overhaul of bogie type $i \in I$.
- $v_{l,e}$: Initial number of bogie replacements for overhaul number $e \in E_i$ of type $i \in I$ during period $t \in T$.
- $z$: Average number of yearly work hours per employee.
- $\beta$: Input factor that takes into account the lost capacity due to corrective overhauls and breaks. $0 \leq \beta \leq 1$.

Auxiliary variables

- $m_y^t$: Number of employees that are hired temporary and don’t have a fixed contract in aggregated period $y \in Y$.
- $S_i$: Turn-around stock of bogies of type $i \in I$.
- $U_{l,t,e}$: Number of excess bogie replacements of bogie type $i \in I$, at the end of period $t \in T_i^t$, with bogies that have been subjected to overhaul $e \in E_i$.
  \[ i.e. \; U_{l,t,e} = \sum_{t = a_l}^{t} x_{l,t',e} - \sum_{t = a_l}^{t} D_{l,t',e}, \]
- $w_t$: Number of labor hours that are allocated to period $t \in T$.
- $W_y$: Number of labor hours available in aggregated period $y \in Y$.

Decision variables

- $x_{l,t,e}$: Number of bogie replacements of bogie type $i \in I$ during period $t \in T_i^t$, with bogies that have been subjected to overhaul $e \in E_i$.
C.2. 30-YEAR NEDTRAIN BOGIE OVERHAUL PLANNING HEURISTIC

In this section, we will explain the heuristic that combines the NedTrain bogie overhaul planning method with the partly rolling horizon concept in order to generate a 30-year bogie overhaul planning. The heuristic is written in pseudo code and with help of some notes, the heuristic is explained.

1. Set $i = 1, t = 1$ and $e = g_i$.

2. ‘In this step the replacement deadline for the period $t$ is determined. The replacement deadline can be an input parameter which is collected with help of the information system of NedTrain ($D_{i,t,e}^d$) or a result of previous replacements ($x_{i,t-q_{i,e-1},e-1}$).’

   If $e = g_i$
   
   Then
   
   Set $D_{i,t,e}^d = D_{i,t,e}^d$ \hspace{1cm} (C.1)

   Else if
   
   $e = g_i + 1$
   
   $t \leq \min(a_i + q_{i,e-1}, p_i)$
   
   Then
   
   Set $D_{i,t,e}^d = D_{i,t,e}^d$ \hspace{1cm} (C.2)

   Else If
   
   $e = g_i + 1$
   
   $t > a_i + q_{i,e-1}$
   
   $t \leq p_i$
   
   Then
   
   Set $D_{i,t,e}^d = x_{i,t-q_{i,e-1},e-1} \hspace{1cm} (C.3)$

   If $e > g_i + 1$

   Then
   
   Set $D_{i,t,e}^d = x_{i,t-q_{i,e-1},e-1} \hspace{1cm} (C.4)$

3. ‘In this step the initial replacement rate per year is calculated and allocated to the period. This step corresponds with the first step of constraint 3 in Section 5.3.2. This initial replacement rate is allocated to each period in order to create a replacement schedule with minimal deviations.’

   The initial production per period is denoted by $v_{i,t,e}$ and is described in equation (C.5).

   $$v_{i,t,e} = \left\lfloor \frac{\sum_{k=t-(t\ Mod\ 13)+1}^{t-(t\ Mod\ 13)+13} D_{i,k,e}}{13} \right\rfloor \hspace{1cm} (C.5)$$
The production per period must satisfy constraints (C.7), (C.8) and (C.9). Constraint (C.7) denotes the maximum number of replacements per period Constraint 2 in Section 5.3.2. Constraint (C.8) denotes the accumulated replacement surplus, when constraint (C.8) is not met, a replacement shortage occurs. As described at constraint 1 in Section 5.3.2 a production shortage is not allowed.

\[ S_i \geq L^t_i \times x_{i,t,a} \]  \hspace{1cm} (C.7)

\[ \sum_{k=1}^{t} x_{i,k,a} \geq \sum_{k=1}^{t} D_{i,k,a} \]  \hspace{1cm} (C.8)

\[ t-(t \mod 13)+1 \sum_{k=t-(t \mod 13)+1}^{t} D_{i,k,e} \geq \sum_{k=t-(t \mod 13)+1}^{t} x_{i,k,e} \]  \hspace{1cm} (C.9)

'Constraint (C.9) ensures that no bogie overhauls are allocated to a period when the total demand of that year is already met.'

3.1. If constraint (C.7) is not satisfied then
Set \( x_{i,t,e} := S_i \) \hspace{1cm} (C.10)

Else
Set \( x_{i,t,e} := g_{i,t,e} \) \hspace{1cm} (C.6)

3.2. If constraint (C.8) is not satisfied and \( x_{i,t,a} + 1 \leq S_i \) then.
Set \( x_{i,t,e} := x_{i,t,e} + 1 \) \hspace{1cm} (C.11)

Else
Set \( x_{i,t,e} := g_{i,t,e} \) \hspace{1cm} (C.6)

3.3. If constraint (C.9) is not satisfied then
Set \( x_{i,t,e} := x_{i,t,e} - \left( \sum_{k=t-(t \mod 13)+1}^{t} x_{i,k,e} - \sum_{k=t-(t \mod 13)+1}^{t} D_{i,k,e} \right) \)  \hspace{1cm} (C.12)

Else
Set \( x_{i,t,e} := g_{i,t,e} \) \hspace{1cm} (C.6)
4. ‘In this step a possible production shortage is solved. Because a fixed replacement rate is preferred, the extra replacements needed to have no replacement shortage is divided over the previous periods. This step corresponds to the second step in constraint 3 in Section 5.3.2.’

Let $U_{i,t,e}$ be the gap between the cumulative demand and production in period $t$.

$$U_{i,t,e} = \sum_{k=1}^{t} x_{i,k,e} - \sum_{k=1}^{t} D_{i,k,e} \quad (C.13)$$

Set $k = t - 1$

4.1. If

$$U_{i,t,e} < 0 \quad (C.14)$$

Then go to 4.2, else go to step 5.

4.2. ‘The extra replacements are to be divided over the past periods. However it depends on the period number over how much periods the gap can be divided. This is because the production planning is made once a year. So a problem can only be detected once a year. If a gap is identified in period 14, only over the first 13 periods the gap can be divided. The period $t$ itself is not considered in this step because the number of replacements already is increased with one bogie in step 3.2.’

If

$$x_{i,k,e} = v_{i,k,e} \quad (C.15)$$

$$x_{i,k,e} < x_{i,t,e} \quad (C.16)$$

$$x_{i,k,e} + 1 \leq S_{i} \quad (C.17)$$

Then

Set $x_{i,k,a} := x_{i,k,a} + 1$ And $k := k - 1$

Else

Set $k := k - 1$

If $t \leq 26$ And $k = 1$ go to step 4.3, else go to step 4.1.

If $t > 26$ And $k = t - (t \mod 13) - 13$ go to step 4.3, else go to step 4.1.

‘The two last lines of step 4.2. ensures that each period with a negative $U_{i,t,e}$ can only divide its replacement shortage over the past periods of that same year and previous year. This is because when the problem is detected, the period is within the planning horizon of 26 periods and can only divide its replacements shortage over the periods with a smaller $t$. For example, if $U_{i,30,a} < 0$, then the replacement shortage can only be divided over periods $14 \leq t \leq 29$.’
4.3. ‘This step is an interation of step 3.2.’

If

\[ U_{i,t,e} < 0 \]  \hspace{1cm} \text{(C.14)}

\[ x_{i,t,e} + 1 \leq S_i \]  \hspace{1cm} \text{(C.17)}

Then

Set \( x_{i,t,e} := x_{i,t,e} + 1 \) \hspace{1cm} \text{(C.11)}

Else If

\[ U_{i,t,e} = 0, \text{ go to step 5 else set } k := t - 1 \text{ and go to step 4.4.} \]

4.4. ‘This step is an interation of step 4.2.’

If

\[ U_{i,t,e} < 0 \]  \hspace{1cm} \text{(C.14)}

\[ x_{i,k,e} < x_{i,t,e} \]  \hspace{1cm} \text{(C.16)}

\[ x_{i,k,e} + 1 \leq S_i \]  \hspace{1cm} \text{(C.17)}

Then

Set \( x_{i,k,e} := x_{i,k,e} + 1 \text{ And } k := k - 1 \)

Else

Set \( k := k - 1 \)

If \( t \leq 26 \text{ And } k = 1 \text{ go to step 5, else go to step 4.4.} \)

If \( t > 26 \text{ And } k = t - (t \text{ mod } 13) - 13 \text{ go to step 5, else go to step 4.4.} \)

‘Step 4.3 and 4.4 are the same steps as 3.2 and 4.2 and serve as an additional layer of production when } U_{i,t,e} \text{ is still lower than } 0. \text{ After these steps no additional layer is added because in practice to most of the periods the maximum replacement rate is already allocated.’}

5. If \( t < p_i \text{ Then } t := t + 1 \text{ and go to step 2, else go to step 6.} \)

6. If \( e < k_i \text{ Then } e := e + 1 \text{ and go to step 2, else go to step 7.} \)

7. If \( i < 71 \text{ Then } i := i + 1 \text{ and go to step 2, else stop heuristic.} \)
C.3. NedTrain bogie overhaul planning heuristic – Example

Assume the values for parameter $D_{i,t,e}$ as shown in Table C.1. Table C.1 shows a fragment of the total demand in the first three year of an example bogie. In this example the number if spare bogies ($S_i$) is equal to 6.

Table C.1: Example of Demand, initial replacement rate and replacement rate at $t=20$

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<thead>
<tr>
<th>$t$</th>
<th>8</th>
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<td>$g_{i,t,e}$</td>
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<tr>
<td>$x_{i,t,e}$</td>
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</tbody>
</table>

The example starts at $t = 20$ with $\sum_{k=1}^{t} D_{i,k,e} = 70$ and $\sum_{k=1}^{t} x_{i,k,e} = 62$.

3. The initial replacement rate is calculated and set to 6. Formula (C.6) ensures that the replacement rate is equal to 6 as well. $v_{i,20,e} = x_{i,20,e} = 6$.

3.1. Constraint (C.7) is satisfied because $x_{i,20,e} \leq S_i = 6$.

3.2. Constraint (C.8) is not satisfied because $\sum_{k=1}^{20} x_{i,k,e} < \sum_{k=1}^{20} D_{i,k,e}$, however $x_{i,20,e} + 1 > S_i$, so $x_{i,20,e} = 6$.

3.3. Constraint (C.9) is satisfied because $\sum_{k=20-(20\% Mod\ 13)+1}^{20} x_{i,k,e} = 42$ and $\sum_{k=20-(20\% Mod\ 13)+1}^{20} D_{i,k,e} = 83$.

4. $U_{20,t,e} = \sum_{k=1}^{20} x_{i,k,e} - \sum_{k=1}^{20} D_{i,k,e} = 68 - 70 = -2$

4.1. $U_{20,t,e} < 0$, go to step 3.2.

4.2. For $14 \leq k \leq 19$, nothing changes because constraints (C.16) and (C.17) are not satisfied.

For $12 \leq k \leq 13$ the replacement rate increases with one bogie.

For $1 \leq k \leq 12$ the replacement rate does not change because constraint (C.14) is not satisfied because $U_{20,t,e} = 0$.

4.3. go to step 4 because constraint (C.14) is not satisfied because $U_{20,t,e} = 0$.

5. Because $t = 20$, the next step in the heuristic is step 2 with $t = 20 + 1 = 21$.

The result after application of the heuristic is shown in Table C.2. Because the number of spare bogies is 6, and period 18 until 23 exceeds that number, the production in earlier periods must be higher than the initial production. This is done in periods 9 until 13.

Table C.2: Example of demand, initial replacement rate and replacement rate at $t=39$.

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XII
C.4. Workload and Total Costs Formulas

\[ w_t = \sum_{i \in I_t} \sum_{e \in E_i} n_{i,e} \cdot x_{i,t,e} \quad \forall t \in T \]  
\[ W_y = \sum_{t \in T_y} w_t \quad \forall y \in Y \]  
\[ m^t_y = \frac{W_y - (m^f \cdot z \cdot \beta)}{z \cdot \beta} \quad \forall y \in Y \]  
\[ TRC = \sum_{y \in Y} (c^W_y \cdot W_y + c^{WT}_y \cdot m^t_y) + \sum_{i \in I | a_i > 1} c^a_i \cdot S_i + \sum_{i \in I} \sum_{t \in T} \sum_{e \in E_i} c_{i,t,e} \cdot x_{i,t,e} \]  
\[ + \sum_{i \in I} \sum_{t \in T} \sum_{e \in E_i} c_{i,t,e} \cdot x_{i,t,e} \]  

(C.18)  
(C.19)  
(C.20)  
(C.21)
APPENDIX D – SCREENSHOTS INTERFACE DATA INPUT TOOL
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**Stap 1. Rauwe data**

**Stap 2.**

**UserForm1**

- **Selecteer een materieel serie:** ICR
- **Wat is het eerste jaar dat deze serie gaat uittassen?**
- **Hoe groot is de productie (dikvormig uitgedrukt in 4-weken-perioden)?** INTEGERS!
- **Hoeveel kW’s per jaar wordt er door deze materieel serie gereden (per bak)?** 28000
Is er een treintype dat nog niet in de maximale dump staat maar die in de komende 5 jaar gaat infaseer?

Treinserie naam:  
Aantal type draaistellen:  
Aantal draaistellen type 1:  
Aantal draaistellen type 2:  
Aantal draaistellen type 3:  
Aantal draaistellen type 4:  
Aantal draaistellen type 5:  
Aantal draaistellen type 6:  
Aantal draaistellen type 7:  
Aantal draaistellen type 8:  
Infaseer jaar:  
Hoe groot is de productie leadtime uitgedrukt in 4-weken-periodes? INTEGERS!
Hoewel KM’s per jaar wordt er door deze materiaal serie gereden (per bak)?

Cancel  Next