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Deciding on turn-around stock levels using advanced demand models and expediting repair policies

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Deciding on Turn-around Stock Levels Using Advanced Demand Models and Expediting Repair Policies

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In theory, theory and practice are the same.
In practice, they are not.

Albert Einstein

Preface

This report is the result of a graduation project that has been conducted at NedTrain in completion of the Master Operations Management & Logistics at Eindhoven University of Technology. I'm glad that I had to possibility to graduate within this company and I would like to thank all the people that made this project possible.

Some people however, deserve some extra attention. At first Geert-Jan van Houtum, who is more than my first supervisor. He made it possible for me to do an exchange semester at the National Taiwan University. He is also the one that convinced me to do the Honors Track in Design and from September 2013 he will also be my supervisor during my LMS project. Second, Engin Topan, who was interested in this research from the very first moment and always had some good comments to improve the report. Last but not least, from the TU/e, I would like to thank Joachim Arts. The amount of mathematics and mathematical techniques that I learned the last half year is incredible. He was not only there to teach me the tricks of the trade but also to discuss certain thoughts about the project. I am really happy that I had the opportunity to work with him.

No project within a company without a company supervisor. Many thanks go to Bob Huisman. After a chat with Bob, there was always material for thought but also a lot of advices for the moment that 'we are a manager at some company'. He taught us the alpha skills that the betas sometimes miss. I would also like to thank Guido Aerts, who is a walking encyclopedia when it comes to trains and spare parts. From the SCO I would like to thank Joost Florie, Erik Dielissen, Robert Vialle, Peter Adriaansen, Vincent Janssen and Frank Stafleu, who gave me the practical insights and collected the data for me.

I would like to thank my fellow interns at NedTrain. We were not only able to help each other where necessary but it I also liked the many little chats while having a coffee.

Next I would like to thank my friends, the ones I already had before I came to Eindhoven and the ones that I met during my studies. It was always nice to relax with you, whether this was in Rosmalen, in The Villa or in 'Het Koffiehok'. I'm sure we will keep seeing each other in the future.

However, all this would not have been possible without the support of my parents and my brother. Sometimes you need a safe home to go to and let all other things behind. I'm glad that I have this safe home where the door is always open.

Last but not least, I would like to thank my girlfriend Mirjam. You were always there to listen to my 'struggles', help me to solve them and willing to wake up early. I'm sure, we are a team, and will always be!

Martijn van Aspert

Abstract

In this research, conducted at NedTrain B.V., we investigated how the size of the turn-around stock for repairable spare parts can be determined. Several authors (e.g. Sherbrooke (1968), Rustenburg et al. (2001) and Thonemann et al. (2002)) have shown that cost savings can be achieved when turn-around stock decisions are made using a system approach instead of an item approach. In this research, a multi-item model, based on the single-item model of Arts et al. (2013), has been developed which can be used for taking turn-around stock decisions. The model features the possibility to assign dynamically different repair lead-times to repair jobs: an expedited repair lead-time or a regular repair lead-time. The advantage of the possibility to assign different lead-times is that expensive items can get expedited lead-times such that less turn-around stock is needed for these items and thus costs can be saved.

The multi-item model has been tested in two business cases in which investment costs using the current decision-making logic have been compared to investment costs that result from using the multi-item model. In the first business case demand follows a Poisson Process and from the results it can be concluded that 53% investment cost savings in turn-around stock can be achieved. In the second business case a Markov Modulated Poisson Process is used to model demand. From the results in that case it can be concluded that investment cost savings of 46% can be achieved.

Keywords: Maintenance, Spare Parts, Inventory Control, Turn-around Stock, Expediting Policy, Markov Modulated Poisson Process, Capital Goods, Linear Programming, Dynamic Programming, Decomposition Column Generation

Executive Summary

Introduction

NedTrain faces the problem that in the current situation it is not clear how turn-around stock decisions for repairable spare parts are taken. Turn-around stock decisions for repairable spare parts have e.g. to be taken when new train series are ordered, when there are revision periods or when train series are completely overhauled. Based on information of e.g. the train manufacturer, the logistic planner makes a decision on the so-called turn-around stock levels: the amount of repairable spare parts that should be acquired. The planner has to find turn-around stock levels such that investment cost are minimized, but also that service levels are met.

Because of the absence of a clear decision rule, the Supply Chain Operations (SCO) department of NedTrain now considers using a clear decision rule to support turn-around stock decisions. One of the difficulties when turn-around stock decisions for spare parts have to be made, is that demand rates fluctuate along the lifetime of a train (e.g. during revision periods, demand rates for spare parts are much higher). At this moment neither these lifetime-varying demand rates nor the fact that the repair shop is able to assign priorities to repair jobs, i.e., to expedite repair jobs for certain spare parts, are taken into account.

In this research a multi-item model has been developed that incorporates the fluctuating demand environment and the the possibility to expedite repair jobs. The model of Arts et al. (2013) is used as a building block for the multi-item model.

Conclusions

The multi-item model that has been developed, aims at minimizing investment costs in turn-around stock levels while constraints with respect to the expected number of backorders and expected number of expedites are taken into account. The expected number of backorders roughly corresponds to the number of trains that is down, waiting for a part.

Two business cases have been investigated in which the investment costs using the current decision-making logic have been compared to the investment costs that result from using the model. To compare the results from both methods, the service level in terms of expected number of backorders that is achieved using the current decision-making logic is used as a constraint in the multi-item model. By setting the expected number of backorders constraint like that, we make sure that the multi-item model performs at least as good as the current decision-making logic.

In the first business case it has been investigated whether an extension in turn-around stock is needed for the upcoming revision of the Sprinter LightTrain. It turns out that an extension in turn-around stock is needed. Using the current decision-making logic, the investment in turn-around stock would amount to €2.29 million whereas using the new multi-item model the investment costs would be €1.07 million. This means that an estimated cost saving of €1.22 million (53%) can be achieved. Results of this business case have been presented to managers of the SCO, who were interested in a further implementation of this model.

In the second business case, it has been investigated what the turn-around stock levels should have been in case NedTrain had to buy the spare parts at the same moment as the trains series was ordered. In that case not only demand during the revision period, but also demand due to unplanned failures during the non-revision period has to be taken into account. In this case, it turns out that using the current decision-making logic this would have lead to an investment of €4.13 million whereas the investment using the new multi-item model requires €2.23 million, an estimated cost saving of €1.90 million (46%). It should however be noted that the model was less applicable in this case. To use the model in cases like this second business case, the model should first be further extended by taking into account separate service levels for the non-revision and revision period.

Two reasons can be mentioned why cost savings can be achieved when the new model is used. Firstly, a system approach instead of an item approach is used. In the system approach a target service level is set on the system as a whole instead of a service level per item. Using the system approach will lead to the fact that the focus of management is for the systems (trains) as a whole instead of parts separately. Secondly, due to the possibility to assign dynamically different lead-times to repair jobs, expensive items can get an expedited lead-time more often such that less turn-around stock is needed for these items and thus costs can be saved.

Since the model that was used for business case one, holds promise for implementation at NedTrain, a decision-support tool (software) has been developed that is based on this model. The tool can support logistic planners of NedTrain to make turn-around stock decisions using the system approach in situations where new spare parts have to be ordered.

Recommendations

Based on the conclusions, the following recommendations are given to NedTrain:

Implementation of the decision-support tool: Based on the cost savings that can be realized when the new model is used, it is recommended to NedTrain to use the decision-support tool that has been developed. The tool can support logistic planners when making turn-around stock decisions using the system approach and by that saving on investment costs in turn-around stock.

Other recommendations that are given to NedTrain, based on things that were notified during the research are the following:

Demand data: It is recommended to store demand data in Xelus Parts for a longer period than the current five years and to collect data even when demand is not fulfilled by NedTrain itself, such that these demand data can be used when turn-around stock decisions have to be made. Currently, when e.g. a revision period is upcoming, NedTrain is not able to consult data either because it has not been collected or because the last revision period is more than five years ago. These data however can be useful when turn-around stock decisions have to be made.

Parts identification: When parts are used at more indenture levels of the configuration, different identification numbers are assigned to these parts. However it is not clear how the lower level identification numbers are linked to higher level identification numbers. Therefore it is recommended to clarify how identification numbers at different indenture levels are linked to each other.

Lead-times used: At this moment in Xelus Parts, 20 working days are used as regular repair lead-time for repairable spare parts. As mentioned by managers from the NedTrain Components Company, this repair lead-time is based on old data and can possibly be reduced. It is recommended to investigate what a plausible repair lead-time is. The result of this could also be that the advices regarding re-buys for spare parts, given by Xelus Parts, are more useful than they are now when the value is changed in Xelus Parts.

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1

Introduction and Research Questions

In this chapter, first a general introduction to NedTrain is given in section 1.1. In section 1.2, the spare parts and maintenance processes within NedTrain are discussed. In section 1.3 the relevant literature that was investigated in the literature research (Van Aspert, 2013), is briefly discussed and in section 1.4 the main and underlying research questions are discussed. The relation with previous research is shown in section 1.5 and in section 1.6 the business entities and spare parts that are involved in this research are discussed. In section 1.7 an outline of this report is given.

1.1 Company Background

After a collaboration that started in 1917, Hollandsche IJzeren Spoorweg Maatschappij and Maatschappij tot Exploitatie van Staatsspoorwegen merged as NV Nederlandse Spoorwegen (NS, Dutch Railways) in 1937. In 2011, NS had a turnover of €3.35 billion and a profit of €211 million. In Figure 1.1 the organization chart of NS is shown. NedTrain B.V. (NedTrain), till 1999 known as NS Materieel is a limited company and full subsidiary of Nederlandse Spoorwegen (NS). NedTrain has a turnover of about €500 million and employs over 3000 FTEs. For over 165 years NedTrain has specialized in maintaining, servicing, cleaning and overhauling rolling stock. NedTrain maintains over 2800 coaches at several locations in The Netherlands. These locations are classified as follows:

- **Components Company Tilburg:** NedTrain has its own Components Company located in Tilburg (NedTrain Componenten Bedrijf, NCB) where parts are refurbished and repaired. Afterwards, these parts are stored at the National Logistics Center (Landelijk Logistiek Centrum, LLC).
- **Refurbishment & Overhaul (R&O) Workshop Haarlem:** At this repair shop trains are completely revised and modernized. Also maintenance on wheel sets and bogies is performed at this location.
- **Maintenance Depots:** There are four strategically located Maintenance Depots (OBs) in The Netherlands, where amongst others scheduled and unscheduled maintenance takes place.
- **Service Companies:** Around 30 service sites (SBs) are located next to the railway network. At these locations repairs and daily checks are performed. Also cleaning trains takes place at these sites.

Supply Chain Operations

Next to these locations NedTrain also has a Supply Chain Operations (SCO) department which consists of a logistics department and a purchasing department. The SCO department is also responsible for the supply of ready-for-use parts from the LLC to the OBs & SBs.

In Figure 1.2 the organization chart of NedTrain can be found.

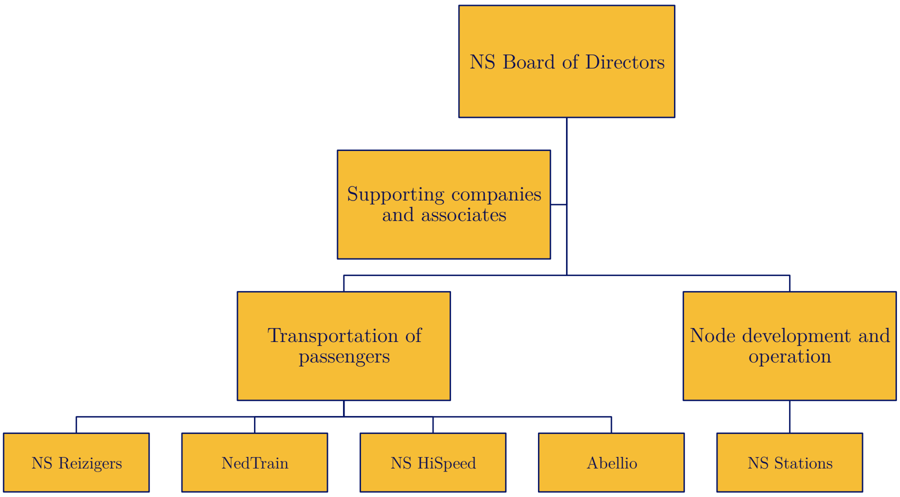

Figure 1.1 – Organization chart of Nederlandse Spoorwegen

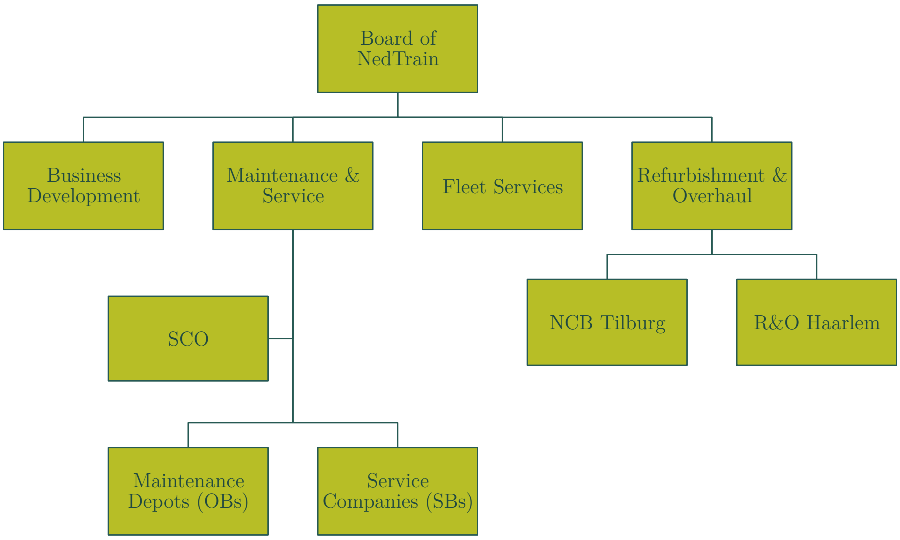

Figure 1.2 – Organization chart of NedTrain

1.2 Spare Parts and Maintenance Process at NedTrain

To be able to perform maintenance actions, spare parts are needed which can be replaced immediately after after a part has failed or has been rejected by inspection and to cover demand during the repair lead-time, in case other parts also fail. Within NedTrain several types of spare parts are classified. Furthermore, maintenance is conducted at several locations. In this section first the different types of spare parts are discussed. Then the maintenance process of a train and its parts is discussed briefly, followed by a description of the different 'suppliers' within the NedTrain maintenance supply chain.

1.2.1 Types of Spare Parts

NedTrain maintains different types of spare parts which are classified as follows. First, a distinction is made between *main parts* and *car bodies*. Rolling stock units (trains) consist of these two types of parts. Main parts are physical parts that are *uniquely* identified, have their own (maintenance and) revision period and are individually followed during their life cycle, e.g. due to legal restrictions or rules imposed by the manufacturer. Examples of these kind of parts are bogies, wheel sets and compressors. Car bodies also have their own maintenance and revision period, but the parts of which car bodies and main parts consist do not have their own maintenance and revision period. However, since we are interested in the parts that are used in car bodies and main parts, in the remainder of the report we will refer to car bodies and main parts as a whole and so refer to it as a train. Trains consist of consumable spare parts, repairable spare parts and construction parts. Repairable spare parts are items that are repaired instead of discarded when they have failed or have been rejected by inspection, whereas consumables are parts that are discarded and replaced by a completely new item. A construction part is “the piece of a repairable part that functions as structural bearing” (Arts and Driessen, 2011, p. 7).

Another characteristic of the spare parts at NedTrain, is that the demand frequency is very low. For around 80% of the parts, there is no demand during a period of two years (Arts and Driessen, 2011). This means that demand is intermittent. Besides, demand is known to be very lumpy. This means that when demand for a part occurs the size of this demand is quite variable. A reason that can be mentioned for that is aging of parts.

1.2.2 Maintenance Supply Chain

After procurement of trains, service and maintenance need to be performed on these trains. Trains visit a service company (SB) every day. During the night, trains are cleaned and small technical checks are performed at these service companies. When certain parts need to be replaced, this is done at the service company, if this is not possible, a visit to one of the maintenance depots is scheduled.

Around every three months trains go into Short Cycle Maintenance (ShCM) which is conducted at maintenance depots (OBs). During ShCM, a cluster of technical maintenance actions is performed. Maintenance actions that have to be performed on a cyclical basis with a frequency of minimally once every two years are classified as Short Cycle Periodic Maintenance (ShCPM) and maintenance actions that have to be performed on a cyclical basis with a frequency of once every two years or less are classified as Long Cycle Periodic Maintenance (LCPM). Periodic maintenance actions are performed at the OBs and the R&O workshop. When certain parts from the train need to be replaced (e.g. due to failure or for preventive maintenance), these parts are taken from the train and replaced by ready-for-use (RFU) parts. The parts that are taken from the train are sent to the repair shop (the NCB). This process has been depicted in Figure 1.3.

As mentioned before, when maintenance is performed on trains, demand for spare parts from the service companies and maintenance depots arises. This demand is fulfilled either from the stock point at the service location (SB or OB) or – in case there are no spare parts available – from the central warehouse (the LLC) in Tilburg. This central warehouse is supplied by three different types of suppliers: The NCB in Tilburg, External Repair Shops and External Suppliers. A more detailed overview of the spare parts supply chain is provided in Figure 1.4.

Next to the daily, short term and long term maintenance actions, at some moments during the life cycle of a train, car bodies (and their parts) and main parts are completely refurbished and overhauled. These actions are performed in one of the following repair shops: at the repair

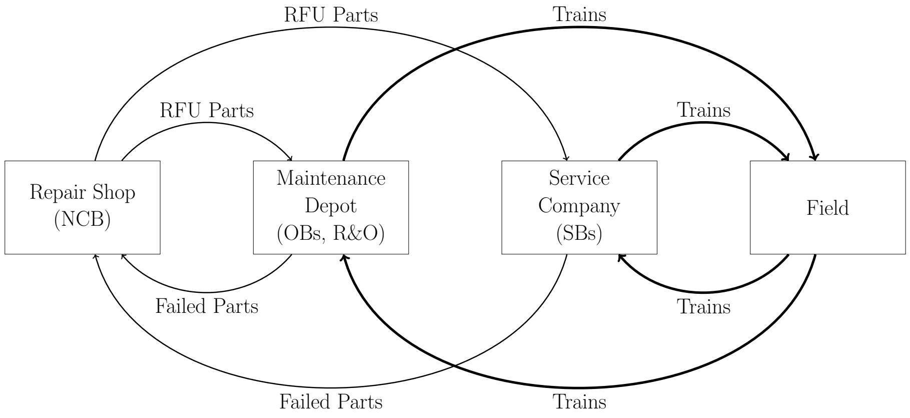

Figure 1.3 – Maintenance Process at NedTrain

shop in Tilburg, where *parts* are refurbished and repaired and in the Refurbishment & Overhaul Workshop in Haarlem, where *car bodies* and *main parts* are refurbished.

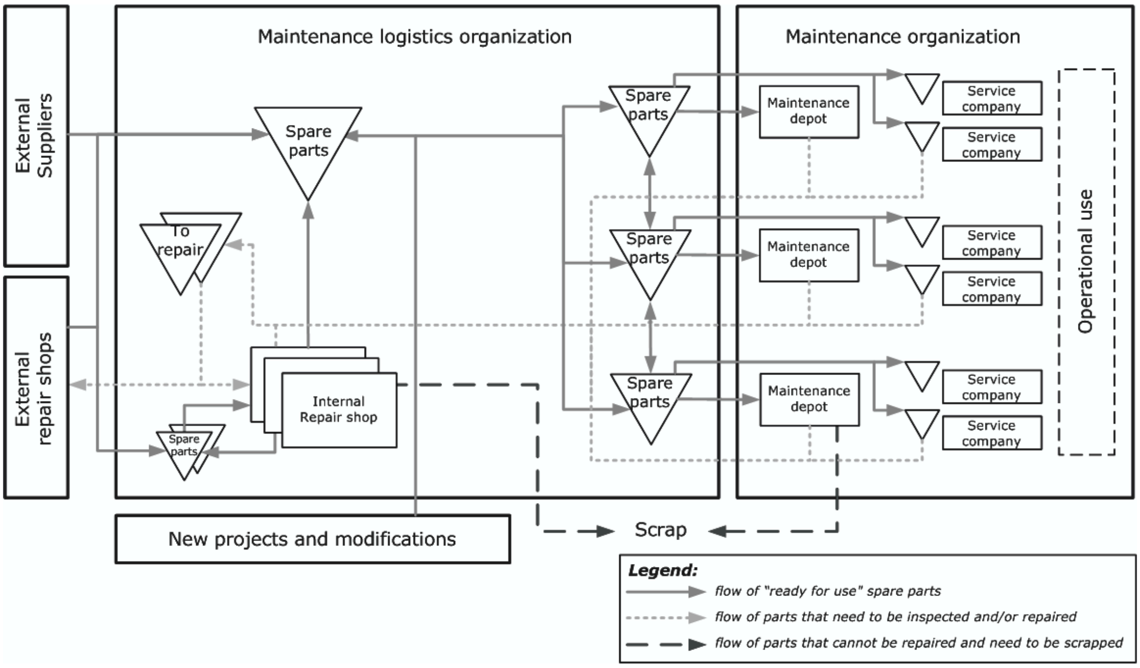

Figure 1.4 – Overview of NedTrain spare parts supply chain (Arts and Driessen, 2011)

1.3 Literature Review

In this section the parts from the literature review (see Van Aspert, 2013) that are most relevant for this thesis are discussed.

1.3.1 Demand Modeling

When data has been collected and one has information on e.g. mean demand and (repair) lead-times, several models can be used to calculate turn-around stock levels in case demand follows a Poisson Process (see e.g. Sherbrooke (1968), Muckstadt (1973), Wong et al. (2007)

and Van Houtum and Hoen (2008)). In these models it is assumed that demand (or failures) follow a (compound) Poisson Process with a constant rate. However it may be the case that the demand rate or demand intensity depends on other factors such as stage in the lifecycle of a product, weather, economic factors or other factors.

To take these factors into account, a Markov Modulated Poisson Process (MMPP) instead of a normal Poisson Process can be used to model demand. Fischer and Meier-Hellstern (1993) describe an MMPP as follows:

> "A Markov Modulated Poisson Process can be constructed by varying the arrival rate of a Poisson Process according to an m-state irreducible continuous time Markov chain which is independent of the arrival process. When the Markov chain is in state i, arrivals occur according to a Poisson Process with rate λ_i. The MMPP is parameterized by the m-state continuous-time Markov chain with infinitesimal generator Q and the m Poisson arrival rates $\lambda_1, \lambda_2, \dots \lambda_m$."

They also define the MMPP as a Markov renewal process: The distribution of the time between the $(k-1)$st and kth arrivals depends on the state of the Markov chain at these moments and is not exponential (Fischer and Meier-Hellstern, 1993).

Yechiali and Naor (1971) and Neuts (1971) were the first to apply different demand rates by using a MMPP in queuing theory. Song and Zipkin (1992) and Song and Zipkin (1996) study the evaluation of turn-around stock policies in a multi-echelon environment (Central Warehouse and multiple Local Warehouses) with state dependent demands. In the former paper they evaluate a multi-echelon system where the demand rate at the lowest hierarchal level depends on the state of the underlying Markov chain and they show how the steady-state performance of the system can be computed assuming the policies used at each location are all state independent. In the latter paper, which is a follow-up on the 1992 paper of Song and Zipkin, an evaluation method for a two-echelon inventory system is presented. Again the turn-around stock policies at the Local Warehouses do not depend on the state, however the policy of the Central Warehouse depends on the state of the underlying Markov Chain.

Song and Zipkin (1993) also present an inventory model where the demand rate depends on a certain state variable, which they call the state-of-the-world variable. In their paper they derive optimal policies and provide algorithms to compute the optimal policies. They formulate a model where the state is defined by two variables: The current state-of-the-world and the inventory level. The state-of-the-world variable forms a discrete-state-space, continuous-time Markov chain. Song and Zipkin (1993) show that a world-dependent (i.e. state-dependent) turn-around stock policy is the optimal policy in case there are only linear unit holding costs and no fixed order costs.

To conclude, in Song and Zipkin (1992) only an evaluation method for a multi-echelon inventory system is given where the demand rate depends on the current state-of-the-world but the inventory policy does not depend on the state-of-the-world. In Song and Zipkin (1996) also only an evaluation method is given for a two-echelon inventory system where the demand rate depends on the current state-of-the-world, however the inventory policy at the Central Warehouse does depend on the current state-of-the-world. The inventory policy at the Local Warehouse is still state-independent. In Song and Zipkin (1993) optimal policies for a single-echelon inventory system with and without fixed order costs are presented. Also algorithms to compute the optimal policies are presented in this paper.

1.3.2 Two-source Inventory System with Overflow Bypass

Moinzadeh and Schmidt (1991) and Song and Zipkin (2009) describe a single-item inventory system with Poisson demand and linear order costs. The system has two sources: a normal source and an emergency source, which has a shorter lead-time but is more expensive to use than the normal source. An important note however is, that it is assumed that more information about the outstanding orders – the orders that are in the pipeline to the stock point – is available. Song and Zipkin (2009) mention that with the increasing use of GPS (global positioning system) and RFID (radio frequency identification) orders can be tracked and traced more accurately and that this information can be used in inventory planning.

The system described by Song and Zipkin (2009) works as follows: After demand has occurred, a normal order or an emergency order is placed. Normal orders pass the normal source and the emergency source, however emergency orders only pass the emergency source. The decision whether an order is a normal order or an emergency order is made as follows: In the model two turn-around stock levels are defined: one for the normal source, s_1, and one for the emergency source s_2. The inventory position of the normal source is equal to the net inventory plus the total number of outstanding orders: $IP_1 = IN + N$, see Figure 1.5. The inventory position of the emergency source only includes the outstanding orders that will arrive at the stock point within T_2 time units, the time it takes from the emergency source to the stock point: $IP_2 = IN + N_2$. The number of outstanding orders before the emergency source is: $N_1 = N - N_2$.

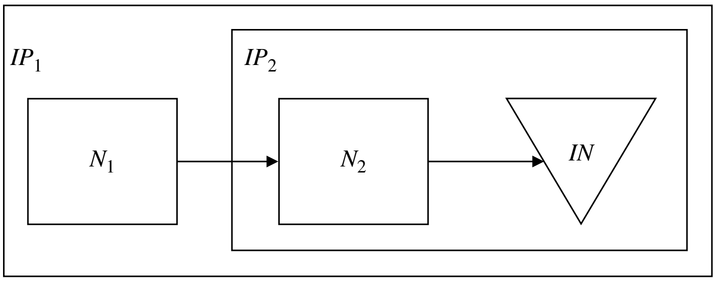

Figure 1.5 – Inventory positions (Song and Zipkin, 2009)

The system maintains $IP_1 = s_1$ and $IP_2 \geq s_2$. When demand has occurred but before the order is placed the inventory positions of both sources, IP_1 and IP_2, are checked. If after the fulfillment of the order $IP_2 < s_2$ an emergency order is placed and the normal source is bypassed.

Thus as long as $IP_2 \geq s_2$ an normal order is placed. Since we know that $IP_1 = IN + N = s_1$, $IN = s_1 - N$. We can show that as $IP_2 = s_1 - N_1 < s_2$ an emergency order is placed. From this it can be concluded that a normal order is placed when the number of outstanding orders before the emergency source is smaller than the difference between the two turn-around stock levels, or expressed using the variables, when $N_1 < s_1 - s_2 = u_1$, see Figure 1.6.

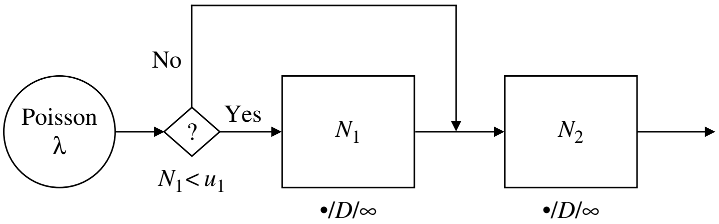

Figure 1.6 – Open network of queues for backorders (Song and Zipkin, 2009)

The costs of the system depend on the number of orders that are placed, the number of orders that are placed using the emergency source, the on hand stock and the number of backorders.

To compute the expected on hand stock and expected number of backorders, the distribution of N is needed, which is the joint distribution of (N_1, N_2). The utilization of the emergency source can be seen as a $M|G|c|c$ queue with $c = u_1$, where customers arrive according to a Poisson Processes and where $c = u_1$ denotes the number of servers, or in this case, the level at which the normal source will be omitted and thus demand is 'lost' at the normal source. Then the utilization $\eta(u_1)$ is denoted by the Erlang loss probability: $\eta(u_1) = \frac{\rho_1^{u_1}/u_1!}{\sum_\ell^{u_1} \rho_1^\ell/\ell!}$ where $\rho_1 = \lambda T_1$ is the demand during the time it takes from the normal source to the emergency source.

Moinzadeh and Schmidt (1991) have shown that for a fixed u_1, the cost function is convex in s_1. They have also provided an algorithm that searches over u_1 for the best turn-around stock level of the normal source, s_1, to minimize costs.

In their paper Song and Zipkin (2009) discuss the use of Markov Modulated demand. In this research, also Markov Modulated demand is used, however, in comparison to Song and Zipkin (2009), in this research the threshold level u_1 depends on the state of the Markov chain. Next to Markov Modulated demand, Song and Zipkin (2009) also discuss a two-source inventory model with lost sales, stochastic lead times, exogenous lead times, batch orders, multiple demand classes and more sources.

1.3.3 Stocking and Expediting Policies and Fluctuating Demand

Arts et al. (2013) and Arts (2013, ch. 4)[1] have developed a single-echelon, single-item model in which as well the possibility to expedite repairs as discussed in subsection 1.3.1 and a fluctuating demand environment as discussed in subsection 1.3.2 are taken into account. They propose to model the fluctuating demand environment as a Markov Modulated Poisson Process. The repair lead-time in the repair shop is split up in two parts: a regular part and an emergency part. Arts et al. (2013) propose a policy in which repair jobs are expedited when the number of parts in the repair pipeline equals or exceeds a certain amount, a so-called threshold level.

Arts et al. (2013) propose both an optimal and a heuristic solution procedure to determine the optimal combination of a threshold level and a turn-around stock level for infinite horizon average and discounted cost criteria.

In this research, the heuristic solution to solve the single-item model is used as building block for a multi-item model and is applied in two cases where NedTrain has to take turn-around stock decisions.

1.4 Research Questions

In this section the core of this research project is discussed. We address the following questions:

- What is going to be investigated?
- Why is this important?
- How is this going to be handled?

When new trains are acquired, a team of specialists from NedTrain is formed to take decisions concerning the procurement. One of the decisions to be made by the team, is the number of spare parts that have to be ordered, the so-called turn-around stock level. The desired size of the turn-around stock is decided by maintenance engineers and the SCO department and

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[1] In the remainder of this report this will be referred to as Arts et al. (2013).

also advice given by the rolling stock manufacturer is taken into account. However, how this decision is made is not entirely clear in the current situation. In addition to ordering spare parts when new trains are acquired, sometimes it is also needed to buy extra spare parts for already existing rolling stock. In this case the logistic planner who is responsible for the rolling stock series takes a decision. The way in which this decision is taken, differs per planner and it is also not clear how this decision is made.

Therefore, the SCO department of NedTrain considers using a clear decision rule for the turn-around stock decision, i.e. a rule to support the decision concerning the turn-around stock level of its repairable spare parts. One of the difficulties with determining the turn-around stock levels is that the demand rate for spare parts fluctuates along the lifetime of a train (e.g. during revision periods, the demand is higher). At this moment neither the lifetime-varying demand rates nor the fact that the repair shop is able to assign priorities to parts, i.e. to expedite repair jobs for certain spare parts, is taken into account.

Having a clear decision rule that can support logistic planners within the SCO when taking turn-around stock decisions, is important since this can possibly lead to lower investment costs for repairable spare parts.

As mentioned in subsection 1.3.3, Arts et al. (2013) have provided a single-item model that takes into account a fluctuating demand environment and the possibility to expedite repair jobs. In this research, the single-item model is used as building block for a multi-item model which minimizes the investment costs for turn-around stock. In the model it is taken into account that items utilize the same repair capacity and that the repair shop can assign different lead-times to parts. The investment costs that result from the multi-item model and from the current decision-making logic are compared. A tool that can be used by planners of NedTrain when taking turn-around stock decisions will be developed based on the multi-item model.

This leads to the following research questions:

1. *How can the model of Arts et al. (2013) be extended to a multi-item model in which spare parts utilize the same repair capacity?*
2. *What are the differences between the decision-making logic as used by planners currently and the decision-making logic based on the multi-item model?*
3. *What are the results of the current decision-making logic and the situation in which the multi-item model is used?*
4. *How can a decision support tool for the turn-around stock decision be implemented within NedTrain?*

The model of Arts et al. (2013), which will be used as starting point, has been inspired by the practice at NedTrain. An important characteristic of the practice at NedTrain that is covered in the model of Arts et al. (2013), is the fact that demand rates over the lifetime of a train are not constant but differ along the lifetime of the train. Instead of looking for ways to decrease lead-times or increase capacity while minimizing costs, in this research costs are minimized and the the currently used lead-times and capacity are taken into account.

1.4.1 Underlying Research Questions

The following underlying research questions are supportive to answer the research questions:

1. *How can the fluctuating demand that NedTrain faces be modeled accurately using a Markov Modulated Poisson Process, as given in the model of Arts et al. (2013)?*

2. *How can the repair shop and prioritization accurately be modeled using the expediting policy, as given in the model of Arts et al. (2013)?*
3. *How is the decision regarding the size of the turn-around stock level taken in the current situation?*
4. *What are the investment costs when the current decision-making logic is used and KPIs of interest are taken into account?*
5. *What are the investment costs when the multi-item model is used and KPIs of interest are taken into account?*
6. *How can the multi-item model be translated to a tool that can be used at NedTrain?*
7. *What actions need to be performed during an implementation?*
8. *How should a possible implementation be communicated to the users of the tool?*

The investment costs are the acquisition costs of an item multiplied by the desired size of the turn-around stock for this item. KPIs of interest are the expected number of backorders and the expected number of expedites.

1.5 Relation with Previous Research

Loeffen (2012) investigated whether the currently used min-max interface agreement, which is an *operational* decision tool that assigns priorities to repair jobs, performs better or worse than a lead-time interface agreement. She concluded that the min-max interface agreement performs better on the KPIs she investigated.

In the min-max interface agreement a higher priority to items is given based on the number of items in repair *and* the inventory level. The *strategic/tactical* model that is designed in this research, is based on a lead-time interface agreement and is used to determine the optimal size of the turn-around stock. To take into account the prioritization that is used in the repair shop, two priorities are used in terms of lead-times that are assigned to items. When a new repair job arrives, based on the amount of items in regular repair (i.e. items that were assigned a regular repair lead-time), a regular repair lead-time (normal priority) or an emergency repair lead-time (high priority) is assigned to the repair job.

To conclude, whereas Loeffen (2012) takes the size of the turn-around stock level as given and investigated whether the currently used min-max interface agreement or a lead-time interface agreement performs better as *operational* control mechanism in the repair shop, in this research the operational control of the repair shop is approximated using the two different lead-times and a *strategic/tactical* decision is made on the size of the turn-around stock level.

1.6 Scope

1.6.1 Business Entities Involved

The business entities that are involved in this project are the SCO and the NCB, both located in the greater area of Tilburg. The SCO takes, amongst others, care of the planning and supply of the turn-around stock. The NCB takes care of the revision and if necessary repair of defective parts, such that these are ready-for-use (RFU) again.

1.6.2 Spare Parts Involved

In this project the focus is on *repairable* spare parts of trains of NS (in the remainder of this report it will be referred to as spare parts) that are repaired at the NCB in Tilburg and of which the planning is done by the SCO.

1.7 Outline Report

The remainder of this report is structured as follows: In chapter 2 the practice of ordering spare parts at NedTrain is discussed. In chapter 3, the theoretical model for inventory and repair policy will be discussed, followed by a comparison between this model and practice on a qualitative basis in chapter 4. Two business cases that are executed within NedTrain and the results from these business cases are discussed in chapter 5 and chapter 6. How the theoretical model that has been developed in chapter 3 can be used as a tool in practice is explained in chapter 7. Finally , the conclusions, and recommendations for NedTrain and future research are given in chapter 8.

2

Practice of Ordering Spare Parts at NedTrain

In this chapter, the practice of ordering repairable spare parts is discussed. This practice is derived from interviews that were conducted with planners from the SCO and the NCB. In section 2.1 the decision-making process regarding the initial buy and re-buy of spare parts is explained. In section 2.2 the operations within the NCB are discussed and in section 2.3 the classification of parts is explained.

Note the difference between the levels at which decisions are taken: Decisions regarding the size of the turn-around stock levels are *strategic/tactical* decisions, which are not taken very often, only a few times during the life-time of a train. In contrast, the decisions made in the repair shop are *operational* decisions, since these are taken many more times, on a daily or weekly basis.

2.1 New Buy of Spare Parts

New spare parts are currently bought at different moments: The first moment is when a new train series is ordered. The second moment is when a (first) revision period is scheduled and the third moment is when a complete overhaul of a train series takes place. In the next sections the buy decisions regarding these moments will be discussed.

2.1.1 New Train Series

At the moment that new trains are ordered by NS, NedTrain is part of the procurement team. For the logistics processes concerning the acquisition, a team of specialists (which contains amongst others the maintenance engineer and the reliability engineer) is formed to decide on the amount of spare parts to be ordered.

In some cases it is economically more efficient to order spare parts at the same moment as the train is ordered. This holds e.g. for specific parts that have very high start-up costs, which could become extremely expensive in later stages. Because of this, it is tried to have as few custom-made parts as possible on a train series which enables NedTrain to buy extra parts later in time.

However, it could also be the case that one does not want to order spare parts that are needed later in time, at the moment of ordering the train series. This is, because the manufacturer does not want to share the specifications of the parts at that moment and wants a procurement obligation (i.e. NedTrain has to buy spare parts at the train manufacturer for a fixed period). Due to this, the train manufacturer has a monopoly position and can charge high prices for the spare parts. At that moment the logistic planner and the procurement planner decide whether it is possible to postpone the buying decision and order these parts in later stages, when specifications are released and the procurement obligation has ended. Then, it is possible that parts can be ordered against lower prices at OEMs i.e. the suppliers of the train manufacturer.

After it has been decided whether only turn-around stock is bought to cover demand during the lead-time due to unplanned failures or also parts are bought to cover the high demand during the lead-time of revision periods, the logistic planner gives an advice on the size of the turn-around stock to the procurement planner. This is done, based on a regular repair lead-time of 20 working days (4 weeks) and reliability data (such as failure rate) provided by the OEM. The procurement planner has to order the spare parts at the best conditions (price, lead-times, minimum order quantity etc.) possible. Since the delivery time of these spare parts is long, the orders are placed in an early stage, such that these are available at the LLC, OBs and SBs at the moment that the train is put into use.

It should be noted that currently, when spare parts are ordered for new trains at the moment the train is ordered, demand rates of revision periods mostly are not taken into account, i.e. only demand rates due to unplanned failures are taken into account. Next to the 'monopoly' reason discussed above, another reason why demand rates of revision periods are not taken into account, is that negotiations regarding repair lead-times during revision periods *are not* and *can* hardly not be discussed in advance. Some planners however, mention that it could be useful to make some agreements with respect to repair lead-times during revision periods. In the next section we will see the influence of the possibility to negotiate repair lead-times.

2.1.2 Revision and Overhaul Periods

Based on pre-determined revision periods, certain SKUs are taken from the train, inspected, revised, if necessary repaired at the NCB, and put back on the train. Since demand during such a revision period is much larger than the intermittent demand, which is typical for spare parts, during the non-revision period, a logistic planner from the SCO is asked to investigate whether the current turn-around stock level of the parts to be revised is sufficient, to be able to minimize down-time of a train due to unavailability of RFU-parts.

As a starting point, a worst case scenario is formulated in which a repair lead-time of twenty working days and transportation and administration time of five working days are taken into account such that the total lead-time is 25 working days.

Having these lead-times, the planner determines the weekly demand for spare parts for the revision (this can be done quite accurately since a planning is made how many trains are revised in certain weeks) and the demand due to unplanned failures. Then the planner estimates the turn-around stock level as follows: Suppose the current turn-around stock level ($S^{current}$) is 7 parts and the weekly average demand (λ), which includes both demand due to the revision and due to unplanned failures is 5 parts. The policy safety stock PSS, which will be explained in section 2.2 and takes into account variability in demand due to unplanned failures, is 2 and the total repair lead-time L, is 5 weeks. In this case, the turn-around stock level should be 27 parts (5 weeks of demand times 5 parts per week plus policy safety stock) and thus 20 parts need to be ordered. Let ΔS denote the amount of parts to be acquired:

$$\Delta S = \lambda L + PSS - S^{current} = 5 \cdot 5 + 2 - 7 = 20$$

However, at this moment the logistic planner has not yet talked to the capacity planner of the repair shop, whether it is possible to reduce the repair lead-time to e.g. 2 weeks. If this is possible, the desired turn-around stock level can be decreased to 17 parts (3 weeks[1] of demand times 5 parts per week plus policy safety stock), such that only 10 extra parts need to be ordered:

$$\Delta S = \lambda L + PSS - S^{current} = 5 \cdot 3 + 2 - 7 = 10$$

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[1] 2 weeks lead-time, 1 week transportation and administration

As can be seen, by reducing the lead-time, a reduction of 50% in investment costs can be achieved. This procedure is performed for all spare parts that are revised. Having discussed the amount of parts that need to be ordered, the procurement planner has to order the parts at the best price possible.

Since this whole procedure of negotiating can take some time, because planners at the NCB need time to prepare the work in terms of work specifications to determine the repair lead-time, and the lead-time from the external supplier can be quite long in case extra parts need to be ordered, decisions regarding the turn-around stock levels are taken around one and a half year before the revision period starts.

After the revision period it may be the case that there are too many parts (i.e. the turn-around stock needed for corrective maintenance actions is smaller than the currently available stock). In that case, the surplus stock is stored at the strategic warehouse.

It should be noted that *Xelus Parts*, the software tool that is used by NedTrain for administration regarding planning and demand of parts, also gives an advice regarding buying decisions for repairable spare parts, however these advices are not followed by the planners since they know that these advices are calculated using other parameters, e.g. Xelus parts takes into account the default repair lead-time of four weeks (20 working days).

2.2 Revision and Repair at NCB

At the Nedtrain Components Company (NCB) defective parts are revised and if necessary repaired such that these are ready for use again (RFU-parts). The repair jobs are classified in four different clusters: *1) Mechanics/Pneumatics, 2) Electronic components, 3) Pneumatics (braking systems)* and *4) Air conditioners, compressors, traction and sanitary facilities.*

For each part that is revised and repaired within each cluster, it is determined which repair lead-times are possible. However, since the negotiations take place a long time before the actual revision, it is hard to mention what lead-times are realistic, especially for parts that have not been revised by the NCB yet. Nevertheless, agreements are made and when the negotiations have finished and the revision period is upcoming, the capacity planners at the repair shop start scheduling the repair jobs to make sure that parts can be delivered on time.

When parts are offered to the NCB for revision and repair, lead-times are agreed upon (separate for corrective maintenance and revision periods). The standard lead-time for corrective maintenance actions is 20 working days. For the revision periods, agreements are made as has been discussed above. Although lead-time agreements are made, the operational control at the NCB is not based on lead-times. A min-max interface agreement is used for the *operational* control between the NCB and SCO. In the min-max interface agreement a min-level is given to the NCB by the SCO. The min-level denotes the amount of RFU-parts that should be available in the network. This min-level is equal to the policy safety stock that is calculated by Xelus Parts by the following formulae (Loeffen, 2012):

$$\text{Policy Safety Stock} = PSS = \sigma_L \cdot k \tag{2.1}$$

$$k = \max\left[0, \frac{-1}{\sqrt{2}} \ln\left[\frac{\left(2\sqrt{2}\right)\left(1 - \frac{P_2}{100} \cdot LOT\right)}{\sigma_L\left[1 - \exp\left(\frac{-\sqrt{2} \cdot LOT}{\sigma_L}\right)\right]}\right]\right] \tag{2.2}$$

$$\sigma_L = \sqrt{\frac{\text{effective lead-time}}{22}} \cdot \sqrt{MSE} \tag{2.3}$$

In this formula σ_L denotes the standard deviation of the recurring demand during the lead-time. The recurring demand is demand that occurs due to unplanned failures (corrective maintenance actions) and k denotes the safety factor. How these variables are calculated is shown in Equation (2.2) and Equation (2.3). P_2 denotes the desired fill rate for the parts, which is discussed in section 2.3. LOT is the *forecasted* recurring demand for the current month. Recurring demand is demand due to corrective maintenance actions. The effective lead-time equals the repair lead-time in the NCB plus the administration and transportation time. The number 22 denotes the number of working days in a month. MSE denotes the mean squared error of the forecasted recurring demand.

The max-level is determined by the planner at the NCB and is equal to the min-level plus three months of forecasted demand. More information regarding the min-level and max-level can be found in Loeffen (2012). These min- and max-levels are used to determine the priorities that are assigned to the repair jobs. Let the inventory level of a SKU be the on hand stock minus the backorders ($IN_i = OH_i - BO_i$), $\min_i$ be the min-level, $\max_i$ be the max-level and λ_i be the monthly demand. The min-level is equal to the policy safety stock, the max level is equal to the policy safety stock plus three months of demand.

Table 2.1 – Priority rules NCB

Priority	Inventory level value
1	$IN_i \leq 0$
2	$0 < IN_i < \min_i$
3	$\min_i \leq IN_i \leq \min_i + \lambda_i$
4	$\min_i + \lambda_i \leq IN_i \leq \min_i + 2\lambda_i$
5	$\min_i + 2\lambda_i \leq IN_i \leq \min_i + 3\lambda_i$
999	$IN_i \geq \min_i + 3\lambda_i = \max_i$
100	Parts are waiting for SRUs
300	A lead-time is assigned to the part

Note that the priority of a repair job can change when a new request for the same SKU occurs.

2.3 Classification of Parts

At NedTrain parts are classified along two axes: demand frequency (parts per year) and price (€). When demand for spare parts is high and price is low, the focus is on performance (maximizing the service level). When demand is low and price is high, the focus is on minimizing investment costs. In the other two situations (high price-high demand and low price-low demand) the focus is on a balance between performance and investment, see Table 2.2. This classification is known as the EMC (External Material Class) project and its goal is to find a better balance between inventory value, parts availability and operational costs.

Every item (critical and non-critical) is classified along these two axes. There are three price categories: <€1,000, €1,000 – €3,500 and >€3,500. Demand is divided into four groups: >12 parts per year, 12 – 4 parts per year, 3 – 1 part(s) per year and 0 parts per year. For each of these 12 categories, service levels (fill rates) are defined for both the critical items and the non-critical items, see Table 2.3. Whether a part is critical or non-critical is based on advice given by the OEM and decided by the maintenance engineers and reliability engineers.

Table 2.2 – Parts classification

		Demand frequency	
		High	Low
Price	High	Balance between investment and service level	Focus on minimizing investment costs
	Low	Focus on maximizing service level	Balance between investment and service level

Table 2.3 – Fill rates for critical (non-critical) parts, based on demand frequency and price

Price					
	A3 95.0 (85.0)	B3 90.0 (75.0)	C3 90.0 (75.0)	D3 90.0 (75.0)	Fill rate (%)
€3,500					
	A2 99.0 (98.0)	B2 98.0 (91.0)	C3 95.0 (85.0)	D2 95.0 (85.0)	Fill rate (%)
€1,000					
	A1 99.5 (99.5)	B1 99.0 (99.0)	C1 98.0 (95.0)	D1 98.0 (95.0)	Fill rate (%)
Demand frequency (parts per year)	12	3	0		

3

Model for Inventory and Repair Policy

In this chapter, first the system of interest will be described in section 3.1 followed by assumptions that are made to be able to model this system. Then the single-item model of Arts et al. (2013) will be presented. How this single-item model can be analyzed and optimized will be discussed in section 3.3 and section 3.4. This procedure follows the evaluation and optimization procedure as is described in Arts et al. (2013). In section 3.5 the multi-item optimization model will be presented. For the optimization, we need the results from the single-item model.

3.1 System and Model Description

Let us consider the single-item model of Arts et al. (2013). Defective parts (and thus demand for spare parts) arrive according to a Markov Modulated Poisson Process (MMPP) where the demand rates depend on the state (e.g. a revision period) of a SKU at moment t. The possible states of the Markov Process, which is irreducible, are described by $Y(t)$ and has finite state space $\Theta = \{1, \dots, |\Theta|\}$ with generator matrix $\mathbf{Q}$ whose elements are denoted by q_{ab}. Define $q_a = -q_{aa}$, $q_{\max} = \max_{a \in \Theta} q_a$. When $Y(t) = y$, the demand rate is given by $\lambda(y) \geq 0$. The vector of demand rates is given by $\boldsymbol{\lambda} = (\lambda(1), \dots, \lambda(|\Theta|))$ and $\lambda(y) > 0$ for at least one $y \in \Theta$. Let $\lambda_{\max} = \max_{y \in \Theta} \lambda(y)$. Demand during time interval $(t_1, t_2]$ given state $Y(t_1) = y$ is denoted as $D^y_{t_1,t_2}$ (Arts et al., 2013).

Upon arrival of a defective part, it is decided whether the part is assigned a regular repair lead-time or an expedited repair lead-time. When the number of parts in regular repair, $X(t) = x$, is larger than or equal to a certain threshold level $T(y)$, which depends on the state y, the part is assigned an expedited repair lead-time, which is deterministic and denoted by ℓ_e. In case the repair is not expedited, the part gets an additional regular repair lead-time, which assumed to consist of one phase and to be exponentially distributed with mean $\mathbb{E}[L_r] = 1/\mu$. A constant acquisition cost rate of $C^a > 0$ is incurred. Expediting a repair costs $c_e > 0$ per item and for backordered items a cost of $p > 0$ per item is incurred. Assuming that the additional regular repair lead-time consists of a single exponential phase is called the E-WDT heuristic by Arts et al. (2013).

3.2 Assumptions

In chapter 2 we have discussed the current practice at NedTrain. However to be able to model the system, some assumptions have to be made. In the model described in this chapter, the following assumptions[1] are made:

1. **The OBs, SBs and LLC are modeled as one location**
   When a RFU-part is requested at one of the OBs or SBs but it is not available at that

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[1] Some of the assumptions are also mentioned in (Arts, 2013, ch. 4)

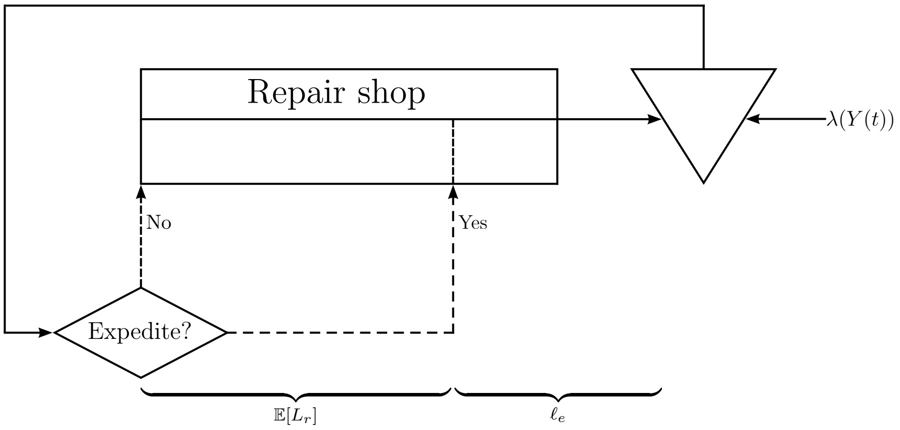

Figure 3.1 – Repairable item inventory system with the possibility to expedite (Arts, 2013, ch. 4)

specific location, NedTrain is able to relocate this RFU-part in relatively short time period by transporting this part from a location where it is available to the location where it is not available. Since NedTrain is interested in the network fill rate, it does not matter *where* a RFU-part is available but *if* a RFU-part is available.

2. **Items are replenished by an $(S-1,S)$ policy, meaning that upon replacement, these are directly sent to the repair shop**
When a RFU-part is used, the defective part is transported to the NCB by the end of the day. Planners at the SCO can see this demand directly, planners at the NCB cannot.

3. **The expedited lead-time is deterministic and the additional regular repair lead-time is exponentially distributed**
The additional regular repair lead-time consists amongst others of waiting for resources. Arts et al. (2013) model this additional repair lead-time by splitting this lead-time into m phases, however they also show that the added value of doing this is small. Therefore in this model the additional regular repair lead-time is assumed to consist of one phase which is exponentially distributed. The expedited repair lead-time consists mainly of pure repair time and transportation and administration time and can therefore be assumed to be fixed and deterministic.

4. **The time horizon is infinite**
The life-time of the train is quite long (several decades). This is relatively long compared to the other measures in the system such as lead-times (repair rates) and demand rates, which are measured in days, weeks or months.

5. **Average demand for spare parts is known in advance and demand is modeled as a Markov Modulated Poisson Process**
A forecast of demand due to unplanned failures is given by the maintenance engineer at the moment spare parts are ordered. During the life-time of trains revision periods are planned and the number of parts to be revised (repaired) is given in advance. During both periods (period with demand only due to unplanned failures (referred to as non-revision period) and revision period) the demand rates differ. During the non-revision period, demand is low and can be modeled as a Poisson Process. During the revision period, demand is relatively high and can also be modeled as a Poisson Process, however a distinction should be made between these two periods. This distinction is made by modeling the demand for spare parts as a Markov Modulated Poisson Process.

6. **When a repair job is expedited, all necessary shop-replaceable units (SRUs) are available**
   When a repair job needs to be expedited, it is assumed that the repair lead-time (and the transportation and administration time) are deterministic. This repair lead-time is the pure repair time and therefore it is assumed that SRUs are available and one does not have to wait for these parts to become available. From Table I.1, we can calculate that for 10.6% of the outstanding orders from January 2013 to May 2013 had Prio 100 and were waiting for SRUs to become available.

7. **The turn-around-stock level S is determined at time $t = 0$ and it is fixed**
   This means that parts can only be ordered once. This is partly justified: For some spare parts costs are quite high later in time (e.g. due to high start-up costs) which makes it economically unattractive to order parts at a later moment in time. However, sometimes the train manufacturer asks high prices for spare parts, which do not make it economical to buy these parts in early stages. In that case NedTrain waits till the specifications of the parts are known and then orders these parts elsewhere.

8. **Parts can always be repaired**
   Over 2012, 3.5% of all parts that were ordered at the NCB, were scrapped. For 45/1060 SKUs, the scrap rate was equal or greater than 50%. Therefore, for some clusters the average within the cluster is quite large. See Table D.1 in Appendix D.

9. **The minimum order quantity for parts is one**
   For 81% of the parts the minimum order quantity (MOQ) is equal to 1. See Table D.2 in Appendix D.

10. **The minimum repair quantity for parts is one**
    According to Guido Aerts of the NCB, it can be stated that the minimum repair quantity is equal to one.

11. **The capacity to store defective parts is infinite**
    At the repair shop there is enough space to store all the defective parts.

3.3 Single-item evaluation: Finding an Optimal Expediting Repair Policy

When evaluating the system, we start with a fixed turn-around stock level S and have to determine the optimal expediting repair policy, i.e. finding threshold levels for which our policy describes to expedite a repair. Recall that expediting a repair costs $c_e > 0$ per item and for backorders a cost rate of $p > 0$ per backordered item is incurred. Let $X(t) = x$ denote the number of parts in regular repair at time t and $Y(t) = y$ be the state at time t. For given S, x and y the backorder penalty costs are determined as follows:

$$\begin{aligned} c_p(x,y) &= p \sum_{k=S-x}^{\infty} (k-(S-x))\,\mathbb{P}\{D^y_{t,t+\ell_e} = k\} \\ &= p \sum_{k=0}^{\infty} (k-(S-x))\,\mathbb{P}\{D^y_{t,t+\ell_e} = k\} \\ &\quad - p \sum_{k=0}^{S-x-1} (k-(S-x))\,\mathbb{P}\{D^y_{t,t+\ell_e} = k\} \end{aligned} \tag{3.1}$$

In Equation (3.1), $\mathbb{P}\{D^y_{t,t+\ell_e} = k\}$ is calculated as explained in Appendix E. Note that $S - x$ denotes the number of parts that is on hand at the stock point at time t or will arrive before $t + \ell_e$.

Define $\mathbb{N}_0 := \mathbb{N} \cup \{0\}$. Now state-space $\mathcal{M} = \{(x, y) \in \mathbb{N}_0 \times \Theta | x \leq M\}$ where M is chosen such that it is optimal to expedite whenever $X(t) \geq M$.

Arts et al. (2013) prove that if $c_e \geq p\mathbb{E}[L_r]$ it is optimal to never expedite a repair job and that if $c_e < p\mathbb{E}[L_r]$ there exists an $M \in \mathbb{N}$ such that whenever $X(t) \geq M$ it is optimal to expedite a repair job upon failure of a part. Intuitively this can be interpreted as follows: when the total backorder penalty costs during the regular repair lead-time are equal or smaller to the costs for expediting, one does not want to expedite a repair job. The other way around the same holds: when expediting a repair is cheaper than the total backorder penalty costs during the repair lead-time, one probably wants to expedite the repair job if there are enough outstanding orders (repair jobs in regular repair).

To determine the costs of a certain expediting repair policy, a recursion will be performed. However, first some extra notation will be introduced: "Since transition rates are bounded, the uniform transition rate technique can be applied to transform the problem of finding an optimal expediting policy to discrete time" (Arts, 2013, ch. 4). "The idea behind uniformization is to choose a new uniform transition rate which is the same for all states and controls with the caveat that sometimes a transition will leave the state unchanged" (England, 2006, p. 53). The uniform transition rate in this problem is set as follows: $\Lambda = \lambda_{\max} + M\mu + q_{\max}$. Time is scaled such that $\Lambda = 1$. When in state (x, y) two decisions can be made, based on the threshold level M: expediting or not expediting.

Let $V_n(x, y)$ be the optimal total cost with n transitions to go and when in state (x, y). Also define $V_0(x, y) \equiv 0$. Using a dynamic programming recursion (Bellman equation) the optimal total costs can be determined as follows (Arts et al., 2013):

$$\begin{aligned} V_{n+1}(x,y) = \quad & c_p(x,y) + \lambda(y)\mathbf{1}_{\{x<M\}} \min\{c_e + V_n(x,y), V_n(x+1,y)\} \\ & + \lambda(y)\mathbf{1}_{\{x=M\}}(c_e + V_n(x,y)) + x\mu V_n(x-1,y) + (M-x)\,\mu V_n(x,y) \\ & + \sum_{y' \in \Theta\setminus\{y\}} q_{yy'} V_n(x,y') + (q_{\max} - q_y + \lambda_{\max} - \lambda(y))V_n(x,y) \end{aligned} \tag{3.2}$$

In this value iteration $\mathbf{1}_{\{\cdot\}}$ denotes the indicator function. The terms in the value iteration can be interpreted as described in Table 3.1.

The value iteration is terminated when one of the following two conditions is met:

$$\frac{\max_{(x,y)\in\mathcal{M}}\left(V_{n+1}(x,y) - V_n(x,y)\right) - \min_{(x,y)\in\mathcal{M}}\left(V_{n+1}(x,y) - V_n(x,y)\right)}{\frac{1}{2}\left(\max_{(x,y)\in\mathcal{M}}\left(V_{n+1}(x,y) - V_n(x,y)\right) + \min_{(x,y)\in\mathcal{M}}\left(V_{n+1}(x,y) - V_n(x,y)\right)\right)} < 10^{-4} \tag{3.3}$$

$$\Lambda \frac{\max_{(x,y)\in\mathcal{M}}\left(V_{n+1}(x,y) - V_n(x,y)\right) + \min_{(x,y)\in\mathcal{M}}\left(V_{n+1}(x,y) - V_n(x,y)\right)}{2} < 10^{-5} \tag{3.4}$$

The first condition measures the relative error, the second condition measures the absolute costs. When S is very large, there are almost no expedites and absolute costs are almost zero. In that case the first condition will not become small enough to stop the iterations.

The $(n+1)$th iteration $(n + 1 \in \mathbb{N}_0)$, for which one of the two conditions is met, is denoted by n^*. The total penalty and expediting cost of this policy can be denoted as follows:

$$C(S) = \Lambda \frac{\max_{(x,y)\in\mathcal{M}}\left(V_{n^*}(x,y) - V_n(x,y)\right) + \min_{(x,y)\in\mathcal{M}}\left(V_{n^*}(x,y) - V_n(x,y)\right)}{2} \tag{3.5}$$

Table 3.1 – Interpretation of terms in the dynamic programming recursion

Term	**Interpretation**
$c_p(x,y)$	Backorder penalty costs incurred based on the current amount of parts in regular repair
$\lambda(y)\mathbf{1}_{\{x<M\}}\min\{c_e+V_n(x,y),V_n(x+1,y)\}$	Costs when a part is expedited or added to the repair pipeline (number of parts changes depending on whether expediting or adding to the repair pipeline is cheaper)
$\lambda(y)\mathbf{1}_{\{x=M\}}(c_e+V_n(x,y))$	Costs when a part is expedited
$x\mu V_n(x-1,y)$	Transition when a part leaves the repair pipeline (number of parts in repair changes)
$(M-x)\,\mu V_n(x,y)$	Transition when neither the number of parts in repair nor the modulating state changes (due to uniformization)
$\sum_{y'\in\Theta\setminus\{y\}} q_{yy'}V_n(x,y')$	Transition when the modulating state changes
$(q_{max}-q_y+\lambda_{\max}-\lambda(y))V_n(x,y)$	Transition when neither the number of parts in repair nor the modulating state changes (due to uniformization)

From the value iteration we cannot only get the total costs related to backorders and expediting but we can also get the vector $\mathcal{T}=(T(1),\ldots,T(|\Theta|))$ containing the threshold levels corresponding to each state. This vector can be derived as follows:

For each x and y the difference $V_{n^*}(x+1,y)-V_{n^*}(x,y)$ is calculated. The smallest x for which this value is smaller or equal to c_e, is the threshold level $T(y)\in\mathbb{N}_0, y\in\Theta$. This can be interpreted as follows: When the backorder penalty costs incurred due to adding a part to the repair pipeline exceed the cost of expediting, the repair of the part is expedited and instead of incurring backorder penalty costs, expediting costs are incurred.

For given S and $\mathcal{T}$, let $EBO(S,\mathcal{T})$ denote the expected number of backorders and $EXP(\mathcal{T})$ the expected number of expedites per time unit. Then the expression for the total penalty and expediting costs as given in Equation (3.5), can also be expressed as:

$$C(S)=pEBO(S,\mathcal{T})+c_eEXP(\mathcal{T}) \tag{3.6}$$

To determine the expected number of expedites, $EXP(\mathcal{T})$, the above value iteration is performed again, however the backorder penalty cost rate p is set to 0, the cost of expediting c_e is set to 1 and the uniform transition rate is set as follows $\Lambda=\lambda_{\max}+\max(\mathcal{T})\mu+q_{\max}$. Since we know $\mathcal{T}$ now, we can use these threshold levels to determine whether a repair job is expedited or repaired as a regular repair. The costs of this policy, which only consist of expediting costs, are as follows:

$$\begin{aligned}V_{n+1}(x,y)=\;&\lambda(y)\mathbf{1}_{\{x<T(y)\}}V_n(x+1,y)+\lambda(y)\mathbf{1}_{\{x=T(y)\}}(1+V_n(x,y))\\&+x\mu V_n(x-1,y)+(\max(\mathcal{T})-x)\,\mu V_n(x,y)\\&+\sum_{y'\in\Theta\setminus\{y\}}q_{yy'}V_n(x,y')+(q_{\max}-q_y+\lambda_{\max}-\lambda(y))V_n(x,y)\end{aligned} \tag{3.7}$$

This allows us to calculate the expected number of repair jobs that is expedited. If we multiply the outcome of this value iteration by the expediting costs c_e we have the expected expediting costs. We can subtract these costs from the total penalty and expediting costs $C(S)$ as calculated in Equation (3.5), which leaves us with the expected backorder costs $pEBO(S, \mathcal{T})$. When these backorder costs are divided by the backorder penalty cost rate p we have the expected number of backorders, $EBO(S, \mathcal{T})$.

Since the total cost of this policy depends on the fixed S, for the total costs, we have to include the acquisition costs:

$$C_{tot}(S) = C^a S + C(S) = C^a S + pEBO(S, \mathcal{T}) + c_e EXP(\mathcal{T}) \tag{3.8}$$

As can be seen in Equation (3.7), the decision whether to expedite a repair job or add it to the queue of regular repairs, depends on $T(y)$. Following the notation of Song and Zipkin (2009) the decision to expedite can also be based on inventory positions: Let $IN(t) = OH(t) - BO(t)$ denote the inventory level (is on hand stock minus backorders) and let $N(t)$ be the total number of outstanding orders (repair jobs). Then define the inventory position of the total system as follows: $IP(t) = IN(t) + N(t)$. The inventory position of the emergency part of the system only includes the number of parts that are on hand at time t or that are in repair and will arrive before $t+\ell_e$: $IP_e(t) = IN(t)+N(t)-X(t)$. The system maintains $IP(t) = S$ (since a fixed turn-around stock level is assumed) and keeps $IP_e(t) \geq S'(Y(t))$. Now we know $S = IN(t) + N(t)$ and thus $IP_e(t) = S - X(t)$. Since we want to keep $IP_e(t) \geq S'(Y(t))$, $S - X(t) \geq S'(Y(t))$ has to hold. This means that when $X(t) \geq S - S'(Y(t)) = T(Y(t))$ an repair job is expedited such that $IP_e(t) \geq S'(Y(t))$. The goal is then to find S and $S'(Y(t))$ such that costs are minimized.

3.4 Single-item Optimization

When p and c_e are given next to the generator matrix $\mathbf{Q}$, the vector with demand rates $\boldsymbol{\lambda}$, the additional regular repair lead-time $\mathbb{E}[L_r]$, the expedited repair lead-time ℓ_e and the acquisition cost rate C^a, the S and $\mathcal{T}$ that minimize $C_{tot}(S)$ (see Equation (3.8)) can be found by performing a golden section search over S and finding the optimal $\mathcal{T}$ for each S using the evaluation method described in the previous section. According to Arts et al. (2013) a greedy algorithm, such as golden section search, can work well. However, since it can be that $C_{tot}(S)$ is not unimodal[2], enumeration should be used to find the optimal solution. In Appendix F it is explained how a lower and an upper bound for S can be found, which can be used when enumeration is performed.

3.5 Multi-item Model and Optimization

In this section, the single-item model as presented in section 3.1 will be extended to a multi-item model. The goal in this multi-item model is to find a combination of inventory (turn-around stock) and expediting policies for the items in the system, such that the total investment costs in turn-around stock are minimized, while an expected number of backorders constraint and an expected number of expedites constraint are taken into account.

To do this, a multi-item optimization problem will be stated and solved using a decomposition and column generation method in which the single-item evaluation and optimization method of the previous sections are used. System approach means that there is a constraint for the system as a whole instead of a constraint per item (which is known as item approach).

Before the multi-item optimization problem is stated, let us first define some additional notation. The set of SKU-s that is taken into account is denoted by I. The number of SKU-s is

---

[2] Consider the problem instance with Poisson demand, with rate $\lambda = 3.45$, $C^a = 7.7$, $\ell_e = 8$, $\mathbb{E}[L_r] = 15$, $p = 37$ and $c_e = 116$, for which the results can be obtained exactly

denoted by $|I|$ and items are numbered by $i = 1, \ldots, |I|$. The same input parameters as given in section 3.1 are used, however now the index i is used to identify the SKU-s.

In the multi-item optimization problem the objective is to minimize total investment costs $\sum_{i \in I} C_i^a S_i$. As mentioned before, two constraints are set: one on the expected number of backorders per time unit and, since not all repair jobs can be expedited at the same time, also a constraint is set on the expected number of expedites per time unit. This results in the following optimization problem:

$$
\begin{array}{llll}
\text{(P)} & \min & \displaystyle\sum_{i \in I} C_i^a S_i & \\
& \text{subject to} & \displaystyle\sum_{i \in I} EBO_i(S_i, \mathcal{T}_i) \leq EBO_{obj} & \\
& & \displaystyle\sum_{i \in I} EXP_i(\mathcal{T}_i) \leq EXP_{obj} & \\
& & T_i(y) \leq S_i & \forall i \in I, \forall y \in \Theta_i \\
& & S_i, T_i(y) \in \mathbb{N}_0 & \forall i \in I, \forall y \in \Theta_i
\end{array}
$$

Let c_{P} denote the optimal cost of problem (P), $\mathbf{S} = (S_1, \ldots, S_{|I|})$ denote the set of optimal turn-around stock levels and $\mathbf{T} = (\mathcal{T}_1, \ldots, \mathcal{T}_{|I|})$ denote the set of vectors that contain the thresholds levels for each item in each state.

The reasoning behind adding the constraint $T_i(y) \leq S_i$ in problem (P) is as follows: Imagine that the threshold level is higher than the turn-around stock level. When demand for a spare part occurs and there are no ready-for-use parts available (the on-hand stock is zero or less), a backorder occurs and a train is down. Since the repair shop has to possibility to expedite repair jobs, in practice, the repair shop will never assign this part a regular repair lead-time but always an expedited repair lead-time, to minimize the downtime for the train. Therefore, in practice, the threshold level is smaller or equal to the turn-around stock level, such that when no ready-for-use parts are available (S_i parts are in regular repair), newly arriving defective parts will always get an expedited repair lead-time.

In the next sections it will be explained how a feasible solution for problem (P) can be found.

3.5.1 Lower Bound

To find a lower bound on the cost of problem (P), c_{P}, a decomposition and column generation method is used. The decomposition method used in this thesis is derived from the method used by Kranenburg and Van Houtum (2007).

First a *Master Problem* is defined in which the variables of problem (P) are expressed as combinations of columns that contain all possible values for the decision variables. The set $K := \mathbb{N}_0$ denotes the set of turn-around stock and expediting policies for the SKU-s $i \in I$ considered in the problem. Let $S_i^k, i \in I, k \in K$ denote the turn-around stock level for SKU i in policy k, let $\mathcal{T}_i^k, i \in I, k \in K$ denote the vector of threshold levels for SKU i in policy k and let $x_i^k \in \{0, 1\}, i \in I, k \in K$ denote the decision variable that indicates whether policy k for SKU i is chosen ($x_i^k = 1$) or not ($x_i^k = 0$). In problem (MP) the integrality constraint on $x_i^k, i \in I, k \in K$ is relaxed, which allows for fractional values of $x_i^k, i \in I, k \in K$ (Kranenburg and Van Houtum, 2007).

$$
\begin{array}{llll}
\text{(MP)} & \min & \sum_{i\in I}\sum_{k\in K} C_i^a S_i^k x_i^k & \\
& \text{subject to} & \sum_{i\in I}\sum_{k\in K} EBO_i(S_i^k, \mathcal{T}_i^k)x_i^k \leq EBO_{obj} & \text{(MP.1)} \\
& & \sum_{i\in I}\sum_{k\in K} EXP_i(\mathcal{T}_i^k)x_i^k \leq EXP_{obj} & \text{(MP.2)} \\
& & \sum_{k\in K} x_i^k = 1 \qquad \forall i \in I & \text{(MP.3)} \\
& & x_i^k \geq 0 \qquad \forall i \in I, \forall k \in K &
\end{array}
$$

Let c_{P}^{LB} denote the optimal cost for problem (MP). Due to the relaxation on the integrality of x_i^k, c_{P}^{LB} is also a lower bound on c_{P}.

Since problem (MP) contains an infinite amount of policies, a restricted master problem (RMP) is introduced that contains, for each SKU $i \in I$, a finite subset of policies which is denoted by $K_i \subseteq K$ and is solved to optimality. It is checked whether problem (RMP) can be improved, by adding new policies (column generation) to K_i. To check whether problem (RMP) can be improved, for each item $i \in I$ a subproblem is solved. In this subproblem, $u_1 < 0$ and $u_2 < 0$ are the dual variables that correspond to Equation (MP.1) and Equation (MP.2) respectively. The dual variable $v_i \geq 0$ denotes the dual variable that corresponds to SKU i in Equation (MP.3). These dual variables are used as input for the subproblem (SUB(i)), which is solved for each SKU $i \in I$.

$$
\begin{array}{llll}
(\text{SUB}(i)) & \min & C_i^a S_i - u_1 EBO(S_i, \mathcal{T}_i) - u_2 EXP(\mathcal{T}_i) - v_i & \\
& \text{subject to} & T_i(y) \leq S_i & \forall y \in \Theta_i \\
& & S_i, \mathcal{T}_i \in \mathbb{N}_0 &
\end{array}
$$

Note that the objective function of (SUB(i)) is almost the same as Equation (3.8) except for the constant v_i. This means that (SUB(i)) can be solved by minimizing Equation (3.8) using $p = -u_1$ and $c_e = -u_2$ and then subtracting v_i. This minimization can be performed using the single-item optimization method that was explained in section 3.4. Let $c_{\mathrm{SUB}(i)}$ denote the cost of an solution to problem (SUB(i)). If $c_{\mathrm{SUB}(i)}$ is negative (i.e. has a negatively reduced cost coefficient), the policy (a column) is added to K_i.

Problem (RMP) and problem (SUB(i)) are solved iteratively until no more policies for SKU-s $i \in I$ have a negatively reduced cost coefficient. As we have seen in section 3.4, the golden section search algorithm can work well to find new good policies. However since $C_{tot}(S)$ can be not unimodal, an optimum can only be found when $C_{tot}(S)$ is solved to optimality by enumeration. When no more policies can be added (i.e. do not have a negatively reduced cost coefficient) using the golden section search, the subproblem is solved to optimality by enumeration for each SKU $i \in I$. When this also yields no new policies, we have found an optimal solution for problem (RMP) which is also optimal for problem (MP).

Creating initial policies

To create initial policies, we start with a feasible and infeasible solution for problem (RMP) to get good LaGrange multipliers. We do so by setting p and c_e such that Equation (MP.1) and Equation (MP.2) are satisfied. It may be possible that due to the high values for p and c_e the constraints are non-binding (i.e. the same optimal solution would have been found without having the constraints and the inequality constraint does not hold with equality). This situation may lead to dual variables that are zero, however positive values for the dual variables (shadow prices) are needed to solve the sub problems. Therefore also an infeasible solution will be created by setting p and c_e such that Equation (MP.1) and Equation (MP.2) are not satisfied. In Appendix G, it is described how p and c_e are set in the feasible and infeasible solution. In both the feasible and infeasible situation, Equation (3.8) is solved for all items $i \in I$, which leads to $2|I|$ policies. Then problem (RMP) is solved to find the shadow prices which are used to solve the subproblems.

3.5.2 Upper Bound

When no more columns can be added to K_i, problem (RMP) is solved one more time to find a lower bound in terms of costs for problem (P). In case there are no fractional solutions for any $x_i^k, i \in I, k \in K_i$, this also is an upper bound for the costs for problem (P). In case there are fractional solutions for any $x_i^k, i \in I, k \in K_i$, there are different ways in which an integer solution can be found: Kranenburg and Van Houtum (2007) propose to take for each SKU the policy with the lowest turn-around stock level for which $x_i^k > 0$ and then do a local search until a feasible solution has been found. Alvarez et al. (2012) and Alvarez et al. (2013) propose to solve (RMP) as a binary integer program. They found good results using the integer problem and it outperformed the greedy heuristic in terms of solution quality. Therefore this approach will also be used in this research to find a near-optimal solution. The integer problem is as follows:

$$
\begin{array}{lll}
\text{(BINRMP)} & \min & \displaystyle\sum_{i \in I} \sum_{k \in K_i} C_i^a S_i^k x_i^k \\
& \text{subject to} & \displaystyle\sum_{i \in I} \sum_{k \in K_i} EBO_i(S_i^k, \mathcal{T}_i^k) x_i^k \leq EBO_{obj} \\
& & \displaystyle\sum_{i \in I} \sum_{k \in K_i} EXP_i(\mathcal{T}_i^k) x_i^k \leq EXP_{obj} \\
& & \displaystyle\sum_{k \in K_i} x_i^k = 1 \qquad\qquad\qquad\qquad \forall i \in I \\
& & x_i^k \in \{0, 1\} \qquad\qquad\qquad\qquad \forall i \in I, \forall k \in K_i
\end{array}
$$

Let c_{P}^{UB} be the cost of problem (BINRMP). The solution of problem (BINRMP) is an upper bound on costs for problem (P). From this solution we also obtain the set of turn-around stock levels $\mathbf{S} = (S_1, \ldots, S_{|I|})$ and the set of threshold levels $\mathbf{T} = (\mathcal{T}_1, \ldots, \mathcal{T}_{|I|})$ for each item $i \in I$. (Recall that $\mathcal{T}_i$ denotes the vector of threshold levels for item $i \in I$).

4

Differences between Practice and Theory

In this chapter the differences between the practice at NedTrain as discussed in chapter 2 and the model of chapter 3 are discussed. In section 4.1 the difference between the item approach that is used by NedTrain and the system approach that is used in the model is discussed. The difference of taking variability into account is discussed in section 4.2. The difference in prioritization, constraints and buy decisions are discussed in section 4.3, section 4.4 and section 4.5 respectively.

4.1 Item Approach vs. System Approach

In the item approach, targets per item are set and the turn-around stock level that is needed to achieve this target and minimizes costs is calculated for each item separately. In the system approach, a system target is set and the goal is to find a combination of turn-around stock levels that minimizes costs but such that the system target is achieved. Sherbrooke (1968, p. 123) mentions that the system approach "focuses management attention on the entire system so that an appropriate combination of system effectiveness and system cost can be selected." Thonemann et al. (2002, p. 1224) conclude that the relative improvement in investment when using a system approach depends mainly on the unit cost: "Inventory systems with high unit cost skewness benefit significantly from the system approach while systems with low unit cost skewness benefit little". A downside mentioned by Thonemann et al. (2002) is that implementing and using the system approach requires much more time, money and skills due to its complexity than using the item approach.

In the current situation NedTrain determines the turn-around stock levels using an item approach. By taking into account the policy safety stock, the item target is taken into account since the policy safety stock is set using the P_2 service measure (fill rate). This fill rate per item is set as given in Table 2.3. Since NedTrain already differentiates between service levels for items, based on price and demand frequency (see Table 2.3), they already gain part of the benefits that are also gained when the system approach is used.

In the NedTrain situation, parts cost prices (internal price) range from €11.61 to €170,792.52. Table 4.1 gives an overview of the differentiation of cost prices of the spare parts at NedTrain. To get an idea of this cost price spread, all SKU-s that were registered in Xelus Parts in June 2013 are round up to the nearest €100. Then the total number of SKU-s that have a rounded cost price of a multiple of €100 are plotted for each multiple of €100. This is graphically shown in Figure 4.1.

As can be seen in Figure 4.1, the cost price data shows a positive skew meaning that it may be beneficial to use a system approach. Thonemann et al. (2002) however also mention that a downside of the system approach is, that implementing and using the system approach requires much more time, money and skills due to its complexity than using the item approach.

Table 4.1 – Differentiation of cost prices of spare parts

Range	Percentage of SKU-s
cost price < €1,000	44.9%
€1,000 ≤ cost price < €3,500	32.4%
€3,500 ≤ cost price	22.7%

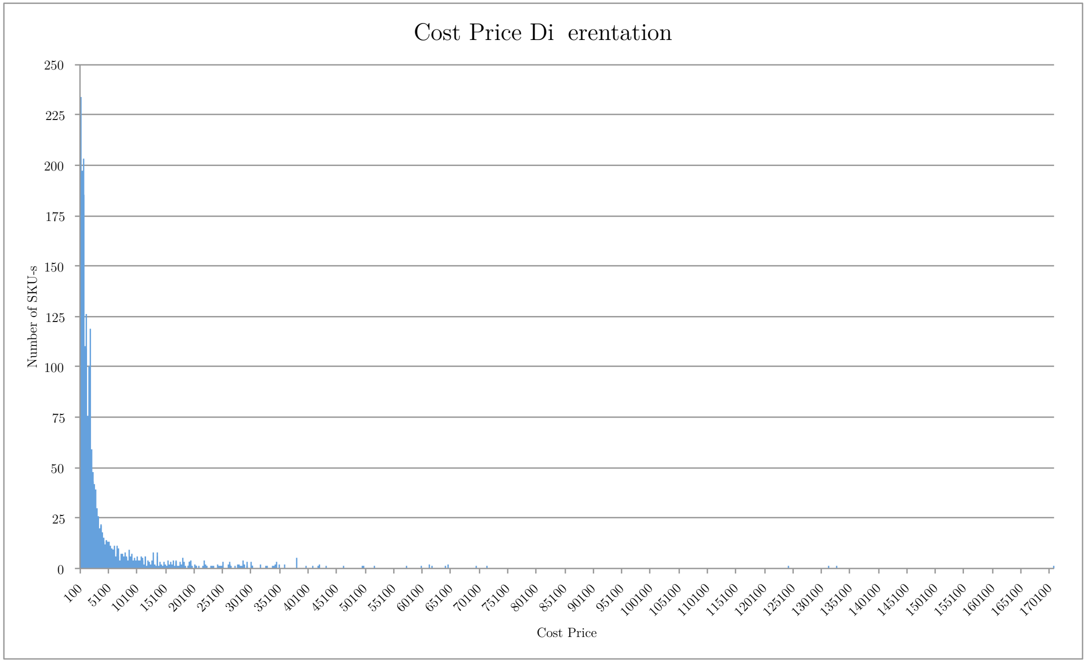

Figure 4.1 – Differentiation of cost prices of spare parts

4.2 Deterministic Demand and Safety Stock vs. Stochastic Demand

At the initial buy, decisions regarding the necessary size of the turn-around stock are based on experience of maintenance engineers and planners and on advice given by the train manufacturer. As can be seen in chapter 2, while making decisions regarding the turn-around stock level, demand is taken into account in a deterministic way. Uncertainty in demand is covered by taking into account the policy safety stock.

During a revision period, demand is assumed to be deterministic as planned demand during the lead-time. Since a schedule is made when trains are being revised, the logistic planner knows how many spare parts are needed per time unit and uses this number in his calculations. The demand due to unplanned failures, which is stochastic, is taken into account by assuring that the turn-around stock level is at least as large as the policy safety stock. Although a schedule is made when trains are being revised, according to the logistic planners there is still variability in demand since the schedule can change during the revision. It can also be the case that replacements are inspection-based and thus that it is not sure whether a ready-for-use part is actually needed or not.

Thus whereas in practice variability in demand is taken into account using the policy safety stock, in the model variability is taken into account by assuming that demand is stochastic and follows a Poisson Process.

4.3 Priorities vs. lead-times

While determining on the size of the turn-around stock level in the deterministic way for a revision, an agreement is made between the SCO and the NCB on what the repair lead-time for an item is. The fact that the NCB works with different priorities is not taken into account. In the non-revision period, a fixed repair lead-time of 20 working days is used by Xelus Parts to give an advice on the desired size of the turn-around stock. Also in that case the prioritization that the NCB uses, is not taken into account.

In the lead-time model that is used in this research, priorities are taken into account by assigning items an expedited repair lead-time, which is deterministic and contains the emergency repair time and transportation and administration time or an additional regular repair lead-time, which is stochastic (exponentially distributed) and contains e.g. the waiting time for shop-replaceable units (SRUs are the parts of which a line-replaceable unit (LRU) consist).

Having these lead-times, the prioritization in the model works as follows: A part gets an emergency lead-time (high priority) when the number of parts in regular repair is equal or higher then a threshold level. In the min-max prioritization, the repair jobs are executed following the priorities (see Table 2.1). When parts have prio 1 or prio 2, it means that the current inventory level is not sufficient to cover demand for the current month and repair jobs for these items need to be expedited. The inventory level is based on the turn-around stock level minus the total number of parts in repair. In contrast, in the lead-time model only the number of parts in *regular* repair is checked. This means that parts in the min-max prioritization are expedited earlier than in the model. Only taking into account parts that will not arrive within the expedited repair lead-time (the parts in regular repair) is quite realistic: when a part which is in the expedited repair lead-time and has only one day left, it does not make sense to expedite another part because the inventory level is below the min-level.

Another important difference is, that in the min-max prioritization, the prioritization can change after a part has been taken into repair, whereas in the lead-time model a priority is assigned once and cannot change after that.

Loeffen (2012) concluded, by performing simulation studies, that due the above-mentioned reasons, the min-max prioritization works better for operational control. However, she also recommended that cost reductions can be made when the turn-around stock levels are optimized using the assumption of expediting and lead-time control.

4.4 Constraints

Whereas in practice a target is set on fill rate, in the model a target is set on the expected number of backorders. Regarding the fill rate that NedTrain uses, it should be noted that this fill rate is determined per batch order: Assume that the fill rate is 98%. In total ten orders for ten spare parts each are placed. For nine of the ten orders, all ten spare parts are directly deliverable, however for one order only nine out of the ten parts were available. In total the fill rate is 99%, however since one order was not complete, only nine out of ten of the orders could be fulfilled, which leads to a fill rate of 90%.

The model takes into account another constraint: The expected number of expedites. In practice such a constraint is not taken into account, even though the priorities that are assigned to repair jobs are tracked, there is not a constraint set on each of the priorities. Of course there are limitations due to workforce constraints however this does not change the prioritization of repair jobs.

4.5 Buy Decisions

In the model new-buy prices as given in catalogues are used to calculate the total investment costs, however in practice price agreements are made and e.g. quantity rebates are possible. This means that the cost prediction by the model, is an upper bound for the real costs that are made when the turn-around stock level advices are taken into account. However, sometimes the MOQ (minimum order quantity) is larger than one, in that case the real costs can be higher than predicted by the model when the turn-around stock level advice is round up.

Another difference is that in practice, for some SKU-s, it is possible to buy extra parts later in time when those are actually needed. This not only holds for the moment when parts are bought for a revision period, but also when it seems that the demand for spare parts due to corrective maintenance is larger than expected. In the model, it is assumed that demand for spare parts due to corrective maintenance does not change over time and that there is no possibility to buy extra parts in later stages.

5

Business Case 1

In this chapter a business case in which the model of chapter 3 can be applied will be discussed. In section 5.1 an introduction to the case will be given, followed by the setup for the business case in section 5.2. In section 5.3 it will be explained how the model was verified and validated. In section 5.4 the base-case scenario will be introduced followed by the results in section 5.5. A conclusion for this business case will be drawn in section 5.6.

5.1 Introduction

Starting the third quarter of 2014, the first revision for parts of the Sprinter Lighttrain (SLT, see Figure 5.1) will take place. At this moment (August 2013) the logistic planner is analyzing whether the current turn-around stock level of the repairable spare parts, which are revised at the NCB during the revision period, is sufficient to keep down-time due to the unavailability of RFU-parts to a minimum. This analysis is carried out as described in subsection 2.1.2. The only analysis that has been carried out yet[1], is the worst case scenario, in which repair lead-times are assumed to be 20 working days. Negotiations regarding repair lead-time agreements haven't taken place yet.

Figure 5.1 – Sprinter Lighttrain

---

[1] This was at the end of May 2013.

The question to be answered by the logistic planner is:

> *"Is an extension in turn-around stock level necessary and if so, what should the size of the extension be, such that costs are minimized and and constraints regarding expected number of backorders and expected number of expedites per time unit are met?"*

5.2 Business Case Setup

Since we are interested in the difference between the As-Is situation (the current situation) and the To-Be situation (the situation in which the model is used), an extra step needs to be made to compare the two situations. Three steps will be followed: 1) The turnaround stock levels are determined as it is done in the current situation. 2) The performance of the current situation in terms of expected number of backorders is evaluated by using the turn-around stock levels of step 1 and the model of chapter 3. 3) The performance in terms of expected number of backorders of the As-Is situation of step 2, is used as input for the expected number of backorders objective in the To-Be situation. By using the performance of the As-Is situation as input for the To-Be situation, we make sure that the performance in the To-Be situation is at least as good as in the As-Is situation. After the third step, we are able to compare the costs of the As-Is situation to the cost of the To-Be situation. The steps are graphically depicted in Figure 5.2 and will be discussed in more detail below.

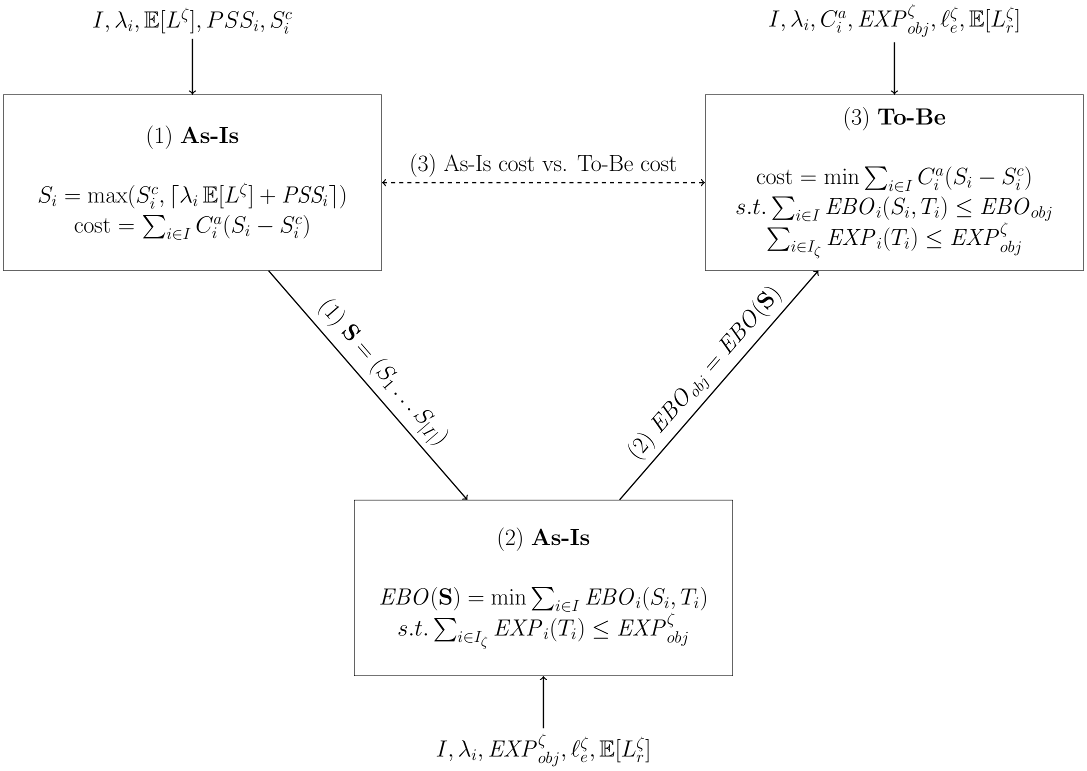

Figure 5.2 – Setup Business Case 1

As can be seen in Figure 5.2, several input parameters are used in each step. We therefore will start with discussing the parameters which we have not yet introduced in chapter 3.

In the repair shop, different clusters exist in which parts are repaired. Let Z denote the set of clusters and $\zeta \in Z$ denote a cluster. In practice an item can go through different clusters while being repaired, however it is assumed that an item uses the capacity of only one cluster[2]. Let I_ζ denote the set of items that belong to cluster $\zeta \in Z$. Then $i \in I_\zeta, I_\zeta \subseteq I$. Let S_i^c denote the current size of the turn-around stock.

In practice the logistic planner and the manager of the NCB agree upon repair lead-times for the items to be repaired. In this case, we will assume that average repair lead-times are agreed upon per cluster and denote these by $\mathbb{E}[L^\zeta]$. In the model of chapter 3, we have two different lead-times: an expediting repair lead-time, which we assume consists of the emergency repair lead-time plus fixed transportation and administration time, and an additional regular repair lead-time. For each cluster, expediting repair lead-times (ℓ_e^ζ) and additional regular repair lead-times ($\mathbb{E}[L_r^\zeta]$) are determined, based on data from the NCB.

Since we have the ability to assign different repair lead-times to repair jobs in the model, but still want to achieve the same average repair lead-time as agreed upon between the logistic planner and the manager of the NCB, we will determine a parameter α which denotes what fraction of total demand may get an expedited repair lead-time such that the average repair lead-time is the same as agreed upon between the logistic planner and the manager of the NCB:

$$\alpha \ell_e + (1-\alpha)\left(\ell_e + \mathbb{E}[L_r]\right) = \mathbb{E}[L]$$

Then α is calculated as follows:

$$\alpha = \frac{\ell_e + \mathbb{E}[L_r] - \mathbb{E}[L]}{\mathbb{E}[L_r]}$$

For each cluster an α is determined and we will denote it as α_ζ. We will use this α_ζ to set the constraint for expected number of expedites per cluster. Let Λ_i denote the total demand during the revision for SKU i and t denote the mean length of the revision period, further more let $\lambda_i^{corrective}$ be the demand rate due to corrective maintenance actions. Then $\lambda_i = \Lambda_i/t + \lambda_i^{corrective}$.

$$EXP_{obj}^\zeta = \alpha_\zeta \sum_{i \in I_\zeta} \lambda_i \quad \forall \zeta \in Z$$

In the current situation, on average 29% of the parts has prio 1 or prio 2 and can be considered as an emergency repair (see Table I.1 in Appendix I how this percentage is determined).

Having the input parameters, we will now discuss the three steps in more detail:

Step 1

We start with the As-Is situation. In the As-Is situation, the turn-around stock levels are determined as explained in chapter 2 using the equation:

$$S_i = \max(S_i^c, \lceil \lambda_i \, \mathbb{E}[L^\zeta] + PSS_i \rceil) \tag{5.1}$$

Since no data was available for the policy safety stocks (PSS) of the items, this value was calculated using Equation (2.1) (the equation to determine the PSS) that was given in section 2.2. However, using that formula and the data as given in Table I.3 in Appendix I, lead to policy safety stocks that were equal to 0.[3] Therefore, it is assumed that all parts are critical parts and that the policy safety stock is 1 for all items, which is the minimum required size for the turn-around stock for critical parts. Let vector $\mathbf{S} = (S_1 \dots S_{|I|})$ denote the turn-around stock

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[2] This assumption has been checked with Guido Aerts from the NCB and was justified by him.

[3] For both the LOT and the MSE the corrective demand rate data was used since the actual values for LOT and MSE were not available.

levels that result from Equation (5.1) and S_i^c the turn-around stock that is already available for SKU i. Then the costs using this policy are equal to:

$$C_{tot}(\mathbf{S}) = \sum_{i \in I} C_i^a (S_i - S_i^c)$$

Step 2

In this business case we only have one Markov Modulating state: the revision period. Since we only have one state, the problem can be relaxed to a model with Poisson demand. In that case, when the turn-around stock level S_i and threshold level T_i are known, the expected number of expedites and expected number of backorders per item are determined as follows:

$$EXP(T_i) = \lambda_i \frac{\left(\lambda_i \, \mathbb{E}[L_r^\zeta]\right)^{T_i} / T_i!}{\sum_{k=0}^{T_i} \left(\lambda_i \, \mathbb{E}[L_r^\zeta]\right)^k / k!} \tag{5.2}$$

$$EBO(S_i, T_i) = \sum_{x=0}^{T_i} c_p(x|S_i) \frac{\left(\lambda_i \, \mathbb{E}[L_r^\zeta]\right)^{x} / x!}{\sum_{k=0}^{T_i} \left(\lambda_i \, \mathbb{E}[L_r^\zeta]\right)^k / k!} \tag{5.3}$$

where

$$c_p(x|S_i) = \sum_{k=S_i-x}^{\infty} (k - (S_i - x)) \, \mathbb{P}\left\{D_{t,t+\ell_e^\zeta} = k\right\} \tag{5.4}$$

In this equation, $D_{t,t+\ell_e^\zeta}$ is Poisson distributed with rate $\lambda_i \ell_e^\zeta$, where ℓ_e^ζ denotes the expedited repair lead-time in cluster $\zeta \in Z$.

Since we are interested in optimizing the performance of the As-Is situation, we want to minimize backorders subject to expediting constraints and find T_i for all items. We use the turn-around stock levels that result from Equation (5.1). The optimization problem can be defined as follows:

$$\begin{array}{llll}
\text{(C)} & \min & \sum_{i \in I} EBO_i(S_i, T_i) & \\
& \text{subject to} & \sum_{i \in I_\zeta} EXP_i(T_i) \leq EXP_{obj}^\zeta & \forall \zeta \in Z \\
& & T_i \leq S_i & \forall i \in I \\
& & T_i \in \mathbb{N}_0 & \forall i \in I
\end{array}$$

This problem is solved using the Decomposition Column Generation method. The master problem for problem (C) can be stated as follows:

$$\begin{array}{llll}
\text{(MPC)} & \min & \sum_{i \in I} \sum_{k \in K} EBO_i(S_i^k, T_i^k) x_i^k & \\
& \text{subject to} & \sum_{i \in I_\zeta} \sum_{k \in K} EXP_i(T_i^k) x_i^k \leq EXP_{obj}^\zeta & \forall \zeta \in Z \\
& & \sum_{k \in K} x_i^k = 1 & \forall i \in I \\
& & x_i^k \geq 0 & \forall i \in I, \forall k \in K
\end{array}$$

From this master problem (MPC) a restricted master problem is constructed as described in section 3.5. The subproblem that is solved for each item $i \in I$ is as follows:

$$\begin{array}{lll} (\text{SUB}(i)) & \min & EBO(S_i, T_i) - u_\zeta EXP(T_i) - v_i \\ & \text{subject to} & T_i \leq S_i \\ & & T_i \in \mathbb{N}_0 \end{array}$$

As we have the turn-around stock level for each item $i \in I$, this subproblem can easily be solved using Equation (5.2) and Equation (5.3) by enumerating T_i from 0 to S_i. u_ζ and v_i are the dual variables that are obtained when the restricted master problem for Problem (C) is solved.

Step 3

In the To-Be situation, we will use the model of chapter 3 to determine the turn-around stock levels for SKU-s $i \in I$. Again, since we only have one Markov Modulating state, we can use the closed form Poisson formulas while doing our calculations. Since we already have spare parts available, denoted by S_i^c, we should take this into account in our model as well as the fact that we differentiate between clusters. For the constraint for expected number of backorders, we use the result of Problem (C)[4]. The multi-item optimization model then becomes:

$$\begin{array}{llll} (\text{P}) & \min & \sum_{i \in I} C_i^a (S_i - S_i^c) & \\ & \text{subject to} & \sum_{i \in I} EBO_i(S_i, T_i) \leq EBO_{obj} & \\ & & \sum_{i \in I_\zeta} EXP_i(T_i) \leq EXP_{obj}^\zeta & \forall \zeta \in Z \\ & & T_i \leq S_i & \forall i \in I \\ & & S_i \geq S_i^c & \forall i \in I \\ & & S_i \geq 1 & \forall i \in I \\ & & S_i, T_i \in \mathbb{N}_0 & \forall i \in I \end{array}$$

Both in the As-Is and To-Be situation, the question when to expedite a repair job can be answered by using the threshold levels T_i that are calculated for each item $i \in I$. When the number of parts already in regular repair is equal or greater than this threshold level, the policy expedites the repair for this item. Note that an extra constraint is added: $S_i \geq 1$. This is because we have assumed that all parts in this business case are critical parts and thus at least one spare part should be on stock for each item.

The three steps are implemented in MATLAB. The input for the model can be inserted in a MS EXCEL-input file. MATLAB loads the information from the file and gives the output. The linear programming problems are solved using GUROBI for MATLAB.

5.3 Verification and Validation

Verification is to check whether the model does what is is expected to do. To check this, extreme values are used as input (e.g. high costs and low demand versus low costs and high demand and few expedites and backorders versus many expedites and backorders as constraints). As expected, the turn-around stock level was high for the high-demand-low-cost items and the

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[4] The lower bound that results from solving the Restricted Master Problem, where fractional solutions are allowed, is taken as input for Problem (P).

turn-around stock level was low for the low-demand-high-cost items. When the constraints for expected number of backorders and expected number of expedites were small, the costs were higher than when the expected number of backorders and expected number of expedites were large.

The results of this implementation of the model were also compared with the results from the implementation of Joachim Arts when the same instance was used. Both implementations lead to the same results.

Validation is performed by checking whether the solutions from the model correspond to the outcomes in the real situation. This is done by checking whether the outcome of step 3 corresponds to the outcome of step 1 and step 2, which represent the real situation. From the results it can be concluded that both the costs and the size of the turn-around stock levels lie in the same order of magnitude and correspond to the real situation.

5.4 Base Case Scenario

Before we discuss the results for this business case, we first give the values for the input parameters that are used in the base case scenario. The lead-times are in working days. For all items the emergency repair lead-times (in working days) were collected from the NCB and can be found in Table I.3 in Appendix I.

The largest expedited repair lead-time of an item in a cluster is chosen to be the emergency repair lead-time for all items in that cluster. By doing this, a conservative decision regarding lead-times is taken. The expedited repair lead-time (ℓ_e^ζ) contains this emergency repair lead-time plus the administration and transportation time. The additional regular repair lead-time ($\mathbb{E}[L_r^\zeta]$) is set to 10 working days for all clusters, such that the maximum repair lead-time that an item will get, is close to the 20 working days which is used in the current worst case scenario. In the base case scenario, we will set the average repair lead-time ($\mathbb{E}[L^\zeta]$) such that the expediting percentage α_ζ is close to the current percentage of parts that is expedited in the repair shop.

The revision length is set to 31 months[5]. The administration and transportation times are set to 5 working days.

See Table 5.1 for the overview of the parameter setting. The input parameters for the items, such as demand rates and new-buy prices can be found in Appendix I.

Table 5.1 – Parameter setting base case scenario for business case 1

Cluster	ℓ_e^ζ	$\mathbb{E}[L_r^\zeta]$	$\mathbb{E}[L^\zeta]$	α_ζ (%)
1	10 (5+5)	10	17	30
2	7 (2+5)	10	14	30
3	8 (3+5)	10	15	30
4	7 (2+5)	10	14	30

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[5] To determine the daily demand, since lead-times are in working days, 22 working days in a month is assumed

5.5 Results

Table 5.2 and Table 5.3 contain the results from the base case scenario of business case 1. Table 5.2 contains the threshold levels, turn-around stock levels and investment costs for the items. When we look at the results, we see that the investment costs in the To-Be situation are around €1.22 million less than in the As-Is situation, which means cost savings of 53%. These cost savings mainly result from the system approach that is used. When we have a closer look at Table 5.2 we see that the turn-around stock levels for expensive items are smaller in the To-Be situation than in the As-Is situation whereas for the cheaper parts, the turn-around stock levels are larger in the To-Be situation than in the As-Is situation. We also see that for expensive items, the threshold levels are lower than for the cheaper items. In Table 5.3, the expected number of backorders and expected number of expedites (as percentage of the demand rate) are given per item. From that, we can conclude that in the To-Be situation, expensive parts are more often expedited than in the As-Is situation. This corresponds with the lower threshold levels we found for the expensive parts in Table 5.2. Also, for the expensive items, the expected number of backorders are higher in the To-Be situation than in the As-Is situation but for cheaper items, the expected number of backorders are lower in the To-Be situation than in the As-Is situation. Sometimes it seems that cheaper parts are also expedited often, however note that an expedite constraint is set per cluster and it thus may be that an item is relatively expensive within that cluster and therefore more often expedited.

Table 5.2 – Results base case scenario business case 1 (1)

				As-Is			To-Be		
Part number	C_i^a	Cluster	S_i^c	T_i	S_i	$C_i^a(S_i - S_i^c)$ (€)	T_i	S_i	$C_i^a(S_i - S_i^c)$ (€)
FA500021	6,716.12	1	2	7	15	87,309.56	10	16	94,025.68
FA500039	6,716.12	1	2	7	15	87,309.56	9	16	94,025.68
FA500427	612.16	2	2	5	7	3,060.80	10	12	6,121.60
FA500435	1,060.40	2	10	6	12	2,120.80	14	19	9,543.60
FA500823	440.72	2	3	4	7	1,762.88	10	12	3,966.48
FA500831	1,522.91	2	3	4	7	6,091.64	8	10	10,660.37
FA500849	956.26	2	2	4	7	4,781.30	9	11	8,606.34
FA502654	4,376.65	2	1	4	7	26,259.90	1	5	17,506.60
FA504304	508.02	1	5	4	8	1,524.06	14	14	4,572.18
FA504833	1,567.13	4	2	4	7	7,835.65	7	10	12,537.04
FA504841	2,688.38	4	2	4	7	13,441.90	6	9	18,818.66
FA505418	1,632.70	4	1	7	12	17,959.70	12	18	27,755.90
FA505517	1,376.97	4	3	15	29	35,801.22	28	41	52,324.86
FA505525	4,353.86	4	3	8	15	52,246.32	0	9	26,123.16
FA506283	2,103.33	3	8	7	13	10,516.65	15	19	23,136.63
FA506309	8,893.10	2	1	4	7	53,358.60	0	3	17,786.20
FA506317	1,866.95	1	13	11	13	-	14	14	1,866.95
FA506457	31,746.38	3	2	4	7	158,731.90	0	2	-
FA506630	314.35	3	2	6	12	3,143.50	23	23	6,601.35
FA506655	541.45	3	1	7	12	5,955.95	18	20	10,287.55
FA506689	23,835.93	3	4	4	6	47,671.86	1	4	-
FA506697	30,895.81	3	2	4	5	92,687.43	0	2	-
FA506721	34,801.66	3	2	4	5	104,404.98	0	2	-
FA506788	34,611.06	3	2	2	3	34,611.06	1	2	-
FA506879	796.58	3	4	6	13	7,169.22	19	22	14,338.44
FA506911	375.42	3	2	7	12	3,754.20	18	20	6,757.56
FA507091	442.68	3	1	10	19	7,968.24	27	31	13,280.40
FA507109	415.16	3	1	10	19	7,472.88	27	31	12,454.80
FA507166	2,142.95	3	1	4	7	12,857.70	8	10	19,286.55
FA507182	895.03	3	1	4	7	5,370.18	11	12	9,845.33
FA507208	2,521.55	3	1	4	7	15,129.30	8	10	22,693.95
FA507216	1,322.24	3	2	4	7	6,611.20	11	12	13,222.40
FA507257	440.17	3	2	4	5	1,320.51	8	8	2,641.02
FA507356	673.47	3	2	4	7	3,367.35	13	13	7,408.17
FA507380	1,461.10	3	3	3	5	2,922.20	7	7	5,844.40
FA507588	86,532.12	2	2	3	5	259,596.36	0	2	-
FA507596	28,119.53	2	1	3	4	84,358.59	0	1	-
FA510228	8,767.16	3	5	11	22	149,041.72	0	11	52,602.96
FA513255	7,703.82	3	5	24	53	369,783.36	20	48	331,264.26
FA550679	1,549.00	2	1	4	7	9,294.00	7	10	13,941.00
FA552410	8,924.00	3	1	4	7	53,544.00	0	3	17,848.00
FA552626	3,960.00	4	2	5	7	19,800.00	0	4	7,920.00
FA552741	1,193.00	4	1	10	18	20,281.00	19	27	31,018.00
FA552824	5,818.00	4	1	5	7	34,908.00	0	4	17,454.00
FA552915	25,611.00	1	0	5	14	358,554.00	0	1	25,611.00
FD089139	12,493.00	1	8	4	8	-	5	8	-
Total investment costs:						2,291,691.23			1,071,699.07

Table 5.3 – Results base case scenario business case 1 (2)

			As-Is		To-Be	
Part number	C_i^a	Cluster	$EBO_i(S_i,T_i)$	$EXP_i(T_i)$	$EBO_i(S_i,T_i)$	$EXP_i(T_i)$
FA500021	6,716.12	1	0.564	29%	0.813	11%
FA500039	6,716.12	1	0.564	29%	0.645	16%
FA500427	612.16	2	0.440	20%	0.033	1%
FA500435	1,060.40	2	0.428	38%	0.086	2%
FA500823	440.72	2	0.260	30%	0.028	0%
FA500831	1,522.91	2	0.260	30%	0.107	3%
FA500849	956.26	2	0.260	30%	0.057	1%
FA502654	4,376.65	2	0.260	30%	0.207	80%
FA504304	508.02	1	0.392	30%	0.027	0%
FA504833	1,567.13	4	0.300	32%	0.099	7%
FA504841	2,688.38	4	0.321	32%	0.169	13%
FA505418	1,632.70	4	0.649	30%	0.103	5%
FA505517	1,376.97	4	0.803	32%	0.167	1%
FA505525	4,353.86	4	0.613	34%	0.363	100%
FA506283	2,103.33	3	0.602	29%	0.161	1%
FA506309	8,893.10	2	0.260	30%	0.531	100%
FA506317	1,866.95	1	0.062	0%	0.031	0%
FA506457	31,746.38	3	0.416	31%	1.407	100%
FA506630	314.35	3	0.424	33%	0.005	0%
FA506655	541.45	3	0.564	24%	0.030	0%
FA506689	23,835.93	3	0.369	22%	0.357	76%
FA506697	30,895.81	3	0.204	10%	0.355	100%
FA506721	34,801.66	3	0.204	10%	0.355	100%
FA506788	34,611.06	3	0.092	21%	0.175	51%
FA506879	796.58	3	0.465	39%	0.047	0%
FA506911	375.42	3	0.564	24%	0.030	0%
FA507091	442.68	3	0.768	28%	0.033	0%
FA507109	415.16	3	0.768	28%	0.033	0%
FA507166	2,142.95	3	0.416	31%	0.180	3%
FA507182	895.03	3	0.416	31%	0.057	0%
FA507208	2,521.55	3	0.416	31%	0.180	3%
FA507216	1,322.24	3	0.416	31%	0.057	0%
FA507257	440.17	3	0.204	10%	0.021	0%
FA507356	673.47	3	0.416	31%	0.028	0%
FA507380	1,461.10	3	0.148	23%	0.066	0%
FA507588	86,532.12	2	0.117	24%	0.307	100%
FA507596	28,119.53	2	0.263	22%	0.685	100%
FA510228	8,767.16	3	0.725	31%	1.205	100%
FA513255	7,703.82	3	1.036	35%	1.497	45%
FA550679	1,549.00	2	0.260	30%	0.080	6%
FA552410	8,924.00	3	0.374	30%	0.733	100%
FA552626	3,960.00	4	0.411	19%	0.236	100%
FA552741	1,193.00	4	0.686	29%	0.088	1%
FA552824	5,818.00	4	0.440	20%	0.252	100%
FA552915	25,611.00	1	0.382	46%	6.581	100%
FD089139	12,493.00	1	0.457	32%	0.650	21%
Total EBO:			19.453		19.357	

From the base case scenario as given in Table 5.1 on page 34, we vary values for some input parameters (while keeping the rest constant) to see the effect of these parameters on the investment costs. The input parameters that are varied and the values that are assigned to these parameters are given in Table 5.4.

Table 5.4 – Parameter settings (sets of instances)

Input parameter	Values
Transportation and administration time (working days)	3, 4, 5, 6, 7
Additional regular repair lead-time (working days)	5, 10, 15
Expedite percentage α (%)	10, 20, 30, 40, 50
Revision length (months)	25, 28, 31, 34, 37

In the next sections the influence of varying the parameters will be discussed. Since we are interested in the difference between the investment cost in turn-around stock in the As-Is and the To-Be situation, we will express this difference in terms of cost savings, which can be determined as follows:

$$\text{Cost savings} = \frac{\text{As-Is costs} - \text{To-Be costs}}{\text{As-Is costs}} \times 100\%$$

Transportation and administration time

According to managers of Supply Chain Operations, transportation and administration time is one of the parameters that can be changed most easily. Currently some logistic planners use 7 working days, however according to the managers, this can as least be reduced to 5 or even less. Therefore 5 working days is used in the base case scenario. When the transportation and administration times are changed, also the expedited repair lead-time (ℓ_e^ζ) changes since this parameter consists of the emergency repair lead-time and transportation and administration time. Also the average repair lead-time ($\mathbb{E}[L^\zeta]$) changes since this parameter contains the expedited repair lead-time. The As-Is and To-Be costs when transportation and administration times are changed, are graphically depicted in Figure 5.3.

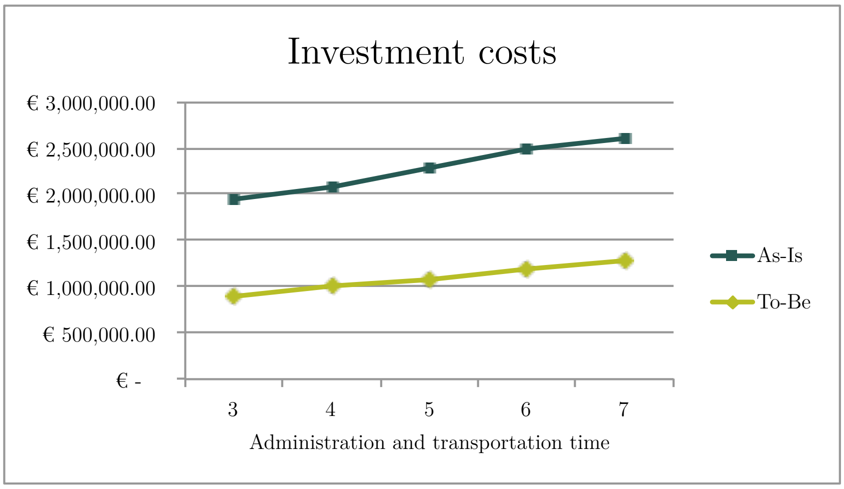

Figure 5.3 – Investment costs when administration and transportation time is varied from 3 to 7 workingdays

As can be seen in Figure 5.3, when the administration and transportation time increases, investment costs also increase. The increase in investment costs can be explained as follows:

When the transportation time increases, both the expedited repair lead-time and the normal repair lead-time (which is equal to the expedited repair lead-time plus the additional regular repair lead-time) increase. As the repair lead-times increase, more turn-around stock is needed to cover demand during the repair lead-time. The cost savings are on average 52%, which means €1.19 million.

Additional regular repair lead-time

The current number of working days that is used for the normal repair lead-time (emergency repair lead-time plus the *additional* regular repair lead-time) is 20 working days. However it has been mentioned by Guido Aerts from the NCB that this value probably can be reduced. Therefore, in the base case scenario already 10 working days *additional* regular repair lead-time was used instead of 15 working days. However, now we will see the influence of a shorter and a longer *additional* regular repair lead-time (and thus a longer regular repair lead-time). We keep the expediting percentage, α_ζ, constant to 30%, which causes the average repair lead-time ($\mathbb{E}[L^\zeta]$) to change when the additional regular repair lead-time changes. The As-Is and To-Be turn-around stock investment costs are graphically depicted in Figure 5.4.

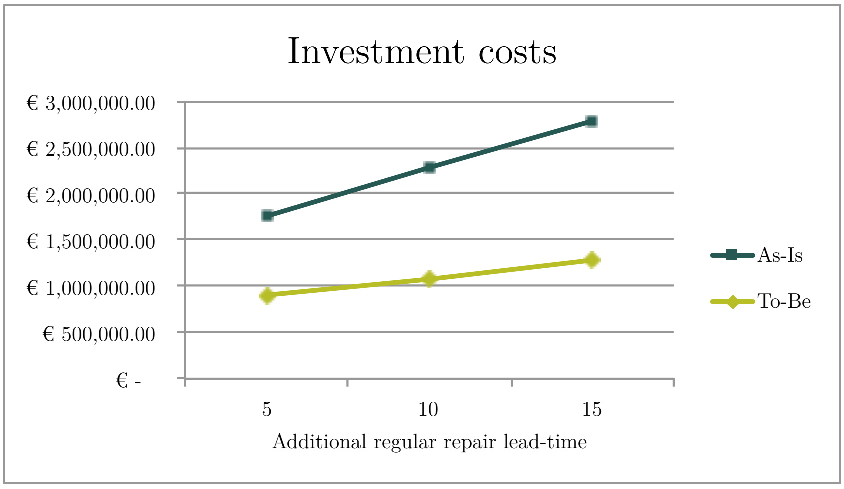

Figure 5.4 – Investment costs when the additional regular repair lead-time is set to 5, 10 and 15 working days

As can be seen in Figure 5.4, when the additional regular repair lead-time increases, investment costs also increase. The reason for the increase is as follows: When the additional regular repair lead-time increases, more turn-around stock is needed to cover demand during the repair lead-time, and thus investment costs are higher. The average cost savings between the As-Is situation and the To-Be situation are on average €1.19 million which comes down to an average cost saving percentage of 52%.

Average repair lead-time and the expedite percentage α (%)

The agreement with respect to the average repair lead-time determines which fraction of demand should get an expedited repair lead-time. During a revision period of a train series, the number of repair jobs that is expedited may be larger than the currently used 29%[6] since capacity within the repair shop is dedicated for the revision. However, it might also be the case that less capacity is available (e.g. the workforce is smaller). Therefore, we will check what happens

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[6] See Table I.1 in Appendix I how this number is determined.

to the investment costs in turn-around stock when the expediting percentage is changed. Since the expediting percentage in this business case depends on the average repair lead-time that is agreed upon, this repair lead-time is changed such that α changes and has the same value in each cluster. See Table 5.5 where the different average repair lead-times and corresponding expediting percentages are depicted. In Figure 5.5 the investment costs, for different expediting percentages, are graphically depicted for the As-Is and the To-Be situation.

Table 5.5 – Average repair lead-times versus expediting percentages

Cluster	ℓ_e^ζ	$\mathbb{E}[L_r^\zeta]$	$\mathbb{E}[L^\zeta]$				
			$\alpha = 10\%$	20%	30%	40%	50%
1	10	10	19	18	17	16	15
2	7	10	16	15	14	13	12
3	8	10	17	16	15	14	13
4	7	10	16	15	14	13	12

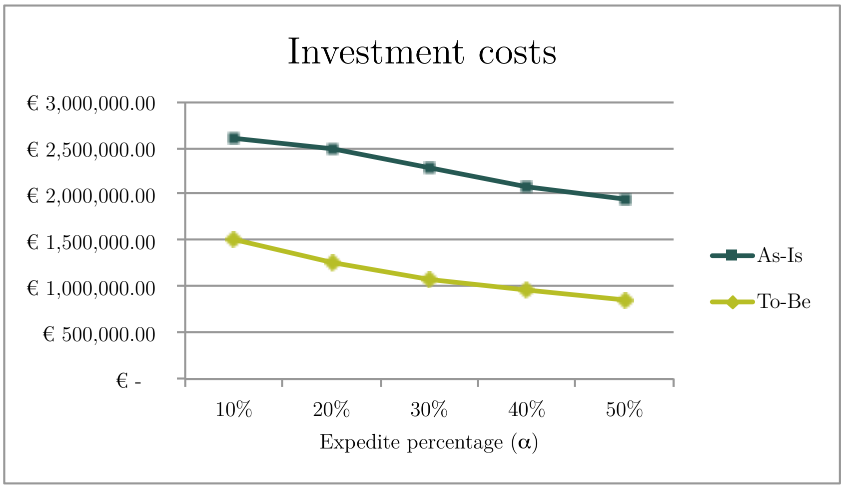

Figure 5.5 – Investment costs when the percentage of parts that can be expedited within a cluster is varied from 10% to 50%

As can be seen in Figure 5.5 when α is increased, and thus the average repair lead-time is decreased, investment costs reduce. This reduction in investment costs can be explained as follows: When the average repair lead-time decreases, more items can get an expedited repair lead-time and thus less turn-around stock is needed to cover demand during the repair lead-time. The average cost savings are €1.14 million or, in percentages, 51%.

Revision length

At this moment the revision of the SLT is planned to take place within 31 months in total. We will investigate the influence of the mean length of the revision period on investment costs and vary this length from 25 months (31 months minus a half year) to 37 months (31 months plus a half year). See Figure 5.6 for the results of these instances.

As can be seen in Figure 5.6, when the length of the revision period increases, the investment costs reduce. This reduction in investment costs be explained as follows: When the length of the revision period increases, but the total demand due to the revision stays the same, the monthly demand for spare parts decreases, which means that less turn-around stock is needed to cover demand during the repair lead-time. The average cost savings are 52% or €1.20 million.

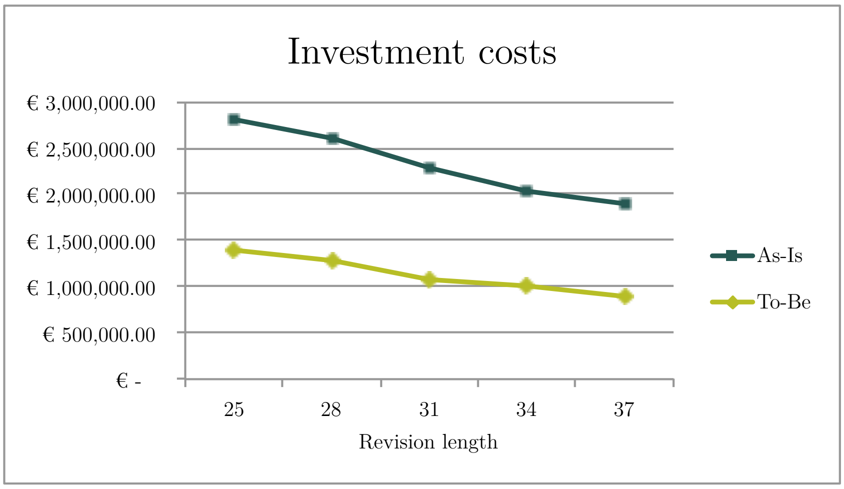

Figure 5.6 – Investment costs when the revision length is varied from 25 to 37 months

A side note, however, should be made. From practical viewpoints it is not possible to change the revision length easily. The reason for this is, that the length of the revision period depends mainly on the capacity that is available at the Refurbishment and Overhaul Workshop in Haarlem. The revision has to take place within the period that Haarlem has capacity to carry out the revision of the system (train) as a whole.

General remarks

For each set of instances, we determined the upper bound on costs which is a feasible solution for problem (P) and results from solving the restricted master problem as a binary problem. We also determined the lower bound on costs for problem (P). We calculated the relative gap between this upper bound and lower bound on costs:

$$\text{GAP} = \frac{\text{upper bound} - \text{lower bound}}{\text{lower bound}} \times 100\%$$

From all instances that have been investigated, the average GAP is 0.43% and the maximum GAP is 1.30%. From this it can be concluded that solving the restricted master problem as binary problem performs quite well.

Compared to the sum of demand rates, which is 28.76 per unit time, we found quite high values for expected number of backorders. This is probably the result of assuming that the policy safety stock is equal to 1 for each item. We increased the policy safety stock to 4 to see whether increasing the policy safety stock improves the performance. For the base case scenario we tested this instance. We still achieved cost savings of 47%, which means €1.63 million. The investment costs, however, increased from €2.29 million to €3.50 million in the As-Is situation and from €1.07 million to €1.87 million in the To-Be situation while the total expected number of backorders reduced from 19.36 to 2.52 per time unit.

5.6 Conclusion and Applicability for NedTrain

In the introduction, we stated the question that has to be answered by the logistic planner:

> *"Is an extension in turn-around stock level necessary and if so, what should the size of the extension be, such that costs are minimized and constraints regarding*

> *expected number of backorders and expected number of expedites per time unit are met?"*

From the base-case scenario results we can conclude that an extension in turn-around stock is necessary to satisfy the constraints. Using the current decision-making logic, this investment will cost €2.29 million. When the multi-item model is used, this investment will cost €1.07 million, which is a relative cost saving of 53%.

Next to the base-case, also other instances have been tested. From these instances, it can be concluded that the investment costs savings that can be achieved range from 42% to 56%. On average the savings are 51% (standard deviation is 3%). This means that it can be attractive to use this multi-item model in which turn-around stock levels are determined using a system approach.

The model and intermediate results of the model have already been presented to managers of the SCO. The managers were interested in the model and the cost savings that could be achieved. An important note made by the managers is, that they are interested in the fill rate that can be achieved using the model. In practice, a target is set on fill rate whereas the model now uses expected number of backorders as constraint. Nevertheless, they were interested in the final results and a tool, based on this model, which they can use to make turn-around stock decisions. Therefore we will develop a decision-support tool that can be used by NedTrain. In chapter 7 it will be explained how this tool can be implemented at NedTrain, such that logistic planners can use advices generated by this tool and take these advices into account when making turn-around stock decisions.

6

Business Case 2

In this chapter a second business case in which the model of chapter 3 can be applied will be discussed. The setup for this chapter is the same as for the previous chapter. In section 6.1 an introduction to the case will be given, followed by the setup for the business case in section 6.2. In section 6.3 it will be explained how the model was verified and validated. In section 6.4, the base case scenario will be introduced and the results of this base case scenario are presented in section 6.5. A conclusion for this business case will be drawn in section 6.6.

6.1 Introduction

In this second business case, we will investigate what the size of the turn-around stock levels should have been in case NedTrain was able to buy all repairable spare parts at the moment the train series were ordered. Then the planner should take into account that demand rates will fluctuate during the life-time of a train. In this case we will, per item, take two different demand rates into account: The demand rate for ready-for-use parts when all Sprinter Lighttrains are in operation and demand occurs when a corrective maintenance action has to take place and the demand rate for ready-for-use parts when the revision period (as discussed in the previous chapter) is taking place.

The question now to be answered by the logistic planner is:

> *"What should the size of the turn-around stock level be, given that during revision periods, the demand rate for ready-for-use parts is much higher than during non-revision periods and such that constraints regarding the expected number of backorders and expected number of expedites per time unit are met?"*

6.2 Business Case Setup

Again we are interested in the difference between the As-Is situation (the current situation) and the To-Be situation (the situation in which the model is used). Three steps will be followed from which we can finally compare the situations: 1) The turnaround stock levels are determined as it is done in the current situation. Since the planner wants to make sure that enough spare parts are on stock during the revision period, the revision demand rate is used as input to determine the turn-around stock levels. 2) The performance of the current situation in terms of expected number of backorders is evaluated by using the turn-around stock levels of step 1 and the model of chapter 3. This means, that we take into account that the revision and non-revision period have different demand rates, and thus do not use only one demand rate as we did in step 1. 3) The performance in terms of expected number of backorders of the As-Is situation is used as constraint for the expected number of backorders in the To-Be situation. After the third step,

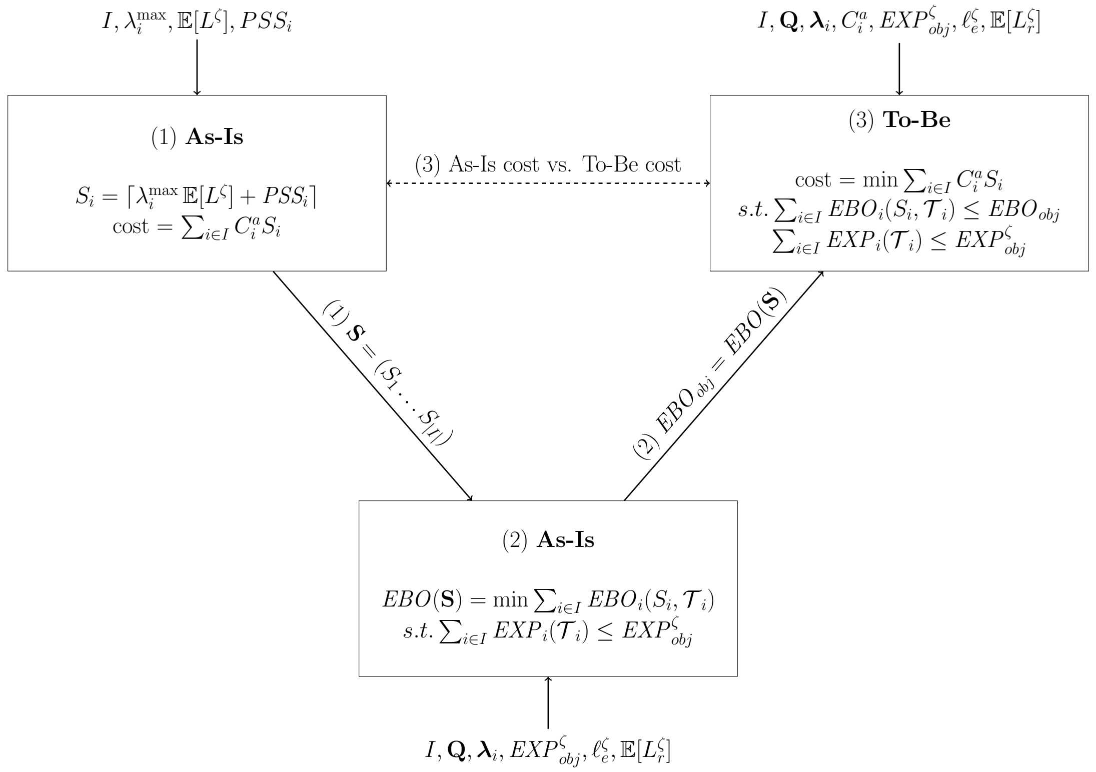

Figure 6.1 – Setup Business Case 2

we are able to compare the costs of the As-Is situation to the cost of the To-Be situation. The steps are graphically depicted in Figure 6.1 and will be discussed in more detail below.

The biggest difference with business case 1 is, that in this business case demand is assumed to follow a Markov Modulated Poisson Process. Two different states are defined: First the state of the non-revision period which is denoted by $y = 1$ and second the state of the revision period which is denoted by $y = 2$. Then the state space can be defined as $\Theta = \{1, 2\}$. The demand rate during the revision period changes when the length of the revision period is changed. Therefore we will define a few more variables which we need to determine the input parameters. Let t_1 be the mean length of the non-revision period and t_2 be the mean length of the revision period. This SLT case is a special case, since for this train series revision for all parts is performed every six years. Therefore it should hold that $t_1 + t_2 = 6$ years (72 months or 1584 working days). Let $\lambda_i(1)$ denote the average demand rate for ready-for-use parts for SKU i due to corrective maintenance actions in the non-revision period[1]. Let Λ_i denote the total demand during the revision for SKU i. Then $\lambda_i(2) = \Lambda_i/t_2 + \lambda_i(1)$ denotes the average demand during the revision period. Let $\boldsymbol{\lambda}_i = (\lambda_i(1), \lambda_i(2))$ be the vector that contains the demand rates for SKU i. Then $\lambda_i^{\max} = \max_{y \in \Theta} \lambda_i(y)$. Having the lengths of the periods, the generator matrix $\mathbf{Q}$ can be defined as follows:

$$\mathbf{Q} = \begin{pmatrix} -1/t_1 & 1/t_1 \\ 1/t_2 & -1/t_2 \end{pmatrix}$$

Let α denote the fraction of total expected demand within a cluster that the NCB is able

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[1] In Table I.3, this variable is denoted with $\lambda_i^{corrective}$.

to expedite[2]. Then the expected number of expedites objective per cluster is set as:

$$EXP^{\zeta}_{obj} = \alpha \sum_{i \in I_\zeta} \bar{\lambda_i} \qquad \forall \zeta \in Z$$

Where $\bar{\lambda_i}$, which denotes the time-average demand, can be determined as explained in Appendix H.

Having the input parameters, the three steps are discussed in more detail:

Step 1

In the As-Is situation the turn-around stock levels are determined as discussed in chapter 2. However, we now have to take into account the fact that the demand rate during the revision and the non-revision period differ. We choose to use the maximum demand rate since by doing that, we dimension on the demand rate during the revision period, which also was done in the first business case. However, we should take into account that during the revision period more parts are expected to be expedited and thus have smaller lead-times. Therefore we would assume the lead-time to be used is $L^\zeta = \mathbb{E}[L^\zeta] = \alpha \ell^\zeta_e + (1-\alpha)(\ell^\zeta_e + \mathbb{E}[L^\zeta_r])$. Then the turn-around stock level for SKU i is determined as:

$$S_i = \lceil \lambda_i^{\max} \, \mathbb{E}[L^\zeta] + PSS_i \rceil \tag{6.1}$$

Let $\mathbf{S} = (S_1 \ldots S_{|I|})$ denote the turn-around stock levels that result from Equation (6.1). Then the costs are equal to:

$$C_{tot}(\mathbf{S}) = \sum_{i \in I} C^a_i S_i$$

Instead of using the maximum demand rate ($\lambda_i^{\max}$) we can also choose to use the average demand rate. In section 6.5, we will discuss the result when $\bar{\lambda_i}$ instead of $\lambda_i^{\max}$ is used in the As-Is situation.

Step 2

Again, we are interested in optimizing the performance of the As-Is situation. The objective is to minimize backorders subject to expediting constraints. The turn-around stock levels that result from Equation (6.1) are used as input. The optimization problem can be defined as follows:

$$\begin{array}{llll}
\text{(C)} & \min & \displaystyle\sum_{i \in I} EBO_i(S_i, \mathcal{T}_i) & \\
& \text{subject to} & \displaystyle\sum_{i \in I_\zeta} EXP_i(\mathcal{T}_i) \leq EXP^{\zeta}_{obj} & \forall \zeta \in Z \\
& & T_i(y) \leq S_i & \forall i \in I, \forall y \in \Theta \\
& & T_i(y) \in \mathbb{N}_0 & \forall i \in I, \forall y \in \Theta
\end{array}$$

Also in this case, the problem is solved using the Decomposition Column Generation method. The master problem for problem (C) can be stated as follows:

---

[2] Note that in this case α is an input parameter whereas in Business Case 1, α is calculated from the average repair lead-time within a cluster that is agreed upon between the NCB and the SCO

$$
\begin{array}{llll}
\text{(MPC)} & \min & \displaystyle\sum_{i\in I}\sum_{k\in K} EBO_i(S_i^k,\mathcal{T}_i^k)x_i^k & \\
& \text{subject to} & \displaystyle\sum_{i\in I_\zeta}\sum_{k\in K} EXP_i(\mathcal{T}_i^k)x_i^k \le EXP_{obj}^{\zeta} & \forall\zeta\in Z\\
& & \displaystyle\sum_{k\in K} x_i^k = 1 & \forall i\in I\\
& & x_i^k \ge 0 & \forall i\in I,\forall k\in K
\end{array}
$$

From this master problem (MPC) a restricted master problem is constructed as described in section 3.5. The subproblem that is solved for each item $i \in I$ is as follows:

$$
\begin{array}{llll}
\text{(SUB}(i)) & \min & EBO(S_i,\mathcal{T}_i) - u_\zeta EXP(\mathcal{T}_i) - v_i & \\
& \text{subject to} & T_i(y) \le S_i & \forall y\in\Theta\\
& & T_i(y) \in \mathbb{N}_0 & \forall y\in\Theta
\end{array}
$$

As we have the turn-around stock level for each item $i \in I$, this subproblem can easily be solved using Equation (3.6) by enumerating $T_i(y)$ from 0 to S_i with $p = 1$ and $c_e = -u_\zeta$. u_ζ and v_i are the dual variables that are obtained when the restricted master problem for Problem (C) is solved.

Step 3

In the To-Be situation we will use the result of Problem (C) as the constraint for expected number of backorders. The model of chapter 3 will be used to minimize investment costs and determine the turn-around stock levels for SKU-s $i \in I$. The only difference between the model of chapter 3 and the model that is used in this case is, that in this case we have a constraint for the expected number of expedites per cluster. Then the optimization model is as follows:

$$
\begin{array}{llll}
\text{(P)} & \min & \displaystyle\sum_{i\in I} C_i^a S_i & \\
& \text{subject to} & \displaystyle\sum_{i\in I} EBO_i(S_i,\mathcal{T}_i) \le EBO_{obj} & \\
& & \displaystyle\sum_{i\in I_\zeta} EXP_i(\mathcal{T}_i) \le EXP_{obj}^{\zeta} & \forall\zeta\in Z\\
& & T_i(y) \le S_i & \forall i\in I,\forall y\in\Theta_i\\
& & S_i \ge 1 & \forall i\in I\\
& & S_i, T_i(y) \in \mathbb{N}_0 & \forall i\in I,\forall y\in\Theta_i
\end{array}
$$

For each item, a threshold level per state (revision or non-revision period) is calculated for which our policy describes to expedite a repair job. Note that also here an extra constraint is added: $S_i \ge 1$. This is because we have assumed that all parts in this business case are critical parts and thus at least one spare part should be acquired for each item.

Also for this case, the three steps are implemented in MATLAB. The input for the model can be inserted in a MS EXCEL-input file. MATLAB loads the information from the file and gives the output. The linear programming problems are solved using GUROBI for MATLAB.

6.3 Verification and Validation

For this case the same verification and validation methods are used as in business case 1. However, next to the extreme value tests, the Markov Modulating model has also been verified by comparing the results of the Markov Modulating model to the close form solutions given by the Poisson Model. This was done by taking a two-state Markov Modulating chain with equal transition rates and equal demand rates. The results from the recursion program as described in chapter 3, were equal to the results from the closed form solutions of the Poisson model.

6.4 Base Case Scenario

Before the results for this second business case are discussed, first the values for the input parameters that are used for the base case scenario are presented. Again, the lead-times are in working days. In the base case scenario, the emergency repair lead-times are the same as in the first business case and the administration and transportation times are set to 5 working days. The *additional* regular repair lead-time differs per cluster. This is due to the fact that in that case the regular repair lead-times per cluster ($\ell_e^\zeta + \mathbb{E}[L_r^\zeta]$) are the same in each cluster, which is the case at NedTrain. We have chosen to set this value to 25 working days (20 working days regular repair lead-time and 5 working days administration and transportation time), the values that are currently used at NedTrain. In the base case scenario, the revision length is set to 31 months (the non-revision period to 41 months) and the expedite constraint is set to 29%, the fraction of repair jobs that has prio 1 or prio 2 (see Table I.1 in Appendix I). See Table 6.1 for the values of the input parameters per cluster. The input for the items that are used in this business case can again be found in Table I.3 in Appendix I.

Table 6.1 – Parameter setting base case scenario for business case 2

Cluster	ℓ_e^ζ	$\mathbb{E}[L_r^\zeta]$
1	10 (5+5)	15
2	7 (2+5)	18
3	8 (3+5)	17
4	7 (2+5)	18

6.5 Results

Below, in Table 6.2 and Table 6.3, the results of the base case scenario are presented. Table 6.2 contains the threshold levels, $\mathcal{T}_i = (T_i(1), T_i(2))$, turn-around stock levels and investment costs for the items. From the results, we can see that the investment costs in the To-Be situation are around €1.90 million less than in the As-Is situation, which means cost savings of 46%. Like in the first business case, the cost savings mainly result from the system approach that is used: In the To-Be situation the turn-around stock levels of expensive parts are smaller than in the As-Is situation whereas for the cheaper items, in the To-Be situation the turn-around stock levels are larger than in the As-Is situation. As can be seen in Table 6.3, this results however in the fact that in the To-Be situation, expected number of backorders for expensive items are higher than in the As-Is situation. For cheaper items it holds the other way around, in the To-Be situation cheaper items are less backordered than in the As-Is situation. It can also be concluded that the threshold levels are in general lower in the revision period ($y = 2$) than in the non-revision period. Also repair jobs for expensive parts are more often expedited than cheaper parts in the To-Be situation. For some expensive parts, even in the non-revision period ($y = 1$), the threshold level is low, which means that also in the non-revision period many repair jobs are expedited (such that less turn-around stock is needed). Also here note that it seems that sometimes cheaper parts are also expedited often, this is due to the fact that an expedite constraint is set per cluster and it thus may be that an item is relatively expensive within that cluster and therefore more often expedited.

Table 6.2 – Results base case scenario business case 2 (1)

			As-Is			To-Be		
Part number	C_i^a	Cluster	$\mathcal{T}_i$	S_i	$C_i^a S_i$ (€)	$\mathcal{T}_i$	S_i	$C_i^a S_i$ (€)
FA500021	6,716.12	1	(18,9)	18	120,890.16	(22,17)	22	147,754.64
FA500039	6,716.12	1	(18,10)	18	120,890.16	(22,18)	22	147,754.64
FA500427	612.16	2	(9,6)	9	5,509.44	(17,15)	17	10,406.72
FA500435	1,060.40	2	(17,12)	17	18,026.80	(27,23)	27	28,630.80
FA500823	440.72	2	(9,6)	9	3,966.48	(17,15)	17	7,492.24
FA500831	1,522.91	2	(9,6)	9	13,706.19	(14,12)	14	21,320.74
FA500849	956.26	2	(9,6)	9	8,606.34	(15,13)	15	14,343.90
FA502654	4,376.65	2	(9,6)	9	39,389.85	(6,2)	6	26,259.90
FA504304	508.02	1	(10,6)	10	5,080.20	(17,17)	17	8,636.34
FA504833	1,567.13	4	(10,8)	10	15,671.30	(14,11)	14	21,939.82
FA504841	2,688.38	4	(10,7)	10	26,883.80	(12,8)	12	32,260.56
FA505418	1,632.70	4	(17,11)	17	27,755.90	(25,19)	25	40,817.50
FA505517	1,376.97	4	(40,25)	40	55,078.80	(59,46)	59	81,241.23
FA505525	4,353.86	4	(21,14)	21	91,431.06	(10,0)	10	43,538.60
FA506283	2,103.33	3	(17,10)	17	35,756.61	(26,25)	26	54,686.58
FA506309	8,893.10	2	(9,6)	9	80,037.90	(4,0)	4	35,572.40
FA506317	1,866.95	1	(10,6)	10	18,669.50	(15,15)	15	28,004.25
FA506457	31,746.38	3	(10,7)	10	317,463.80	(1,0)	1	31,746.38
FA506630	314.35	3	(15,9)	15	4,715.25	(28,28)	28	8,801.80
FA506655	541.45	3	(15,9)	15	8,121.75	(26,25)	26	14,077.70
FA506689	23,835.93	3	(8,5)	8	190,687.44	(2,0)	2	47,671.86
FA506697	30,895.81	3	(6,4)	6	185,374.86	(1,0)	1	30,895.81
FA506721	34,801.66	3	(6,4)	6	208,809.96	(1,0)	1	34,801.66
FA506788	34,611.06	3	(4,4)	4	138,444.24	(1,0)	1	34,611.06
FA506879	796.58	3	(18,11)	18	14,338.44	(29,26)	29	23,100.82
FA506911	375.42	3	(15,9)	15	5,631.30	(27,25)	27	10,136.34
FA507091	442.68	3	(25,15)	25	11,067.00	(41,36)	41	18,149.88
FA507109	415.16	3	(25,15)	25	10,379.00	(41,38)	41	17,021.56
FA507166	2,142.95	3	(10,6)	10	21,429.50	(15,15)	15	32,144.25
FA507182	895.03	3	(10,7)	10	8,950.30	(16,16)	16	14,320.48
FA507208	2,521.55	3	(10,7)	10	25,215.50	(14,13)	14	35,301.70
FA507216	1,322.24	3	(10,7)	10	13,222.40	(15,14)	15	19,833.60
FA507257	440.17	3	(6,4)	6	2,641.02	(11,11)	11	4,841.87
FA507356	673.47	3	(10,7)	10	6,734.70	(16,16)	16	10,775.52
FA507380	1,461.10	3	(6,4)	6	8,766.60	(9,9)	9	13,149.90
FA507588	86,532.12	2	(6,5)	6	519,192.72	(0,0)	1	86,532.12
FA507596	28,119.53	2	(6,5)	6	168,717.18	(1,0)	1	28,119.53
FA510228	8,767.16	3	(29,18)	29	254,247.64	(12,0)	12	105,205.92
FA513255	7,703.82	3	(71,42)	71	546,971.22	(65,35)	65	500,748.30
FA550679	1,549.00	2	(9,6)	9	13,941.00	(14,12)	14	21,686.00
FA552410	8,924.00	3	(9,5)	9	80,316.00	(4,0)	4	35,696.00
FA552626	3,960.00	4	(9,6)	9	35,640.00	(5,0)	5	19,800.00
FA552741	1,193.00	4	(25,17)	25	29,825.00	(38,31)	38	45,334.00
FA552824	5,818.00	4	(9,6)	9	52,362.00	(4,0)	4	23,272.00
FA552915	25,611.00	1	(17,9)	17	435,387.00	(5,0)	5	128,055.00
FD089139	12,493.00	1	(10,6)	10	124,930.00	(7,3)	7	87,451.00
Total investment costs:					4,130,873.31			2,233,942.92

Table 6.3 – Results base case scenario business case 2 (2)

			As-Is		To-Be	
Part number	C_i^a	Cluster	$EBO_i(S_i, \mathcal{T}_i)$	$EXP_i(\mathcal{T}_i)$	$EBO_i(S_i, \mathcal{T}_i)$	$EXP_i(\mathcal{T}_i)$
FA500021	6,716.12	1	0.151	33%	0.227	3%
FA500039	6,716.12	1	0.226	28%	0.256	2%
FA500427	612.16	2	0.121	32%	0.008	0%
FA500435	1,060.40	2	0.249	26%	0.030	1%
FA500823	440.72	2	0.112	32%	0.007	0%
FA500831	1,522.91	2	0.112	32%	0.036	3%
FA500849	956.26	2	0.112	32%	0.022	1%
FA502654	4,376.65	2	0.112	32%	0.085	73%
FA504304	508.02	1	0.143	24%	0.009	0%
FA504833	1,567.13	4	0.178	18%	0.032	5%
FA504841	2,688.38	4	0.115	25%	0.040	18%
FA505418	1,632.70	4	0.158	31%	0.036	4%
FA505517	1,376.97	4	0.229	32%	0.048	1%
FA505525	4,353.86	4	0.238	29%	0.086	94%
FA506283	2,103.33	3	0.157	34%	0.060	0%
FA506309	8,893.10	2	0.112	32%	0.101	98%
FA506317	1,866.95	1	0.155	25%	0.040	0%
FA506457	31,746.38	3	0.138	22%	0.980	96%
FA506630	314.35	3	0.180	33%	0.006	0%
FA506655	541.45	3	0.162	33%	0.014	0%
FA506689	23,835.93	3	0.082	27%	0.396	90%
FA506697	30,895.81	3	0.059	23%	0.384	93%
FA506721	34,801.66	3	0.059	23%	0.384	93%
FA506788	34,611.06	3	0.056	6%	0.137	87%
FA506879	796.58	3	0.165	29%	0.019	0%
FA506911	375.42	3	0.162	33%	0.008	0%
FA507091	442.68	3	0.214	31%	0.013	0%
FA507109	415.16	3	0.214	31%	0.014	0%
FA507166	2,142.95	3	0.080	30%	0.038	0%
FA507182	895.03	3	0.138	22%	0.020	0%
FA507208	2,521.55	3	0.138	22%	0.060	1%
FA507216	1,322.24	3	0.138	22%	0.035	1%
FA507257	440.17	3	0.059	23%	0.004	0%
FA507356	673.47	3	0.138	22%	0.020	0%
FA507380	1,461.10	3	0.067	24%	0.029	1%
FA507588	86,532.12	2	0.109	16%	0.342	100%
FA507596	28,119.53	2	0.086	15%	0.312	93%
FA510228	8,767.16	3	0.289	28%	0.347	99%
FA513255	7,703.82	3	0.406	30%	0.351	41%
FA550679	1,549.00	2	0.112	32%	0.036	3%
FA552410	8,924.00	3	0.085	39%	0.153	99%
FA552626	3,960.00	4	0.112	32%	0.040	98%
FA552741	1,193.00	4	0.273	27%	0.035	1%
FA552824	5,818.00	4	0.121	32%	0.109	95%
FA552915	25,611.00	1	0.223	33%	1.192	100%
FD089139	12,493.00	1	0.168	25%	0.270	55%
Total *EBO*:			6.914		6.869	

As was done in the first business case, also in this business case we will vary some parameters of the base case scenario while keeping the other parameters constant to see the effect of these parameters on the investment costs.

When doing the experiments for the regular repair lead-times (see below), the computation time was on average around 10 hours. Since this model is less applicable for NedTrain (which will be discussed in section 6.6) than the model of chapter 5 but we still want to know what the effect is of varying input parameters on the investment costs, we choose to only use the items of cluster 1, to limit the computation times. By choosing only the items of cluster 1, it is expected that one can still benefit from the system approach, since the new buy prices of these parts range from 508.02 to 25,611.00. Then the values that are used for the repair lead-times in this smaller base case scenario can be found in Table 6.4. The expediting percentage is set to 29% and the length of the revision period to 31 months. The input parameters that are varied with respect to the smaller base case scenario and the values that are assigned to these parameters are given in Table 6.5.

Table 6.4 – Parameter setting smaller base case scenario for business case 2

Cluster	ℓ_e^ζ	$\mathbb{E}[L_r^\zeta]$
1	10 (5+5)	15

Table 6.5 – Parameter settings (sets of instances)

Input parameter	Values
Expedite percentage α (%)	19, 24, 29, 34, 39
Revision length (months)	25, 28, 31, 34, 37
Transportation and administration time (working days)	3, 4, 5, 6, 7

The investment cost savings are again expressed as:

$$\text{Cost savings} = \frac{\text{As-Is costs} - \text{To-Be costs}}{\text{As-Is costs}} \times 100\%$$

Regular repair lead-times

Since, according to managers of the NCB, the regular repair lead-time can be decreased from 20 to 10 days, we will determine what this means for the investment costs in turn-around stock. We will also see what the investment costs are when the regular repair repair lead-time is set to 15 working days. The results are graphically depicted in Figure 6.2. Since we already had the results for these instances when all items were included, we here will use these results instead of the results from the smaller base case scenario.

As can be seen in Figure 6.2, when the regular repair lead-time is reduced from 20 working days to 15 and 10 working days, investment costs also reduce. This reduction in investment can be explained as follows: When the regular repair lead-time decreases, less turn-around stock is needed to cover demand during the repair lead-time. The average cost savings are 43%, which means €1.51 million.

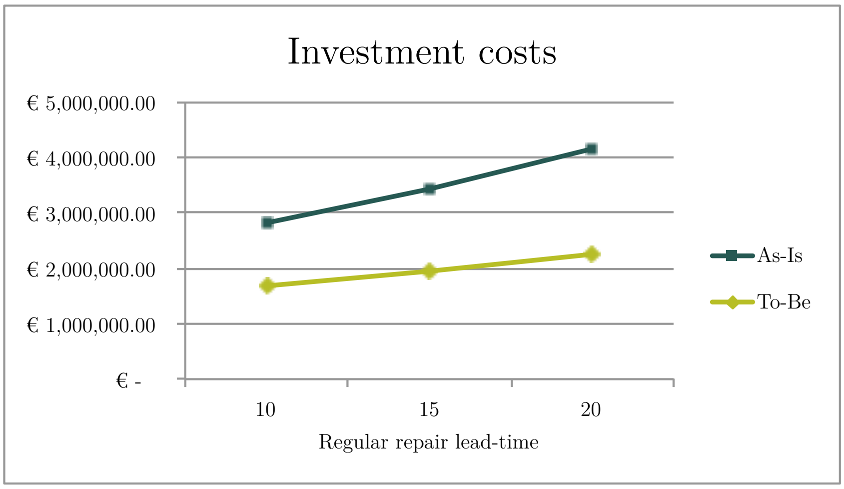

Figure 6.2 – Investment costs when the regular repair lead-time is set to 10, 15 and 20 working days

From here, the results are from the smaller base case scenario, i.e. the base case scenario that only consists of the items of cluster 1.

Expedite percentage α (%)

In the current situation, the number of repair jobs that is expedited is 29%. Now we will investigate what happens when more or less repair jobs can be expedited. The results are graphically depicted in Figure 6.3.

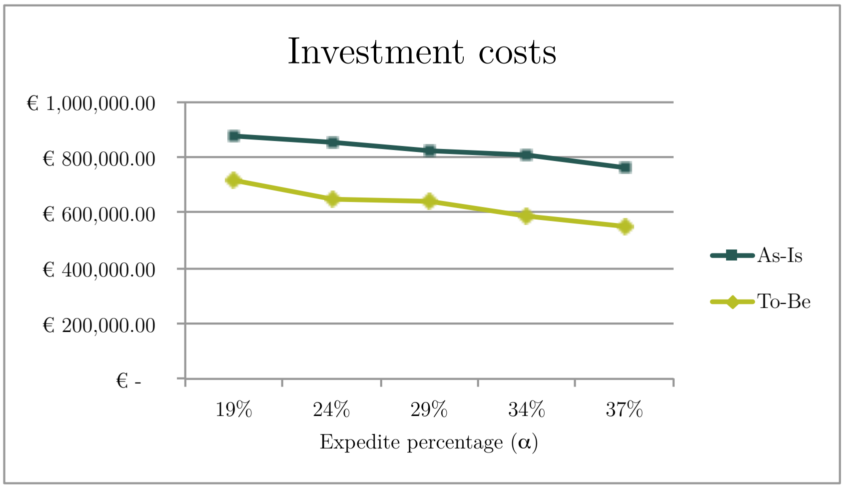

Figure 6.3 – Investment costs when the percentage of parts that can be expedited within a cluster is varied from 19% to 39%

As can be seen in Figure 6.3, when the expedite percentage becomes larger, the investment costs reduce. This can be explained as follows: When the expedite percentage is increased, more repair jobs are expedited more repair jobs can get the expedited repair lead-time. When parts can be repaired faster, less turn-around stock is needed to cover demand during the repair lead-time. The average cost savings are €200 thousand or in percentages, 24%

Revision length

As we discussed for the first business case, at this moment the revision of the SLT is planned to take place within 31 months in total. Again, we will investigate the influence of the mean length of the revision period on investment costs and vary this length from 25 months (31 months minus a half year) to 37 months (31 months plus a half year). See Figure 6.4 for the results of these instances.

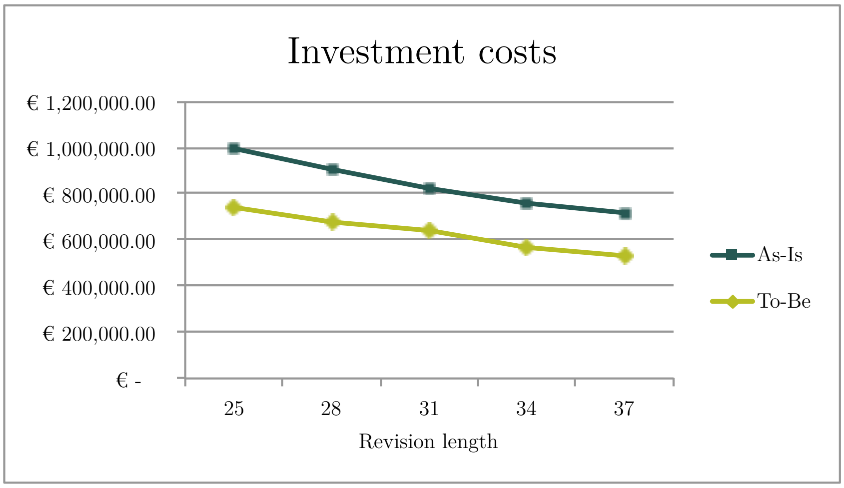

Figure 6.4 – Investment costs when the revision length is varied from 25 to 37 months

As can be seen in Figure 6.4, the investment costs reduce when the length of the revision period increases. This decrease in investment costs be explained as follows: When the length of the revision period increases, but the total demand due to the revision stays the same, the monthly demand for spare parts decreases. The average cost savings are 25% or €218 thousand.

Remember the remark that was made in section 5.5 that from practical viewpoints it is not possible to change the revision length easily.

Transportation and administration time

Also for this second business case we will investigate the influence of the length of the transportation and administration times that are taken into account. When the transportation and administration times are changed, the expedited repair lead-time (ℓ_e^ζ) changes since this parameter consists of the emergency repair lead-time and transportation and administration time. The As-Is and To-Be costs are graphically depicted in Figure 6.5.

As can be seen in Figure 6.5, when the administration and transportation time increases, investment costs also increase. The increase in investment costs can be explained as follows: When the transportation time increases, the expedited repair lead-time increases, which means that more turn-around stock is needed to cover demand during the repair lead-time. The cost savings are on average €207 thousand, or in percentages, 25%.

Using $\bar{\lambda}_i$ in the As-Is situation

As was discussed in section 5.2 at step 1, also $\bar{\lambda}_i$ instead of $\lambda_i^{\max}$ can be used to determine the turn-around stock levels in the As-Is situation. We have tested this for the smaller base case scenario.

The performance in terms of expected number of backorders in the As-Is situation when the average demand rate ($\bar{\lambda}_i$) was used, was much worse than in the situation in which the maximum

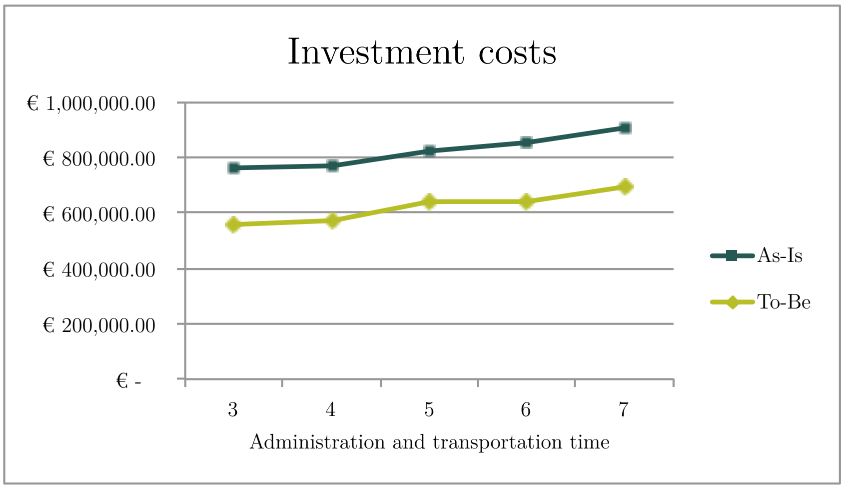

Figure 6.5 – Investment costs when administration and transportation time is varied from 3 to 7 workingdays

demand rate ($\lambda_i^{\max}$) was used. In the situation with the average demand rate, expected number of backorders per time unit were almost nine times as high as in the situation were the maximum demand rate was used (1.06 versus 10.29).

General remarks

Also for this second business case, for all instances, the GAP is determined based on the lower bound and the upper bound on costs when the restricted master problem is solved:

$$\text{GAP} = \frac{\text{upper bound} - \text{lower bound}}{\text{lower bound}} \times 100\%$$

For the instances where all items were included (the instances where the regular repair lead-times were varied), the average GAP is 0.19% and the maximum GAP is 0.25%. For the other instances, the average GAP is 0.85% and the maximum GAP is 1.86%. From this it can be concluded that solving the restricted master problem as binary problem performs quite well.

In the three cases where the smaller base case scenario was used, it seems that at the mid-point (29% expedite percentage in Figure 6.3, 31 months revision length in Figure 6.4, and 5 working days transportation in Figure 6.5, which all correspond to the base case scenario) there is a small ‘bump’ in the graph. We have investigated why this ‘bump’ occurs. The reason can be found in the expected number of backorders that results from the evaluation of the As-Is situation which is used as constraint in the To-Be situation. For the base case scenario the expected number of backorders constraint is 1.06 whereas for the other cases, the expected number of backorders constraint was on average 1.25. When less backorders are allowed, this means that more turn-around stock is needed and thus the investment cost is higher.

Also note that on average the savings were 25% in the cases where the smaller base case scenario was used whereas in the case where all items were included (where the regular repair lead-times were analyzed) the savings were 43%. From this, it can be concluded that in the case when only the items from cluster 1 were included, the benefits from using the system approach were less than when all items were included.

Also in this second business case, we found quite high values for expected number of backorders compared to the sum of average demand rates, which is 1.54 per time unit in the smaller base-case scenario. A probable reason for this is, that we assume a policy safety stock of 1 for each item (the policy safety stocks were not known for the items used in this case). Therefore, also for this business case we increased the policy safety stock to 4 to see whether increasing the policy safety stock improves the performance. For the smaller base case scenario we tested this instance. We still had cost savings of 17%, which is €169 thousand. The investment costs increased from €826 thousand to €988 thousand in the as-is situation and from €637 thousand to €818 thousand in the To-Be situation while the total expected number of backorders reduced from 1.06 to 0.14 per time unit.

6.6 Conclusion and Applicability for NedTrain

As mentioned in the introduction, the planner has to answer the following question:

> *"What should the size of the turn-around stock level be, given that during revision periods, the demand rate for ready-for-use parts is much higher than during non-revision periods and such that constraints regarding the expected number of backorders and expected number of expedites per time unit are met?"*

From the results in Table 6.2 and Table 6.3, we learn that when the current decision-making logic is used to determine the turn-around stock sizes, investment costs are around €1.90 million higher than when the new model is used.

However, concerning the applicability, it should be noted that this model cannot be applied right away at NedTrain. Next to the high computation time, also the model should be adapted. During a revision period it is important for NedTrain that downtime due to unavailability of RFU-parts is kept as low as possible since extra down-time would delay the production schedule for the revision period. However in this model expected number of backorders are not determined per modulating state but as an average over the modulating states. Therefore, it could be the case that during the revision period expected number of backorders are much higher than the expected number of backorders constraint, but this is covered by low expected number of backorders during the non-revision period and thus is the expected number of backorders constraint still satisfied.

Therefore, when one wants to apply this model in practice, an important note should be made: If an 'overall' backorder constraint is set instead of a backorder constraint per modulating state (i.e. revision and non-revision period) management should accept that an overall service level is achieved but that these service levels (in terms of expected number of backorders) could differ during the two different periods (states) with more expected number of backorders in the revision period. Another important note that influences the applicability is the following: The model assumes that it is economically attractive to buy all items at once. However this does not hold for all items as has been discussed in section 2.1.

7

Implementation

In this chapter it will be discussed how the model of chapter 5 can be implemented as a decision-support tool at NedTrain. At first the tool itself will be explained. The tool consists of a MS Excel file that has to be filled in and a graphical user interface (GUI) for the Matlab program such that it can easily be used by planners. Then it will be stated which actions need to be performed to be able to implement the tool, how the use of the tool should be communicated to the logistic planners and how the users can be involved for further improvement of the tool.

7.1 The decision-support tool

The decision-support tool that has been developed, can help planners when they have to take turn-around stock decisions, e.g. when new parts have to be bought for a revision period of when a complete overhaul for a train series is going to take place and new parts have to be ordered.

The tool uses the optimization method as is explained in step 3 of section 5.2. However, the only difference is, that now a constraint on expected number of backorders has to be defined by the user. This will be done by introducing a parameter β that determines which percentage of total expected demand can be backordered. Next we will discuss the input that the user has to enter into a pre-formatted MS Excel file which has to be loaded when the Matlab tool is started. After that we will show how this tool works including screenshots of the tool. Last we will discuss the output that the tool delivers.

7.1.1 The Input

A pre-formatted MS Excel file is used to enter the data. It consists of 5 sheets. In the first sheet an explanation is given of how the MS Excel file should be used. In the second, the third and the fourth sheet, the user is asked to enter data with respect to the items, the repair lead-times, the backorder constraint and the length of the revision period. In the fifth sheet the data is converted such that it can be used in the Matlab model. If the input is used as variable in the model, also the symbol will be given. Now we will discuss the three sheets in which data has to be filled in and how this results in the data in the fourth sheet (the sheet that contains the data which is used by the Matlab model.

Sheet 'Items'

Input that is entered in this sheet, is used to determine the input which is eventually loaded in the Matlab model.

- **Codenummer:** This is the id number of the part as it is registered in Xelus Parts

- **Nieuwprijs:** This is the new-buy price (C_i^a)
- **Landelijke voorraad:** This is the currently available turn-around stock within the network (S_i^c)
- **Revisievraag (totaal):** This is the total demand during the revision period (Λ_i)
- **Correctieve vraag (jaarlijks):** This is the average demand for RFU-parts due to corrective maintenance actions on a yearly basis
- **Cluster:** This is the cluster of the repair shop where the part is being repaired

Sheet 'Levertijden'

The data that is entered in this sheet, is used to determine the repair lead-times which are used in the MATLAB model.

- **Spoed reparatie:** This is the number of working days that is needed for an emergency repair
- **Regulier reparatie:** This is the number of working days it takes for a regular repair
- **Transport & Administration:** This is the number of working days that is taken into account for transportation and administration
- **Gewenste gemiddelde reparatietijd:** This is the average repair lead-time that is agreed upon between the NCB and the SCO and from which the expediting percentage (α^ζ) will be determined

Sheet 'Parameters'

The data that is entered in this sheet is loaded in the MATLAB model.

- **Percentage van de totale vraag dat gebackordered mag worden:** This is the percentage of total demand that is allowed to be backordered (β)[1]
- **Lengte revisie periode (maanden):** This is the length of the revision period in months.

Sheet 'Input'

This sheet only contains the data which is eventually loaded in the MATLAB model. The user cannot change the data in this sheet.

- **Ca:** This is the new-buy price (C_i^a)
- **daily λ_total:** This is the average daily demand which is calculated from the revision demand and the corrective demand (λ_i). To determine the average demand from the revision period per working day, the total demand during the revision period (Λ_i) should be divided by the length of the revision period in months times 22 working days per month.
- **Sc:** Currently available turn-around stock (S_i^c)

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[1] Then the expected number of backorders objective, $EBO_{obj} = \beta \sum_{i \in I} \lambda_i$.

- **Le:** Expediting repair lead-time (ℓ_e^ζ)
- **E[Lr]:** Additional regular repair lead-time ($\mathbb{E}[L_r^\zeta]$)
- **E[L]:** Average repair lead-time that is agreed upon ($\mathbb{E}[L^\zeta]$)
- **ζ:** number Cluster number (ζ)
- **Cluster:** Cluster name

7.1.2 Using the tool

After the input has been entered into the MS Excel file, the tool (GUI) can be opened and the data can be loaded. When the tool has been opened, one will see the following window (see Figure 7.1).

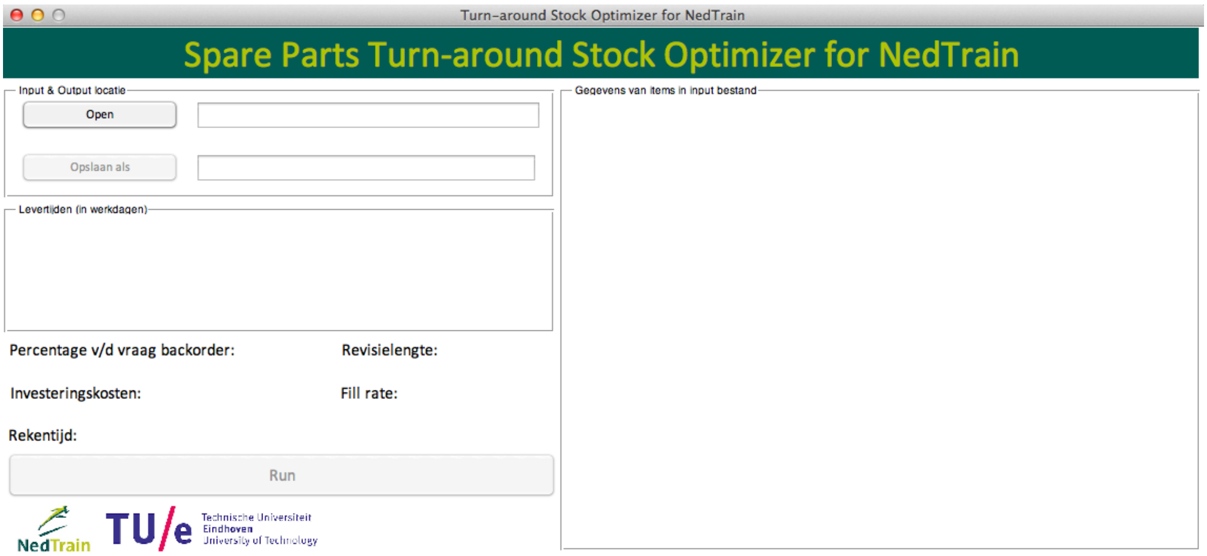


Figure 7.1 – Screenshot when the tool is started

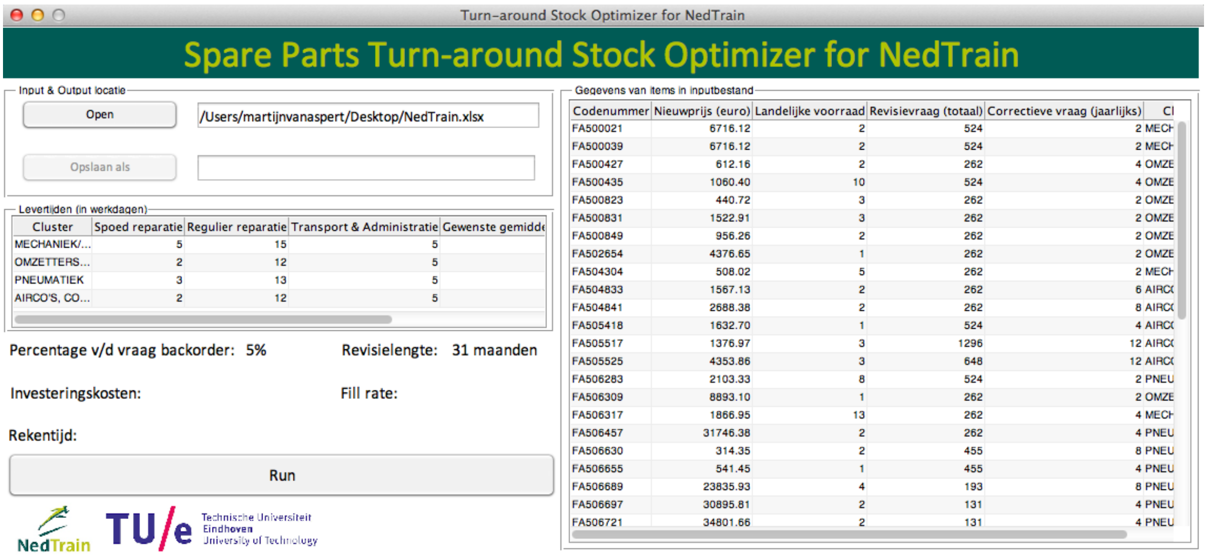
When the user clicks 'Open' she can select the MS Excel file in which she has entered all information. On the right side of the window, the data which was entered in the 'Items' sheet is presented such that the user can check whether the right data is loaded. Also the data from the 'Levertijden' sheet is shown as well as the percentage of parts that can be backordered and the length of the revision period (see Figure 7.2).

When the data have been loaded and these are the correct data, the turn-around stock levels can be determined by clicking on the button 'Run'. A message will be shown, which says that the turn-around stock levels are being calculated. When the calculation has finished, the computation time will be shown. In the window in which first the input was shown, now the extension in turn-around stock is shown for each item, next to some more information which will be discussed in the next section. The user can switch between the input and output by clicking the button 'Input/Output' (see Figure 7.3).

7.1.3 The Output

The output data consists of the following:

- **Codenummer:** This is the id number of the part as it is registered in Xelus Parts



Input & Output locatie

/Users/martijnvanaspert/Desktop/NedTrain.xlsx

Levertijden (in werkdagen)

Cluster	Spoed reparatie	Regulier reparatie	Transport & Administratie	Gewenste gemidde
MECHANIEK/...	5	15	5	
OMZETTERS...	2	12	5	
PNEUMATIEK	3	13	5	
AIRCO'S, CO...	2	12	5	

Percentage v/d vraag backorder: 5%

Revisielengte: 31 maanden

Investeringskosten:

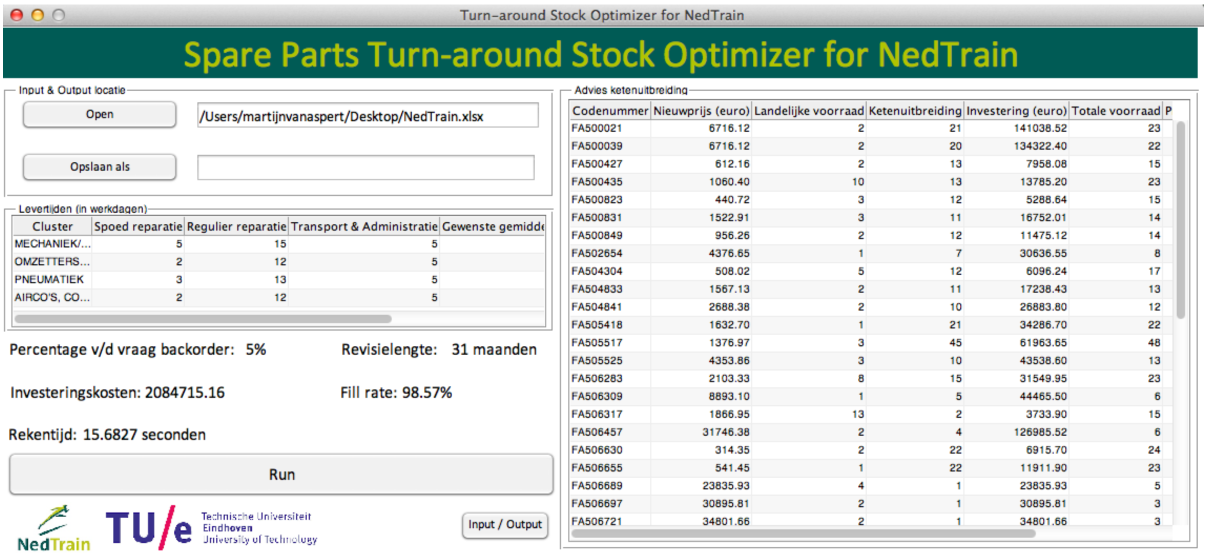
Fill rate:

Rekentijd:

Gegevens van items in inputbestand

Codenummer	Nieuwprijs (euro)	Landelijke voorraad	Revisievraag (totaal)	Correctieve vraag (jaarlijks)	Cl
FA500021	6716.12	2	524	2	MECH
FA500039	6716.12	2	524	2	MECH
FA500427	612.16	2	262	4	OMZE
FA500435	1060.40	10	524	4	OMZE
FA500823	440.72	3	262	2	OMZE
FA500831	1522.91	3	262	2	OMZE
FA500849	956.26	2	262	2	OMZE
FA502654	4376.65	1	262	2	OMZE
FA504304	508.02	5	262	2	MECH
FA504833	1567.13	2	262	6	AIRC
FA504841	2688.38	2	262	8	AIRC
FA505418	1632.70	1	524	4	AIRC
FA505517	1376.97	3	1296	12	AIRC
FA505525	4353.86	3	648	12	AIRC
FA506283	2103.33	8	524	2	PNEU
FA506309	8893.10	1	262	2	OMZE
FA506317	1866.95	13	262	4	MECH
FA506457	31746.38	2	262	4	PNEU
FA506630	314.35	2	455	8	PNEU
FA506655	541.45	1	455	4	PNEU
FA506689	23835.93	4	193	8	PNEU
FA506697	30895.81	2	131	4	PNEU
FA506721	34801.66	2	131	4	PNEU

Figure 7.2 – Screenshot when the input data is loaded



Input & Output locatie

/Users/martijnvanaspert/Desktop/NedTrain.xlsx

Levertijden (in werkdagen)

Cluster	Spoed reparatie	Regulier reparatie	Transport & Administratie	Gewenste gemidde
MECHANIEK/...	5	15	5	
OMZETTERS...	2	12	5	
PNEUMATIEK	3	13	5	
AIRCO'S, CO...	2	12	5	

Percentage v/d vraag backorder: 5%

Revisielengte: 31 maanden

Investeringskosten: 2084715.16

Fill rate: 98.57%

Rekentijd: 15.6827 seconden

Advies ketenuitbreiding

Codenummer	Nieuwprijs (euro)	Landelijke voorraad	Ketenuitbreiding	Investering (euro)	Totale voorraad	P
FA500021	6716.12	2	21	141038.52	23	
FA500039	6716.12	2	20	134322.40	22	
FA500427	612.16	2	13	7958.08	15	
FA500435	1060.40	10	13	13785.20	23	
FA500823	440.72	3	12	5288.64	15	
FA500831	1522.91	3	11	16752.01	14	
FA500849	956.26	2	12	11475.12	14	
FA502654	4376.65	1	7	30636.55	8	
FA504304	508.02	5	12	6096.24	17	
FA504833	1567.13	2	11	17238.43	13	
FA504841	2688.38	2	10	26883.80	12	
FA505418	1632.70	1	21	34286.70	22	
FA505517	1376.97	3	45	61963.65	48	
FA505525	4353.86	3	10	43538.60	13	
FA506283	2103.33	8	15	31549.95	23	
FA506309	8893.10	1	5	44465.50	6	
FA506317	1866.95	13	2	3733.90	15	
FA506457	31746.38	2	4	126985.52	6	
FA506630	314.35	2	22	6915.70	24	
FA506655	541.45	1	22	11911.90	23	
FA506689	23835.93	4	1	23835.93	5	
FA506697	30895.81	2	1	30895.81	3	
FA506721	34801.66	2	1	34801.66	3	

Figure 7.3 – Screenshot when the output data is presented

- **Nieuwprijs:** This is the new-buy price (C_i^a)
- **Landelijke voorraad:** The is the currently available turn-around stock (S_i^c)
- **Ketenuitbreiding:** This is the advice concerning the additional turn-around stock that should be acquired. It is the difference between the required size of the turn-around stock minus the currently available turn-around stock: ($S_i - S_i^c$)
- **Investering:** This is the investment cost in additional turn-around stock ($C_i^a(S_i - S_i^c)$)
- **Totale voorraad:** This denotes the total turn-around stock in the network (S_i)
- **Prioriteitsdrempel:** This is the threshold value which denotes that if that amount of items are already in regular repair, the next demand for that item should be expedited (T_i)

- **Itemnummer:** This is a follow-up number which is used within the model to identify the items (i)

Next to the output information per item, also the investment costs will be shown. As was discussed in the conclusion of chapter 5, managers of the SCO are also interested in the fill rate that can be achieved. Therefore, the aggregate fill rate that can be achieved is also presented. In Appendix J, it is explained how the aggregate fill rate can be determined.

The output data can be saved in two ways. The user can copy the data from the output window and save it in an MS Excel file for example. Another way is, that the output can be saved using the button 'Opslaan als'. Then the user can specify a location where a `.csv` file containing the output is saved.

7.2 Actions to be performed during implementation

If NedTrain is planning to use the tool, it will support logistic planners by taking turn-around stock decisions. The greatest difference between the current decision-making logic and the methods used in the tool is the item approach and the system approach, which was discussed in section 4.1.

However, before the tool can be used by planners, it is important that planners know how to use the tool. Therefore it should be explained to the users what data is needed to use the tool and how the output of the tool should be interpreted. The first step which has to be taken is a presentation to the planners and other users in which the tool will be explained. In this presentation the emphasis should be on putting the right data in the correct form in the MS Excel file. For example, it is important that the time-units are used correctly (e.g. lead-times in working days, revision length in months etc.). Also interpreting the output in the right way is a topic which should be discussed. It also has to be explained clearly, that in the system approach the focus is on a service level for the system as a whole, not on a service level per item (item approach) and that equal aggregate service levels can be achieved in the item and system approach but in the system approach with lower costs.

The second step is, that the users are going to use the tool and have the possibility to ask questions during a training session. Since the tool has not been tested in practice yet, it is important to gather information among the users during this training session about things that are not clear to them, while using the tool. It should also be investigated where the tool can be improved. After that, the tool can be improved such that an improved version of the tool can later be presented to the users.

Next to the training sessions, also a manual will be given to the users, in which it is explained how the tool can be used and what the required input is. In this manual it is also explained what output is generated by the tool and how this output should be interpreted.

The presentation and training session can be held on one day. Based on the improvements to be made, the tool has to be adapted which will take a few days. Afterwards the improved tool has to be presented which can again be done in one day.

8

Conclusions & Recommendations

In this chapter, conclusions and recommendations based on this research are given. In section 8.1, conclusions are drawn, based on the research questions that were formulated in section 1.4. In section 8.2, recommendations for NedTrain and recommendations for future research are given.

8.1 Conclusions

The objective of this research was to extend the model of Arts et al. (2013) to a multi-item model that can be used at NedTrain to take turn-around stock decision. Next to this, differences between the current decision-making logic and the methods used in the new multi-item model have been investigated. A tool based on the new multi-item model has been developed, which can be used by planners at NedTrain as a decision-support tool to take turn-around stock decisions.

We will now discuss the main conclusions per research question as given in chapter 1.

Research Question 1

How can the model of Arts et al. (2013) be extended to a multi-item model in which spare parts utilize the same repair capacity?

In this research, the model of Arts et al. (2013) has been extended to a multi-item optimization problem in which the objective is to minimize investment costs. In the multi-item model, constraints are set on the expected number of backorders and on the expected number of expedites, i.e. the expected number of repair jobs that is expedited. Since spare parts (repair jobs) have to share capacity within a repair cluster in the repair shop, an expediting constraint is set per repair cluster.

Research Question 2

What are the differences between the decision-making logic as used by planners currently and the decision-making logic based on the multi-item model?

Differences between the current decision-making logic and the methods used in the new multi-item model consist among others of the following:

Whereas in the current decision-making logic, turn-around stock decisions are based on deterministic lead-times and deterministic demand, the multi-item model takes stochastic demand and stochastic lead-times into account. It is important to take variability into account since in reality, demand will not be deterministic. Another important difference between the current logic and the logic of the multi-item model is that in the model a system approach is used, whereas in practice an item approach is used. This means that an aggregated service level is set for the system as a whole instead of a target service level per item.

Concerning the service levels, in the current logic, a network fill rate is used whereas in the multi-item model expected number of backorders is used as service level. It could be valuable to use the expected number of backorders instead of fill rate, since the expected number of backorders roughly corresponds to the number of trains that is down waiting for a part, whereas fill rate only tells something about the share of demand that can be fulfilled immediately.

Research Question 3

What are the results of the current decision-making logic and the situation in which the multi-item model is used?

Due to the differences as discussed above, it was expected that different investment costs would result from both methods. To show these differences, the investment costs using the current decision-making logic and using the new multi-item model have been investigated in two different business cases. To compare the two decision-making logics, the expected number of backorders that resulted from the current decision-making logic were set as a constraint for the expected number of backorders when the new model was used, such that the performance of the new model in terms of expected number of backorders was at least as good as using the current decision-making logic.

In the first business case, it has been investigated whether an extension in turn-around stock is needed for the upcoming revision of the Sprinter LightTrain. It turns out that an extension in turn-around stock is needed. Using the current decision-making logic, the investment in turn-around stock would amount to €2.29 million whereas using the new multi-item model the investment costs would be €1.07 million. This means that an estimated cost saving of €1.22 million (53%) can be achieved.

The expected number of backorders that resulted from the current decision-making logic (and was set as constraint when the multi-item model was used) was quite high compared to demand rates. To investigate whether we still can achieve the same estimated cost savings when the expected number of backorders is low compared to demand rates, we manually increased the turn-around stock levels from the current decision-making logic such that a better performance in terms of expected number of backorders can be achieved. As expected, the expected number of backorders that resulted from the current decision-making logic was low compared to demand rates. Total investment costs increased in both situations however the savings that could be achieved still amounted to an estimated 47% (€1.63 million).

In the second business case, it has been investigated what the turn-around stock levels should have been in case NedTrain had to buy the spare parts at the same moment as the trains series was ordered. In that case not only demand during the revision period, but also demand due to unplanned failures during the non-revision period has to be taken into account. In this case, it turns out that using the current decision-making logic this would have lead to an investment of €4.13 million whereas the investment using the new multi-item model requires €2.23 million, an estimated cost saving of €1.90 million (46%). It should however be noted that the model was less applicable in this case. To use the model in cases like this second business case, the model should first be further extended by taking into account separate service levels for the non-revision and revision period.

Research Question 4

How can a decision support tool for the turn-around stock decision be implemented within NedTrain?

For the model that is used to take turn-around stock decisions in business case 1, a tool has been developed that can be used by planners as a decision-support tool when taking turn-around stock decisions. The tool consists of a graphical user interface and of an MS Excel file in which the required data can be entered by the user. Before the tool actually can be used, a presentation and training session should be held to explain how the tool works.

8.2 Recommendations

In this section, the recommendations for NedTrain and recommendations for future research are presented.

8.2.1 Recommendations for NedTrain

The main recommendation that is given to NedTrain is the following:

Implementation of the decision-support tool: As Loeffen (2012) already recommended in her thesis, NedTrain should search for optimal values for the turn-around stock levels. In this research, a multi-item model has been developed to determine the optimal turn-around stock levels such that investment costs can be minimized. A decision support-tool based on this model has been developed. It is recommended to NedTrain to use this decision-support tool which can support logistic planners when taking turn-around stock decisions using a system approach such that investment costs savings can be achieved.

Next to the main recommendation, also other recommendations can be given to NedTrain. These recommendations are based on things that were notified during the process of data gathering:

Demand data: It is recommended to NedTrain to store demand data for a longer period and to collect data even when demand is not fulfilled by NedTrain itself. The reasoning for this recommendation is threefold: First, for the SLT, no demand data was registered for the repairable spare parts, since broken parts were replaced by the train manufacturer during the warranty period. These replacements were not registered in Xelus Parts. Therfore planners were not able to see demand rates for these spare parts. Second, when fluctuations in demand rates during the life-time of a train have to be taken into account, it could be valuable when data regarding demand rates during previous peaks can be used. However, at this moment demand data is saved for only the last five years and then it is deleted. For e.g. the SLT, the inter-revision term is six years which means that this data is not available during the next revision period. Third, when certain long-term demand patterns are visible for older train series, these can possibly be used to forecast demand for newer train series (e.g. when degradation for parts of older train series is known, this can imply something about the degradation of parts for newer train series).

Parts identification: When parts are used at more indenture levels of the configuration, different identification numbers are assigned to these parts. However it is not clear how the lower level identification numbers are linked to higher level identification numbers. Therefore it is recommended to clarify how identification numbers at different indenture levels are linked to each other.

Lead-times used: At this moment in Xelus Parts, 20 working days are used as regular repair lead-time for repairable spare parts. As was mentioned by managers from the NCB, this repair lead-time is based on old data and can possibly be reduced. It is recommended to investigate what a plausible repair lead-time is. The result of this could also be that the advices regarding re-buys for spare parts, given by Xelus Parts, are more useful than they are now when the value is changed in Xelus Parts.

8.2.2 Recommendations for Future Research

Constraints per state: At this moment an overall constraint is set on the expected number of backorders. This could lead to the fact that during the non-revision period the expected number of backorders is relatively low and during the revision period relatively high, but since an average is taken, the constraint is still satisfied. However, especially during a revision period (period with peak demand), one does not want to have more backorders than expected since strict schedules are made for the revision of the trains. More backorders than expected will then lead to less availability than expected. Therefore it is recommended to extend the model with expected number of backorder constraints per state.

Costs for backordering: We have not taken into account costs for backordering and expediting while minimizing the turn-around stock investment cost. It could be interesting to take costs for backordering and expediting into account. When backorder costs are taken into account, it should be noted that these can be ‘asymmetric’. Since we use expected number of backorders, this means that actual backorders can be higher than agreed upon (i.e. than the expected number of backorders constraint). When backorders are higher than agreed upon, extra costs are incurred. However when less backorders occur than agreed upon, there is no reward for having less backorders than agreed upon. This means that backorder costs are asymmetric.

Multi-system approach: Now only the SLT has been taken into account, however more trains series are maintained by NedTrain. It could be interesting to extend the model to a model for multiple trains series where a service level constraint is set per train series. This might be even more interesting when it is the case that spare parts can be used at more than one train series. This is especially interesting when spare parts become increasingly standardized.

Relaxation of assumptions: Several assumptions have been made, however some assumptions can possibly be relaxed to improve the model. E.g. now, the repair lead-time for all items within a cluster is the same, it could be interesting to verify what the effect is when minimum and maximum repair lead-times per item are taken into account. It could also be interesting to take multi indenture levels into account, such that the availability of shop replaceable units can be taken into account.

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A

List of Abbreviations

EMC	External Material Class
KPI	Key Performance Indicator
LCPM	Long Cycle Periodic Maintenance
LLC	National Logistics Center (Landelijk Logistiek Centrum)
LRU	Line-replaceable Unit
MMPP	Markov Modulated Poisson Process
MOQ	Minimum Order Quantity
NCB	NedTrain Components Company (NedTrain Componenten Bedrijf)
NS	Dutch Railways (Nederlandse Spoorwegen)
OB	Maintenance Depot (Onderhoudsbedrijf)
OEM	Original Equipment Manufacturer
OH	On hand stock
RFU	Ready-for-use
R&O	Refurbish & Overhaul
SB	Service Company (Servicebedrijf)
SKU	Stock Keeping Unit
SLT	Sprinter Lighttrain
SCO	Supply Chain Operations
ShCM	Short Cycle Maintenance
ShCPM	Short Cycle Periodic Maintenance
SRU	Shop-replaceable Unit
TU/e	Eindhoven University of Technology (Technische Universiteit Eindhoven)

B

List of Definitions

Acquisition cost Cost for acquiring a new part (contrary: Cost price)

Backorders Demand that cannot be fulfilled when the on-hand stock is zero or less

Car bodies Complete trains (rolling stock units) except the main parts

Cluster Group within the repair shop that repairs certain parts, e.g. pneumatic parts

Construction parts The piece of a repairable part that functions as structural bearing

Consumable spare parts Spare parts that are discarded and replaced by a completely new item

Cost price Price for a part that is used internally for financial reports

Expedited lead-time Emergency repair lead-time plus transportation and administration time

Expedites Number of repair jobs that were assigned an expedited lead-time

Inventory level On-hand stock minus backorders (this can be negative)

Main parts Parts that are uniquely identified, have their own (maintenance and) revision period and are individually followed during their life cycle

Min-max interface agreement Operational control mechanism for the repair shop, where the inventory level is kept between a minimum and a maximum level

Network The repair shop, stock of defective parts and the warehouse for ready-for-use parts

On-hand stock Stock that is readily available at the warehouse

Overhaul Revise and repair of an item if necessary

Policy Safety Stock Stock that is need to cover demand during the repair lead-time

Ready-for-use parts Parts that have been repaired and/or revised and can be installed on rolling stock units

Refurbishment Complete modernization of a rolling stock unit

Regular repair Parts that did not get an expedited lead-time

Repairable spare parts Spare parts that are repaired instead of discarded when they are defect

Revision period Period in which all trains and parts of these trains of a certain train series are revised and if necessary repaired

Rolling stock units Train coaches and locomotives

System approach A service level constraint is set for the system as a whole

Threshold level Value that indicates that a repair job should get an expedited lead-time when the number of parts in regular repair is equal or greater than this value

Turn-around stock Total number of spare parts in the network, i.e. defective parts and ready-for-use parts

Xelus Parts Software tool used at NedTrain for demand planning

C

List of Variables

$BO(t)$	Backorders at time t
$C(S)$	Backordering and expediting cost for a policy with turn-around stock level S
C^a	Acquisition cost of an SKU
$C_{tot}(S)$	Total cost for a policy with turn-around stock level S
c_e	Cost of expediting one part
$c_p(x, y)$	Backorder penalty cost rate when number of parts in regular repair and state is (x, y)
$D^y_{t_1,t_2}$	Demand during time interval $(t_1, t_2]$ given $Y(t_1) = y$, $y \in \Theta$
$EBO(S, \mathcal{T})$	Expected number of backorders for a policy with turn-around stock level S and thresholds $\mathcal{T}$
$EXP(\mathcal{T})$	Expected number of expedites for a policy with thresholds $\mathcal{T}$
$\mathbb{E}[L_r]$	Additional regular repair lead-time
$\mathbb{E}[L]$	Average repair lead-time
I	Set of SKU-s
$IN(t)$	Inventory level at time t
i	Index of SKU $i \in I$
k	Safety factor
LOT	Forecasted recurring demand
ℓ_e	Expedited repair lead-time
M	Threshold level (in dynamic recursion)
$\mathcal{M}$	State space containing possible combinations of (x, y) given x parts in repair and given state $y \in \Theta$
max	Max level (min level plus three months of demand)
min	Min level (equal to policy safety stock)
$OH(t)$	On hand stock at time t
PSS	Policy safety stock
p	Backorder penalty cost rate
$\mathbf{Q}$	Generator matrix for Markov Modulated Poisson Process
q_{ab}	Element of $\mathbf{Q}$
S	Turn-around stock level
S^c	Current turn-around stock level
$T(y)$	Threshold level when state is $y \in \Theta$
$\mathcal{T}$	Vector containing threshold levels

t_1	Mean length of non-revision period
t_2	Mean length of revision period
$V_n(x, y)$	Optimal total cost with n transitions to go when number of parts in regular repair and state is (x, y)
$X(t)$	Number of parts in regular repair at moment t
x	Number of parts in regular repair
x_i^k	Decision variable whether policy k is chosen for SKU i. Note that x in this case has nothing to do with the number of parts in regular repair and k has nothing to do with the safety factor
$Y(t)$	State at moment t
y	State
α	Share of demand that is expedited
Λ	Uniformization rate
Λ_i	Total demand during revision for SKU i
$\boldsymbol{\lambda}$	Vector of demand rates
$\lambda(y)$	Demand rate in state $y \in \Theta$
$\lambda(1)$	Demand rate during non-revision period
$\lambda(2)$	Demand rate during revision period
$\bar{\lambda}$	Average demand rate
μ	Regular repair rate $(1/\mathbb{E}[L_r])$
Θ	State space of Markov Modulated Poisson Process
σ_L	Standard deviation of the recurring demand during lead-time L

D

Assumptions

Table D.1 – Scrap rates of parts, January 2012 – December 2012

Cluster	Scrapped	Ordered	Scrap Rate (%)	Average Scrap Rate (%)	Standard Deviation (%)
Air Conditioners	3	172	0.4	2.0	10.0
Mechanics	159	12191	1.3	6.0	18.0
Electronics	717	9545	7.5	9.0	22.0
Pneumatics	450	15366	2.9	3.9	10.8
Total	1329	37814	3.5	6.3	17.1

Table D.2 – Minimum Order Quantities (for parts for which the cluster is known)

MOQ	SKUs
1	1766
2	45
3	13
4	8
5	160
6	1
7	1
8	2
10	57
15	1
20	8
25	4
32	1
40	1
50	6
300	1
Unknown	92
Total	2167

E

Determining $\mathbb{P}\{D^y_{t,t+\ell_e} = k\}$

In this appendix it is shown how $\mathbb{P}\{D^y_{t,t+\ell_e} = k\}$ can be determined numerically. The same procedure is exactly the same described in Arts et al. (2013, ch. 4).

Let $p_{y,y'}(k, \ell_e) = \mathbb{P}\{D^y_{t,t+\ell_e} = k|Y(t + \ell_e) = y'\}$ be the (y, y')-entry of the matrix $\mathbf{P}(k, \ell_e)$. Then the matrix generating function $\tilde{\mathbf{P}}(z, \ell_e) = \sum_{k=0}^{\infty} \mathbf{P}(k, \ell_e)z^k$ satisfies (e.g. Fischer and Meier-Hellstern, 1993):

$$\tilde{\mathbf{P}}(z, \ell_e) = \exp([\mathbf{Q} - (1 - z)\mathrm{diag}(\lambda)]\ell_e)$$

The probabilities $\mathbb{P}\{D^y_{t,t+\ell_e} = k|Y(t + \ell_e) = y'\}$ can be obtained from $\tilde{\mathbf{P}}(z, \ell_e)$ by numerical inversion using the LATTICE-POISSON algorithm of Abate and Whitt (1992) which uses the approximation:

$$\mathbb{P}\{D^y_{t,t+\ell_e} = k|Y(t + \ell_e) = y'\} \approx$$

$$\frac{1}{2kr^k}\left\{\tilde{\mathbf{P}}(r, \ell_e) + (-1)^k\tilde{\mathbf{P}}(-r, \ell_e) + 2\sum_{n=1}^{k-1}(-1)^n \mathrm{Re}(\tilde{\mathbf{P}}(r \exp\left(\frac{n\pi\imath}{k}\right), \ell_e))\right\}$$

Where $\imath = \sqrt{-1}$, $0 < r < 1$ and $\mathrm{Re}(x)$ denotes the real part of the complex number x. The absolute error in this approximation is bounded by $\frac{r^{2k}}{1-r^{2k}}$ and so by choosing $r = 10^{-\gamma/(2k)}$, we obtain an accuracy of approximately $10^{-\gamma}$. Then the needed probability $\mathbb{P}\{D^y_{t,t+\ell_e} = k\}$, can be found by un-conditioning:

$$\mathbb{P}\{D^y_{t,t+\ell_e} = k\} = \sum_{y' \in \Theta} \mathbb{P}\{D^y_{t,t+\ell_e} = k|Y(t + \ell_e) = y'\}\,\mathbb{P}\{Y(t + \ell_e) = y'|Y(t) = y\}$$

F

A Lower and Upper Bound on S

In this appendix it is described how a lower and an upper bound on the optimal turn-around stock S^* can be found. The procedure is exactly the same described in Arts et al. (2013, ch. 4).

Refer to the process in steady state, e.g. $\mathbb{P}\{Y = y\} = \lim_{t\to\infty} \mathbb{P}\{Y(t) = y\}$. Let the random variable $D(L)$ denote demand in an interval of length $L \geq 0$ when the modulating chain of demand is in steady state, i.e.,

$$\mathbb{P}\{D(L) \leq k\} = \sum_{y\in\Theta} \mathbb{P}\{Y = y\}\,\mathbb{P}\left\{D^y_{t,t+L} \leq k\right\}$$

A lower bound of $C_{tot}(S)$ is given by the average holding and backorder penalty cost rates of the system with turn-around stock S under the feasible policy of expediting everything against zero expediting cost:

$$C_{LB}(S) := C^a S + p\,\mathbb{E}\left[(D(\ell_e) - S)^+\right]$$

When the expediting costs are included, an upper bound for $C_{tot}(S)$ is obtained:

$$C_{UB}(S) := C_{LB}(S) + c_e\bar{\lambda}$$

Here $\bar{\lambda} = \sum_{y\in\Theta} \lambda_y\,\mathbb{P}\{Y = y\}$ is the long run average demand per time period. In Appendix I it is explained how $\bar{\lambda}$ can be calculated. Let $S^* := \text{argmin}_{S\in\mathbb{N}_0} C_{tot}(S)$ denote the optimal turn-around stock. An upper bound to $C_{tot}(S^*)$ is obtained by minimizing $C_{UB}(S)$. The S that minimizes $C_{UB}(S)$ (as well as $C_{LB}(S)$) can be easily found as $C_{UB}(S)$ is convex. We denote this minimizer $\hat{S}$ and it is the smallest integer that satisfies the newsvendor inequality.

$$\mathbb{P}\left\{D(\ell_e) \leq \hat{S}\right\} \geq \frac{p - C^a}{p}$$

Since $C_{LB}(S)$ is convex, it is easy to find the greatest $S \leq \hat{S}$ and smallest $S \geq \hat{S}$ such that $C_{LB}(S) \geq C_{UB}(\hat{S})$. This will provide lower and upper bounds respectively on S^*. Furthermore, if $C(S) \leq C^a$ for some $S \in \mathbb{N}_0$, then $S^* \leq S$.

G

Determining p and c_e

Assume Poisson demand, let $D(\ell_e)$ denote the demand during the expedited lead-time. We want to minimize the following function (let $D_{t,t+\ell_e} = D(\ell_e)$):

$$f(S) = C^a S + p\,\mathbb{E}\left[(D(\ell_e) - S)^+\right] \tag{G.1}$$

Let S^* denote the optimal value of S that minimizes Equation (G.1). Since we know that $f(S)$ is convex in S, we also know that $f(S^*+1) \geq f(S^*)$ and thus $f(S^*+1) - f(S^*) \geq 0$.

$$\begin{aligned}
f(S^*+1) - f(S^*) &= C^a(S^*+1) - C^a S^* + p\,\mathbb{E}\left[(D(\ell_e) - (S^*+1))^+\right] - p\,\mathbb{E}\left[(D(\ell_e) - S^*)^+\right] \\
&= C^a + p \sum_{k=S^*+2}^{\infty} (k - S^* - 1)\,\mathbb{P}\{D(\ell_e) = k\} \\
&\quad - p \sum_{k=S^*+1}^{\infty} (k - S^*)\,\mathbb{P}\{D(\ell_e) = k\} \\
&= C^a + p \sum_{k=S^*+2}^{\infty} (k - S^*)\,\mathbb{P}\{D(\ell_e) = k\} \\
&\quad - p\ \mathbb{P}\{D(\ell_e) \geq S^*+2\} \\
&\quad - p \sum_{k=S^*+1}^{\infty} (k - S^*)\,\mathbb{P}\{D(\ell_e) = k\} \\
&= C^a - p\ \mathbb{P}\{D(\ell_e) \geq S^*+2\} - p\ \mathbb{P}\{D(\ell_e) = S^*+1\} \\
&= C^a - p\ \mathbb{P}\{D(\ell_e) \geq S^*+1\}
\end{aligned}$$

Since we know that $f(S^*+1) - f(S^*) \geq 0$, the following holds:

$$\begin{aligned}
C^a - p\ \mathbb{P}\{D(\ell_e) \geq S^*+1\} &\geq 0 \\
C^a - p\,(1 - \mathbb{P}\{D(\ell_e) \leq S^*\}) &\geq 0 \\
C^a &\geq p\,(1 - \mathbb{P}\{D(\ell_e) \leq S^*\}) \\
\frac{C^a}{1 - \mathbb{P}\{D(\ell_e) \leq S^*\}} &\geq p
\end{aligned} \tag{G.2}$$

G.1 Feasible Solution

To create a feasible solution we want to have a probability of 99% that $D(\ell_e) \leq S^*$. Since we know C^a we can determine p by solving Equation (G.2). However since we have $|I|$ items and we want p as high as possible, we choose for C^a, $C^a_{\max} = \max_{i \in I} C^a_i$.

For c_e we also want to have a high value to make sure that Equation (MP.2) is satisfied. We know that it may be optimal to expedite when $c_e < p\,\mathbb{E}[L_r]$. We use this inequality to determine c_e as follows:

$$c_e = 0.99p\,\mathbb{E}[L_r]_{\min}$$

Where $\mathbb{E}[L_r]_{\min} = \min_{i\in I}\mathbb{E}[L_r]_i$.

G.2 Infeasible Solution

To create an infeasible solution we want to have a small probability that $D(\ell_e) \leq S^*$, therefore we set the probability to 1%. Again, since we know C^a we can determine p by solving Equation (G.2) with C^a as $C^a_{\max} = \max_{i\in I} C^a_i$.

For c_e we also want to have a low value to make sure that Equation (MP.2) is not satisfied. Again, we use the inequality to determine c_e as follows but now we take only 50% of the value of p such that expediting is even cheaper:

$$c_e = 0.5p\,\mathbb{E}[L_r]_{\min}$$

Where $\mathbb{E}[L_r]_{\min} = \min_{i\in I}\mathbb{E}[L_r]_i$.

H

Determining $\bar{\lambda}_i$

Given the $N \times N$ generator matrix $\mathbf{Q}$ and the column vector with demand rates $\boldsymbol{\lambda}$ for a given item, the average demand can be calculated as follows (note that for convenience, the index i is omitted):

Let π denote the vector with steady state probabilities and $\mathbf{e} = (1, 1, \ldots, 1)$. Then the following two equations have to be solved:

$$\begin{aligned} \pi\mathbf{Q} &= 0 \\ \pi\mathbf{e}^{\mathrm{T}} &= 1 \end{aligned}$$

This can be done by solving

$$\pi\mathbf{T}_{n,m} = (0, 0, \ldots, 1)$$

Where

$$\mathbf{T}_{n,m} = \begin{cases} \mathbf{Q}_{n,m} & m = 1, \ldots, N-1 \\ \mathbf{e}^{\mathrm{T}} & m = N \end{cases}$$

Then

$$\begin{aligned} &\pi = (0, 0, \ldots, 1)/\mathbf{T}_{n,m} \\ &\bar{\lambda} = \pi\boldsymbol{\lambda} \end{aligned}$$

I

Input for Experiments

I.1 Prioritization of Repair Orders January - May 2013

Table I.1 shows the sum of the number of repair orders that were assigned a certain priority during that month. As is mentioned in Table 2.1 priorities 100 and 300 are not based on inventory level but are identifications: prio 100 means that SRUs are missing to continue the repair job, prio 300 means that these repair jobs have a certain lead-time when they should be ready for use. If the probability that a certain SKU is needed for a repair job equals 49% or greater, it is checked whether these SRUs are available. If the probability is less, it is not checked and there is a probability that the repair job gets assigned prio 100 while it is being repaired. When the SRUs are available, the prio is put back to 1, 2, 3, 4, 5. Note that prio 999 is not included in Table I.1. This is because prio 999 orders are set but do not have any priority i.e. these are not taken into repair.

According to Guido Aerts, it can be assumed that when a part got assigned prio 1 or prio 2, these were repaired immediately.

Table I.1 – Prioritization of repair orders January - May 2013

	January	February	March	April	May
prio 1	3	0	1	3	4
prio 2	743	836	643	1370	823
prio 3	420	601	298	672	353
prio 4	508	468	247	636	390
prio 5	305	302	177	432	309
prio 100	278	299	250	434	308
prio 300	555	681	503	738	462
Total	2812	3187	2119	4285	2649
$\frac{\text{prio 100}}{\text{Total}}$	10%	9%	12%	10%	12%
$\frac{\text{prio 1+prio 2}}{\text{Total}}$	27%	26%	30%	32%	31%

I.2 Item Information Business Cases

In Table I.2 and Table I.3 information that is used as input for the experiments can be found.

Table I.2 – Cluster names and numbers

Cluster name (Dutch)	Cluster name (English)	Cluster number
Mechaniek/Pneumatiek	Mechanics/Pneumatics	1
Omzetters/Electronica	Switches/Electronics	2
Pneumatiek	Pneumatics	3
Airco's, Compressoren, Tractie	Air cons, Compressors, Traction	4

Table I.3 – Information per part

Part number	C_i^a	S_i^c	Cluster	Emergency repair lead-time	Λ_i	$\lambda_i^{corrective}$ (yearly)
FA500021	6,716.12	2	1	1	524	2
FA500039	6,716.12	2	1	1	524	2
FA500427	612.16	2	2	1	262	4
FA500435	1,060.4	10	2	1	524	4
FA500823	440.72	3	2	1	262	2
FA500831	1,522.91	3	2	1	262	2
FA500849	956.26	2	2	1	262	2
FA502654	4,376.65	1	2	1	262	2
FA504304	508.02	5	1	5	262	2
FA504833	1,567.13	2	4	2	262	6
FA504841	2,688.38	2	4	2	262	8
FA505418	1,632.7	1	4	2	524	4
FA505517	1,376.97	3	4	2	1296	12
FA505525	4,353.86	3	4	2	648	12
FA506283	2,103.33	8	3	2	524	2
FA506309	8,893.1	1	2	1	262	2
FA506317	1,866.95	13	1	1	262	4
FA506457	31,746.38	2	3	2	262	4
FA506630	314.35	2	3	1	455	8
FA506655	541.45	1	3	1	455	4
FA506689	23,835.93	4	3	2	193	8
FA506697	30,895.81	2	3	2	131	4
FA506721	34,801.66	2	3	2	131	4
FA506788	34,611.06	2	3	2	62	4
FA506879	796.58	4	3	1	524	8
FA506911	375.42	2	3	1	455	4
FA507091	442.68	1	3	1	779	4
FA507109	415.16	1	3	1	779	4
FA507166	2,142.95	1	3	2	262	4
FA507182	895.03	1	3	1	262	4
FA507208	2,521.55	1	3	1	262	4
FA507216	1,322.24	2	3	1	262	4
FA507257	440.17	2	3	1	131	4
FA507356	673.47	2	3	1	262	4
FA507380	1,461.1	3	3	1	131	6
FA507588	86,532.12	2	2	2	131	8
FA507596	28,119.53	1	2	2	131	4
FA510228	8,767.16	5	3	3	910	4
FA513255	7,703.82	5	3	3	2330	8
FA550679	1,549.00	1	2	1	262	2
FA552410	8,924.00	1	3	2	262	1
FA552626	3,960.00	2	4	2	262	2
FA552741	1,193.00	1	4	2	786	4
FA552824	5,818.00	1	4	2	262	4
FA552915	25,611.00	0	1	1	517	0
FD089139	12,493.00	8	1	3	262	6

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Determining γ

The fill rate, the probability that the on hand stock is greater than zero, will be denoted by γ and can be determined as follows:

$$\gamma_i(S_i, T_i) = \mathbb{P}\{OH_i > 0\} = \sum_{x=0}^{T_i} \mathbb{P}\{D(\ell_e) < S_i - x\} \frac{\left(\lambda_i \, \mathbb{E}[L_r^{\zeta}]\right)^x / x!}{\sum_{k=0}^{T_i} \left(\lambda_i \, \mathbb{E}[L_r^{\zeta}]\right)^k / k!}$$

Having the fill rates for all items, the aggregate fill rate, $\gamma(\mathbf{S}, \mathbf{T})$, can be determined as follows. Let Λ be the sum of all demand rates: $\Lambda = \sum_{i \in I} \lambda_i$.

$$\gamma(\mathbf{S}, \mathbf{T}) = \sum_{i \in I} \frac{\lambda_i}{\Lambda} \gamma_i(S_i, T_i)$$