MASTER

The design of a logistic support system

Kusters, R.A.M.

Award date:
2011

Eindhoven, October 2011

The Design of a Logistic Support System

by
Rik A.M. Kusters

Student identity number 0664541

in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

Supervisors:
dr.ir. R.J.I. Basten, TU/e, School of Industrial Engineering
prof.dr.ir. G.J. van Houtum, TU/e, School of Industrial Engineering
ir. J.J. Arts, TU/e, School of Industrial Engineering
ir. B. Huisman, NedTrain, Maintenance Development

TUE. School of Industrial Engineering.
Series Master Theses Operations Management and Logistics

Subject headings: Maintenance, Supply chain management, Line replaceable unit-definition, Level of repair analysis, Spare parts, Spare systems, Mixed integer programming

The Design of a Logistic Support System

The joint problem of Line Replaceable Unit definition, Level Of Repair Analysis and Spare Parts Stocking

Author
ing. R.A.M. Kusters
School of Industrial Engineering
Eindhoven University of Technology
r.a.m.kusters@student.tue.nl

No pains, no gains
If little labour, little are our gains:
Man's fortunes are according to his pains.
Robert Herrick (1591–1674)

Preface

The report you are about to read, is the result of my graduation project in completion of the Master Operation Management and Logistics at the School of Industrial Engineering, University of Technology Eindhoven. The graduation project is carried out at the Maintenance Development departement of NEDTRAIN B.V. established in Utrecht. I would not have achieved my current results of the project without the help of a group of people. Therefore, hereby I would like to express my sincere gratitude to them.

From University of Technology Eindhoven, I would like to thank Rob Basten, my first supervisor. During the project I got to know Rob as a passionate researcher, who challenged me but meanwhile was really helpful and a great person to talk to, which with some regularity resulted in meetings running out of time. I would also like to thank Geert-Jan van Houtum, my second supervisor, for providing directions during my Masters, and for his critical comments on the reports during the project. Finally I would like to thank Joachim Arts, my third supervisor, for providing insights on NEDTRAIN, his help on some of the mathematical problems, and for his useful comments on the reports during the project.

From NEDTRAIN I would like to thank Bob Huisman for enabling me to develop my own independent research, and for providing insights on all kinds of processes at NEDTRAIN. Hereby, Bob was a true source of inspiration with all the great practitioner-stories, and some short courses on algorithms. I would also like to thank Jan de Vries, who replaced Bob during his well deserved vacation, and connected me with the right people in order to conduct the business case. Furthermore, I would like to thank all employees from NEDTRAIN who contributed to the project by providing insights and data. Finally, I would like to thank all other interns from the maintenance development department, for their interest, and discussion on all kinds of topics during the coffee-breaks.

It is only three years ago that I started at the University of Technology Eindhoven. During these years I worked with a number of people on projects. Because of my busy (training)schedule, I guess that it was sometimes frustrating for them to work with me. Therefore, I would like to thank all of them for their flexibility and collaboration during these projects.

Since this project is the end of my life as a student, I would like to thank family and friends for their support during this period. Special thanks to my parents and sisters, who always showed intrest and provided support during my whole life such that I could pursue my goals.

Rik Kusters

Abstract

This Master thesis presents a model description and optimization procedure for the design of a logistic support system for capital goods. Given the high down-time costs of capital goods, in general they are *repaired by replacement*, meaning that upon failure a so-called *Line Replaceable Unit* (LRU) is replaced from the system by a spare part. The failed LRU is then repaired or discarded somewhere in the repair network. In the case that the LRU is repaired, this is done by replacing child components, which are called *Shop Repairable Units* (SRUs). It could be that repair capabilities such as repair-tools, test-tools and knowledge are required to repair LRUs and SRUs. In order to achieve a certain availability of the installed base, spare parts may be put on stock. Furthermore, spare system could be required to achieve the target availability. The decision which components to replace from the system upon failure is called the *LRU-definition*. The decision as whether to repair or discard components, and where to this in the repair network is called *Level Of Repair Analysis* (LORA). We propose a Mixed Integer Program (MIP) to solve the joint problem of LRU-definition and LORA. Furthermore, we extend the literature on spare parts stocking by measuring the *operational availability* and by making the number of spare systems a decision variable. We present an iterative optimization procedure to solve the joint problem of LRU-definition, LORA, and spare parts stocking integrally. Finally, we use our model to solve two business cases from NEDTRAIN and gain managerial insight on the design of a logistic support system.

Keywords Maintenance, Supply chain management, Line replaceable unit-definition, Level of repair analysis, Spare parts, Spare systems, Mixed integer programming.

Executive Summary

NEDTRAIN B.V. is a 100% subsidiary of the NS GROUP. The core business of NEDTRAIN is maintaining, cleaning and overhauling railway rolling stock in the Netherlands. Since 2005, the NS GROUP acquired two new train series, namely the Sprinter Light Train (SLT) and a high-speed train called the V250. Both train series are acquired from system integrators. Previous generation train series were designed in-house, and therefore the construction was aligned with the logistic support system of NEDTRAIN. The construction of previous generation trains was such that accessability of components was high. Thus, exchanging subsystems, such as bogies and modules was relatively fast. Hence, subsystems were defined as so-called Line Replaceable Units (LRUs), meaning that upon failure of the system a subsystem (LRU) was replaced by a spare part. Next, the failed subsystem is disassembled and the failed sub-components, the so-called Shop Repairable Units (SRUs), are repaired in the repair facility of NEDTRAIN.

The new train series acquired from system integrators have a different construction compared to previous generation trains maintained by NEDTRAIN. Therefore, NEDTRAIN is wondering whether it should adapts it logistic support system given the construction of a certain train series. The strategical decisions that service companies, such as NEDTRAIN are facing while designing their logistic support system are:

1. Whether a component should be defined as either, LRU, SRU, or structure part.
2. Where to execute the repair and maintenance process for the installed base within the repair network.
3. Where to place capabilities such as repair tools, testing tools and knowledge.
4. Whether a component should be repaired or discarded upon failure.

The tactical question that service companies, such as NEDTRAIN, are facing while designing the logistic support system is:

5. Where to place spare parts on stock and how many.

The five decisions summed up above and the ambition of NEDTRAIN to make decision from a life cycle cost perspective have led to the following problem definition:

How should the logistic support system of a service company, such as NEDTRAIN, be designed, in such a way that a certain target operational availability is satisfied and the life cycle costs are minimized?

In this thesis we present a model formulation capable of designing a logistic support system, hereby covering all five decisions. Decisions 2 till 4 are already covered in literature on *level of repair analysis* (LORA). In addition to the literature on LORA, we included the decision whether a component should be defined as either, LRU, SRU, or structure part (decision 1). The tactical question deals with where and how many spare parts to place on stock, and is extensively discussed in literature. However, in addition to the literature we introduce the possibility to install spare systems and measure the *operational availability*. The life cycle costs taken into account are: repair, transport, discard, capability, spare parts holding, and spare systems holding costs.

By using our optimization procedure, we solve two business cases from NEDTRAIN. The first business case concerns a high-speed train with 4 indenture levels, consisting out of more than 1,500 component, a target availability of 16 systems, and a serial three-echelon repair network. The data used in this first business case is from the V250 high-speed train operated by NS HISPEED. The second business case concerns a commuter train with 4 indenture levels, consisting out of more than 1,500 components, a target availability of 121 systems, and a divergent three-echelon repair network. The data used in the second business case is from the SLT commuter train operated by NS REIZIGERS, however a significant amount of data is taken from the V250 because not all data of the SLT is present yet. Besides, in some cases when data was present the lack of structure in this data made it hard to use it as input for the business case.

The results from the business cases indicate that the current paradigm to replace first indenture components upon failure of a system is far from optimal. Instead, the highest indenture components should be replaced, resulting in 54% lower costs. The cost reduction is realized by lower spare parts holding costs, because the highest indenture components are significantly cheaper than first indenture components. Furthermore, the results of the business cases show that a significant amount of components (about 37%) should be discarded upon failure. As a result, these components and their child-components do not have to be transported to the repair facility but instead are replaced by a new one at the first echelon. Regarding spare parts stocking and the installation of spare systems, the business cases show that taking into account the holding costs associated with them while performing an LRU-definition and LORA, on average results in 3.5% lower costs. Furthermore, by comparing the current settings regarding spare parts and spare systems of the V250 with our high-speed train business case, we show that potential savings of 40% on holding costs are possible by using our solution.

In summary our recommendations to NEDTRAIN are:

- Define deliverables regarding the supply of data to system integrators.
- Do not define the first indenture components as LRU, instead define the highest indenture components as LRU.
- For each LRU and SRU investigate whether it should be discarded.
- Use our method to solve the joint problem of LRU-definition, LORA, and spare parts stocking integrally, such that efficient solutions for the design of a logistic support system can be found within hours.

Contents

1 Introduction **1**
- 1.1 NedTrain . . . 2
- 1.2 Problem situation and motivation . . . 6
- 1.3 Problem definition . . . 8
- 1.4 Scope . . . 9
- 1.5 Outline of the thesis . . . 10

2 Literature review, research objective and questions **11**
- 2.1 Literature review . . . 11
- 2.2 Research objectives and questions . . . 16
- 2.3 Methodology . . . 17
- 2.4 Contribution . . . 18

3 Model description and notation **20**
- 3.1 Breakdown structure and failure behavior . . . 20
- 3.2 Line Replaceable Unit-definition . . . 21
- 3.3 Level Of Repair Analysis . . . 23
- 3.4 Spare parts stocking . . . 25
- 3.5 Cost factors . . . 26
- 3.6 Assumptions . . . 27

4 Optimization **28**
- 4.1 Line Replaceable Unit-definition and LORA . . . 28
- 4.2 Spare parts stocking . . . 30
- 4.3 Solving the joint problem iteratively . . . 36
- 4.4 Implementation and validation . . . 38

5 Business Case **40**
- 5.1 Current way of working at NEDTRAIN . . . 40
- 5.2 Non-economic LRU-definition LORA, and spare parts stocking . . . 41
- 5.3 Characteristics of NEDTRAIN . . . 42
- 5.4 Assumption validation . . . 47
- 5.5 Instance Generator . . . 48
- 5.6 Experiments . . . 52
- 5.7 Managerial insights . . . 63

6 Conclusion and recommendations **68**
6.1 Conclusions . . . 68
6.2 Recommendations . . . 69

A Notation **71**

B Linearization IP **73**

C Implementation EBO-curves using a double linked list **74**

D Characteristics distributions **76**

E Distributions fitting **78**

List of Figures

1.1 Business structure of NS GROUP . . . 2
1.2 Value Maintenance Concept . . . 4
1.3 Work in process NEDTRAIN . . . 5
1.4 Multi-indenture structure . . . 5
1.5 NEDTRAINs Service Supply Chain . . . 6
1.6 Pictures of the new train series . . . 7

2.1 Venn diagram literature . . . 16
2.2 Research model Mitroff . . . 17

3.1 Indenture structure . . . 20
3.2 Example Indenture structure . . . 23
3.3 LRU-structure . . . 23
3.4 Multi-echelon repair network . . . 24
3.5 Echelon levels aggregated . . . 24

4.1 Iterative procedure . . . 28
4.2 Multiple EBO-curves . . . 31
4.3 Multiple EBO-curves including lower envelope . . . 32
4.4 Multiple EBO-curves including convexification of lower envelope . . . 32
4.5 Two EBO-curves for two SRUs . . . 32
4.6 One EBO-curve for two SRUs . . . 33
4.7 Availability curve: Installed Base versus System Approach . . . 35

5.1 Histogram lead time suppliers . . . 44
5.2 Histogram lead time repair facility . . . 44
5.3 Histogram failure rate . . . 46
5.4 Computation time CPLEX, iterative procedure . . . 56
5.5 Computation time spare parts stocking problem, iterative procedure . . . 56
5.6 Availability curve: installed base approach high-speed train . . . 58
5.7 Availability curve: installed base approach commuter train . . . 61
5.8 LSAR common-source database . . . 64
5.9 Replacement time components as a function of the indenture level . . . 65

C.1 UML-diagram POINT and CURVE . . . 74
C.2 Double linked list . . . 75
C.3 Double linked list, after marginal analysis . . . 75

D.1 Histogram of component price per indenture level 76
D.2 Histogram of replacement times per indenture level 77

E.1 Distribution fit on component price first indenture 78
E.2 Distribution fit on the annual failure rate 79
E.3 Distribution fit on the fraction of repair costs divided by the new price 79
E.4 Distribution fit on the repair lead time 80
E.5 Distribution fit on lead time suppliers 80

List of Tables

3.1 Example calculation annual repair and replacement rate 23

4.1 CPLEX non-default parameters 39

5.1 Characteristics repair network: number of locations and shipment times 43
5.2 Breakdown structure: number of components per indenture level 45
5.3 Breakdown structure: Number of occurrences of a component 45
5.4 Component price per indenture level 46
5.5 Replacement times per indenture level 47
5.6 Deterministic parameters 48
5.7 Random parameters 49
5.8 Experimental settings: Varied parameters 49
5.9 Experiment scenarios 53
5.10 Best solution heuristic 1 versus heuristic 2 55
5.11 Best solution high-speed train logistic support system 56
5.12 LRU-definition and repair/discard decision high-speed train 57
5.13 Level of repair/discard high-speed train 58
5.14 Annual spare part stocking high-speed train 58
5.15 Best solution commuter train logistic support system 59
5.16 LRU-definition and repair/discard decision commuter train 60
5.17 Level of repair/discard commuter train 60
5.18 Spare part stocking commuter train 60

Chapter 1

Introduction

This Master thesis presents the results of a study that is performed at NEDTRAIN. NEDTRAIN is a maintenance company for rolling stock and is a subsidiary of the NS (the Netherlands Railways). NEDTRAIN is responsible for the maintenance of almost all passenger rolling stock in the Netherlands, which has the following main characteristics:

- High price: approximately €10 million for a commuter train and €20 million for a high speed train
- High downtime costs: when rolling stock is unavailable, while the customers of NEDTRAIN need it in their transportation process, significant costs are incurred, due to, for example rescheduling of fleet and staff, acquisition of other transport modalities, and redemptions to customers.
- Technical complexity: about 2,500 modules, components, and sub-components per train, of which a large number can be defined as high-tech (i.e. hydraulic, electronic and computerized)
- Long life cycle: about 25–35 years

Given these four characteristics, it is extremely important to NEDTRAIN to design the logistic support system such that the Life Cycle Costs (LCC) are minimized, while a certain availability requirement is met. In general, service companies define Service Level Agreements (SLA) in which the minimal availability of the installed base is contracted. In the case of NEDTRAIN, a SLA with its customers NS REIZIGERS (NSR) and NS HISPEED (NSH) states, that at least a certain amount of rolling stock needs to be available during the rush hours.

The four characteristics of the rolling stock maintained by NEDTRAIN, are applicable to most advanced capital goods. During their exploitation, capital goods such as MRI-scanners, airplanes, lithography machines, and trains, are subject to failure. Preventive maintenance is frequently used to keep the capital good in an operational state. Both preventive and corrective maintenance actions require resources such as facilities, tools, knowledge, and engineers. In addition, spare parts and spare systems are required in order to guarantee availability of the installed base. In this thesis, we will focus on the trade-offs present in maintenance organizations, such as NEDTRAIN, regarding replacing, repairing, purchasing, and stocking of maintenance significant components. We develop a mathematical model that represents these trade-offs, and which can be used by maintenance organizations, such as NEDTRAIN to minimize the LCC of the installed base.

This chapter gives an introduction to this Master thesis. It starts with a description of NEDTRAIN in Section 1.1, describing its business structure, the services provided by NEDTRAIN and a description of its service supply chain. Then, in Section 1.2, the problem situation and motivation behind this Master thesis is discussed. Based upon the problem situation, a problem definition is presented in Section 1.3. Next, in Section 1.4 the scope of this thesis project is defined, and in Section 1.5 the outline of this report is presented.

1.1 NedTrain

This Master thesis is the result of a project conducted at NEDTRAIN at the department MAINTENANCE DEVELOPMENT which is part of the business unit FLEET SERVICES. In this section, a company description of NEDTRAIN is presented.

1.1.1 Company description

NEDTRAIN B.V., headquartered in Utrecht, is a 100% subsidiary of the NS GROUP. NEDTRAIN has existed for more than 150 years, but operates under the name NEDTRAIN since 1999. The core business of NEDTRAIN is maintaining railway rolling stock in the Netherlands. In Figure 1.1 the business structure of the NS GROUP is depicted. The mission of the NS GROUP is: “transporting more passengers safely, punctually and comfortably via attractive stations” (NS, 2010). The segment Passenger services comprises domestic passenger services provided by NS REIZIGER (NSR), international and domestic passenger services provided by NS HISPEED, passenger services abroad provided by ABBELIO and rolling stock maintenance carried out by NEDTRAIN. NS FINANCIAL SERVICES LTD. (NSFSC), is the main supporting company of the

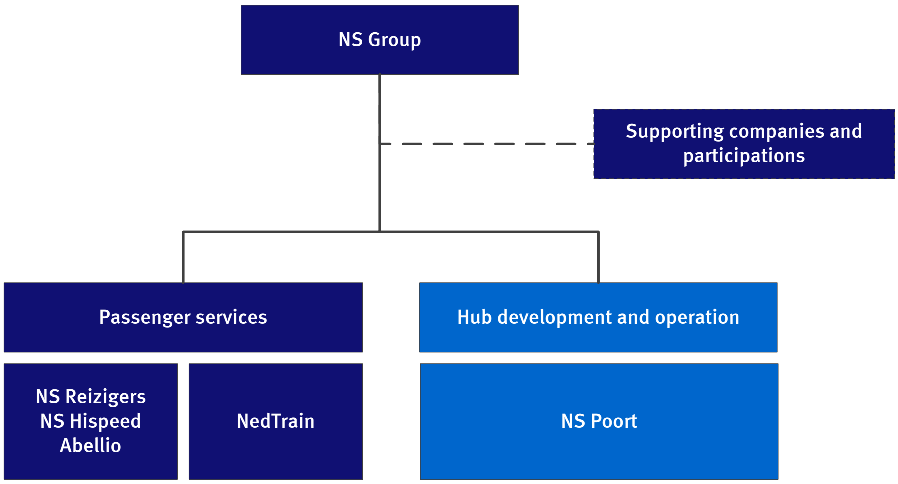


Figure 1.1: Business structure of NS GROUP (NS, 2010)

NS GROUP. It is the owner of most of the rolling stock that is used by NSR and maintained by NEDTRAIN. As the structure implies, the business units of the segment passenger services are working together intensively. However, every business unit operates on an individual basis (profit center) and each unit has its own objectives. NEDTRAIN also has external customers, which are not a member of the NS GROUP. Some key figures about NEDTRAIN are (Arts and Driessen, 2011):

- Number of full time employees: 3,400 FTE
- Turnover: €475 million/year
- Kilometric performance: 15,500 million/year
- Installed base: > 2,850 coaches (>250,000 seats)

1.1.2 Services

NEDTRAIN is responsible for maintaining, cleaning and revision of rolling stock. There are five types of services (maintenance actions) provided by NEDTRAIN:

First line service (24-48 hrs) On a daily basis, rolling stock is inspected, repaired, and cleaned.

Short cyclical periodic maintenance (2-3 months) Short cyclical periodic maintenance is carried out after a certain mileage or period of time. During short cyclical periodic maintenance, the focus is on checking and cleaning the components. These inspections ensure the safety, quality and reliability of rolling stock in line with the specific contractual agreements made with NEDTRAINs customers.

Long term maintenance (5 years) During long term maintenance, major alterations to train sets, interior upgrades, and overhauling or replacement of worn parts are executed.

Failures (failure-based) When a failure occurs during the usage of the rolling stock, the criticality of that part is considered. When a part is critical, the rolling stock is transported to a repair facility. In case of a part which is not critical, it is replaced during the next short cyclical periodic maintenance.

Damage repair (accident-based) After inspection of the damaged rolling stock, which is caused by an accident, NEDTRAIN estimates repair costs and advices customers on whether to repair the damaged rolling stock (either by NEDTRAIN or other parties) or to discard it. In case that the damage repair is performed by NEDTRAIN, the damaged train is transformed in the same condition as before the accident.

On a more conceptual level, the deliverables of NEDTRAIN are availability, capability and reliability of the rolling stock. Availability is expressed in the number of seats available, or in the percentage of fleet available to the customer. Availability is delivered by, or in other terms depending on, all services provided by NEDTRAIN. Capability can be defined as the tangible configuration provided by NEDTRAIN, which enables customers to provide services themselves. Capability is delivered mainly by long term maintenance, during this type of maintenance; modifications are made to the configuration. Reliability is the ability to perform the required functions when needed. In case of NEDTRAIN, reliability can be expressed as the percentage of time the planned operational fleet is performing the required functions when needed. The value of NEDTRAIN for its customers is equal to the cumulative value of these three deliverables. In Figure 1.2 the value of the maintenance concept of NEDTRAIN is depicted in a graph. The

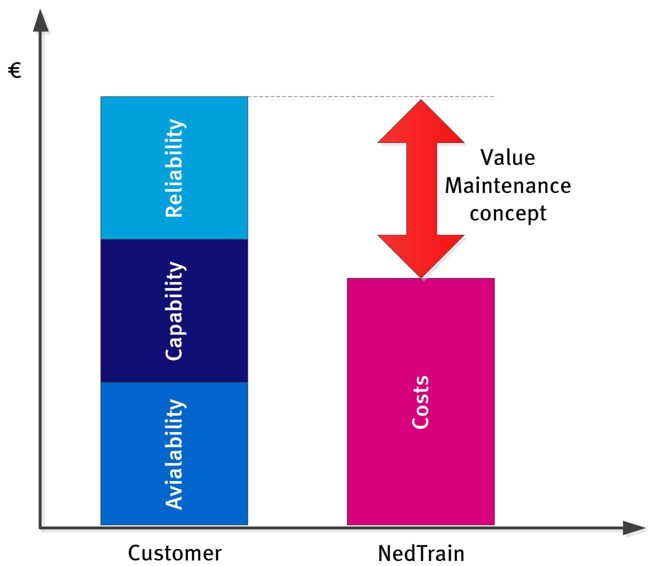


Figure 1.2: Value Maintenance Concept

value of the maintenance concept of NEDTRAIN, is equal to the difference between the value of the deliverables of NEDTRAIN from a customer perspective, and the costs made to realize these deliverables.

1.1.3 Objectives

According to the NS annual report of 2010 (NS, 2010), NEDTRAIN in cooperation with NSR and NS HISPEED should be able to produce overall savings of at least €50 million a year for the NS GROUP (no term is mentioned). The primary focus of NEDTRAIN over the next three years is to achieve operational excellence in its current activities. In other terms, the objective of NEDTRAIN is to increase the value of the maintenance concept. This can be achieved by increasing the value of the three deliverables (capability, reliability and availability). Or by bringing down the costs, obviously these two actions are not mutually exclusive. Of the three deliverables, the availability is within scope of this Master thesis. The most important performance indicator regarding the availability is the number of (un)available coaches. In Figure 1.3 the historical performance on unavailability, is represented by a graph. The objective of NEDTRAIN is that only 200 of the 2,850 coaches are unavailable, hence the target system availability is 93%.

1.1.4 Installed base

The installed base NEDTRAIN maintains, consist of 2,850 coaches. They can be characterized by a multi-indenture structure, as depicted in Figure 1.4a. The indenture level is the level in the system structure. Given the high downtime costs of capital goods, in general they are *repaired by replacement*. Meaning that a defective component is replaced by a component from stock, so that the capital good can be used again after a relatively simple replacement. The defective

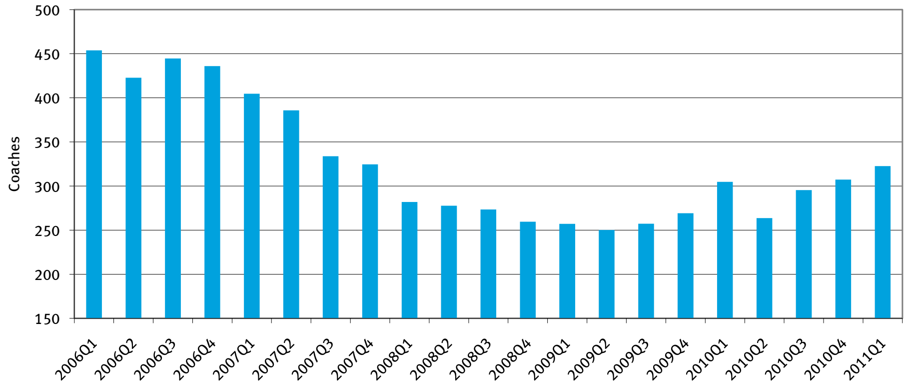
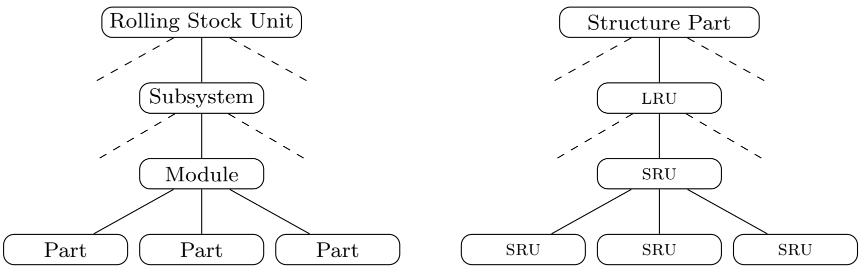


Figure 1.3: Work in process NEDTRAIN (number of coaches)



(a) Installed base NEDTRAIN

(b) LRU-definition

Figure 1.4: Multi-indenture structure

component is then repaired some where in the repair network. The parts which are exchanged during maintenance, are called Line Replaceable Units (LRU). The term LRU originates from the defense sector, the United States Department of Defense (1996, MIL-PRF-49506) provides the following definition: *An LRU is an essential support item which is removed and replaced at the field level to restore the end item to an operational ready condition. Conversely, a non-LRU is a part, component, or assembly used in the repair of an LRU, when the LRU has failed and has been removed from the end item for repair.* Muckstadt (1973) mentions the so-called Shop Repairable Units (SRUs). An SRU is a component or assembly which can be removed from the LRU and can be repaired in a repair shop. Hence, in terms of United States Department of Defense (1996) an SRU is a non-LRU. In addition, NEDTRAIN uses the term 'structure part' to identify parts that are neither LRU nor SRU. From Basten (2009) we know that this term is also used at THALES. Hence, we use the term structure part to indicate a part that is not prone to failure and furthermore is not replaced. In Figure 1.4b an example of an LRU-definition is presented using our naming convention.

1.1.5 Repair Network

The repair network of NEDTRAIN consists of four echelons. It is schematically depicted in Figure 1.5.

Echelon 1: Service Points (SB's) (Service Bedrijven in Dutch) are executing first line ser-

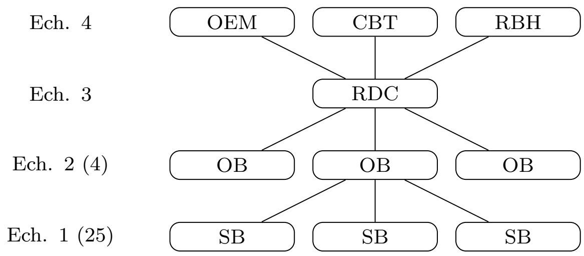


Figure 1.5: NEDTRAINs Service Supply Chain (number of locations)

vices, such as cleaning and direct repair of defective systems. Direct repair means that no components are replaced. Instead, components are repaired while still being mounted on the train (e.g. resetting a system). As a result no components need to be stocked at the SB's.

Echelon 2: Maintenance Companies (OB's) (Onderhouds Bedrijven in Dutch) at the maintenance companies, both preventive maintenance, such as short cyclical maintenance, and corrective maintenance are executed. Maintenance is performed using a repair by replacement strategy. At the OB's only LRUs are exchanged. Therefore only LRUs need to be stocked.

Echelon 3: Central Warehouse (RDC) (Regionaal Distributie Centrum in Dutch) a facility where LRUs and SRUs are kept on stock. The RDC is supplied by the various Original Equipment Manufactures (OEMs), a component repair shop from NEDTRAIN (CBT), and a revision company of NEDTRAIN (RBH).

Echelon 4: Component Repair Shop (CBT) (Componenten Bedrijf Tilburg in Dutch) repairs failed components, such as transformers and dampers.

Echelon 4: Revision Company (RBH) (Revisie Bedrijf Haarlem in Dutch) overhauls main components such as bogies and complete coaches.

1.2 Problem situation and motivation

Since 2005, the NS GROUP acquired two new train series, namely the Sprinter Light Train (SLT) which is a train used for commuter trajectories and a high speed train called the V250. In Figure 1.6 the SLT (a) and the V250 (b) are depicted. Both train series are acquired from system integrators, the SLT from the consortium BOMBARDIER & SIEMENS and the V250 from ANSALDOBREDA. Previous generation train series where designed in-house, and therefore the construction was aligned with the logistic support system of NEDTRAIN. Compared to rolling stock abroad, the design of previous generation rolling stock of NEDTRAIN deviates. The design of rolling stock maintained by NEDTRAIN was such that accessability of components was high. Thus, exchanging subsystems, such as bogies and modules was relatively fast. As a result, *both subsystems and their modules were defined as LRU, meaning that upon failure either the subsystem or the module could be replaced directly*[1]. The decision whether to replace the subsystem is made in the repair shop. In case that the failed system can be repaired by

[1] In the spare part literature the assumptions is made that the failure of a system is caused by one LRU only.

(a) SLT

(b) V250

Figure 1.6: Pictures of the new train series

replacing the module, the module becomes the LRU. When the failed component is not an offspring component of the module the entire subsystem is replaced.

Due to the fast exchange of components, there is less need to consolidate maintenance tasks. The advantage of this maintenance concept is that the lifetime of all components is fully exploited, because a component is not replaced due to a shorter lifetime of other components. Maintenance organizations abroad focus more on clustering maintenance activities since exchanging components is more time-consuming, because of the construction. Hence, the life-time of the components is only partially exploited. Further, there is a tendency to define subsystems as LRU, because multiple modules are in the same cluster.

As mentioned in Section 1.1.3, NEDTRAIN in cooperation with NSR and NS HISPEED should produce operational savings of at least €50 million per year. Therefore, NEDTRAIN is seeking models to asses whether its current configuration of the logistic support system can be improved. In addition, as a result from the acquisition of rolling stock from system integrators, the construction differs from previously in-house designed train series. Therefore NEDTRAIN is wondering how it should design their logistic support system, given a specific train series, and its construction. The design of a logistic support system is highly complex because of the interaction between decisions, the enormous solution space and the large set of costs. Therefore NEDTRAIN is seeking for a Decision Support System (DSS) which enables NEDTRAIN to minimize the LCC by designing the logistic support system, while meeting the SLA contracted with its customer. The decisions regarding the design of the logistic support system can be decomposed in strategic, tactical and operational decisions. Since the focus is on the design, only strategic and tactical decisions will be within scope. The strategical decisions that service companies, such as NEDTRAIN are facing while designing their logistic support system are:

1. **Whether a component should be defined as either, LRU, SRU, or structure part.**

2. **Where to execute the repair and maintenance process for the installed base within the repair network.** This repair network is fixed, and thus decisions to open or close facilities is not within scope of this decision. In the case of NEDTRAIN, the decision seems to be straightforward since NEDTRAIN already has a repair network which is capable of maintaining an installed base of 2,850 coaches. However, within this service network a certain degree of freedom exists on where to physically execute the repair and maintenance process.

3. **Where to place capabilities such as repair tools, testing tools and knowledge.** These resources which will be referred to as capabilities in the remainder of this report, enable certain repair actions and maintenance processes. These capabilities are capital intensive; therefore this strategic decision is crucial for service companies.

4. **Whether a component should be repaired or discarded upon failure.** In terms of NEDTRAIN, the decision is whether a component should be classified as consumable or repairable. This question is related to the previous two decisions (i.e. when a component is discarded upon failure no repair capabilities and repair facilities are needed).

The tactical question that service companies, such as NEDTRAIN, are facing while designing the logistic support system is:

5. **Where to place spare parts on stock and how many.**

Given the ambition of NEDTRAIN to make decisions from an LCC-perspective, NEDTRAIN is seeking for a DSS which addresses the stated strategic and tactical questions, and can be used to minimize the LCC, by (re)designing the logistic support system. In summary, the DSS should:

i Create awareness not only within NEDTRAIN, but within the entire NS GROUP such that the LCC of the fleet of the NS GROUP is minimized from an enterprise perspective.

ii Determine which parameters are most relevant while designing the logistic support system.

iii Optimize the logistic support system of NEDTRAIN, thereby improving the return on investment, which is the main objective of the NS GROUP.

1.3 Problem definition

The problem situation described in Section 1.2 leads to the following problem definition:

*How should the logistic support system of a service company, such as NEDTRAIN, be designed, in such a way that a certain target **operational availability** is satisfied and the **life cycle costs** are minimized?*

1.3.1 Operational availability

The operational availability is a constraint defined by the customers of NEDTRAIN, and it is defined in the SLA. In the case of the SLT the customer is NSR, and for the V250 the customer is NS HISPEED. The operational availability for both NSR and NS HISPEED is expressed in the number of passengers. This number is then converted to the number of trains which should be available. For the V250 the operational availability must at least be 16 trains, where there are 19 trains acquired by the NS HISPEED (i.e. one train is considered as work in process at NEDTRAIN, and the other two are used as standbys). For the SLT the operational availability must at least be 121 where 131 trains are acquired by the NSR.

1.3.2 Life cycle costs

The objective is to minimize the life cycle costs. The life cycle costs within scope are:

- Operational Expenses (OPEX)
  - Repair Expenses: material and labor costs associated with the repair of components
  - Transportation Expenses: cost of transporting components
  - Discarding Expenses: material costs for components which are discarded
- Capital Expenses (CAPEX)
  - Rolling Stock (including spare systems): the annual depreciation of the initial investment in systems
  - Spare parts: the annual depreciation of the initial investment in spare parts
  - Repair tools: the annual depreciation of the initial investment in repair tools
  - Testing tools: the annual depreciation of the initial investment in testing tools

Not all CAPEX are on the balance sheet of NEDTRAIN. The rolling stock is on the balance sheet of NSFSC, and some of the spare parts are on the balance sheet of NSR and NS HISPEED. Although not present on the balance sheets, we also take into account the investment in knowledge which is necessary to conduct replacement and repair of components.

1.4 Scope

The Master thesis is focused on the design of a logistic support system, given the construction of a system. Hence, we do not take into account constructional decisions. The design of a logistic support system is covered by the five decisions stated in Section 1.3. Hereby, the OPEX and CAPEX as defined in Section 1.3.2 are within scope.

From a maintenance perspective, both preventive and corrective maintenance are within scope. However, only maintenance using *repair by replacement* is within scope, thereby not taking into account direct repairs. In terms of NEDTRAIN, the short cyclical periodic maintenance and failure-based maintenance is within scope. The clustering of maintenance activities, which can be done in case of preventive maintenance, is out of scope. Furthermore, as is common in the service part literature, we assume uncapacitated repair capabilities. The reasoning behind these assumptions will be explained in Chapter 3.

From the perspective of NEDTRAIN, two train series are within scope, namely the SLT and the V250. The four echelon levels, out of which the repair network of NEDTRAIN exists are within scope, thereby the complete repair network of NEDTRAIN is within scope. Hereby, we aggregate on echelon level, and do not consider the locations individually, which is a strategic decision of NEDTRAIN to prevent internal competition.

1.5 Outline of the thesis

The remainder of this report is organized in the following way. In Chapter 2, we discuss the relevant literature and identify gaps within the literature. Furthermore, elaborating on these gaps, research questions and objectives are stated. In Chapter 3, the problem description for the joint problem of LRU-definition, LORA, and spare parts stocking and the corresponding notation will be discussed. Next, in Chapter 4 the optimization procedure to solve the joint problem is discussed. In Chapter 5, we discuss two business cases from NEDTRAIN, which we solve using our mathematical model and optimization procedure. Finally, in Chapter 6 we end the thesis with conclusions and recommendations.

Chapter 2

Literature review, research objective and questions

In section 1.2, we identified the following decisions regarding the design of a logistic support system:

(i) Whether a component should be defined as either, LRU, SRU, or structure part.

(ii) Whether to repair or discard upon failure

(iii) Where to install capabilities

(iv) Where to repair failed components

(v) Where to place spare parts and how many

Decision (i) is the called LRU-definition, representing the decision what components to replace from the system during maintenance. Decisions (ii)-(iv) are addressed in the literature on Level Of Repair Analysis (LORA). The final decision (v) is known in the literature as the spare parts stocking problem. In this chapter, first a literature review is presented in Section 2.1, where the subjects LRU-definition, LORA, and spare parts stocking are discussed. Within the literature review, gaps are identified between the needs present in practice and the literature. These gaps form the foundation of the research objective and questions, which are stated in Section 2.2. Then, in Section 2.3, the methodology which is used to solve the research questions is discussed, followed with a discussion on the contribution of this thesis to both literature and practice in Section 2.4.

2.1 Literature review

In this section we will discuss the three subjects mentioned above: LORA in Section 2.1.1, spare part stocking in Section 2.1.2, and finally the integral problem of LORA and spare parts stocking in Section 2.1.3. The LRU-definition is not addressed from an economical perspective in any literature we are aware of, and therefore is not further discussed in this section.

2.1.1 Level Of Repair Analysis

The LORA is typically performed in the design phase of a capital good, to get insight into the Life Cycle costs (LCC). However, it can also be performed after the design phase to further improve the logistic support system. LORA is an analytical methodology which addresses the following decisions: (i) whether a component should be repaired or discarded upon failure, (ii) where to repair a failed component (if it is repaired) and (iii) where to install capabilities such as test-equipment and tools. The objective of LORA is to minimize the LCC.

The first paper on LORA is by Barros (1998). She presents an Integer Programming (IP) formulation to solve multi-echelon, multi-indenture level problems. The model, which is also used by Barros and Riley (2001), includes fixed and variable costs. The fixed costs are independent of the number of failures (repairs and discards) whereas the variable costs increase with the number of failures. Fixed costs for discarding components are assumed to be zero, the variable cost for discarding a component are equal at all echelon levels. Variable costs are incurred on component level, while fixed costs are incurred on indenture level. This latter assumption is not valid for most real-life cases, because fixed cost are usually associated with one or multiple components, possibly at multiple indenture levels. Saranga and Dinesh Kumar (2006) present an IP formulation similar to Barros (1998). However, in the former model fixed costs are incurred at component level. Barros (1998) solves the LORA using a commercial solver (LINDO), Barros and Riley (2001) solve it using a branch and bound procedure, and Saranga and Dinesh Kumar (2006) solve it using genetic algorithms.

Basten et al. (2009c) generalize the two models formulating the LORA such that fewer restrictions on resource-component relation exist. Using a commercial solver (CPLEX), Basten et al. (2009c) show that large instances can be solved using their formulation. The use of metaheuristic as opted by Barros and Riley (2001) and Saranga and Dinesh Kumar (2006) becomes even more otiose, through the minimum cost flow model with side constraints as presented by Basten et al. (2011a). The minimum cost flow model is based upon the IP model from Basten et al. (2009c), however formulating it as a minimum cost flow model reduces computation time significantly (the minimum cost flow model is an IP in itself, however for the sake of simplicity we refer to it as minimum cost flow). Another advantage of the minimum cost flow formulation compared to the IP formulation is that it models the network exactly, where it is aggregated on echelon level in the case of the IP formulation. Basten et al. (2011a), show that costs can be reduced with up to 7% at maximum by modeling the exact network instead of the aggregated network in case of an unbalanced network. An unbalanced network can be defined as a network in which parents have a different number of children. In the case of a balanced network, modeling the exact network only reduces costs with 1.2% at maximum. Furthermore, Basten et al. (2011b) present practical extension to the minimum cost flow formulation of Basten et al. (2011a). The extension consist out of the probability of unsuccessful repair, the probability of no-fault found, finite resource capacities, multiple failure modes per component and the option of outsourcing repair.

Brick and Uchoa (2009) combine the capacitated facility location problem with the LORA problem. They assume a single-echelon repair network and two-indenture system structure. Where the repair network is modeled as an exact network. The combination of the facility location problem and the LORA is not relevant for us, so we will base our work on the model of Basten et al. (2009c).

2.1.2 Spare parts stocking problem

The spare parts stocking problem for capital goods is discussed in literature extensively. In this literature review, we discuss the so-called Multi-Echelon Techniques for Recoverable Item Control (METRIC) stream of literature on the spare parts stocking problem.

The paper by Sherbrooke (1968) on METRIC, is considered as the seminal paper on the spare parts stocking problem for capital goods. Sherbrooke (1968) presents a multi-item, single-indenture inventory model for a two-echelon system consisting of a number of operating sites and a central depot. The target of METRIC is to find the most cost effective allocation of spare parts in a network, such that a target availability of the installed base is achieved. Hereby, METRIC uses the number of expected backorders to approximate the availability. A backorder occurs when a spare part is requested but not available. When referring to availability in METRIC, the supply availability is meant: $\frac{\text{MTBM}}{\text{MTBM}+\text{MSD}}$, where MTBM is the mean time between maintenance and MSD is the mean supply delay. Since an LRU backorder at the operating sites results in an unavailable system, Sherbrooke (2004) defines the supply availability as follows:

$$A = 100 \prod_{c \in \omega} \left(1 - \frac{EBO_c(s_c)}{NZ_c}\right)^{Z_c} \tag{2.1}$$

where A is the availability expressed in percentage of time, ω is the set of LRUs, N is the number of systems, Z_c is the number of occurrences of LRU c in a system, and $EBO_c(s_c)$ is the number of expected backorders for LRU c given that s_c spare parts are put on stock.

As shown by Sherbrooke (2004, p. 40) maximizing the availability is approximately equivalent to minimizing the number of expected backorders. As a result of minimizing the number of expected backorders, the problem can be decomposed into subproblems per LRU. The subproblems are solved using the marginal approach, also known as the greedy procedure in the literature. Using marginal analysis, an EBO-curve of spare parts costs versus expected backorders is constructed. The idea behind marginal analysis is that the "biggest bang for the buck" is selected, when putting a spare part on stock at each iteration. Hence, at each iteration the decrease in backorders per holding costs is computed: $\frac{EBO_c(s_c-1)-EBO_c(s_c)}{hc_c}$, for all LRUs, and the highest marginal value is selected, were hc_c denotes the holding costs of component c. As soon as the expected number of backorders is such that the target availability is achieved, the construction of the EBO-curve is stopped. The marginal approach results in an EBO-curve with a convex set of efficient points. Because this EBO-curve is not a continuous function, the achieved availability in generally is somewhat higher than the target availability, which is called overshoot.

A key assumption of METRIC is that the failures at the operating sites follows a Poisson proces. Therefore, the demand at higher echelon levels also follows a Poisson process. Hence, the number of components in repair is Poisson distributed for the locations where repairs are performed, because leadtimes are i.i.d. and Palm's theorem. However, the number of backorders is not Poisson distributed, as a result of which the computation of the number of components in the pipeline becomes complicated. The components in the pipeline are the components that are sent to a higher echelon level for repair, and are not replaced by a functioning component yet. In METRIC (Sherbrooke, 1968) the number of components in resupply is approximated by a Poisson distribution. Muckstadt (1973) presents MOD-METRIC an extension of METRIC with multi-indenture formulation. The development of VARI-METRIC (Slay, 1980; Graves, 1985; Sherbrooke, 1986) results in a more accurate approximation, compared to METRIC and MOD-METRIC, due to a two-moment fit on the number of components in the pipeline, using a negative binomial distribution. The number of components in the pipeline can also be determined exactly (Graves, 1985; Rustenburg et al., 2003). However, computing the number of components in resupply is computational intensive, and furthermore the VARI-METRIC approximation leads to almost the same solution (Wong et al., 2007).

The optimization procedure for general cases with multi-item, multi-indenture, and multi-echelon settings is somewhat less discussed in literature. For a two-echelon, two-indenture setting Sherbrooke (2004) provides an optimization procedure. Muckstadt (2005, pp. 104–105) is the first to describe an optimization procedure for general cases, only assuming two-indentures. Furthermore, Basten et al. (2009b, appendix A) uses the idea from Muckstadt (2005) and explain it in a more extensive way, meanwhile allowing for a multi-indenture setting. In our model we use the optimization procedure of Basten et al. (2009b) which will be discussed in Section 4.2.1.

2.1.3 Integral problem

Alfredsson (1997) was the first to integrate the decision on where to repair and where and how many spare parts to put on stock. Alfredsson (1997) assumes a two-echelon network and single-indenture product structure. Repairing a certain component requires a specific tester, however also a multi-tester is available. These multi-testers can be used for different components and can be upgraded at additional cost to test more items. Alfredsson (1997) further assumes that components sharing the same tester are repaired at the same echelon level. The lead time consists of a constant transportation time, repair facility turnaround time, waiting time and test time. Alfredsson (1997) uses a M/M/s-queue (i.e. resources are capacitated) to determine the waiting times. The backorder probabilities are then computed using a METRIC approach. The LCC consists of operating costs, investment in spare parts and testers and upgrading costs of the multi-testers. Alfredsson (1997) decomposes the non-linear problem into sub-problems for which an efficient solution is obtained. Marginal analysis is used to determine the optimal stock quantities.

Basten et al. (2009b) present an optimal approach for the joint LORA and spare parts stocking problem. The model from Basten et al. (2009b) is based upon the LORA model from Basten et al. (2009c) and VARI-METRIC. Compared with Alfredsson (1997), the model from Basten et al. (2009b) allows for multi-indenture, and multi-echelon settings. Furthermore, the later model is less restrictive on the component resource relation. Similar to Alfredsson (1997), the optimal algorithm of Basten et al. (2009b) is based upon decomposition of the problem.

Basten et al. (2009a) present an iterative algorithm which is based upon the LORA model of Basten et al. (2009c), and VARI-METRIC. The model allows for a multi-echelon network and multi-indenture structure. The procedure of the iterative algorithm is, to first run the LORA without taking into account the holding costs. Next, given the repair/discard decision from the LORA, the spare parts stocking problem is solved using VARI-METRIC. The holding costs associated with the optimal stock quantities are then discounted to the variable costs used in the LORA. Then a second iteration is executed, as a result of the increased variable costs associated with the previously made repair/discard options, it is reasonable that other repair/discard options will be chosen. After the LORA, again a VARI-METRIC is executed. This iterative procedure is repeated until the stopping criterion is met. The costs obtained by the iterative procedure on average are 2.73% lower than the sequential approach (i.e. performing a LORA and VARI-METRIC sequentially and only one iteration) with a maximum of almost 35%.

The optimal algorithm from Basten et al. (2009b) provides an average cost reduction of 0.26% compared to the iterative algorithm from Basten et al. (2009a). Hence, the quality of the iterative algorithm (heuristic) from Basten et al. (2009a) is considered as good. Therefore, in our models we use the iterative procedure by Basten et al. (2009a) to solve the joint problem of LORA and spare parts stocking.

2.1.4 Conclusion

From the five decisions regarding the design of a logistic support system, as stated in the introduction of this chapter, four are discussed in the literature. Literature on LRU-definition is lacking, and in both literature on LORA and spare part stocking, implicitly the assumption is made that the LRUs are defined a-priori. Furthermore, the replacement time is not taken into account in both literature on LORA and spare parts stocking.

LORA is a relatively new topic in the literature. However, in the last years model formulations on LORA are developed which meet the requirements from practice. The IP formulation from Basten et al. (2009c) has the least number of restrictions regarding component-resource constraints. Basten et al. (2011a) present a minimum cost flow model with side constraints, based upon the IP formulation from Basten et al. (2009c). In addition to the IP formulation, the minimum cost flow model models the repair network exactly. Since there is no need to model the network exact (we aggregate on echelon level) and because extension of the IP is more straightforward, we opt for using the model formulation from Basten et al. (2009c).

A huge amount of literature exists on the spare parts stocking problem, initiated by METRIC. Furthermore, extensions of METRIC, such as MOD-METRIC and VARI-METRIC, resulted in an accurate and widely applicable spare parts stocking problem formulation. Therefore, we opt to use VARI-METRIC. The optimization procedure of Basten et al. (2009b) is used to solve the spare parts stocking problem.

We are aware of three papers that discuss the integral problem of LORA and spare parts stocking. The first paper on the integral problem is from Alfredsson (1997), however this model does not meet the requirement from practice. Both the optimal approach and iterative approach from Basten et al. (2009b) and Basten et al. (2009a) respectively, are based upon the LORA model from Basten et al. (2009c) and the spare parts stocking model VARI-METRIC. Since the iterative procedure is close to optimal and extension of the iterative procedure is more straightforward than the optimal approach, we opt for the use of the iterative procedure in our model.

2.2 Research objectives and questions

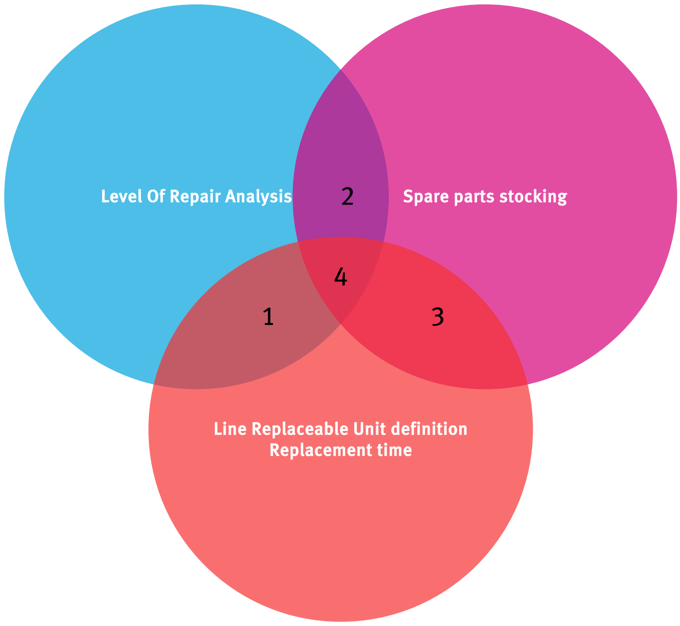


Figure 2.1: Venn diagram literature

Based upon the literature review, the gaps within the literature are identified. In Figure 2.1, a Venn diagram is depicted, containing three sets which represent the subjects of this Master thesis. Both LORA and the spare parts stocking problem are discussed in the literature, as well as the joint problem (subset 2) of these two subjects. The economical tradeoff in LRU-definition is not covered in the literature. As a result, subsets 1, 3, and 4 are also not covered in the literature. Hereby the gaps in the literature are identified, and correspondingly the research objectives in Section 2.2.1 and questions in Section 2.2.2 are stated.

2.2.1 Research objective

Based upon the business case and the gaps in the literature the following research objective is stated:

Develop a mathematical model that can be used by maintenance organizations, such as NEDTRAIN, to analyse and optimize the joint problem of line replaceable unit definition, level of repair analysis and spare part stocking.

2.2.2 Research questions

The first research question is already answered in the literature review discussed in Section 2.1:

1. **Which models are available in the literature on the joint problem of LRU-definition, level of repair analysis and spare parts stocking, which could be**

used by maintenance organizations, such as NEDTRAIN?

As discussed in the literature review, the literature does not take into account the replacement time. Furthermore the LRU-definition is not covered in the literature. Therefore the following research questions are defined:

2. **How can we extend the current models found in the literature, in such a way that the LRU-definition is incorporated into the joint problem of level of repair analysis and spare parts stocking?**

3. **How can we extend the current models found in the literature, in such a way that they take into account replacement times?**

The final research question aggregates previous questions. The ultimate goal is to be able to solve large instances with assumptions applicable to maintenance organizations such as NEDTRAIN.

4. **How can we incorporate LRU-definition, research question 2, and replacement time, research question 3, into the joint problem of level of repair analysis and spare parts stocking, and thereby design the logistic support system of a maintenance organization such as NEDTRAIN?**

2.3 Methodology

The research questions are answered while using the methodology of Mitroff et al. (1974). In Figure 2.2 the research model from Mitroff et al. (1974) is depicted. We explain our

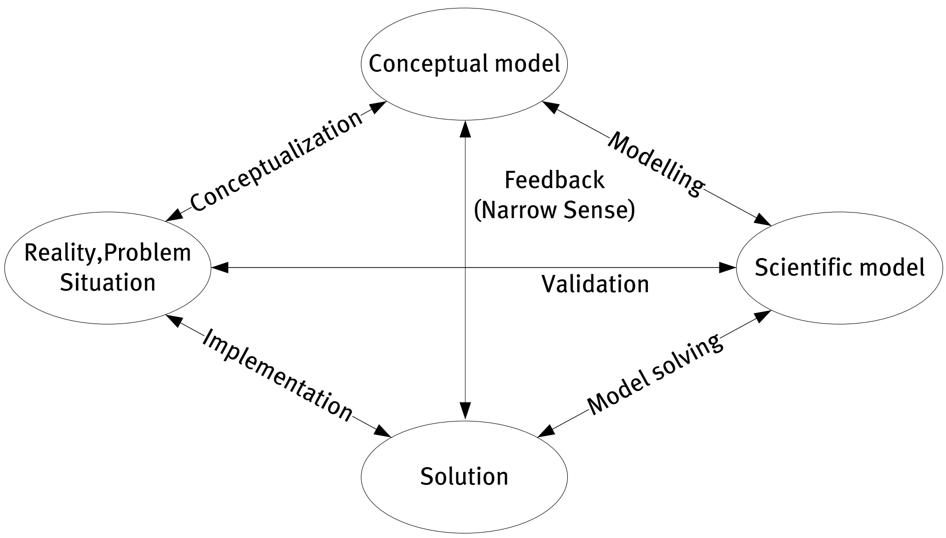


Figure 2.2: Research model Mitroff et al. (1974)

methodology using the four phases defined by Mitroff et al. (1974):

Conceptualization During the conceptualization phase, a conceptual model of the problem situation is made. The structure of the problem is identified and a decision on which aspects are relevant and irrelevant is taken. The conceptual model represents a further degree of abstraction from reality and will be capable of generating one or more scientific models (Sagasti, 1973). At the end of the conceptualization phase, research question 1 will be answered. Furthermore, the data required in the solution phase is gathered.

Modelling In the modelling phase the actual mathematical model is developed. This model will be partly based on existing models from literature, however extension are required in order to meet the research objective. The scientific model is a formalized representation of both reality and the conceptual model, and its correspondence to them is the most critical link of the Operation Research process (Sagasti, 1973). The modelling phase is the most extensive phase, afterwards research questions 2, 3, and 4 will be answered.

Model solving After modelling the conceptualized problem situation, the model can be used to solve instances. In our case, instances for NEDTRAIN will be solved, in order to gain managerial insights. Hence, also we validate our model solving these NEDTRAIN instances.

Implementation During the implementation phase, knowledge and managerial insights regarding the research questions will be reported and presented to various stakeholders.

2.4 Contribution

In the literature review, a number of gaps within the literature regarding the design of a logistic support system were identified. In this Master thesis, we will fill these gaps, and thereby contribute to the literature in the following way:

- Because no literature exists on the incorporation of the LRU-definition and the associated replacement time into LORA and the spare parts stocking problem, our model contributes to the economical trade-off present in defining LRUs.
- Our model contributes to the spare parts stocking literature by measuring the system availability in number of systems instead of percentage, and by measuring the operational availability instead of the supply availability.
- Furthermore, we contribute to the spare parts literature by making the number of systems installed a decision variable.

In summary the contribution of this Master thesis to the literature can be stated as follows:

- By integrating the LORA and spare parts stocking problem and incorporating both LRU-definition, replacement time, and spare systems, we introduce a trade-off in repair costs, replace costs, capability costs, spare parts costs, and spare system costs (while taking into account the replacement time).

The contribution of this Master thesis to maintenance organizations such as NEDTRAIN is as follows:

- Our mathematical model identifies all relevant decisions and associated costs concerning the design of a logistic support system. Thereby, providing structure in the decision making process of designing a logistic support system.

- As a result of our experiments, we gained new insights on which components to replace upon failure of a system.
- By conducting a sensitivity analysis, using our mathematical model, the relevant parameters for the design of a logistic system are identified. Furthermore, insights on the costs associated with parameters which are estimated incorrectly are gathered. As a result maintenance organizations such as NEDTRAIN, are able to asses the priority of gathering data to determine the parameters correctly.
- As a result of the incorporation of LRU-definition, we provide criteria for defining LRUs, SRUs, and structure parts.

The contribution of the Master thesis to NEDTRAIN can be described as follows:

- The managerial insights obtained by the high-speed and commuter train business cases can be used to design the logistic support system of the V250 and SLT.
- By showing the potential improvement by using our model, awareness is created within the NS GROUP.
- The implementation model built can be used as a prototype of a decision support system for designing logistic support systems.
- Main characteristics of both the repair network and installed based are determined. These characteristics can be used in all kinds of business cases.

Chapter 3

Model description and notation

In this chapter, the joint problem of LRU-definition, LORA, and spare parts stocking will be described and notation will be introduced. In Section 3.1 the breakdown structure and failure behavior of a capital good will be discussed. Next, in Section 3.2 the LRU-definition is described and explained using examples. The LORA is discussed in Section 3.3. Furthermore, the spare parts stocking problem and the relevant costs factors are discussed in Sections 3.4 and 3.5, respectively. This chapter ends with a summary of the most important model assumptions in Section 3.6.

3.1 Breakdown structure and failure behavior

In general, prior to the delivery of capital goods, system integrators provide a so-called breakdown structure. Based upon this breakdown structure, the maintenance organization of the capital good designs the logistic support system. A breakdown-structure is a Bill Of Material (BOM), containing all maintenance significant components $c \in C$ of the system (capital good). The system is denoted by $c = 0$ and the components by $c > 0$. The breakdown structure is a multi-indenture structure showing the parent-child relationship between components. Where a parent component is a holonymy of child components (i.e. the child components are parts of the parent component). Let $I = \{0, \dots, i_{\max}\}$ be the set of indenture levels of the indenture structure, with the system being at the lowest indenture level $i = 0$. In Figure 3.1 a multi-indenture structure is depicted. The components at indenture level i are denoted by $C_i \subset C$.

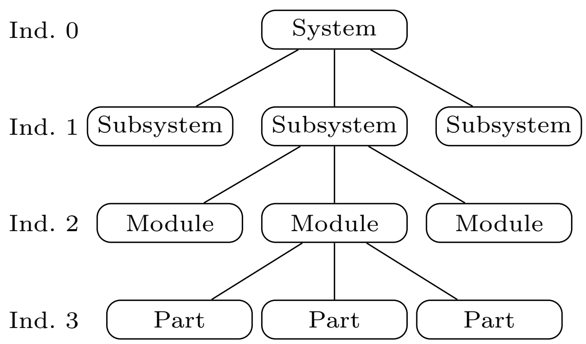


Figure 3.1: Indenture structure

We assume that each component has one unique parent, and thus we exclude the possibility of commonality. As a result, the indenture structure is a tree. The number of occurrences of component c in the system is denoted by $Z_c \geq 1$. The set of direct child components of a component c is denoted by Γ_c. At the highest indenture level ($i_{\max}$) this set is empty ($\Gamma_c = \emptyset$). The set of offspring components of a component c is denoted by Φ_c, obviously also this set is empty ($\Phi_c = \emptyset$) at the highest indenture level. Note that $\Gamma_c \subset \Phi_c$, and for all $c \in C_i$ with $i \geq i_{\max} - 1$ it holds that $\Gamma_c = \Phi_c$.

We assume that all components within the indenture structure (including the system itself) can fail, and that the failed components can always be isolated. Hence, we assume that a component can fail individually and cannot be repaired by replacing one of its offspring components. Failures occur according to a Poisson process, and the individual failure rate of the entire installed base for component c is denoted by $m_c \geq 0$. In the case that a component c is childless ($\Gamma_c = \emptyset$) the individual failure rate is greater than zero ($m_c > 0$), otherwise modeling this component does not make sense.

Remark 3.1 Assumption spare parts stocking
The assumption that components fail individually and thus cannot be repaired by replacing a child component deviates from the assumption made in the literature on spare parts stocking, e.g. VARI-METRIC. In VARI-METRIC it is assumed that a component with child components fails due to one of these child components . The conditional probability that a component c being repaired will result in a fault isolation of components $b \in \Gamma_c$, in VARI-METRIC, is denoted by $q_{c,b}$. In VARI-METRIC it is assumed that $\sum_{b \in \Gamma_c} q_{c,b} = 1$, because only components at the highest indenture level fail individually. Where under our assumption that components at all indenture level could fail individually, $\sum_{b \in \Gamma_c} q_{c,b} \leq 1$. ◇

3.2 Line Replaceable Unit-definition

We assume that a *repair by replacement* policy is used to maintain the system. This means that upon failure, a component is replaced by a spare part. The components replaced from the system are called Line Replaceable Units (LRUs). The failed LRUs can be repaired by replacing its failed sub-components, which are called Shop Repairable Units (SRUs). When a component fails individually it is repaired directly, without replacing offspring components. For each component, one of the following three possible LRU-definitions is made (i.e. mutually exclusive):

- LRU: component c is defined as Line Replaceable Unit: component c is replaced from the system when component c fails, or possibly when one of its offspring SRU components fails.
- SRU: component c is defined as Shop Repairable Unit: one of the ancestors of c is defined as LRU and c is replaced from its corresponding LRU or SRU parent upon failure.
- Structure Part: component c is not replaced or repaired, hence the individual failure rate should be zero ($m_c = 0$).

The LRU-definition is represented by defining $g \in G$ for all $c \in C$ where $G = \{$LRU, SRU, structure part$\}$. It is assumed that a component defined as structure part only has LRU children. Since failures may occur at multiple indenture levels, possibly component c is defined as LRU while one of its offspring components Φ_c is also defined as LRU. Note that we allow that the system itself can also be defined as LRU, since the system is also part of the indenture structure. We require the following decision variables for the LRU-definition:

$$Z_{c,g} = \begin{cases} 1 & \text{if for component } c \text{ definition } g \text{ is made;} \\ 0 & \text{otherwise.} \end{cases}$$

The set of components defined as LRU $\{c \in C \mid Z_{c,\text{LRU}=1}\}$ is denoted by ω.

Based upon the LRU-definition $Z_{c,g}$ and the individual annual failure rate m_c the annual replacement rate λ_c can be determined. The annual replacement rate is the rate with which a component is repaired by replacement, either as LRU or SRU. However, in the case that the component is the highest indenture SRU, it is repaired directly. The annual replacement rate for components defined as LRU or SRU can be computed recursively, starting with the components at the highest indenture level:

$$\lambda_c = m_c + \sum_{b \in \Gamma_c} \lambda_b \cdot Z_{b,\text{SRU}}, \ \forall c \in C \mid Z_{c,\text{LRU}} + Z_{c,\text{SRU}} \geq 1 \tag{3.1}$$

The intuition behind Equation 3.1 is that a component is replaced when failing individually (m_c), and furthermore is replaced when one of its SRU child components ($b \in \Gamma_c \mid Z_{b,\text{SRU}=1}$) fails ($\lambda_b$). Obviously, the annual replacement rate of structure parts is zero.

We further explain the relationship between the LRU-definition, the individual annual failure rate, the cumulative annual failure rate, and the annual replacement rate using Example 3.1.

Example 3.1 Replacement rate, two LRU-definitions
A system consists of eight relevant components spread at four indentures levels, as depicted in Figure 3.2. The individual annual failure rate m_c, the LRU-definition $Z_{c,\text{LRU}}$, and accordingly the annual replacement rate λ_c for these components are depicted in Table 3.1.

We distinguish two LRU-definitions, namely (a) and (b). As a result of the different LRU-definitions, the annual replacement rates (λ_c) for components B_2 and C differ. LRU-definition (a) is such that all components failing individually are defined as LRU. As a result the annual replacement rate for each component is equal to the the individual annual failure rate. LRU-definition (b) is such that all components on indenture level 1 are defined as LRU. As a result, upon failure of components $\Phi_{B_2} = \{C, D_1, D_2, D_3\}$, first component B_2 is replaced in case of LRU-definition (b). The annual replacement rate of component $B_2 = m_{B_2} + \lambda_C$, where $\lambda_C = m_C + \lambda_{D_1} + \lambda_{D_2} + \lambda_{D_3} = 1 + 1 + 3 + 1 = 6$ and thus $\lambda_{B_2} = 0 + 6 = 6$.

The indenture structure obtained by omitting the structure parts from the breakdown structure as a result from the LRU-definition, is called LRU-structure. In Figure 3.3 the LRU-structure for both LRU-definition (a) and (b) are depicted. In case of LRU-definition (a) both A and B_2 are omitted from the breakdowns structure because they are defined as structure parts. The remaining components are all defined as LRU, as a result the LRU-structure of LRU-definition (a) becomes single-indenture. In case of LRU-definition (b) only structure part A is omitted from the breakdown structure. ◇

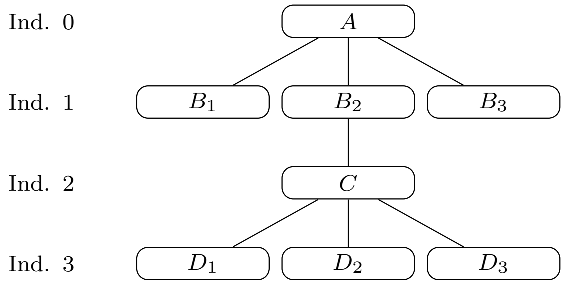


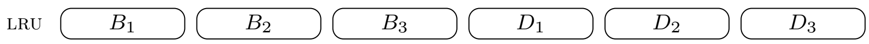
Figure 3.2: Example Indenture structure

Table 3.1: Example calculation annual replacement and repair rate for LRU-definitions (a) and (b)

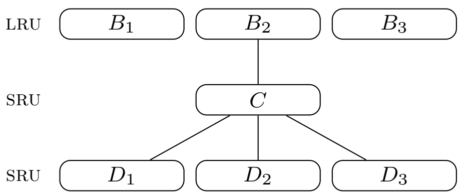
Component	m_c	(a) $Z_{c,\text{LRU}}$	(b) $Z_{c,\text{LRU}}$	(a) $Z_{c,\text{SRU}}$	(b) $Z_{c,\text{SRU}}$	(a) λ_c	(b) λ_c
A	0	0	0	0	0	0	0
B_1	1	1	1	0	0	1	1
B_2	0	0	1	0	0	**0**	**6**
B_3	2	1	1	0	0	2	2
C	1	1	0	0	1	**1**	**6**
D_1	1	1	0	0	1	1	1
D_2	3	1	0	0	1	3	3
D_3	1	1	0	0	1	1	1

3.3 Level Of Repair Analysis

We consider a multi-echelon repair network, such as depicted in Figure 3.4. Let $E = \{1, \ldots, e_{\max}\}$ be the set of echelon levels in the repair network, with the operating sites being at the lowest echelon level $e = 1$ and the Original Equipment Manufacturer (OEM) being at the highest echelon level, $e_{\max}$. The locations are denoted by $l \in L$, where $l \in L_e$ denotes the location(s) at echelon level e. The set of child locations of location l is denoted by $m \in \Pi_l$. Furthermore, the set of operating sites supplied by location l, either directly or via offspring locations is denotes by $m \in \Theta_l$. It is assumed that the repair network is symmetric, meaning that all locations at a certain echelon level have the same number of child locations and iden-



(a) LRU-definition (a)



(b) LRU-definition (b)

Figure 3.3: LRU-structure

tical demand processes. Furthermore, it is assumed that the repair network is fixed, and thus no possibility to open or close locations exist.

In general, maintenance organizations use uniform decisions regarding LORA for locations on the same echelon level. The most important reason is that the locations at a certain echelon level have the same characteristics, in particular the same demand intensities. In addition, making decisions on echelon level instead of location level, is a well founded choice because it prevents unwanted internal competition between locations at the same echelon level. Since maintenance organizations use uniform decisions for locations at the same echelon level, we aggregate the LORA decisions on echelon level. In Figure 3.5 an aggregated repair network is depicted.

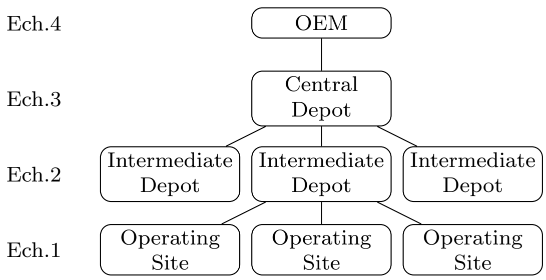


Figure 3.4: Multi-echelon repair network

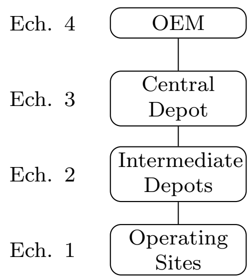


Figure 3.5: Echelon levels aggregated

The total number of systems installed at the operating sites is denoted by T. The number of systems installed at a operating site $l \in L_1$ is denoted by T_l. Upon failure of a system, the LRU associated with the failure is exchanged at one of the operating sites. Note, that the annual replacement rate and thus the arrival rate at the operating sites depends on the LRU-definition. The assumption is made that replacing LRUs is not clustered, and thus exchange of LRUs is performed sequentially.

The replaced LRU is repaired by replacing its failed SRU somewhere in the repair network or is discarded. When the LRU is repaired by replacing its failed SRU, also this SRU can be either repaired or discarded. The replacement lead time associated with replacing an LRU at the operating sites is denoted by $K_c \geq 0$. Both the replacement lead time and repair lead time are i.i.d. random variables and include the time to isolate the failure. The probability of successful repair is assumed to be 100%. Furthermore, it is assumed that failed components are only moved stream-upwards (i.e. from echelon level e to echelon level $e+1$). Possibly, LRUs and SRUs are discarded upon failure, as a result a new component should be acquired. The replenishment lead times associated with discarding components are i.i.d. random variables. In summary, upon exchange of a component, one of three possible decisions $d \in D$ can be made:

- Discard: component c is scrapped and a new one is acquired.
- Repair: component c is repaired at echelon e by replacing its defective child $b \in \Gamma_c$ with an operating one (or by repairing c directly). Again, one of the possible decisions $d \in D$ should be made for component b at the same echelon level e.

- Move: component c is moved to echelon level $e+1$. At echelon level $e+1$, a decision needs to be taken. Note that the 'move' option does not exist at the highest echelon level ($e_{\max}$).

The set D_e consist of all decisions available at echelon e. For all $e \in E$ with $e \neq e_{\max}$: $D_e = D = \{\text{discard, repair, move}\}$. Furthermore, $D_{e_{\max}} = \{\text{discard, repair}\}$. We define:

$$X_{c,e,d} = \begin{cases} 1 & \text{if for component } c \in C \text{ at echelon } e \in E \text{ decision } d \in D \text{ is taken;} \\ 0 & \text{otherwise.} \end{cases}$$

The capabilities that are required to replace or repair components are defined by $r \in R$. The capabilities are assumed to be uncapacitated. The set maintenance tasks is denoted by $j \in J$, where $J = \{\text{repair,replace}\}$. Let Ω_r be the set of tuples (c, j), such that $(c, j) \in \Omega_r$ if and only if component $c \in C$ requires capabilities $r \in R$ in order to perform maintenance task $j \in J$. We define:

$$Y_{r,e} = \begin{cases} 1 & \text{if capability } r \in R \text{ is installed at echelon level } e \in E\text{;} \\ 0 & \text{otherwise.} \end{cases}$$

3.4 Spare parts stocking

In order to satisfy the average target availability of T systems, both components defined as LRU or SRU may be put on stock (stocking structure parts is useless since no demand to these components exist). We assume that a continuous review, one-for-one replenishment $(S-1,S)$ base stock policy is used at all locations. Furthermore, at the operating sites spare systems can be put on stock, such that upon failure of a system, a spare system becomes operational and replaces the failed system (cold-redundancy). The assumption is made that the demand rate is independent of the number of spare systems acquired. We introduce the decision variable $S_{c,l}$ which is defined as follows:

$$S_{c,l} = \text{the number of spare parts/systems of component } c \in C\text{, located at location } l \in L.$$

Remember that components (spare parts) are represented by $c > 0$ and (spare) systems are denoted by $c = 0$. The number of backorders at location $l \in L_1$ as a function of the number of spare parts/systems is denoted by $BO_{c,l}(S_{c,l})$ and correspondingly the expected number of backorders is denoted by $EBO_{c,l}(S_{c,l})$. The operational availability in number of systems at location $l \in L_1$ is denoted by $\hat{A}_l$, and the operational availability in number of systems of the entire installed base $\hat{A}$ is the weighted average of the availabilities at the operating sites (based on the number of systems installed):

$$\hat{A} = \sum_{l \in L_1} \frac{T_l}{T} \cdot \hat{A}_l \tag{3.2}$$

Given the decision where to repair or discard components, the relevant locations to stock spare parts can be determined. We assume that a component is always repaired or discarded at one echelon level only. As a result, for some components the demand at some locations will be zero. When, for example, a component is replaced at location l^e, and repaired/discarded at location l^r, then there will be one path between these locations, and only stocking the component at that path, including locations l^e and l^r is relevant (Basten et al., 2009b).

The annual replacement rate and thus the demand to spare parts depends on the LRU-definition and LORA decisions made. The assumption is made that demand of LRUs at the operating sites is spread over the operating sites based on the number of systems installed at a location. Hence, the annual replacement rate for LRUs at the operating sites is:

$$\lambda_{c,l} = \frac{T_l}{T} \cdot \lambda_c,\ \forall c \in \omega,\ \forall l \in L_1 \tag{3.3}$$

The demand arising out of the exchange of LRUs to LRUs at the higher echelon levels $e \in E = \{2 \ldots e_{max}\}$ is calculated recursively starting at the second echelon level:

$$\lambda_{c,l} = \sum_{m \in \Pi_l} \lambda_{c,m} \cdot \sum_{d \in D} X_{c,e,d},\ \forall c \in \omega,\ \forall l \in L_e \mid e \geq 2 \tag{3.4}$$

The demand arising out of the exchange of LRUs to SRUs throughout the repair network, also depends on the repair decisions made in the LORA and is equally spread over the locations based upon the annual replacement rate at the corresponding operating sites:

$$\lambda_{b,l} = \frac{\sum_{m \in \Theta_l} \lambda_{c,m}}{\lambda_c} \cdot \lambda_b \cdot \sum_{d \in D} X_{c,e,d},\ \forall b \in \Phi_c \mid c \in \omega,\ \forall l \in L \tag{3.5}$$

As a result of the symmetry in the annual replacement rate at location level, maximizing the target average availability T of the entire installed base implies maximizing the target average availability T_l at the operating sites $l \in L_1$.

3.5 Cost factors

Our objective is to minimize the LCC of the installed base while meeting the target average availability of T operational systems. The LCC consist of four costs types:

- Variable cost $vc_{c,e,d} > 0$ which are incurred when taking decision $d \in D$ for component $c \in C$ at echelon level $e \in E$. The variable costs represent, for example, the labor and material cost to repair components, the transport costs to move components, and the costs to acquire a new component.

- Fixed cost $fc_{r,e} > 0$ for installing resource $r \in R$ at echelon level $e \in E$. The fixed costs represent, for example, the costs associated with the investment in knowledge and tools to be able to repair components.

- Replacement cost $rc_c > 0$ which are incurred when component $c \in C$ is replaced (i.e. when component $c \in C$ is defined as LRU). The replacement costs represent, for example, the labor costs associated with replacing a component.

- Spare parts and system holding cost $hc_{c,l} > 0$, which are incurred when putting a part or system $c \in C$ on stock at location $l \in L$. The holding costs represent, for example, the investment in spare parts and spare systems and the costs associated with the risk and space required to stock them.

3.6 Assumptions

In summary the most important assumptions are:

- Components have one unique parent, thereby excluding the possibility of commonality.
- Components fail according to a Poisson process with constant rate.
- It is possible that a component fails while no subcomponent fails.
- Components are repaired by replacement, and the repairs are performed sequentially (i.e. no clustering) and are always successful.
- Failed components are only moved stream-upwards (i.e. from echelon level e to echelon level $e + 1$).
- The replacement and repair times are i.i.d. random variables and include the time to isolate the failure.
- The replacement and repair capabilities are uncapacitated.
- A continuous review, one-for-one replenishment ($S - 1$,S) base stock policy is used at all locations.
- The spare systems are cold-redundant, hence the demand rate is independent of the number of spare systems installed.

Chapter 4

Optimization

In the previous chapter the problem description and notation of the joint problem of LRU-definition, LORA, and spare parts stocking is discussed. In this chapter we discuss how this problem can be solved. The joint problem cannot be solved as an integral problem because of non-linear spare parts stocking constraints. Therefore, we decompose it into two subproblems. The first subproblem is the joint problem of LRU-definition and LORA, which we discuss in Section 4.1. After solving the first subproblem, the spare parts stocking problem is solved, which we discuss in Section 4.2. Next, the output of the second subproblem is used to get an improved solution from the first problem; and so on. In Figure 4.1 the resulting iterative procedure is schematically depicted. The idea behind this procedure, based upon Basten et al. (2009a), is that by iteratively solving the two subproblems and providing holding costs estimates to the LRU-definition and LORA subproblem, the problem is integrally solved. In Section 4.3 the iterative procedure is discussed in more detail.

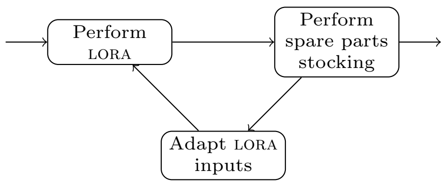


Figure 4.1: Iterative procedure (from: Basten, 2009)

4.1 Line Replaceable Unit-definition and LORA

The joint problem of LRU-definition and LORA is formulated as an Mixed Integer Program (MIP) and can be solved using a commercial MIP solver, e.g. CPLEX. The LORA formulation we use is from Basten et al. (2009c), however in addition to their formulation we incorporate the LRU-definition. In Section 4.1.1 the model formulation of the LRU-definition and LORA is presented.

4.1.1 Model formulation

The mathematical model of the integral problem of LRU-definition and LORA is defined as follows:

$$\min \sum_{c\in C}\sum_{e\in E}\sum_{d\in D} vc_{c,e,d}\cdot\lambda_c\cdot X_{c,e,d} + \sum_{r\in R}\sum_{e\in E} fc_{r,e}\cdot Y_{r,e} + \sum_{c\in C} rc_c\cdot\lambda_c\cdot Z_{c,\text{LRU}} \tag{4.1}$$

subject to:

$$Z_{c,\text{LRU}} + Z_{c,\text{SRU}} = 1,\ \forall c\in C \mid m_c > 0 \tag{4.2}$$

$$Z_{c,\text{LRU}} + Z_{c,\text{SRU}} \leq 1,\ \forall c\in C \tag{4.3}$$

$$Z_{b,\text{SRU}} \leq Z_{c,\text{LRU}} + Z_{c,\text{SRU}},\ \forall c\in C,\ \forall b\in\Gamma_c \tag{4.4}$$

$$Z_{c,\text{SRU}} = 0,\ \forall c\in C_0 \tag{4.5}$$

$$m_c \leq Z_{c,\text{LRU}}\cdot\lambda_c + Z_{c,\text{SRU}}\cdot\lambda_c,\ \forall c\in C \tag{4.6}$$

$$\lambda_c = m_c + \sum_{b\in\Gamma_c}\lambda_b\cdot Z_{b,\text{SRU}},\ \forall c\in C \tag{4.7}$$

$$\sum_{d\in D} X_{c,1,d} \geq Z_{c,\text{LRU}},\ \forall c\in C \tag{4.8}$$

$$X_{c,e,\text{move}} = \sum_{d\in D_{e+1}} X_{c,e+1,d},\ \forall c\in C_1,\ \forall e\in E\setminus e_{max} \tag{4.9}$$

$$X_{c,1,\text{repair}} = \sum_{d\in D_1} X_{b,1,d},\ \forall c\in C|\Gamma_c\neq\emptyset,\ \forall b\in\Gamma_c \tag{4.10}$$

$$X_{c,e+1,\text{repair}} + X_{b,e,\text{move}} = \sum_{d\in D_{e+1}} X_{b,e+1,d},\ \forall c\in C|\Gamma_c\neq\emptyset,\ \forall b\in\Gamma_c,\ \forall e\in E\setminus e_{\max} \tag{4.11}$$

$$X_{c,e,d} \leq Y_{r,e}, \forall r\in R,\ \forall(c,\text{repair})\in\Omega_r,\ \forall e\in E \tag{4.12}$$

$$Z_{c,\text{LRU}} \leq Y_{r,1},\ \forall r\in R,\ \forall(c,\text{replace})\in\Omega_r \tag{4.13}$$

$$X_{c,e,d}, Y_{r,e,d}, Z_{c,\text{LRU}}, Z_{c,\text{SRU}} \in\{0,1\},\ \forall c\in C,\ \forall e\in E,\ \forall d\in D,\ \forall r\in R \tag{4.14}$$

The objective function minimizes the annual sum of variable, fixed, and replacement costs. The first and third term of the objective function and Equation 4.6 are non-linear, because of the LRU-definition. However, these terms can be linearized by adding two variables and some constraints as shown in Appendix B. For the sake of readability we omit the required additional notation in this section.

Constraints (4.2)-(4.6) represent the LRU-definition. Constraint 4.2 guarantees that each component failing individually is defined as either LRU or SRU. Constraint 4.3 ensures that components are defined as either LRU or SRU. In the case that a child component $b\in\Gamma_c$ is defined as SRU, Constraint 4.4 assures that its parent component c is either defined as LRU or SRU.

Constraint 4.5 assures that the system itself can only be defined as either LRU or structure part. If component $c \in C$ fails individually ($m_c > 0$), Constraint 4.6 assures that component $c \in C$ is either defined as LRU or SRU. Constraint 4.7 defines the repair and replacement rate.

The LORA is represented by Constraints (4.8)-(4.13). Constraint 4.8 guarantees that a decision $d \in D$ is made for a component when it is defined as LRU. Constraint 4.9 assures that when moving a component from echelon level e, a decision is taken for that component at the next higher echelon level $e + 1$. Constraint 4.10 assures that when repairing component $c \in C$ at echelon level 1, also a decision for its child component(s) is taken at echelon level 1. Constraint 4.11 assures that a repair decision is taken for component b when its is either moved from a lower echelon level, or in case that its parent component c is repaired at the same echelon level. Constraint 4.12 and 4.13 assure that the required capabilities are installed for the corresponding repair and replacement maintenance actions respectively.

4.2 Spare parts stocking

In Section 3.4 the model description and notation of the spare parts stocking problem has been discussed. Given the decisions made by the LRU-definition and LORA we solve the spare parts stocking problem using VARI-METRIC. The decisions from the LRU-definition and LORA are made on echelon level. In contrast, the decisions regarding the spare parts stocking are made on location level. The exact network is used because we want to take into account the pooling effect. Assuming that the repair network is divergent, stocking components at a higher echelon level pools the variance of the demand at the various locations at the lower echelon level. When not modeling the exact network, but instead aggregating on echelon level, the repair network is modeled as a serial network and all locations at one echelon level are represented by a single location. Hence, by aggregating on echelon level demand is pooled while in reality this is not the case because of a divergent repair network with multiple operating sites.

Since VARI-METRIC is extensively explained in the literature (e.g Sherbrooke, 2004; Muckstadt, 2005), in this section we will focus on the extensions required to mathematically represent the model description. The solution procedure we use to solve VARI-METRIC is the marginal approach as presented by Basten et al. (2009b), which we discuss for the sake of self-containedness in Section 4.2.1. The first extension required to VARI-METRIC is the incorporation of replacement time, which we discuss in Section 4.2.2.1. Compared to the system approach from VARI-METRIC, which determines where and how many spare parts to put on stock, our approach also determines the number of systems to be installed. Therefore, we call our spare parts stocking problem the installed base approach. In Section 4.2.2.2 we present our installed base approach.

4.2.1 Marginal analysis

The target of VARI-METRIC is to find the most cost effective allocation of spare parts in a network, such that a target availability of the installed base is achieved. As explained in Section 2.1.2, maximizing the availability is approximately equivalent to minimizing the sum of EBOs from LRUs at the operating sites (see, e.g., Sherbrooke, 2004, pp. 33–40). Marginal analysis is used to produce a convex trade-off curve of spares investment costs versus expected LRU backorders at the operating sites, the so-called EBO-curves. In this section, for the sake of self containedness, we present the explanation of the marginal analysis based on Basten et al. (2009b):

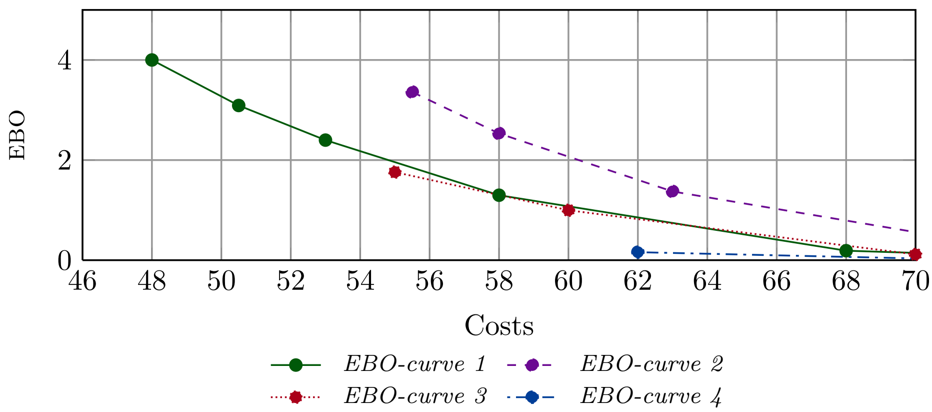


Figure 4.2: Multiple EBO-curves (Basten et al., 2009b)

As a result of minimizing the sum of LRU backorders, the problem can be decomposed in subproblems per LRU family, where an LRU family is an LRU including its offspring. The construction of an EBO-curve for a single component works as follows. We start with an initial stock (usually zero), from which spare parts are added one-by-one. Hereby, a spare part is added to stock at the location that yields the highest reduction of total expected backorders at the operating sites. In case of multi-echelon, we first construct an EBO-curve for the highest echelon level. Then, for each number of spare parts at the highest echelon level, spare parts are added at the next lower echelon level, resulting in multiple EBO-curves, as depicted in Figure 4.2. Now, the lower envelope of the resulting curves should be determined and all non-convex points should be removed, so that one convex EBO-curve remains. The lower envelope of a set of functions $f_i(x)$ is the function $f(x)$ given by their pointwise minimum $f(x) = \min_i f_i(x)$. In Figure 4.3 the lower enveloppe of a number of EBO-curves is depicted, and Figure 4.4 shows the convexification of the lower envelope. In the case of a multi-indenture system, first for each component on the highest indenture level an EBO-curve is constructed. These curves are then merged using marginal analysis, where points of the individual curve are concurrently added to the overall curve. The criteria used is the ratio of decrease in expected backorders as experienced by the parent component to increase in costs. Because, all individual EBO-curves are convexified, the overall EBO-curve is convex too. After that, for each LRU family an EBO-curve is constructed, again marginal analysis is used to merge these curves. Hence, we obtain a single EBO-curve which represents the optimal backorder level for a certain investment. In Figure 4.5 as an example two EBO-curves are depicted and Figure 4.6 shows the results of applying marginal analysis.

4.2.2 Extensions

In this section the extensions on the spare parts stocking required to represent the model description from Section 3.1 will be presented. First in Section 4.2.2.1 the incorporation of replacement times into the spare parts stocking problem is discussed. Next, in Section 4.2.2.2 our installed base approach is discussed.

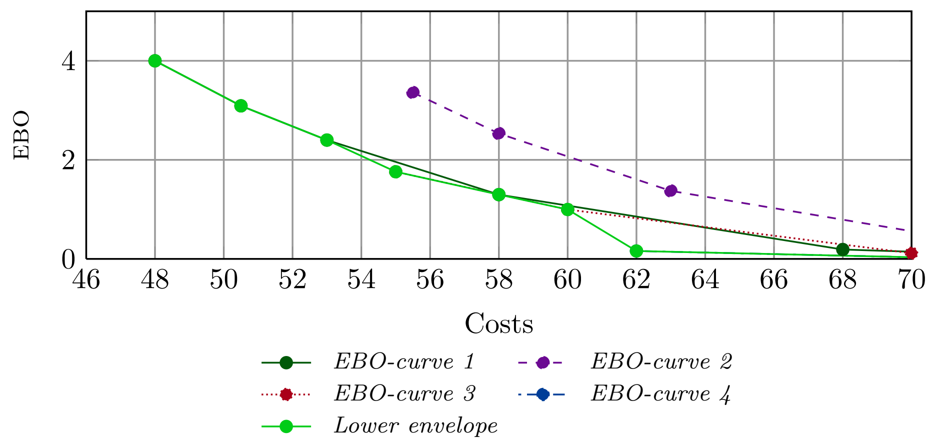


Figure 4.3: Multiple EBO-curves including lower envelope (Basten et al., 2009b)

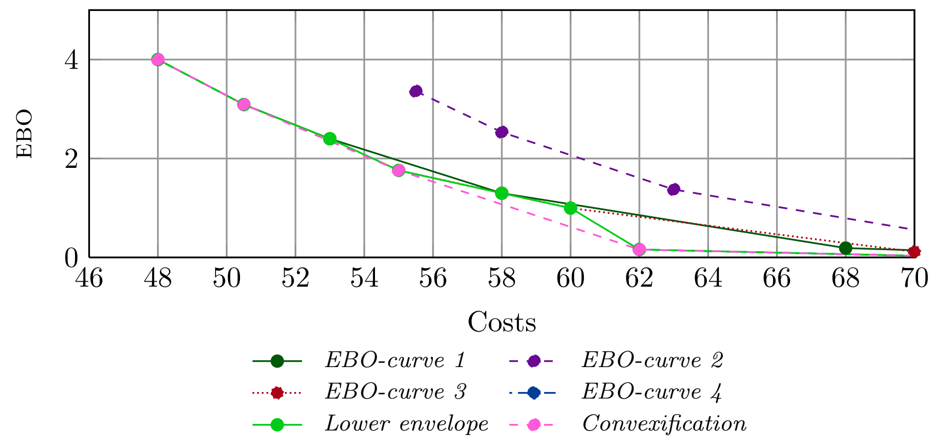


Figure 4.4: Multiple EBO-curves including convexification of lower envelope (Basten et al., 2009b)

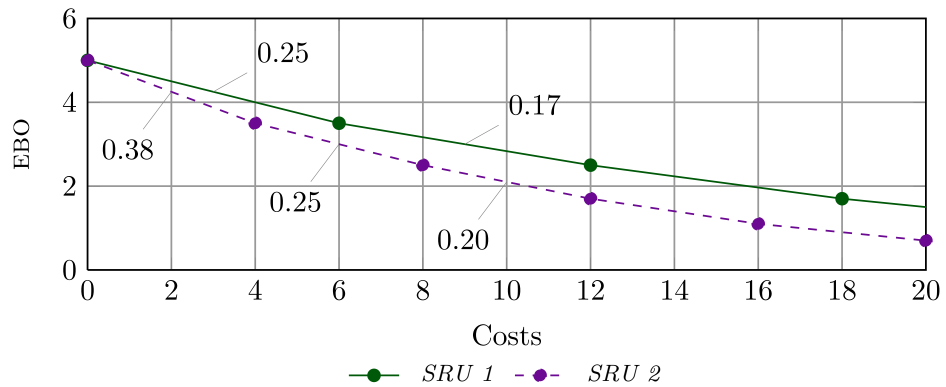


Figure 4.5: Two EBO-curves for two SRUs: a number next to the line segment shows the EBO reduction per dollar (Basten et al., 2009b)

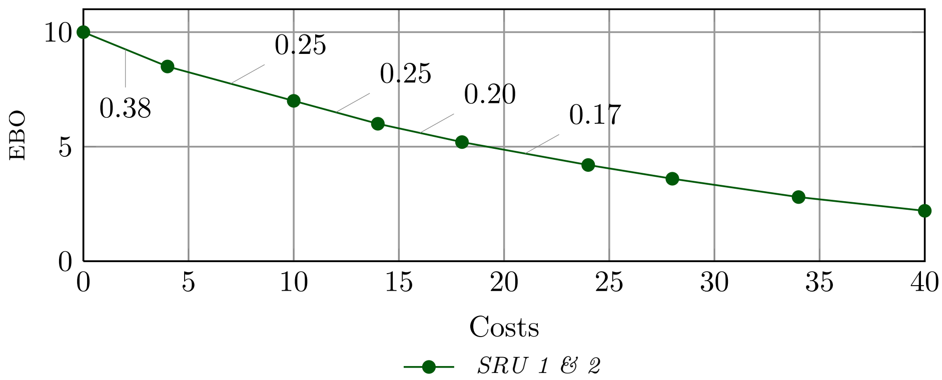


Figure 4.6: One EBO-curve for two SRUs: a number next to the line segment shows the EBO reduction per dollar (Basten et al., 2009b)

4.2.2.1 Replacement time

The objective of VARI-METRIC is to maximize the supply availability: $100 \cdot \frac{\text{MTBM}}{\text{MTBM+MSD}}$, where MTBM is the mean time between maintenance and MSD is the mean supply delay. The supply availability A_l at the operating sites $l \in L_1$ can be calculated as follows:

$$A_l(S_{c,l}) = 100 \cdot \left(\prod_{c \in \omega} \left(1 - \frac{EBO_{c,l}(S_{c,l})}{T_l Z_c} \right)^{Z_c} \right) \tag{4.15}$$

Obviously $A(S_{c,l}) = 0$ when $EBO_{c,l}(S_{c,l}) > T_l \cdot Z_c$ for any $c \in \omega$. In the remainder of this report we omit the location index l in the availability function $A(S_{c,l})$ for notational convenience.

Remark 4.1 Concavity of $A(S_c)$ in S_c for any $c > 0$
As a result of the convexification of the EBO-curves in the marginal analysis, we observed in our experiments that $A(S_c)$ is concave in S_c for any $c > 0$. Therefore, we know that the availability increase per dollar becomes smaller at each subsequent point on the availability curve $A(S_c)$ for $c > 0$.

In contrast to VARI-METRIC, our objective is to maximize the operational availability: $100 \cdot \frac{\text{MTBM}}{\text{MTBM+MSD+MRT}}$, where MRT is the mean replacement time. Compared to VARI-METRIC, we consider not only the time waiting for spares, but also the replacement time (see Research Questions 2). Remember from Section 3.3 that replacing LRUs is not clustered, and thus exchange of LRUs is assumed to be performed sequentially. Hence, we state the operational availability as follows:

$$A(S_c) = 100 \cdot \left(\left(\prod_{c \in \omega} \left(1 - \frac{EBO_c(S_c)}{T Z_c} \right)^{Z_c} \right) - \frac{\sum_{c \in \omega} K_c \lambda_c}{T} \right) \tag{4.16}$$

Instead of focusing on the percentage availability, many maintenance organizations define operational availabilities in number of systems. The operational availability expressed in number of systems $\hat{A}$ can be calculated as follows:

$$\hat{A}(S_c) = T \cdot \left(\prod_{c \in \omega} \left(1 - \frac{EBO_c(S_c)}{T Z_c} \right)^{Z_c} \right) - \sum_{c \in \omega} K_c \lambda_c \tag{4.17}$$

As a consequence of the addition of the replacement time, it is possible that a target availability of T systems cannot be achieved by putting more spare parts on stock. Availabilities close to T are required in practice. Therefore, we introduce the option to install spare systems, where the number of spare systems is denoted by S_0. As a consequence of the addition of spare systems, target mean availabilities of T systems can be satisfied. The availability expressed in number of systems, can now be expressed as follows:

$$\hat{A}(S_c) = (T + S_0) \cdot \left(\prod_{c \in \omega} \left(1 - \frac{EBO_c(S_c)}{(T + S_0) Z_c} \right)^{Z_c} \right) - \sum_{c \in \omega} K_c \lambda_c \tag{4.18}$$

where S_0 is the number of spare systems put on stock. The intuition behind Equation 4.18 is that the expected number of backorders $EBO_c(S_c)$ is independent of the number of spare systems, and that the expected number of backorders are spread over $T + S_0$ (spare) systems with equal probability. Note that this is an approximation, because of the probability that the number of failed systems is higher than the number of spare systems. However, the approximation error will be very small, since the sum of expected backorders $\sum_{c \in \omega} EBO_c$ is relatively low at the points we are interested in (i.e. $\hat{A} = T$).

The probability that the target availability is satisfied can be approximated by fitting a distribution to the expected backorders and the variance of backorders (see for example de Smidt-Destombes et al., 2010), the number of systems in repair, and the number of spare system:

$$P\left(\hat{A} \geq T \mid S_c\right) \approx P\left(\sum_{c \in \omega} BO_c + \lambda_c \cdot K_c \leq S_0 \mid S_c\right) \tag{4.19}$$

However, as indicated this is a approximation, due to the probability that multiple backorders are associated with one system.

Remark 4.2 Convexity of $A(S_c)$ in S_c for $c = 0$
From numerical analysis we know that $A(S_0)$ is convex and increasing in S_0. Therefore, we know that the availability increase per dollar becomes larger at each subsequent point on the availability curve $A(S_0)$.

4.2.2.2 Installed Base Approach

In the previous section we introduced the term spare systems. In addition to the number of spare systems required due to the replacement time, it could be that acquiring a spare system results in a higher availability increase per invested capital, than acquiring a spare part. Hence, we introduce the term installed base approach, which refers to our approach which in addition to the system approach from VARI-METRIC, also has degree of freedom on the number of systems which should be acquired ($T + S_0$).

The main idea behind the installed base approach is that the availability-increase per dollar of putting spare parts on stock ($\Delta_{S_c} \forall c \in C \setminus 0$) are compared with the availability-increase per dollar of installing a spare system (Δ_{S_0}). We know that once the availability-increase per dollar of putting spares on stock is lower than the availability-increase per dollar of putting a spare system on stock, from that point on it is always more cost efficient to put a spare

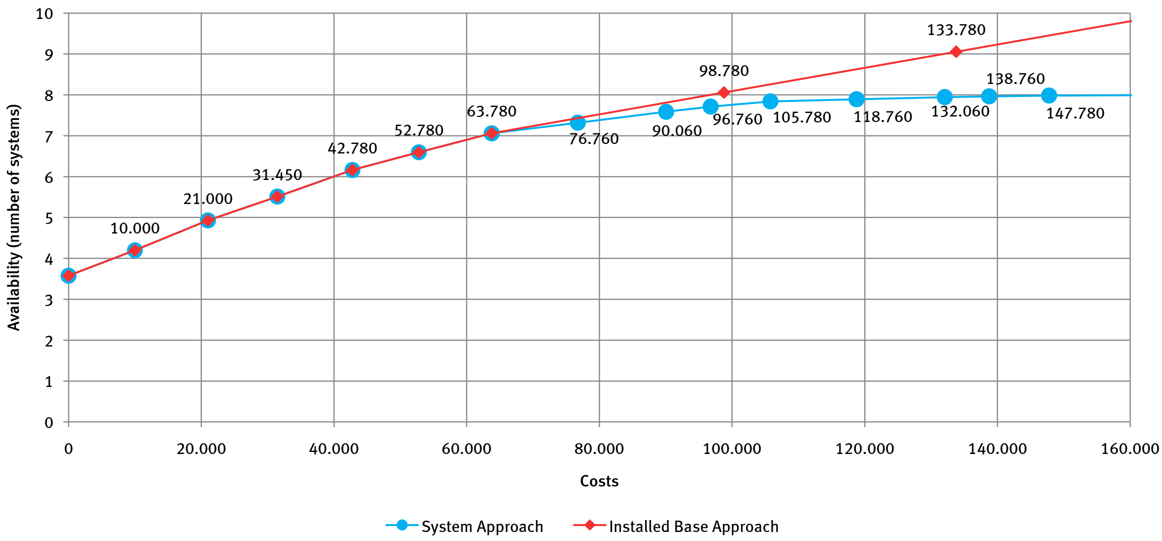


Figure 4.7: Availability curve: Installed Base versus System Approach

system on stock. Hence, when $\Delta_{S_0} > \Delta_{S_c}$ for all $c \in \omega$, the installed base approach instals spare systems.

In Figure 4.7 the availability curves for both the system approach and the installed base approach are depicted. To the point with which cost of 63.780 are associated, both the system and installed base approach obtain the same availabilities. However, because the availability-increase per dollar of the efficient points from the system approach availability curve becomes smaller than the availability-increase per dollar of installing spare systems, afterwards better solutions are obtained by the installed base approach. In this case, for example, the costs associated with an availability of 8 systems costs 98.780 when using an installed base approach and 132.060 ($A = 7,99$) when using a system approach. Hence, in this case using the installed base approach leads to a cost reduction of 25.2% compared to using the system approach.

When the target availability is indeed 8 systems, there is a significant overshoot when using the installed base approach. In general the overshoot of the installed base approach is larger then using the system approach, since typically installing systems becomes efficient close to the target availability. Furthermore, the availability increase associated with installing spare systems is close to one. Therefore, when the overshoot of the optimal solution obtained by the installed base approach is large, this overshoot can be reduced by repeating the whole optimization procedure while using initial spare system quantities equal to the optimal solution obtained before. Sherbrooke (2004) discusses a similar approach for instances where the overshoot obtained by the system approach is large, due to stocking expensive components at the last iteration of the marginal approach.

Remark 4.3 Installed base approach
When constructing an availability curve using marginal analysis, we obtain a curve with efficient points $p \in P = \{1, \ldots, q, \ldots, |P|\}$. From the point q that installing a spare system yields a higher availability per dollar increase compared to putting a spare part on stock, for each subsequent point installing a spare system will always yield a higher availability. This

follows directly from our observation that $A(S_c)$ is concave and increasing in S_c for $c > 0$ (Remark 4.1), and that $A(S_c)$ is convex and increasing in S_0 (Remark 4.2).

4.3 Solving the joint problem iteratively

In Sections 4.1 and 4.2, we discussed the LRU-definition and LORA subproblem and the spare parts stocking subproblem, respectively. In practice, the two subproblems are solved sequentially. Meaning that first the LRU-definition is made then given the LRU-definition the LORA is performed, and finally given the LRU-definition and the LORA decisions the spare parts stocking problem is solved. Hence, the sequential procedure used in practice consists of three steps. Given that we solve the joint problem of LRU-definition and LORA as an integral problem, our sequential procedure consists of two steps.

In addition to the sequential procedure, in this section we present an iterative procedure that is based on the iterative procedure of Basten et al. (2009a). The idea behind the iterative procedure is that first the LRU-definition and LORA building block is solved. Next, given the LRU-definition and LORA decisions the spare parts stocking problem is solved. Afterwards, using a feedback loop spare part costs estimates are fed back to the LRU-definition and LORA. As a result, while conducting the LRU-definition and LORA for the second time, the spare part costs are taken into account and the problem is implicitly solved jointly. This procedure is continued until the spare part costs estimates are accurate enough or until no better solution is found anymore. The algorithm used to solve the joint problem of LRU-definition, LORA, and spare part stocking iteratively consists of the following parts:

- The LRU-definition and LORA building block, discussed in Section 4.1.
- The spare parts building block VARI-METRIC, discussed in Section 4.2.
- A feedback loop.
- The stopping criteria.

We propose two heuristics, both heuristics use the same LRU-definition, LORA, and VARI-METRIC building blocks. However, the feedback loops used by them are different. In Section 4.3.1 we present the first heuristic, and in Section 4.3.2 we present the second heuristic. The stopping criteria is discussed in Section 4.3.3.

4.3.1 Heuristic 1

The basic idea of the feedback loop used in heuristic 1 is that the costs obtained by solving the spare parts stocking problem can be decomposed into costs resulting from the LRU-definition and costs resulting from the LORA. The logic behind this decomposition is, that the number of spare systems required (and thus the spare system cost) are mainly determined by the LRU-definition as a result of the replacement time associated with this definition. Therefore, the spare system costs are fed back to the replacement costs. Furthermore, since the repair/discard decision made by the LORA mainly determine the spare parts required, the spare part holding costs are fed back to the variable costs.

Given the annual replacement time obtained by solving the LRU-definition and LORA, a lower bound on the number of spare systems, $S_{0,l}^{\text{LB}}$ is calculated in the spare part stocking problem. The lower bound on the number of spare system is: $S_0^{\text{LB}} \geq \lceil \sum_{c \in C} \lambda_{c,l} K_c \rceil$. Furthermore, as a result of our installed base approach, it is possible that more spare systems than the lower bound are installed. Because, only components defined as LRU result in replacement time, the spare system costs are decomposed to these LRUs. At the end of iteration j, we set the replacement costs feedback variable $rc_{c,j}^s$ for which $Z_{c,\text{LRU}} \cdot \lambda_c > 0$ to $rc_{c,j}^s = \frac{\sum_{l \in L} hc_{0,l} S_0}{\sum_{c \in C} \lambda_c}$. By iteratively updating the replacement costs the spare system costs, as a result of defining a component as LRU are taken into account by means of the estimates provided by $rc_{c,j}^s$.

As proposed by Basten et al. (2009a), the spare part costs are fed back to the variable cost of the LORA. The idea is that as a result of this feedback loop the spare part costs are taken into account when performing the LORA. Thus, the feedback variable $vc_{c,e,d,j}^s$ represents an estimate of the spare part costs associated with taking decision d for component c at echelon level e. After each iteration j we set the variable cost feedback variable $vc_{c,e,d,j}^s$ for each tuple (c, e, d) with $d \in$ {repair,discard} for which $X_{c,e,d} > 0$ $X_{c,e,d} > 0$: $vc_{c,e,d,j}^s = \frac{\sum_{l \in L_e} hc_{c,l} S_c}{\lambda_c}$. For all other repair and discard decisions, we set $vc_{c,e,d,j}^s = vc_{c,e,d,j-1}$.

4.3.2 Heuristic 2

Compared to heuristic 1, heuristic 2 already takes into account the required number of spare systems in the LRU-definition and LORA. Therefore, the system costs associated with the lower bound on the number of systems: $\sum_{l \in L} s_{0,l}^{\text{LB}} \cdot hc_{0,l}$ are added to the objective function in the LRU-definition and LORA building block.

After performing the LRU-definition and LORA, the spare part stocking problem is solved. The resulting spare part costs obtained by solving the spare parts stocking problem are fed back to the variable cost of the LORA. Also the spare parts system costs associated with the systems installed on top of the lower bound are fed back to the variable cost of LORA. The reasoning behind this mechanism, is that the spare systems in addition to the lower bound are installed because it is more efficient compared to spare parts. Therefore, we consider them as spare part costs.

After each iteration j we set the variable cost feedback variable $vc_{c,e,d,j}^s$ for each tuple (c, e, d) with $d \in$ {repair,discard} for which $X_{c,e,d} > 0$ and $X_{c,e,d} > 0$: $vc_{c,e,d,j} = \frac{\sum_{c \in \omega} \sum_{l \in L_e} hc_{c,l} S_c}{\lambda_c} + \frac{\sum_{l \in L_e} hc_{0,l} (s_{0,l}^* - s_{0,l}^{\text{LB}})}{\sum_{c \in \omega} \sum_{l \in L} \lambda_{c,l}}$, where s_0^* is the optimal number of spare systems installed (based upon the installed base approach). For all other repair and discard decisions, we set $vc_{c,e,d,j}^s = vc_{c,e,d,j-1}$.

The stopping criterion used is discussed in Section 4.4.

4.3.3 Stopping criterion

We use the same stop criterion as Basten et al. (2009a). For the sake of self-containdness, we will discuss it briefly in this section. In the stopping criterion the following two conditions should both be satisfied:

1. After each iteration, we store the solution if it is better than the best we have found thus far. We may stop our algorithm if we did not find a better solution during j_1 iterations.
2. In each iteration, we update the spare parts holding costs estimates that we add to the replacement costs in the LRU-definition inputs and to the variable costs in the LORA inputs. We assume that these estimates are accurate enough if the total spares parts holding costs that is part of the LRU-definition and LORA solution ($rc^s_{c,e,d,j} \cdot \lambda_c \cdot Z_{c,g} + vc^s_{c,e,d,j} \cdot \lambda_c \cdot X_{c,e,d}$) deviates less than p% from the spare parts holding costs that is calculated in the spare parts stocking problem after the LRU-definition and LORA are solved ($\sum_{c \in C} \sum_{l \in L} hc_c \cdot S_{c,l}$). We may stop calculations j_2 iterations afterwards.

We choose $j_1 = j_2 = 10$ and $p = 1\%$ because Basten et al. (2009a) empirically found that these values result in a good stop criterion.

4.4 Implementation and validation

All models and algorithms discussed in this chapter are implemented, tested, and validated. Given the large size of the implementation models, in this section we will only discuss the most essential and crucial elements of it. In Section 4.4.1 the implementation of the LRU-definition and LORA mathematical model as presented in Section 4.1 is discussed. Next, in Section 4.4.2 the data structure used to solve the spare part stocking problem as presented in Section 4.2 is discussed. Furthermore, in Section 4.4.3 the implementation of the integral problem is discussed. The validation of the implementation models is discussed in Section 4.4.4. Finally, a discussion on the extension of our implementation model to a more comprehensive DSS is held in Section 4.4.5.

4.4.1 LRU-definition and LORA

The LRU-definition and LORA are implemented in CPLEX 12.2, using the callable library in C++. The main reasons for using the CPLEX solver are that the problem is NP-hard (e.g. see Basten et al., 2009c) and therefore a powerful solver is needed. Furthermore, within the NS GROUP licences of CPLEX are available. To be able to solve large instances, instead of using the default CPLEX parameters values the parameters are set according to Table 4.1. The Integrated Development Environment (IDE) used is Microsoft Visual 2010 Ultimate, however the tool set used to compile the code originates from Microsoft Visual 2008[1].

4.4.2 Spare parts problem

The spare parts stocking problem is programmed in C++, again the IDE used is Microsoft Visual 2010 Ultimate. The implementation model is programmed such that it is capable of solving large instances (e.g. our business case, see Chapter 5). Our implementation algorithm is based upon the marginal analysis as discussed in Section 4.2.1. The EBO-curves from the marginal analysis are represented by double linked lists in the implementation model. The data-points constructed in the linked list only contain a minimal amount of data. Otherwise, it would be impossible to solve large instances in a 32-bits Windows environment where the maximum RAM allocated to the algorithm is 2 Gb. In Appendix C an UML-diagram and the corresponding double linked list are depicted together with an explanation.

[1] CPLEX 12.2 is not compatible with Microsoft Visual 2010 Ultimate

Table 4.1: CPLEX non-default parameters

CPLEX parameter	Value	Comment
MemoryEmphasis	True	To prevent out of memory problems, the memory emphasis option is enabled.
WorkMem	120	To prevent out of memory problems, the maximum amount of central memory, in megabytes, that CPLEX may use before swapping to disk files is set to 120 megabyte.
NodeFileInd	3	Node file on disk and compressed.
TimeLimit	600	The time limit is set to 600 seconds, when no optimal solution is found within the time limit the best integer solution is taken[2].

4.4.3 Integral problem

Like the LRU-definition, LORA, and spare parts stocking problem, also the integral problem is implemented in C++. The integral problem consist of an LRU-definition and LORA object, and a spare parts problem object, which are iteratively created. The integral problem stores the solution of the two building blocks, and updates the feedback variables. The results are stored in text-files, which makes it easy to analyze the solutions using a spreadsheet.

4.4.4 Validation

To validate the LRU-definition and LORA implementation, various instances are created using an instance generator. Next, these instances are solved by our implementation model, the solutions are then checked upon feasibility and optimality. The spare parts stocking problem is validated in two ways. First, we validate the pipeline calculations with tables from Sherbrooke (2004). Next, the optimization procedure is validated by numerically checking all values using a spreadsheet.

4.4.5 Decision Support System

As a result of implementing the mathematical model in C++, NEDTRAIN is able to implement it as a DSS. The only part missing between the tool delivered and a DSS, is a Graphical User Interface (GUI). However, this GUI is crucial for the degree of acceptance, because the understandability of the solution provided by the mathematical model will be increased. Therefore, upon implementation of a DSS first a GUI should be developed.

[2]As a result of some experiments we know that CPLEX just before the time limit does something 'smart' and finds the optimal solution in most cases (also see Kalvelagen, 2011).

Chapter 5

Business Case

Two new train series were acquired by the NS GROUP in the past years. In 2008 a new commuter train, the SLT, was introduced by NSR and in 2011 a new high speed train, the V250, will be introduced by NS HISPEED. Both the SLT and the V250 are or will be maintained by NEDTRAIN. Given that the construction of both train series deviate from previously implemented train series, NEDTRAIN wants to review its logistic support system. Hereby, the objective of NEDTRAIN is to minimize the LCC of both train series, while meeting the SLAs defined in contracts with NSR and NS HISPEED. In this chapter, the mathematical model as described in Chapter 3 is applied to two business cases of NEDTRAIN. The business cases are solved by the iterative procedure from Chapter 4. Thereby managerial insights are generated for NEDTRAIN, regarding the design of their logistic support system.

In Section 5.1 the current way of designing the logistic support system at NEDTRAIN is described. Next, in Section 5.2 the non-economical variant of LRU-definition, LORA, and spare parts stocking will be discussed. Then, in Section 5.3 the characteristics of the installed base and the repair network of NEDTRAIN are discussed, in Section 5.4 the assumptions of our mathematical model are validated. The characteristics of NEDTRAIN are used by the instance generator to generated representative instances, the instance generator is discussed in Section 5.5. In Section 5.6 the setup and results of the experiments are discussed. The chapter is ended with managerial insights derived from this business case in Section 5.7.

5.1 Current way of working at NEDTRAIN

As mentioned in Section 1.2, both the SLT and V250 are acquired from system integrators. The SLT is acquired from the consortium BOMBARDIER & SIEMENS, and the V250 is acquired from ANSALDOBREDA. The system integrator is responsible for the design of the train, and the integration of products and systems. Prior to the design, the NS GROUP and the system integrator define deliverables in terms of Reliability, Availability, Maintainability, and Safety (RAMS), which are included in a contract. In addition, an upper bound for the LCC is defined, including maintenance costs (e.g. material consumption and labor costs) and energy consumption. Upon the introduction of new train series, NEDTRAIN received a large amount of documentation and data, such as maintenance programs and breakdown structures. Using this information, maintenance engineers from NEDTRAIN design the logistic support system for a particular train series. In contrast to the model presented in Chapter 3, the design of the logistic support system does not deal with the strategic question where to execute the maintenance and repair of systems and components. This decision is made prior, and is not reconsidered when introducing a new train series.

During the design of the logistic support system, maintenance engineers are facing problems regarding information and data supply. Recommendations to solve the problems regarding data and information are made in Section 5.7.1. Although the supply of the required information and data is contracted with the system integrator, not all required data is provided. As a result, educated guesses are needed to overcome the lack of information and data. The acquisition of information and data is such a troublesome process because of all the different stakeholders involved and their interests. The system integrator, for example, needs to acquire all data from the OEM. Because the OEM is not willing to provide technical details about the system provided, the system integrator can not gather all data requested by NEDTRAIN. One of the most important reasons to not share technical data, is that the OEM is interested in being the service company for the systems supplied by them.

While gathering data for the business case, the current way of designing a logistic support system was reviewed. The most important finding is that no standard framework is used by the maintenance engineers. Decisions are mainly taken based upon experience and intuition of the maintenance engineer. The decision, where and how much spare parts to put on stock, is made in consultation with the maintenance engineers, procurement experts and a logistic expert. The logistic experts calculates the required amount of stock, these calculations however are made using an item-approach thereby not explicitly taking into account the component costs. However, implicitly the component costs are taken into account in the consultation between the three parties, since the component costs are one of the grounds upon which the final decision is taken.

The resulting deliverables of the design of a logistic support system at NEDTRAIN, are:

- LRU-definition, in the spare part list the LRU-definition is incorporated by defining for each component whether it is an LRU or not.
- Consumable repairable definitions, where a consumable is a component being discarded upon failure and a repairable a component being repaired upon failure.
- (Initial) spare part list, a list that contains all maintenance significant components and strategic components, and the amount that should be put on stock.
- Make or buy reports, in these reports which are made by specialized project-teams from NEDTRAIN, the decision as whether to outsource or insource is discussed and accordingly an advise is presented.

5.2 Non-economic LRU-definition LORA, and spare parts stocking

Prior to conducting the LRU-definition, LORA, and spare parts stocking optimization from an economical perspective, a so-called non-economical variant should be executed. In a non-economical LRU-definition and LORA, the degree of freedom of the economical variant is determined. Basten (2009, pp. 110-111), identifies a number of criteria that are used in a non-economic LORA in practice by an OEM. However, the criteria mentioned by Basten (2009) are not relevant to a maintenance organization such as NEDTRAIN. Based upon our observations at NEDTRAIN we define one criteria for the LRU-definition and three for the LORA that could be used in the non-economic variant from a maintenance organization perspective:

- Detection, is it possible to detect failure of the component. If not, the component should not be included in the indenture structure, thereby making it impossible to define the component as LRU or SRU.
- Knowledge, is the knowledge present to repair the component. If not, the repair option should be excluded in the LORA.
- Quality, is it possible to repair/overhaul the component to the level quality level 'as new'. If not, the repair option should be excluded in the LORA
- Regulation, is it possible to install capabilities at a certain location given the regulation. If not, installing the capabilities should be excluded in the LORA

The latter criterion, is one that is specific to NEDTRAIN. The service points (the lowest echelon level) are not owned by NEDTRAIN. In addition, the geographical positions is such that strict regulations makes it impossible to install capabilities to repair components. Therefore the option to repair components at the first echelon level should be excluded in the economical optimization.

The non-economical spare part stocking, consist of the identification of strategic spare parts. These strategic spare parts are required, when for example a system is damaged by accidents. As a result of such accidents parts fail individually and therefore should be replaced in totality. Hence, some strategic spare parts need to be stocked.

5.3 Characteristics of NEDTRAIN

The business case exist out of two train series, namely a high-speed train such as the V250, and a commuter train such as the SLT. The business case is represented by various experiments that are generated by an instance generator. This instance generator represents the characteristics of NEDTRAIN, which we present in this section. In Section 5.3.1, the characteristics of the repair network are discussed, and in Section 5.3.2, the characteristics of the installed base are discussed. Most of the characteristics are based on data from the V250 and SLT.

5.3.1 Repair network

In this section, the characteristics of the repair network of NEDTRAIN will be discussed: the echelon structure, location structure, capabilities, and the repair times and costs.

5.3.1.1 Echelon structure

As discussed in the company description (Section 1.1.5), NEDTRAIN has a repair network consisting of four echelon levels. For both the high-speed train and commuter train the echelon structure is the same. Since the first echelon of these four echelons is limited in its capabilities due to regulations, we leave this echelon level out of scope in our business case. Hence, three echelon levels remain representing the OB's (first echelon), RDC (second echelon), CBT, RBH and the OEM (third echelon).

5.3.1.2 Location structure

The location structure of the repair network of NEDTRAIN is depicted in Table 5.1. We distinguish two cases, the first case is a repair network for a commuter train, typically these trains are used in the urban agglomeration (multiple sections) and therefore commuter trains have a medium size repair network. The second case is a repair network for a high-speed train, which is used on one section only, therefore typically the high-speed train has a small repair network. The shipment times presented are applicable to both cases, and represent the shipment time from the echelon level where they are stated to one echelon level upwards. The number of locations and the shipment times that are stated in Table 5.1 are estimates provided by logistic experts from NEDTRAIN.

Table 5.1: Characteristics repair network: number of locations and shipment times (in working days)

Echelon	# Loc. (commuter)	# Loc. (high-speed)	Shipment times
1	2	1	2 days
2	1	1	2 day
3	1	1	-

5.3.1.3 Capabilities

The relevant echelon levels and their capabilities for the commuter and high-speed train cases are:

- **First echelon level:** Maintenance companies (OB's), which have the capability to exchange LRUs.
- **Second echelon level:** Central warehouse (RDC), where spare parts can be stored.
- **Third echelon level:** Repair (CBT) and overhauling (RBH) companies, which have capabilities to repair/overhaul LRUs and SRUs.

Since tools regarding exchange of components in general are supplied together with the trains, we only consider capabilities to repair components. The cost associated with the capabilities to repair components are €35 million per location. This amount is an estimate provided by experts from NEDTRAIN.

5.3.1.4 Lead times suppliers

In Figure 5.1, a histogram of the planned lead times across SKUs (in working days) from the suppliers is depicted. The average supplier lead time is 67.1 working days (13 weeks) and the standard deviation is 41.9 working days (8 weeks). The histogram is based upon a data set containing all lead times from maintenance significant items from external suppliers. Hence, the histogram is both applicable to the commuter and high-speed train cases.

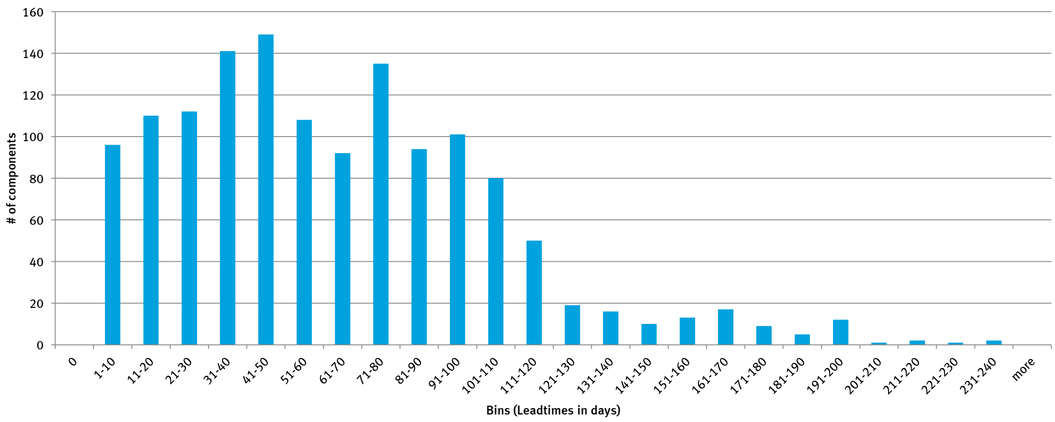


Figure 5.1: Histogram lead time suppliers: $\mu = 67.1$ days, $\sigma = 41.9$ working days

5.3.1.5 Repair lead times and costs

The data of the repair lead times and costs, originates from the repair facility from NEDTRAIN (CBT) and includes data regarding components being repaired in the upcoming year. Hence, this data does not include components for either the V250 or SLT, however the data is representative for both the high-speed and commuter train cases. The data regarding the repair lead time consist out planned lead times (that are based upon historical lead times). In Figure 5.2, a histogram of the planned lead times (in working days) from the repair facility at the third echelon is depicted. The average repair lead time is 21.82 working days (4 weeks) and the standard deviation is 25.18 working days (5 weeks). The characteristics of the repair

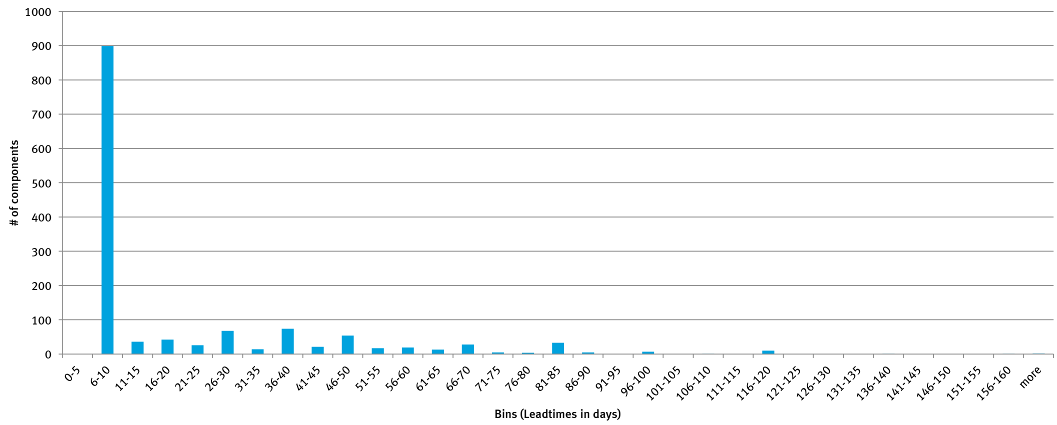


Figure 5.2: Histogram lead time repair facility: $\mu = 21.82$ working days, $\sigma = 25.18$ working days

costs are determined by computing the fraction of the repair cost compared to the new price of the components. The mean of this fraction is 0.45, meaning that repairing a component on average does costs 0.45 of the new price of that component. Furthermore, the standard deviation of the fraction is 0.35 (i.e. for some components repairing is more expensive than discarding). Note that the repair costs as a function of the new price, does not include the costs to move the component to the repair facility nor does it included the associated holding costs.

Table 5.2: Breakdown structure: number of components per indenture level

Indenture level	# Components	# Childless components
1	81	9
2	738	365
3	589	272
4	94	94
Total	**1,502**	

5.3.2 Installed Base

In this section, the characteristics of the installed base are discussed: the breakdown structure, component price, failure rate, tools, and replacement times.

5.3.2.1 Breakdown structure

Since the breakdown structure for the V250, provided by the system integrator is the most complete and detailed available, this breakdown structure is used to determine the characteristics of both a high-speed train and commuter train. In Table 5.2 a summary of the breakdown structure of the V250 is depicted, in total 1,502 maintenance significant items are identified for the V250. In Table 5.3, the average number of occurrence of components for each indenture level is depicted.

Table 5.3: Breakdown structure: Number of occurrences of a component

Ind.	Avg. number of occurrences
1	5.36
2	5.15
3	4.99
4	7.48

5.3.2.2 Component price

To determine the characteristics of the component price of the installed base, the breakdown structure of the V250 is used and coupled to the price information provided by the system integrator. For about 41% of the maintenance significant components a price was given by the system integrator. In Table 5.4 the average component price, the Coefficient of Variance (CV), the minimum price, and the maximum price are depicted. As one would expect the average component price decreases along the indenture level. However, indenture level 4 is an exception. The higher average component price for this indenture level is caused by the high price of a lateral bumpstop which has a component price of €27.500 and does not have a parent component for which a price is given.

5.3.2.3 Failure rate

The characteristics of the failure rate are based on the FMECA of the V250, provided by the system integrator. The RCM provided by the system integrator is not used, since maintenance tasks are not coupled to components. However, since the FMECA is the most important source

Table 5.4: Component price per indenture level (in euros)

Indenture level	Avg. comp. price	CV	Minimum	Maximum
1	35,000	1.9	40	325,000
2	3,000	3.0	40	110,000
3	500	4.7	40	30,000
4	2,000	3.4	10	27,500

for making the RCM, the failure intensity can be determined by the FMECA. The failure

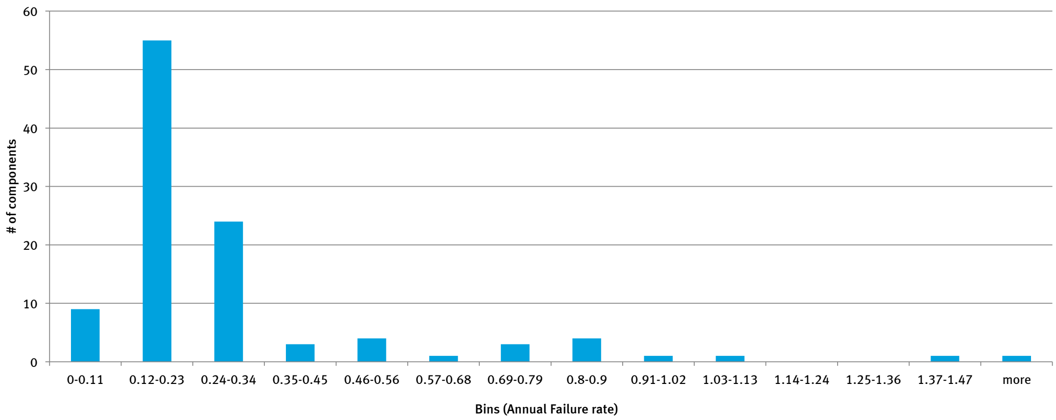


Figure 5.3: Histogram failure rate (based upon FMECA V250) $\mu = 0.3$ failures a year, $\sigma = 0.38$ failures a year

rates in the FMECA are defined for the highest-indenture components only, hereby the system integrator assumes that a module never fails individually. In Figure 5.3, a histogram of the failure rates for the highest-indenture components, is depicted. Only components that fail at least once every ten years are taken into account. Maintenance engineers at NEDTRAIN are aware of the possibility that modules/components fail individually, as a result of accidents. Therefore, they explicitly put them on the initial spare parts list, if applicable. Based on an internal report from NEDTRAIN, which investigates the probability of accidents for the V250, the probability that a complete component fails is determined. The probability that a component(with subcomponents) fails individually is not significant. Therefore we do not take it into account. The average failure rate for the components is 0.3 failures per year, meaning that the MTBM is about 3.3 year.

5.3.2.4 Replacement time

The replacement time includes the time to isolate a failure and to exchange the corresponding LRU. The characteristics of the replacement times are based upon the V250. The average exchange times are determined based on the RCM, and estimates provided by maintenance engineers from NEDTRAIN. The average fault isolation time is an assumption based upon the breakdown structure. In Table 5.5 the average replacement times in hours as a result of the summation of the exchange and fault isolation time, are depicted. Given the construction of rolling stock, it is possible that exchanging a component on indenture level $i + 1$, means that first its corresponding parent component on indenture level i needs to be disassembled.

To determine the probability that first a lower indenture module/component needs to be disassembled, estimates are made by maintenance engineers from NEDTRAIN. For the SLT the probability that a lower indenture component needs to be disassembled first is 0.1, and for the V250 the probability that a lower indenture component needs to be disassembled is 0.2.

Table 5.5: Replacement times per indenture level (in hours)

Ind.	Avg. replacement	Avg. exchange	Avg. fault isolation
1	2.09	2.09	0
2	0.76	0.26	0.5
3	2.05	0.05	2
4	4.08	0.08	4

5.4 Assumption validation

In this section the correspondence of the characteristics of NEDTRAIN and the model presented in Chapter 3, is discussed. We validate our model by checking whether the most critical assumptions are in correspondence with the situation at NEDTRAIN:

- **Commonality:** Commonality regarding components is present in both the V250 and SLT, however only for small non-maintenance significant components which are out of scope anyway. Therefore, the assumption made by our model that there is no commonality, holds.

- **Failure behavior:** It is assumed that components fail according to a Poisson process with a constant rate. Altough NEDTRAIN mainly replaces components preventively, the replacement of a specific component is unplanned because it is inspection based, therefore it is unknown a-priori which parts need to be replaced. Furthermore, Ozkan (2010, p. 7) shows that the majority of unplanned demand at NEDTRAIN has a Poisson distribution. Hence, the assumption that failures occur according to a Poisson process is justified.

- **Repair by replacement:** A repair by replacement strategy is used by NEDTRAIN at the echelon levels within scope.

- **Shipments:** It is assumed that failed components are only moved stream upwards. This assumption holds in the case of NEDTRAIN without any exception. The assumptions that no lateral transhipment or emergency shipments are performed is not true in the case of NEDTRAIN. However, both lateral and emergency shipments are rare and therefore the influence of our assumption is negligible.

- **Repair times:** According to experts at NEDTRAIN the assumption that repair times are i.i.d. random variables is justified. Furthermore, data suggests that the repair times are also independent from other characteristics.

- **Planned lead times:** Our assumption that repair lead times are planned is justified, because NEDTRAIN uses a planned lead time concept.

- **Base stock policy** For the maintenance significant items within scope a base stock policy is used by NEDTRAIN. However, NEDTRAIN does not always use an one-for-one replenishment strategy instead for each component the economic order quantity is determined (which could differ from one).
- **Cold-redundant spare systems:** The assumption that spare systems are cold-redundant is valid in the case of NEDTRAIN, because only systems that are required (i.e. the target availability) are used.

5.5 Instance Generator

Using the characteristics of NEDTRAIN shown in Section 5.3, instances are generated such that the real-life situation at NEDTRAIN is approximated. We present two instance generators. One representing the repair network and installed base of a commuter train, such as the SLT. The other representing a high-speed line such as the V250. However, most of the parameters of the two types of instances are generated in the same way. Therefore, we will present it as one instance generator and highlight the differences between the two instances.

The instance generator consist of both random and deterministic parts. For example, the echelon and location structure are generated deterministically. The repair lead time is an example of a randomly generated parameter. The random parameters are generated independently from each other (e.g. when generating the failure rate, the instance generator does not take into account the cost price of that component). This is justified, because almost no correlation is found between the different parameters in the data.

In Table 5.6 an overview of the most important deterministic parameters for the two business cases, is given. Because, the same indenture structure is used for the high-speed and commuter train instance, both instances have the same number of components and indenture levels. Furthermore, the number of echelon levels is the same, however the location structure deviates, since the commuter train has two locations on the first echelon level. The target availability for the high-speed train instance is 16 trains and 121 trains for the commuter train instance. For all components with children the annual individual failure rate is set to zero. The holding costs are set to 20% of the discard costs (new price) of a component.

Table 5.6: Deterministic parameters

Deterministic parameters	**High-speed train**	**Commuter train**
$\|C\|$	1503	1503
$\|I\|$	4	4
$\|E\|$	3	3
$\|L_e\|$	1;1;1	1;1;2
T	16	121
$m_c,\ \forall c \in C \mid \Gamma_c \neq \emptyset$	0	0
hc_c	$vc_{c,1,\text{discard}} \cdot 0.2$	$vc_{c,1,\text{discard}} \cdot 0.2$

The random parameters are generated based on PDFs which are obtained by fitting distributions on the data. The goodness of fit criterion $\mathcal{X}^2$ is used to select the distributions. The possible distributions are: the exponential, gamma, triangular, uniform and weibull distributions. In Table 5.7 the random parameters and their fitted distributions are presented.

Table 5.7: Random parameters

Random parameter	**High-speed train**	**Commuter train**
$vc_{c,1,\text{discard}}$	exp(34,596)	exp(11,532)
$vc_{c,e,\text{repair}}$	$\Gamma(1.94; 0.24) \cdot vc_{c,1,\text{discard}}$	$\Gamma(1.94; 0.24) \cdot vc_{c,1,\text{discard}}$
$m_c,\ \forall c \in C \mid \Gamma_c = \emptyset$	$\Gamma(1.85; 0.17)$	$\Gamma(1.85; 0.17)$
K_c [indenture level] (hrs.)	exp([2.09;0.76;2.05;4.08])	exp([2.09;0.76;2.05;4.08])
$vc_{c,e,\text{move}}$	$\mathcal{U}(5; 45)$	$\mathcal{U}(5; 45)$
Repair lead time (days)	exp(21.82)	exp(21.82)
Supplier lead time (days)	$\Gamma(2.16; 31.08)$	$\Gamma(2.16; 31.08)$

Furthermore, a sensitivity analysis is performed by varying the random parameters. Instead of changing the parameters directly we scale the PDFs. In Table 5.8 the parameters we vary by scaling them are depicted.

Table 5.8: Experimental settings: Varied parameters (the default values are marked with an *)

Factors	**Values**
$F_{\text{repair costs}}$	$0.8; 1^*; 1.2$
$F_{\text{system cost}}$	$0.8; 1.5^*; 2$
$F_{\text{failure rate}}$	$0.5; 1^*; 2$
$F_{\text{component costs}}$	$0.8; 1^*; 1.2$
$F_{\text{transport costs}}$	$0.5; 1^*; 2$
$F_{\text{repair capabilities}}$	$0; 1^*$
$F_{\text{holding costs}}$	$0.5; 1^*; 2;$

The parameters are generated as follows:

- **Echelons and locations:** The repair network is not randomly generated, instead we use the echelon structure as presented in Section 5.3.1. For an overview of the number of locations see Table 5.1. Recall, that the locations structure for the high-speed and commuter instance deviate.
- **Capabilities:** For 90% of all components capabilities are required to repair them. We randomly assign repair capabilities to components based upon a probability of 0.9. Therefore we consider one repair capability, for which the fixed costs of installing it is set to €35 million per location for locations at the first and second echelon. In the case of the commuter train repair network this means that installing repair capabilities at the first echelon costs €70 million, because of the two locations present at this echelon level. In the sensitivity analysis the factor $F_{\text{repair capabilities}}$ is set to 0, representing the case that no capabilities are required.
- **Breakdown structure:** Based upon the number of components per indenture level, as shown in Table 5.2, we generate a breakdown structure. Regarding the indenture

structure no significant differences between a commuter train and high speed train exists. Therefore, for both instances the breakdown structure mentioned is used. The number of occurrences of a component are generated based on exponential distributions as a function of the indenture level. In Table 5.3 the mean value for each indenture level we use to generated random numbers is depicted.

- **Component prices:** Since, components within the breakdown structure have a parent-child relationship, their component costs can not be generated as an i.i.d. random variable. Therefore, we only use the distribution of component prices for the first indenture level. The fitted exponential distribution on component prices for the first indenture level is depicted in Figure E.1 in Appendix E. The mean parameter of the exponential distribution turns out to be €34,596 (note that this value is the same as the average component price depicted in Table 5.4 although the latter is rounded). As can be seen in the figure, a small number of components has a price higher than €150,000. Typically these are the main transformer, the trailer bogie, and the motor bogie. Since these components are always present, we explicitly take these components into account when generating the instance. Hence, the component prices for these components are not randomly generated. In the sensitivity analysis the component prices are linearly scaled by the factor $F_{\text{component costs}}$, where a higher factor means higher component costs. For the commuter train, we assume that the maintenance significant sub-systems (first indenture components) represent a value of €5 million per system. For the high-speed train, we assume that the maintenance significant sub-systems represent a value of €15 million per system. The system costs for both instances are generated by computing the sum of all maintenance significant sub-system costs and multiplying them with a factor $F_{\text{system cost}} = 1.5$. Hence, we assume that the commuter train costs €7.5 million and the high-speed train costs €22.5 million. As a result of the system cost factor, the non-maintenance significant components are also taken into account. In the sensitivity analysis the factor $F_{\text{system cost}}$ is set to 0.8 to represent the case that it is cheaper to acquire a complete system compared to acquiring all maintenance significant components. Vice versa, by setting the factor $F_{\text{system cost}}$ to 2 we represent the case that acquiring a system is twice the price of all maintenance significant components. The component costs for the second and higher indenture levels are determined recursively. Starting at the second indenture level, the cost of the parent component is decomposed to the child components. Hereby three options exists:

  (i) The sum of child components costs is equal to the cost of the corresponding parent, with a probability of 0.5. Hence, the average child component price is computed directly by dividing the parent component cost by the number of children.

  (ii) The sum of child components costs is higher (with a factor between 1.05 and 1.15) than the cost of the corresponding parent, with probability of 0.25. As a result, we compute the average child component price but multiply this with a random number from the uniform distribution $\mathcal{U}(1.05; 1.15)$.

  (iii) The sum of child components costs is lower (with a factor between 1.05 and 1.15) than the cost of the corresponding parent, with probability of 0.25. As a result, we compute the average child component price but divided this with a random number from the uniform distribution $\mathcal{U}(1.05; 1.15)$.

Next, using a random number generator based upon the PDF of an exponential distribution, with a mean set to the average component price, component prices are randomly generated.

- **Failure rate:** As mentioned in Section 5.3.2.3, it is assumed that only highest indenture components fail. Using the data presented in Figure 5.3, a gamma distribution is fitted on the failure rates. The fitted distribution is depicted in Appendix E in Figure E.2. The gamma distribution turns out to have the following parameters: $\Gamma(1.85; 0.17)$. Each components failure rate is randomly drawn from this distribution. In the sensitivity analysis the failure rate is linearly scaled with factor $F_{\text{failure rate}}$, where setting this factor to 2 represent the case that the failure rate is double the default rate and vice versa setting this factor to 0.5 represents the case that the failure rate is halve the default rate.

- **Replacement time:** The replacement times are generated as a function of the indenture level. An exponential distribution is fitted to the replacement time as a function of the indenture level. The mean values of the replacement time for each indenture level are given in Table 5.5. Using a random number generator based upon the PDF of the exponential distribution for a specific indenture level, replacement times are randomly generated. Furthermore, for components with an indenture level higher than one, we randomly add the replacement time of its corresponding parent on the first indenture level, based on a probability. The probability for the commuter train instances is 0.1 and for the high speed instances this probability is 0.2.

- **Repair costs and times:** The repair costs characteristic is determined by means of the fraction of the new price. Repair costs for childless components are randomly generated by multiplying the new price of a component by this fraction. A gamma distribution is fitted to the repair costs fraction, which is depicted in Figure E.3 in Appendix E. The gamma distribution turns out to have the following parameters: $\Gamma(1.94; 0.24)$ (i.e. the fraction can be higher than 1, meaning that repairing a component is more expensive than discarding it). The repair costs for other components is set equal to the weighted average (based on the arrival rate) of the replace costs of its children: $vc_{c,e,\text{repair}} = \sum_{b \in \Gamma_c} \frac{\lambda_b}{\lambda_c} \cdot rc_b \cdot F_{\text{repair costs}}$. Where, the variable $F_{\text{repair costs}}$ is set to 1 in the default case, thereby assuming that the repair and replacement path have the same costs. In the sensitivity analysis the factor $F_{\text{repair costs}}$ is set to 0.8 to represent the case that repairing a component by replacing its failed child in the repair shop is cheaper than replacing this failed child from the system directly. Vice versa, by setting the factor $F_{\text{repair costs}}$ to 1.2 we represent the case that its more efficient to replace the failed child component from the system compared to repairing its parent by replacing the child in a repair shop. The mean repair times for the childless components are randomly generated based on an exponential distribution, which is fitted on NEDTRAINs repair shop lead times. The fitted exponential distribution is depicted in Appendix E in Figure E.4, and turns out to have a mean value of 21.82 days.

- **Supplier lead times:** Based upon the histogram depicted in Figure 5.1, a gamma distribution is fitted, which is depicted in Appendix E in Figure E.5. The gamma distribution turns out to have the following parameters: $\Gamma(2.16; 31.88)$.

- **Holding costs:** Based upon the component price and an interest rate of 20%, for each component the holding costs are computed. The holding costs are the same at each location. The interest rate of 20% represents the depreciation of the spare parts (CAPEX) and the cost to store the spare parts (OPEX). In the sensitivity analysis the factor $F_{\text{holding costs}}$ is used to linearly scale the holding costs, where a higher factor means higher holding costs.

- **Transport costs:** The transport costs are randomly generated for each component based upon an uniform distribution with parameters: $\mathcal{U}(5; 45)$. In the sensitivity analysis, the transport costs are linearly scaled by the factor $F_{\text{transport costs}}$, where a higher factor means higher transport costs.

5.6 Experiments

In this section, we discuss the experiments conducted using our instance generator and mathematical model, thereby solving the business case from NEDTRAIN. The motivation behind the experiments is twofold: (a) we want to asses the performance of the two heuristics (Section 4.3), and (b) we want to solve the business case of NEDTRAIN and gain managerial insights. Regarding the performance of the two heuristics, we want to examine:

(i) How the iterative procedure performs in case of heuristic 1 compared to the sequential procedure.

(ii) How the iterative procedure performs in case of heuristic 2 compared to the sequential procedure.

(iii) How the first heuristic performs compared to the second heuristic.

Regarding the business case we want to gain insights on:

(iv) How the logistic support system of a high-speed train should be designed.

(v) How the logistic support system of a commuter train should be designed.

(vi) Which parameters are crucial while designing the logistic support system.

In Section 5.6.1, first the experimental settings are discussed. Next, in Section 5.6.2 the results of the experiments are presented.

5.6.1 Experimental settings

In order to determine the performance of the heuristics, all experiments are solved using heuristic 1 and heuristic 2. All instances are solved by the iterative procedure, and thus also the sequential solution for each instance is known (i.e. the first iteration in the iterative procedure is also the sequential solution). As a result of this experimental setup, we are able to answer questions (i)-(iii).

To solve the business case and in order to gain managerial insights, experiments are generated using our instance generator discussed in Section 5.5. In addition to the default scenario we perform a sensitivity analysis by scaling (see Table 5.8) certain parameters. For each scenario, we randomly generated five different instances. We use the same five seeds for our random number generator for each scenario. As a result we are able to compare instances from different scenarios directly.

In Table 5.9, the scenarios, their factors, and the number of instances generated and solved for both the high-speed and commuter train experiments is presented. For the high-speed train all instances are solved. However, for the commuter train it was not possible to solve all 70 instances. The scenario that the failure rate is twice the default cannot be solved at all for the commuter train, because the spare parts stocking problem requires more memory than allowed in a 32-bits Windows environment. Although, in all other cases always a sequential solution is found, in some sensitivity scenarios for the commuter train, CPLEX was not capable of solving the LRU-definition and LORA in the iterative procedure. However, for all scenarios except the scenario that the failure rate factor is 2, at least two instances are solved. As a result we are still able to draw conclusions for these scenarios in our sensitivity analysis.

Table 5.9: Experiment scenarios (number of instances solved/number of instances)

Scenario	**Factor**	**High-speed train**	**Commuter train**
Default	-	5/5	5/5
Repair costs	0.8	5/5	5/5
Repair costs	1.2	5/5	5/5
System costs	0.8	5/5	5/5
System costs	2	5/5	4/5
Failure rate	0.5	5/5	5/5
Failure rate	2	5/5	0/5
Component costs	0.8	5/5	5/5
Component costs	1.2	5/5	5/5
Transport costs	0.5	5/5	5/5
Transport costs	2	5/5	4/5
Repair capabilities	-	5/5	5/5
Holding costs	0.5	5/5	4/5
Holding costs	2	5/5	2/5
Total		**70/70**	**59/70**

5.6.2 Results

In this section we present the results of our experiments. First, we discuss the performance of the heuristics, and next we discuss the results regarding the business case.

Remark 5.1 Higher and lower LRU-definition
When discussing the results regarding LRU-definition, we will use the terms higher and lower LRU-definition. With a higher LRU-definition is meant that higher indenture components are defined as LRU. Vice versa, with a lower LRU-definition is meant that lower indenture components are defined as LRU.

5.6.2.1 Performance heuristics

In this section we present our findings on the performance of the two heuristics:

- **Sequential versus iterative:** In 60% of the default instances the sequential solution already results in the best solution found. In other terms, the iterative procedure in 40% of the default instances finds a better solution compared to the sequential procedure. Remarkably, the sequential solution always finds the best solution in the high-speed train business case, and thus the iterative procedure does not further improve the solution obtained by the sequential procedure. In case of the commuter train instance, in 80% of all instances the iterative procedure finds a better solution than the sequential procedure, with an average cost reduction of 8.8% and a maximum reduction of 23.03%. The sequential performs good, because based upon the replacement and repair costs, almost the highest indenture components are defined as LRU in the LRU-definition and LORA. Defining the highest indenture components as LRU does result in the lowest possible spare parts holding costs, because of the low holding costs of these components. In the commuter train instances the iterative procedure finds a higher LRU-definition compared to the sequential procedure, resulting in lower spare parts holding costs. Furthermore, in one instance the most efficient solution found has a lower LRU-definition resulting in a reduction of spare systems. As a result of taking into account holding costs in the LRU-definition and LORA, the iterative procedure finds 3.5% lower costs on average.

- **Solutions:** In all default instances, heuristic 1 finds the most efficient solution. In Table 5.10 the average costs obtained by heuristic 1 and 2 in the high-speed and commuter train instances is given. Because the sequential procedure obtains the best solution in the high-speed train instances, and because taking into account the number of spare systems in the LRU-definition and LORA as done by heuristic 2 does not result in a different solution, heuristic 1 and 2 have the same objective value. However, in the commuter train case the iterative procedure obtains better solutions than the sequential procedure. Heuristic 1 and 2 find different solutions, since they update their variables differently in the iterative procedure. On average heuristic 1 finds 2.3% lower costs compared to heuristic 2 in the commuter train instances. The solution from the iterative procedure in case of heuristic 1 has a slightly higher LRU-definition resulting in lower spare part costs compared to the sequential solution. In the scenario where the repair capabilities are left out, in case of the commuter train, heuristic 2 is performing better than heuristic 1. However, in all other instances heuristic 1 is performing significantly better, because heuristic 1 also updates the replacement costs where heuristic 1 does not. By adding the spare systems holding costs to the replacement costs, other LRU-definition become more interesting, therefore heuristic 1 in the iterative procedure does find more different and efficient LRU-definitions.

- **Computation time:** Although heuristic 1 more often finds a beter solution in the iterative procedure than heuristic 2. On average both heuristics require the same amount of iterations, because heuristic 2 requires more iterations in case that it finds its best solution in the iterative procedure. Solving the LRU-definition and LORA problem for the default high-speed instances with CPLEX, on average takes 5.5 seconds in the first iteration for heuristic 1, and 6.02 seconds for heuristic 2 in the first iteration. For the default commuter instances, it on average takes CPLEX 4.2 seconds to solve in the first iteration for heuristic 1 and 6.0 seconds in the first iteration for the heuristic 2. The computation time is dominated by the spare parts stocking problem. For the high-speed train case where the cumulative failure rate of the system is 1000 it takes about 10 minutes to solve the spare part stocking problem in the first iteration. In the case of the commuter train where the cumulative failure rate of the system is 7,563 it takes about 25 minutes to solve the spare part stocking problem in the first iteration. In iterations two and higher, the computation time of the LRU-definition and LORA, and the spare parts stocking problem vary. In Figure 5.4, the computation time for multiple iterations for a single commuter-train instance required by CPLEX to solve the LRU-definition and LORA is depicted. Remarkably, after the first iteration heuristic 1 requires more computation time than heuristic 2. For the same commuter-train instance, in Figure 5.5 the computation time of the spare parts stocking problem is depicted. The computation time in the spare parts stocking problem for heuristic 1 is stable, where this is not the case for heuristic 2. The higher computation time of heuristic 2 is caused by a lower LRU-definition leading to more indenture levels compared to the higher LRU-definition of heuristic 1. All computation times are obtained using an Intel Core2Duo E6550 @ 2.33 Ghz processor and 4.0 Gb. of RAM, running on Windows 7.

- **Solvability LRU-definition and LORA:** As a consequence of the iterative procedure parameters used by the LRU-definition and LORA are updated at the end of each iteration. Updating these parameters does not mean that at each subsequent iteration lower costs are obtained (i.e. the heuristics do not have to converge). Considering that the problem is NP-hard, updating parameters and increasing them did result in instances (in the commuter train sensitivity analysis) which could not be solved by CPLEX because of memory problems.

- **Memory spare parts stocking problem:** The memory required for the spare parts stocking problem is mainly determined by the number of EBO-curves and points on the curve that need to be constructed. The number of points on an EBO-curve for a certain component is mainly determined by the demand and repair lead time. In case of a multi-echelon instances for each convex point on an EBO-CURVE for a certain echelon level, another complete EBO-curve needs to be constructed at a lower echelon level. Furthermore, for each convex point on an EBO-curve for a certain indenture level, another complete EBO-curve needs to be constructed at a lower indenture level. Hence, the memory requirements of the spare parts problem does dramatically increase with the number of echelons and indenture levels. Even tough our implementation model is such that the memory requirements are minimized (see Appendix C), in the commuter train instance (with an installed base of 121 train) our implementation model almost needed the maximum memory possible.

Table 5.10: Best solution heuristic 1 versus heuristic 2 (in euros)

	Heuristic 1	**Heuristic 2**
High-speed train	10,965,491	10,965,491
Commuter train	15,027,357	15,374,995

5.6.2.2 Business case: High-speed train

In Table 5.11 the cost results from the best solutions found for the high-speed train business case are depicted. We distinguish a case in which LRUs are freely defined and a case

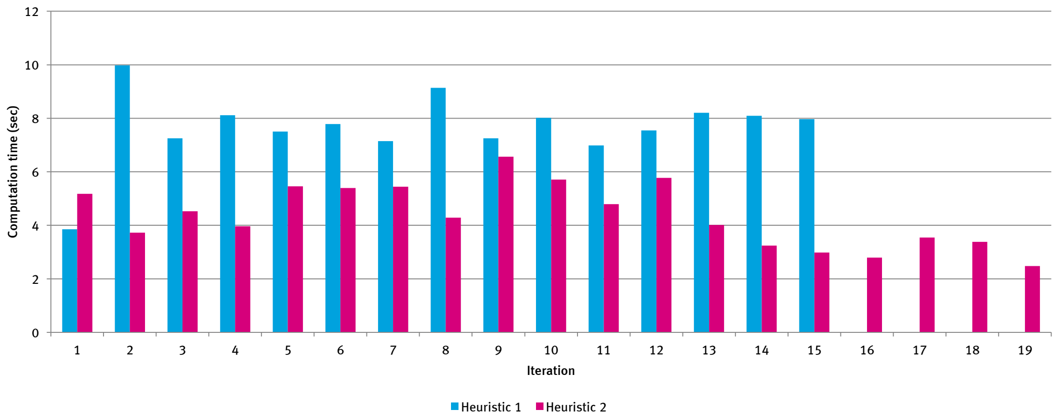


Figure 5.4: Computation time CPLEX, iterative procedure

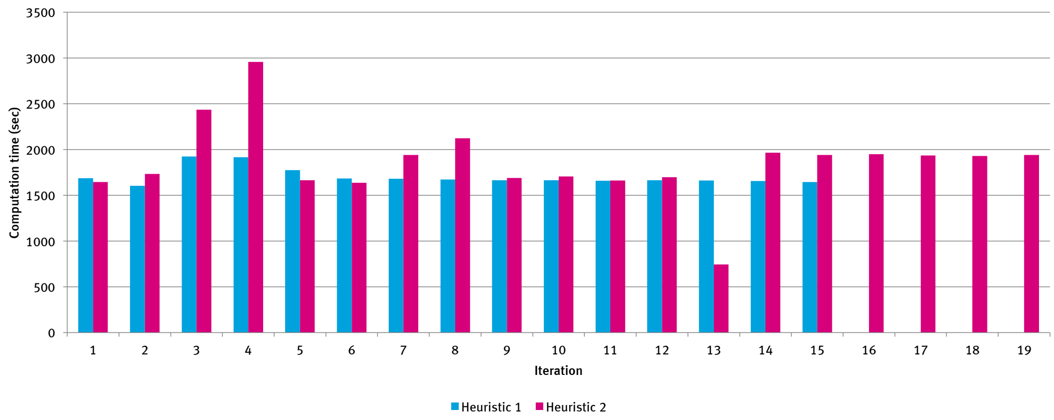


Figure 5.5: Computation time spare parts stocking problem, iterative procedure

in which all first indenture components are defined as LRU. In case that the LRU-definition

Table 5.11: Best solution high-speed train logistic support system (in euros)

Cost Factor	**Free**	**1^{st} indenture**
Repair	2,695,583	2,974,991
Replace	191,707	102,367
Resource	-	3,500,000
Spare parts	4,645,218	15,650,277
Spare systems	3,432,984	3,432,984
Total	**10,965,491**	**25,660,619**

is free, the annual costs are €10,972,646 mainly existing out of €2,695,583 repair costs and €8,085,356 holding costs. When defining all first indenture components as LRU the annual costs are €25,660,619. Hence, defining LRUs freely decreases costs with 57% compared to defining first indenture components as LRU. The holding costs in case of defining first indenture components as LRU are €19,083,261. The holding costs are high because first indenture components are expensive compared to the highest indenture components. Furthermore upon failure of a system, a first indenture component (LRU) is replaced from the system, and next, the second indenture component (SRU) is replaced from the first indenture component, and so on until the fourth indenture component is repaired directly. As a result of defining first indenture components as LRU, the annual replacement rate is larger than zero for all components. Therefore, significantly more components need to be stocked. Defining first indenture components as LRU does result in significant higher total costs, and therefore this option is not further discussed in this section.

- **LRU-definition and repair/discard-decision:** In Table 5.12 the average and standard deviation of the number components defined as structure part, LRU and SRU are shown. Of the 1,503 component present in the indenture structure, 332 components are defined as structure part. Obviously no repair/discard-decision is made for the structure parts. On average 1,000 components are defined as LRU, and 14[1] components are defined as SRU. Because of the LRU-definition the LRU-indenture structure almost is single-indenture.

Table 5.12: LRU-definition and repair/discard decision high-speed train, average number of components and (standard deviation)

	Amount	**Repaired**	**Discarded**
Structure parts	332 (13.6)	-	-
LRUs	1000.4 (15.7)	686.4 (13.3)	314 (12.53)
SRUs	14.4 (4.3)	7.8 (3.3)	6.6 (2.6)
Total	**1503**	**694.2 (17.6)**	**320.6 (12.8)**

- **Level of repair:** In Table 5.13 the number of repairs and discards on echelon level are given. Of the 994 components that are repaired 600 (86%) are repaired at the third echelon level, and 94 components (14%) are repaired at the first echelon. This later group of components does not require repair capabilities. If a component is discarded this done at the first echelon. Meaning that no components are shipped to the third echelon to be discarded, which is logically since the costs to discard a component is equal at all echelon levels. However, it could be that a component with child components is shipped to the third echelon to be repaired, and that one of its child components is discarded at the third echelon. Since, the LRU-definition is such that the LRU-structure is almost single-indenture, a solution where child components are discarded at the third echelon is not observed in any of our instances.

- **Spare parts:** In Table 5.14 the annual holding costs associated with the spare parts for LRUs and SRUs on location level is presented. Most LRUs are stocked at location 3 (59%), and furthermore a significant amount of LRUs is put on stock at location 1 (41%). Given that there are only 14 maintenance significant SRUs, almost no SRUs are stocked. Some SRUs are stocked at the first echelon because they do not require repair capabilities. In Figure 5.6 the availability curve for five high-speed train instances is

[1]According to te LRU-definition there are 171 SRUs, however 156 of these SRUs are not repaired or discarded because their parent component is already discarded

Table 5.13: Level of repair/discard high-speed train, average number and (standard deviation)

Ech.	Repaired	Discarded
1	94.4 (6)	320.6 (13.5)
2	0 (0)	0 (0)
3	599.8 (16.1)	0 (0)

depicted. The differences between the instances are caused by different failure rates and component prices. Instance 1, for example, has the highest annual cumulative failure rate of all instances, and therefore more spare parts are required compared to other instances. The overshoot obtained by the marginal analysis of the average availability is 0.15%.

Table 5.14: Annual spare part stocking holding costs high-speed train (in euros)

	Location 1 (ech. 3)	Location 2 (ech. 2)	Location 3 (ech. 1)
LRUs	1,884,506	1,849	2,719,707
SRUs	760	0	6,978
Total	**1,885,266**	**1,849**	**2,726,685**

- **Spare systems:** Remarkably, only one system is required even though the LRU-definition is such that the replacement lead times are high compared to defining all first indenture components as LRU.

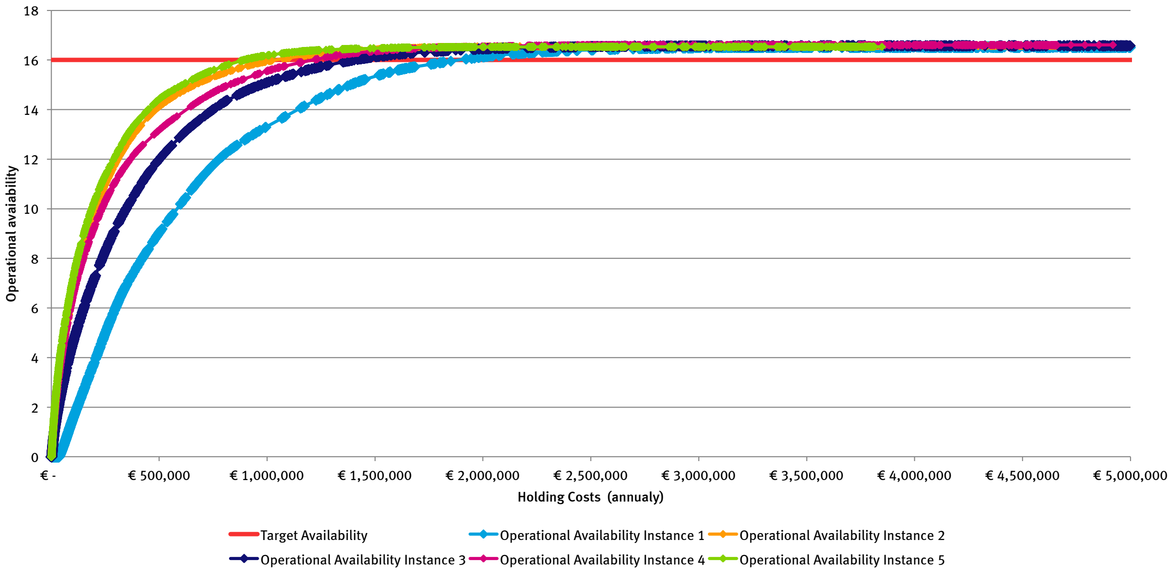


Figure 5.6: Availability curve: installed base approach high-speed train ($s_0 = 1$)

5.6.2.3 Business case: Commuter train

In Table 5.15 the cost results from the best solutions found for the commuter train business case are shown. We distinguish a case in which LRUs are freely defined and a case in which all first indenture components are defined as LRU. In case that the LRU-definition is free, the

Table 5.15: Best solution commuter train logistic support system (in euros)

Cost Factor	Free	1^{st} indenture
Repair	8,062,996	10,488,789
Replace	1,498,424	837,365
Resource	-	-
Spare parts	1,368,695	15,935,227
Spare systems	4,097,242	3,720,936
Total	**15,027,357**	**30,982,317**

annual costs are €15,027,357 mainly existing out of €8,062,996 repair costs and €4,097,242 spare systems holding costs. Although, defining all first indenture components as LRU requires less spare systems, the total annual costs are €30,982,317. Hence, defining LRUs freely results in a cost reduction of 52% compared to defining first indenture components as LRU. The high costs of defining first indenture components as LRU are mainly caused by the high spare parts holding costs. When defining first indenture components as LRU, there will be demand to all components in the indenture structure and more spare parts are required. Furthermore, first indenture components are relatively expensive to put on stock. Clearly, defining first indenture components as LRU does result in significant higher costs, and therefore this option is not further discussed in this section.

- **LRU-definition and repair/discard-decision:** Table 5.16 shows the LRU-definition and repair/discard-decision of the best solutions found. Of the 1,503 component present in the indenture structure, 522 components are defined as structure part. Obviously no repair/discard-decision is made for the structure parts. On average 978 components are defined as LRU, and 3[2] as SRU. Of the 978 LRUs 556 (56.8%) are repaired and 443 (43.2%) are discarded. Given that there are only 3 SRUs on average, the LRU-indenture structure is almost single indenture. In the iterative procedure both a higher and lower LRU-definition are made compared to the sequential procedure. A lower LRU-definition in one of the five default instances led to a decrease of the number of spare systems, resulting in annual costs savings of €4,274,903 (23%). In three out of five instances, a higher LRU-definition was made compared to the sequential solution by the iterative procedure. The higher LRU-definition on average led to a decrease of spare parts holding costs resulting in annual costs savings of €208,903 (1.6%).

- **Level of repair:** In Table 5.17 the number of repairs and discards on echelon level are given. Of the 557 components that are repaired 473 (85%) are repaired at the third echelon level, 8 components (1%) are repaired at the second echelon, and 76 components

[2]According to the LRU-definition there are 181 SRUs, however 178 of these SRUsare not repaired or discarded because their parent component is already discarded.

Table 5.16: LRU-definition and repair/discard decision commuter train, average number of components and (standard deviation)

	Amount	**Repaired**	**Discarded**
Structure parts	521.5 (42.9)	-	-
LRUs	978.25 (45.5)	555.75 (21.7)	422.5 (36.1)
SRUs	3.25 (4.6)	1.5 (3)	1.75 (1.7)
Total	**1503**	**557.25 (21)**	**424.25 (34.7)**

(14%) are repaired at the first echelon. The later two groups of components do not require repair capabilities. Repairing 8 components at the second echelon is not optimal, but as a result of our iterative procedure such a solution may be the best one found. Of the 424 components being discarded, 393 components (92%) are discarded at the first echelon, 22 components (5%) are discarded at the second echelon, and 10 components (2%) are discarded at the third echelon. Discarding components at the second and third echelon level does not make sense, with the exception that the parent component is repaired at these echelon levels. However, this is not the case in any of our instances. Again, the iterative procedure is the cause of these counterintuitive results and discarding these components at the first echelon level would reduce the annual costs (i.e. the transport costs of these 32 components are eliminated).

Table 5.17: Level of repair/discard commuter train, average number and (standard deviation)

Ech.	**Repaired**	**Discarded**
1	76 (15)	392.5 (53)
2	8 (5.6)	22.25 (13)
3	473.25 (15.2)	9.5 (6.5)

- **Spare parts:** In Table 5.18 the annual holding costs associated with the spare parts for LRUs and SRUs on location level is presented. Most LRUs are stocked at echelon 1 (65.6%), and furthermore a significant amount of LRUs is put on stock at location 1 (23.82%). Given that there are only 3 maintenance significant SRUs, almost no SRUs are stocked. In Figure 5.7 the availability curve for five commuter train instances is depicted. The overshoot obtained by the marginal analysis of the average availability is 0.0035%.

Table 5.18: Spare part stocking holding costs commuter train (in euros)

	Loc. 1 (ech. 3)	**Loc. 2 (ech. 2)**	**Loc. 3 (ech. 1)**	**Loc. 4 (ech. 1)**
LRUs	326,016	51,790	449,064	448,789
SRUs	-	-	-	24
Total	**326,016**	**51,790**	**449,064**	**541,825**

- **Spare systems:** In all instances the most efficient solution is to install two spare systems at both operating sites. The two spare systems on each operating site is also the lower bound on spare systems required.

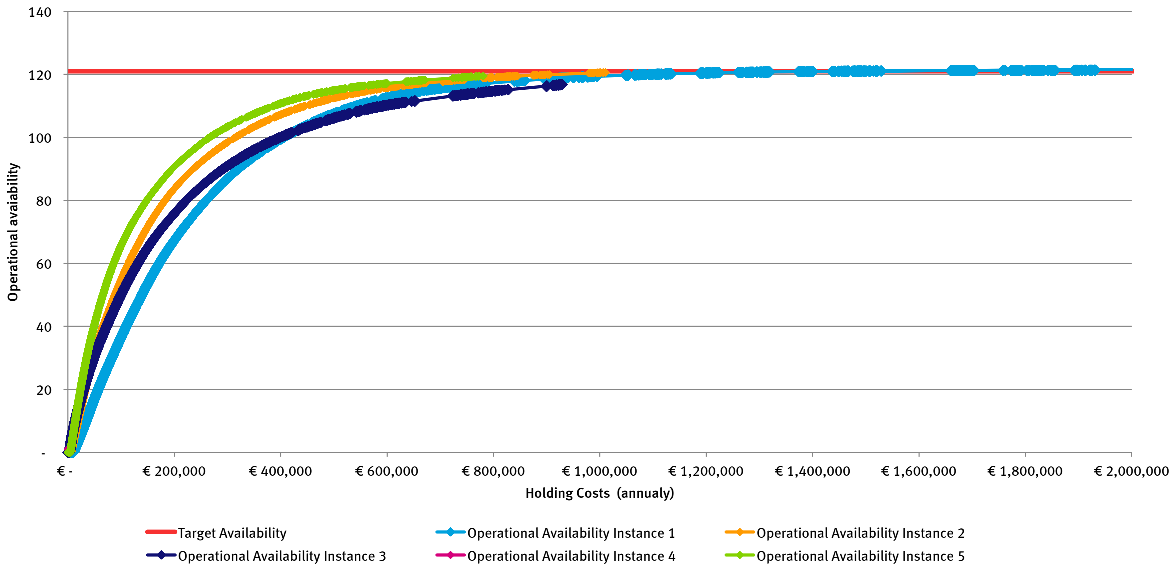


Figure 5.7: Availability curve: installed base approach commuter train ($s_0 = 2,\ \forall l \in L_1$)

5.6.2.4 Sensitivity analysis

In this section we present our findings from the sensitivity analysis performed on the high-speed train and commuter train experiments.

- **Repair costs:** Setting the repair costs factor to 1.2 does not change any decision significantly for both the high-speed and commuter train instances. Also, setting the repair factor to 0.8 does not change any decision significantly for the high-speed train instances. The LRU-definition of the commuter train becomes slightly lower when the repair factor is set to 0.8 compared to the default.
- **System cost:** There is no change in decisions due to a higher or lower system cost value.
- **Failure rate:** When the failure rate factor is set to 0.5 or to 2, decisions regarding LRU-definition and LORA do not change compared to the default factor of 1. However, the required number of spare parts increases with 14%[3] in case of a failure rate factor of 2, and decreases with 21% in case of a failure rate factor of 0.5.
- **Component cost:** Virtually no decisions are changed when changing the component cost factor. Remind that the repair and discard costs are both coupled to the component costs, therefore it is logical that no decision regarding the repair/discard decisions change.
- **Transport costs:** In case of the high-speed train business case, when doubling the transport costs, the number of components which is moved from the first to third echelon level (in order to be repaired) is reduced with 9.6%. This reduction is realized by a

[3]For the commuter train instances it was impossible to set the failure rate factor to two, because of memory limitations. Therefore, the 14% is based upon the high-speed instances only

slightly different LRU-definition, but mainly by discarding 19% more components. Since, the replenishment lead times in general are higher than the repair lead times, slightly more spare parts are required as a result of discarding more components. The total annual costs as a result of double transport costs only increase with 0.6%. When the the transport costs are halved in the high-speed business case, the LRU definition stays the same, but 9% less LRUs are discarded. As a result also 9% more LRUs are shipped to the third echelon where they are repaired. The costs only decrease with 0.1% as a result of halving the transport costs. In the commuter train instance, doubling the transport costs leads to a reduction of 15% of components shipped to the third echelon. This reduction is realized by defining lower indenture components as LRU thereby reducing the number of LRUs. Furthermore, the number of components being repaired is decreased with 12% and the number of components being discarded is increased with 14%. The costs only increase 0.27% as a result of doubling the transport costs. When halving the transport costs in the commuter business case, the LRU-definition becomes higher, resulting in more LRUs. The number of components shipped to the third echelon level is increased with 16%. In total 13% more components are repaired and 14% less components are discarded. The costs decrease 1.3% as a result of halving the transport costs.

- **Repair capabilities:** In case of the high-speed business case, when leaving out the repair capabilities almost all repairs are performed at the first echelon. As a result of the iterative procedure in two out of five instances, a solution is found where also repairs are performed at the third echelon. Obviously this is not optimal, however it is the most efficient solution found by the iterative procedure. As a result of leaving out the repair capabilities 9% more components are repaired. Furthermore, spare part costs are reduced with 13% as a result of repairing at the first echelon because of no shipment (lead times) and because repair lead times are shorter than replenishment lead times (i.e. fewer components are discarded). As a result of leaving out the repair capabilities, the total costs for the high-speed train instance decrease with €533,858 (4.7%), which is significantly less than the repair capability costs of €3.5 million. When leaving out the repair capabilities in the commuter train instance, a somewhat lower LRU-definition is made compared with the default case, resulting in a 2% decrease of LRUs. Furthermore, 14.7% more components are repaired and 26.6% fewer components are discarded. As a result the total costs decrease with €1,701,573 (11.3%), caused by a reduction of the repair costs of 20% and a reduction of 13.4% on spare parts costs. Obviously, installing repair capabilities in the commuter train case is not optimal given the annual cost of €7 million and cost reduction of only €1,701,573.

- **Holding costs:** Setting the holding costs factor to 2 or to 0.5, does not result in a different LRU-definition or LORA decision in case of the high-speed train (i.e. the sequential solution is the best solution found). In case of the commuter train, setting the holding costs factor to 0.5 results in a slightly lower LRU-definition, and setting the holding costs factor to 2 does result in a slightly higher LRU-definition. Obviously the spare parts stocking solution is not influenced by the holding costs factor, since the holding costs for all components are increased with the same factor.

5.7 Managerial insights

In this section, we will discuss the insights we gained during the business case from a managerial perspective.

5.7.1 Data and information

As mentioned in Section 5.1, gathering the required data is a troublesome process, because of the large number of stakeholders involved. However, for both the SLT and the V250 a large amount of data was provided by the system integrators. The data provided by the system integrators for the SLT and V250 are:

- Breakdown structure
- Failure Mode and Criticality Analysis (FMECA)
- Reliability Centered Maintenance (RCM)

In general there is no coupling between the breakdown structure, FMECA, and RCM. This means that there is no (unique) component identification in both the FMECA, and RCM so that the failure mode/maintenance task can be related to a component. The relationship between a failuremode/maintenance task now has to be made via textual information or expert knowledge, hence this is a complex and time consuming process. Furthermore, the data of the SLT is not at system level but at subsystem level (OEM-level). As a result, the gathering and coupling of data becomes even more complex and time consuming. In the defense industry, logistic and logistic related data is stored in a so-called Logistic Support Analysis Record (LSAR) (Jones, 2006). In Figure 5.8 the structure of a LSAR, which is a relational database, is depicted. The starting point of a LSAR is a Computer Aided Design (CAD), combining the CAD with a reliability prediction, an FMECA is generated. Based upon this FMECA, a preventive maintenance program (RCM) is defined. The maintainability prediction, FMECA, and RCM, are the sources of the LSAR. Compared to the situation of NEDTRAIN, the LSAR-framework explicitly couples the different entities. The relationships between the different logistic and logistic related data results in a relational database, where such relational database is not used by either the system integrator nor by NEDTRAIN. Furthermore, the LSAR contains all data from the physical support analysis process. Hence, data such as repair-times, exchange-times and required capabilities is present, where in the case of NEDTRAIN, this data is only present at a high abstract level.

Note that in contrast to what the LSAR-framework from Jones (2006) implies, in our model, the LORA and spare parts problem are solved as an integral problem. The results of the LORA and spare part stocking optimization are stored in the LSAR. As a result the required spare parts, tools & support equipment, facilities can be determined. Furthermore, the LCC can be computed based on all the data stored in the LSAR. In the case of NEDTRAIN, the LCC are calculated using information of the FMECA, and the RCM, hereby the spare part costs, the tools & equipment costs, and facilities costs are not taken into account.

5.7.2 LRU-definition

Based on the results from our experiments, the current paradigm to define first indenture components as LRU is not cost optimal. Instead, we obtain LRU-definitions such that mainly

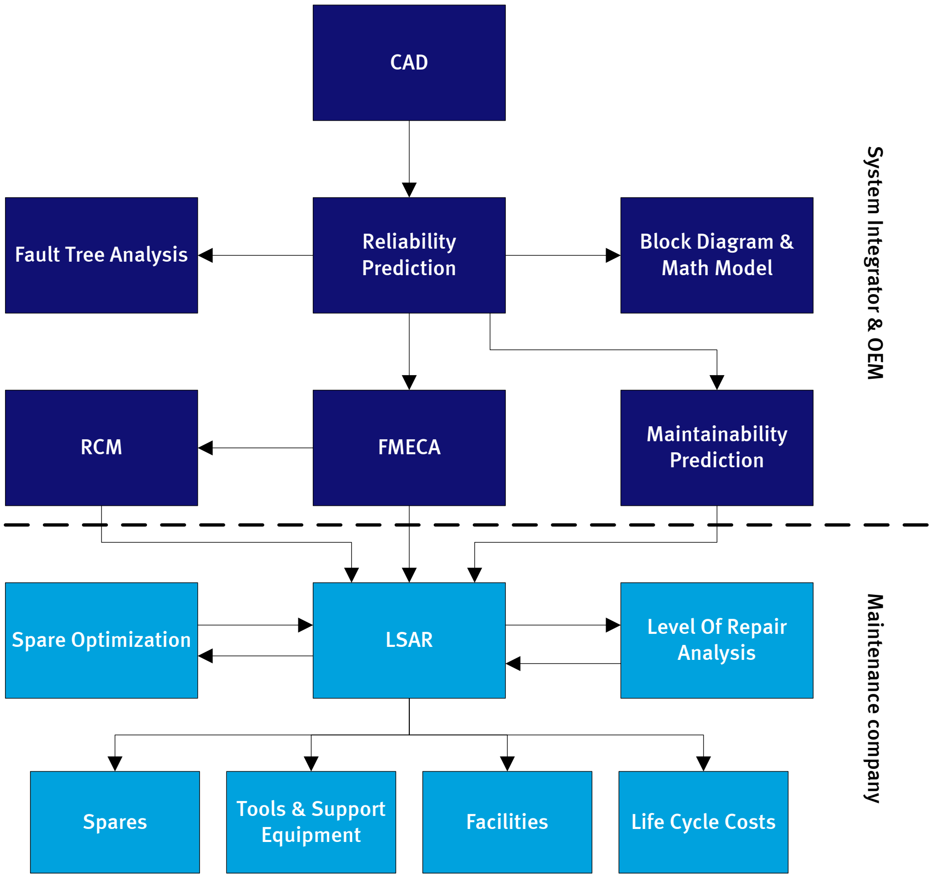


Figure 5.8: LSAR common-source database (Jones, 2006)

highest indenture components are defined as LRU. Compared to defining first indenture components as LRU the LRU-definition obtained by our mathematical model result in 54% lower costs.

Given that the downtime costs for capital goods are high, the replacement time is one of the criteria to define LRU. In our business case we found out that the time to replace a component decreases along the indenture level from the first indenture level to the highest indenture level (i.e. replacing a sub-subsystem occupies more time than replacing a part). However, the time to isolate a failure increases along the indenture level. In Figure 5.9 a graph is depicted showing the relationship between the indenture levels and mean replacement time. Obviously, based on the replacement time one would define second indenture components as LRU such that the replacement time and costs are minimized.

In our experiments it became clear that even tough the replacement costs for second indenture components are more than 80% lower than for fourth indenture components and the replacement costs of third indenture components are more than 50% lower than for fourth indenture components, still defining fourth indenture components as LRU is more cost efficient. When defining fourth indenture components as LRU, the components only need to be replaced and can be directly repaired somewhere in the repair network afterwards. Where in case of defining second/third indenture components as LRU, first the second/third indenture LRU components

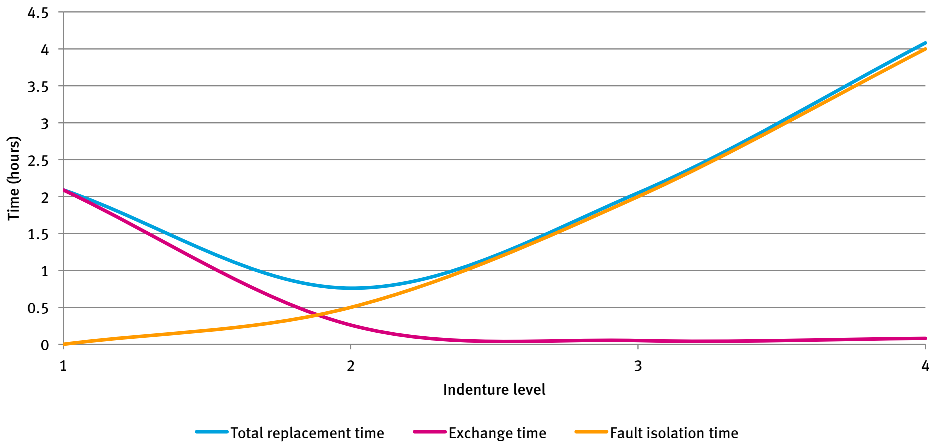


Figure 5.9: Replacement time components as a function of the indenture level (in hours)

need to be replaced from the system and accordingly the failed SRU components need to be replaced from the LRU afterwards. Hence, the repair costs are higher when defining second/third indenture components as LRU compared to defining fourth indenture components as LRU. Besides, when taking into account the number of spare systems that need to be installed as a result of the LRU-definition, defining fourth indenture components in most cases is an efficient solution. However, in some cases it could be that a slightly lower LRU-definition (defining some third indenture components as LRU) reduces the number of spare systems required.

The spare parts holding costs also play an important role in defining LRUs. When defining first indenture components as LRU, these relatively expensive components and all of their SRU subcomponents should be put on stock, resulting in high spare parts holding costs. When defining the highest indenture components as LRU only these relatively cheap components need to be put on stock, resulting in low spare parts holding costs. Although our mathematical model (via an iterative procedure) also takes into account the holding costs when defining LRUs, in the high-speed train business case the holding costs were not required to obtain an efficient LRU-definition. Instead, defining LRUs based on replacement and repair costs already resulted in an efficient LRU-definition, and taking the spare parts holding costs into account in the LRU-definition did not change the LRU-definition. This is the result of the replacement and repair costs characteristics of the high-speed train that imply that defining the highest indenture components as LRU is efficient. Given the serial repair network of the high-speed train, such LRU-definition is also optimal from a spare parts perspective. In case of the commuter train, the iterative procedure does result in better solutions compared to the sequential procedure. Both higher and lower LRU-definitions are found by the iterative procedure compared to the sequential procedure. Where a lower LRU-definition leads to lower spare systems holding costs, and a higher LRU-definition to lower spare parts holding costs. On average taking into account the holding costs in the LRU-definition results in 3.5% lower costs compared to when not taking them into account.

Also the transport costs are an important factor in defining LRUs. When the transport costs are relatively high, it becomes more efficient to define lower indenture components as LRU. Defining lower indenture components means that there are fewer LRUs that need to be shipped to a repair facility.

In summary, the most important managerial insights regarding LRU-definition are:

- The paradigm to replace first indenture components upon failure of a system is far from optimal and results in high replacement, repair and spare part holding costs.
- By taking into account the spare parts holding costs in the LRU-definition on average the total costs are 3.5% lower.
- In case of relatively high transport costs it is efficient to define lower indenture components as LRU such that the number of shipments is decreased.

5.7.3 Level Of Repair Analysis

Given the high investment required to install repair capabilities at a location (€3.5 million annually) in both business cases it was found that repairing components at the third echelon as currently is the practice at NEDTRAIN is optimal. Installing capabilities at the first echelon for the high-speed train, results in costs savings of €533,858 caused by a reduction of spare parts holding costs, which is significantly lower than the investment required. In case of the commuter train, installing capabilities results in costs saving of €1,701,573 caused by a reduction of repair and spare parts holding costs. However, given that there are two operating sites for the commuter train, annual costs for having repair capabilities at the operating sites are €7 million. Obviously, the current repair network of NEDTRAIN is cost optimal.

Although on average repairing a component only costs 45% of discarding a component (excluding costs to move the component to the repair facility), on average 31.5% and 43.2% of the components are discarded upon failure for the high-speed and commuter train respectively. Noteworthy, almost all LRUs with child components defined as SRU are discarded upon failure, such that almost no SRUs remain. For the commuter train more components are discarded compared to the high-speed train, because the commuter train discard costs are lower compared to the transport costs (remind that the repair and discard costs ratio is the same for both business cases). When doubling the transport costs, on average 37.4% and 49.6% of the components are discarded for the high-speed and commuter train respectively. In the case that the transport cost are halve the default value, on average 26.2% and 36.4% of the components for the high-speed and commuter train are discarded.

Discarding components leads to higher spare parts holding costs, since the average replenishment lead time is higher than the average repair lead time. In the high-speed train business case however, taking into account the spare parts holding costs in the LRU-definition and LORA did not result in a better solution compared to not taking into account these costs. However, in the commuter train business case taking into account the spare parts holding costs did result in better solutions.

In summary, the most important managerial insights regarding LRU-definition are:

- Given the high costs associated with installing repair capabilities, installing them at the first or second echelon will not result in a decrease of costs.

- On average 37% of the LRU and SRU components are discarded, hence taking into account the discard option is relevant.
- The transport costs are an important cost factor while making the repair/discard decision.

5.7.4 Spare parts stocking and spare systems

As a result of the LRU-definition and LORA almost only LRUs need to be put on stock, since there are almost no SRUs.

For the high-speed train (V250), the initial spare parts list of NEDTRAIN implies that the annual spare part holding costs will be around €3.5 million. Furthermore, three spare systems are installed at the operating site, resulting in annual spare systems holding costs of €10.2 million. Hence, the total annual holding costs obtained by NEDTRAIN are €13.7 million. Our mathematical model (based upon VARI-METRIC) finds a different solution than the engineers and logistic experts from NEDTRAIN. Only one spare system is installed at the operating site, resulting in annual spare systems holding costs of €3.4 million. Compared to the solution from NEDTRAIN more spare parts are required, namely €4.7 million. Hence, we obtain total annual holding costs of €8.1 million, which is €5.6 million fewer compared to the solution of NEDTRAIN.

For the commuter train (SLT), our most efficient solution is to install two spare systems at both operating sites, where six spare systems more are installed by NEDTRAIN. The spare parts stocking solution is such that the annual spare parts holding costs are only €1,392,020.

Chapter 6

Conclusion and recommendations

This project covers the design of a logistic support system for capital goods. In addition to the literature we include LRU-definition, replacement time and spare systems. This is done by developing a mathematical model for the LRU-definition, coupling this to the existing LORA formulation of Basten et al. (2009c), and extending VARI-METRIC. The mathematical models are implemented, and used to solve business cases of NEDTRAIN, thereby gaining managerial insights. In this chapter we draw conclusions and make recommendations from both a scientific and practical perspective. First in Section 6.1 the conclusions are discussed and in Section 6.2 recommendations are made for both researchers and practitioners.

6.1 Conclusions

The conclusions based upon our research are:

- **LRU-definition:** Based upon the results from our experiments, we have shown that the addition of LRU-definition (research question 2) and thus replacement time (research question 3) leads to a new vision on which components to replace upon failure of a system. From our experiments becomes clear that the current paradigm to define first indenture components as LRU is not the optimal policy and that defining the highest indenture components results in 54% lower costs. Compared to defining the first indenture components as LRU defining the highest indenture components as LRU leads to significantly lower spare parts holding costs.

- **Level Of Repair Analysis:** From the LORA results, we conclude that the current design is determinative on where to repair components. This is due to the huge investment required to install repair capabilities. Furthermore, our experiments suggest that about 37% of the components upon failure should be discarded.

- **Spare parts stocking and spare systems:** Instead of the supply availability, we measure the operational availability (research question 3) in number of systems. Furthermore, the introduction of the installed base, leads to more efficient solutions compared to the system approach. The spare parts and spare systems holding costs should be taken into account while defining LRUs, because on average this results in 3.5% lower costs with a maximum of 23%.

- **Large instances:** Using our mathematical model and optimization procedure we have solved two business cases. Both business cases can be classified as large instances. Hence, we have shown that our model is capable of solving real-life large instances (research question 4).

6.2 Recommendations

First in Section 6.2.1 we discuss the recommendations from a practitioners perspective. Next, in Section 6.2.2 the recommendations from a scientific perspective are discussed.

6.2.1 Practitioner Recommendations

The recommendations made in this section, are for maintenance organizations in general and sometimes are specific to NEDTRAIN.

- **Logistic Support Analysis Record:** Currently, upon acquisition of new rolling stock, data such as breakdown structures, FMECAs, and RCMs are delivered by the system integrator to NEDTRAIN. The data provided by the system integrators are detailed, however the data-structure used is not optimal. Therefore, we recommend NEDTRAIN to define deliverables regarding the supply of data to the system integrators. As a framework the LSAR (e.g Jones, 2006) could be used. The essence of the LSAR is that it is a relational database where keys are used to explicitly model the relationship between components and maintenance activities. As a result our model can be directly applied and deliver cost efficient solutions regarding LRU-definition, LORA, and spare part stocking within hours.
- **LRU-definition and LORA:** The current paradigm to define first indenture components as LRU is far from optimal, given the results of our experiments. Therefore, we recommend NEDTRAIN to define the highest indenture components as LRU. Furthermore, we recommend maintenance organizations to use our model to define LRUs. Crucial parameters for the LRU-definition are: the replacement, repair, discard, and transport costs. Based upon these parameters an LRU-definition and LORA can be performed. To further improve the LRU-definition and LORA decisions, one could also take into account the spare parts and spare systems holding costs while performing an LRU-definition and LORA.
- **Spare part stocking:** In general the decision on how many systems to install and how many spare parts to stock is made separately. As a result of our work, it is possible to solve these two subproblems in one, thereby minimizing the sum of spare parts and spare systems holding costs. Therefore, we recommend maintenance organizations of capital goods, to use our installed base approach instead of using an item or system approach.

6.2.2 Scientific Recommendations

In this section we present some recommendations for further research:

- **Structure parts:** We assume that the repair path between an LRU and the highest indenture component exist of SRUs only. As a result, LRUs and SRUs need to be disassembled step by step, while in reality it could be interesting to skip indenture levels and directly replace the highest indenture component from the LRU. To represent the case that indenture levels are 'skipped' while repairing an LRU, we recommend to extend our model such that components between the LRU and highest indenture component may be defined as structure part.

- **Divergent network:** Although we also dealt with a divergent network in the business case, it could be that a broader divergent network (i.e. more than two locations on the first echelon level) leads to a different LRU-definition because of spare parts pooling effects. In case of a larger number of operating sites it very well could be that by defining lower indenture components as LRU and stocking them centrally, the demand to spare parts is pooled both from a component and location perspective. Therefore, we recommend to use our model to solve instances with more locations on the first echelon level with only one location at the second echelon level.

- **Capacitated capabilities:** In our model we assume that repair lead times are planned. Although, maintenance companies such as NEDTRAIN use planned repair lead time concepts, other maintenance companies do not use planned lead times and therefore our assumption could be invalid to them. Therefore, we recommend to extend our model such that it takes into account capacitated capabilities. We know that regarding LORA, Basten et al. (2011b) allows for capacitated capabilities, and that regarding the spare parts stocking problem also literature is available (e.g. Sleptchenko et al., 2002 and Avşar and Zijm, 2000) on capacitated capabilities.

- **Clustering:** Given, that the repair by replacement strategy at NEDTRAIN is such that replacing multiple LRUs is not clustered, we did not take clustering into account. However, extending our model with the option that it takes into account clustering, would make it more general. Hence, we recommend to extend our model with the option to cluster the replacement of multiple LRU.

- **Replacement at higher echelon levels:** Currently, our model assumes that the replacement of LRUs is performed at the first echelon only. However, it could be that because of expensive capabilities required to replace LRUs, it is more efficient to replace them more central at a higher echelon level.

Appendix A

Notation

Input	**Type**	**Meaning**
C	Set	Components
$C_i \subset C$	Set	Components at indenture level i
Z_c	Integer	Number of occurrences of component c in the system, where $Z_i \geq 1$
Γ_c	Set	Direct subcomponents of component c
Φ_c	Set	Offspring of component c
$I = \{0, \ldots, i_{\max}\}$	Set	Indenture levels, where $i_{\max} > 0$
$E = \{1, \ldots, e_{\max}\}$	Set	Echelon levels, where $e_{\max} > 0$
L	Set	Locations
L_e	Set	Locations at echelon level e
R	Set	Resources
Π_l	Set	Child locations of location l
Ω_r	Set	Set of all tuples (c, j)
Θ_l	Set	of operating sites supplied by location l either directly or via offspring locations
K_c	Real	Replacement time (in years) of component c, where $K_c \geq 0$
m_c	Real	Annual number of direct failures of component c, where $m_c \geq 0$ for all components, and for the childless components $m_c > 0$
T_l	Integer	Target availability at location l (in number of systems)
T	Integer	Target availability entire installed base (in number of systems)
$vc_{c,e,d}$	Real	Variable costs if decision d is made at echelon level e for component c, where $vc_{c,e,d} > 0$
$fc_{r,e}$	Real	Fixed costs for installing resource r at echelon level e, where $fc_{r,e} > 0$
rc_c	Real	Replacement costs, where $rc_c > 0$
hc_c	Real	Annual costs of holding a spare part ($c > 0$) or spare system ($c = 0$), where $hc_c > 0$

Auxiliary	**Type**	**Meaning**
$D = \{\text{discard,repair,move}\}$	Set	LORA decisions
D_e	Set	Possible LORA decisions at echelon level e
$G = \{\text{LRU}, \text{SRU}, \text{structure part}\}$	Set	LRU-definition
$J = \{\text{repair,replace}\}$	Set	Maintenance tasks

Output	**Type**	**Meaning**
λ_c	Real	Annual replacement rate of component c (the rate with which c and its offspring is replaced or repaired)
$Z_{c,g}$	Binary	1, if for component LRU-definition g is chosen, 0 otherwise
$\rho_{c,g}$	Real	The rate with which component c is replaced (g = LRU) or repaired (g = SRU)
$X_{c,e,d}$	Binary	1, if for component c at echelon level e decision d is chosen, 0 otherwise
$\pi_{c,e,d}$	Real	The rate with which for component c decision d is performed at echelon level e
$Y_{r,e}$	Binary	1, if capability r is installed at echelon level e, 0 otherwise
$S_{c,l}$	Integer	The number of spare parts ($c > 0$) and spare systems ($c = 0$) stocked at location l
ω	Set	The set of components defined as LRU
$BO_{c,l}$	Real	Number of back orders of component c at location l
$EBO_{c,l}$	Real	Expected number of back orders of component c at location l

Appendix B

Linearization IP

The objective function 4.1 contains two non-linear expressions. The first one is the multiplication of the individual arrival rate λ_c with $X_{c,e,d}$. The second expression which is non-linear is the multiplication of λ_c with $Z_{c,g}$. In both expressions, λ_c is a variable and $X_{c,e,d}$ and $Z_{c,g}$ are both decision variables. Hence, multiplication of these variables leads to a non-linear expression. To overcome this issue, we introduce two new variable, $\pi_{c,e,d}$ and $\rho_{c,g}$, where the former is replacing the first non-linear expression and the latter is replacing the second non-linear expression. Now the objective function becomes:

$$\min \sum_{c\in C}\sum_{e\in E}\sum_{d\in D} vc_{c,e,d}\cdot\pi_{c,e,d} + \sum_{r\in R}\sum_{e\in E} fc_{r,e}\cdot Y_{r,e} + \sum_{c\in C} rc_c\cdot\rho_{c,\text{LRU}} \tag{B.1}$$

Accordingly the following constraints are added:

$$\pi_{c,e,d} \leq \lambda'_c \cdot X_{c,e,d},\ \forall c\in C,\ \forall e\in E,\ \forall d\in D \tag{B.2}$$

$$\pi_{c,e,d} \leq \lambda_c, \forall c\in C,\ \forall e\in E,\ \forall d\in D \tag{B.3}$$

$$\pi_{c,e,d} \geq \lambda_c - \lambda'_c\cdot(1-X_{c,e,d}),\ \forall c\in C,\ \forall e\in E,\ \forall d\in D \tag{B.4}$$

$$\pi_{c,e,d} \geq 0, \forall c\in C,\ \forall e\in E,\ \forall d\in D \tag{B.5}$$

$$\rho_{c,g} \leq \lambda'_c\cdot Z_{c,g},\ \forall c\in C,\ \forall g\in G \tag{B.6}$$

$$\rho_{c,g} \leq \lambda_c, \forall c\in C,\ \forall g\in G \tag{B.7}$$

$$\rho_{c,g} \geq \lambda_c - \lambda'_c\cdot(1-Z_{c,g}),\ \forall c\in C,\ \forall g\in G \tag{B.8}$$

$$\rho_{c,g} \geq 0, \forall c\in C,\ \forall g\in G \tag{B.9}$$

Now, Constraint 4.6 can be linearized as follows:

$$\lambda'_c \leq \rho_{c,\text{LRU}} + \pi_{c,\text{SRU}},\ \forall c\in C \tag{B.10}$$

Appendix C

Implementation EBO-curves using a double linked list

The EBO-curves (see Section 4.2.1 for a description) in the implementation model are represented by two classes: POINT and CURVE. In Figure C.1, the two classes and their attributes are depicted. Note that both the class POINT and CURVE contain pointers and form a double linked list. In the case of the POINT class these pointers are used to connect the various efficient points from the EBO-curve.

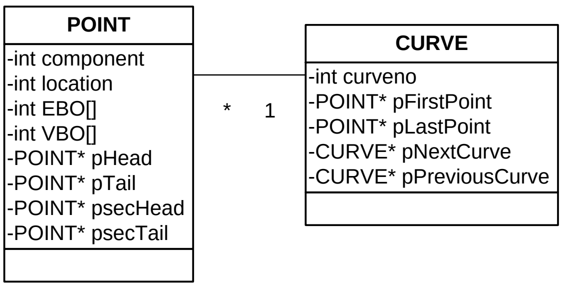


Figure C.1: UML-diagram POINT and CURVE: representing the EBO-curves generated by VARI-METRIC using the marginal approach

In Figure C.2 an example double linked list is depicted. The arrows indicated the pointers pHead (pointing from left to right) and pTail (pointing from right to left). Using the pointers, one can obtain the stock values without having to store an array with stock quantities for each point. The second data-point, for example, represents putting one component on stock at both location 2 and 3. The latest point represents the case that two components are put on stock at location 3, and one component is put on stock at both location 1 and 2.

The pointers psecHead and psecTail are used to connect the efficient points from the different EBO-curves in the marginal analysis. In Figure C.3 an example double linked list representing an EBO-curve after marginal analysis is depicted. Note that points on the EBO-curve after marginal analysis do not have to mean that one component is put on stock compared to the previous point. To determine the stock allocation for a certain point on the EBO-curve after

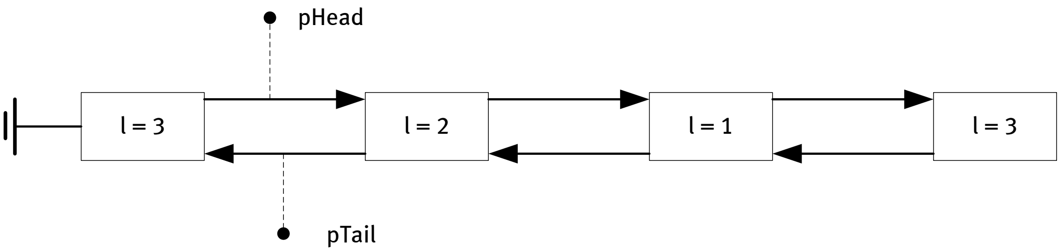


Figure C.2: Double linked list: representing a single EBO-curve

marginal analysis, one should start at that point by first iterating trough the linked list using the pHead pointer, and then proceed to the following efficient point by following the pointer psecHead.

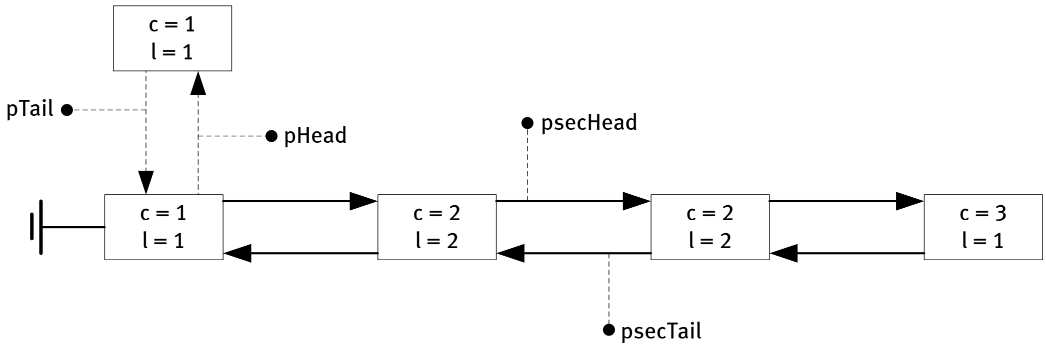


Figure C.3: Double linked list, after marginal analysis: representing two EBO-curve

Appendix D

Characteristics distributions

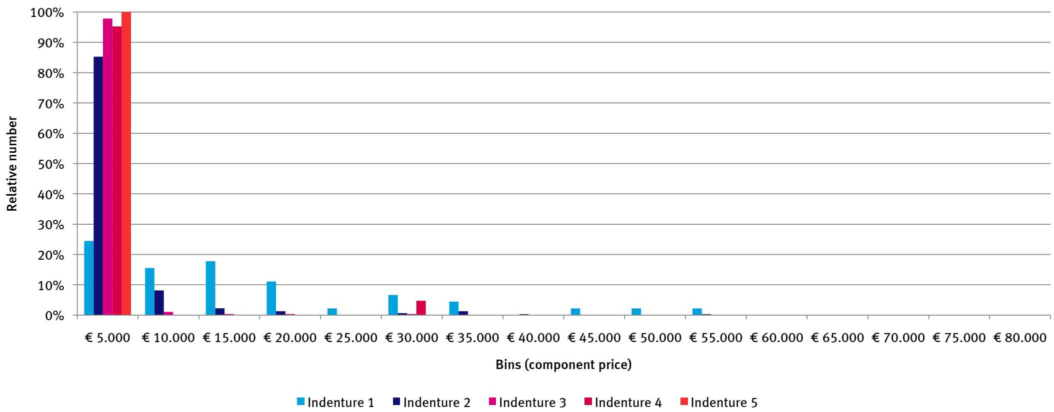


Figure D.1: Histogram of component price per indenture level: the percentage depicted represents the relative number for the corresponding indenture level, which is in the bin of the component price (in total three first indenture components have a higher price than €80k)

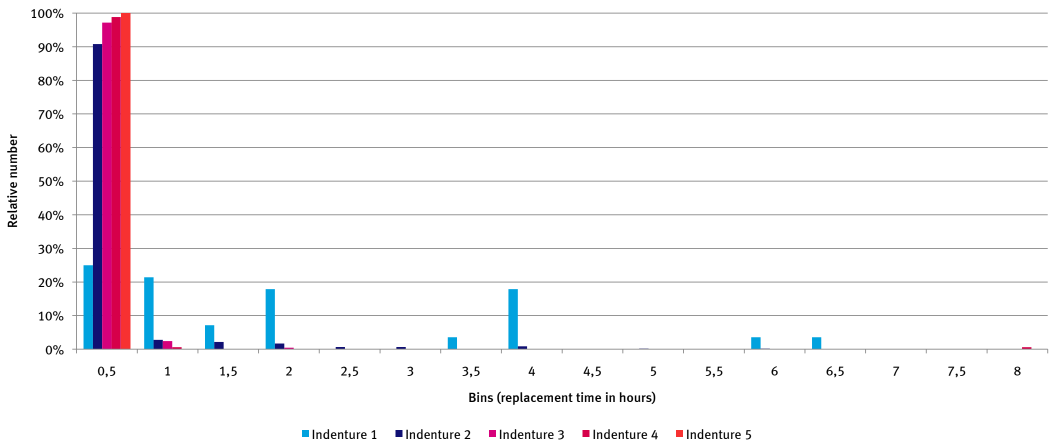


Figure D.2: Histogram of replacement times per indenture level: the percentages depicted in the figure represent the relative number of components which are in the bin of the replacement time

Appendix E

Distributions fitting

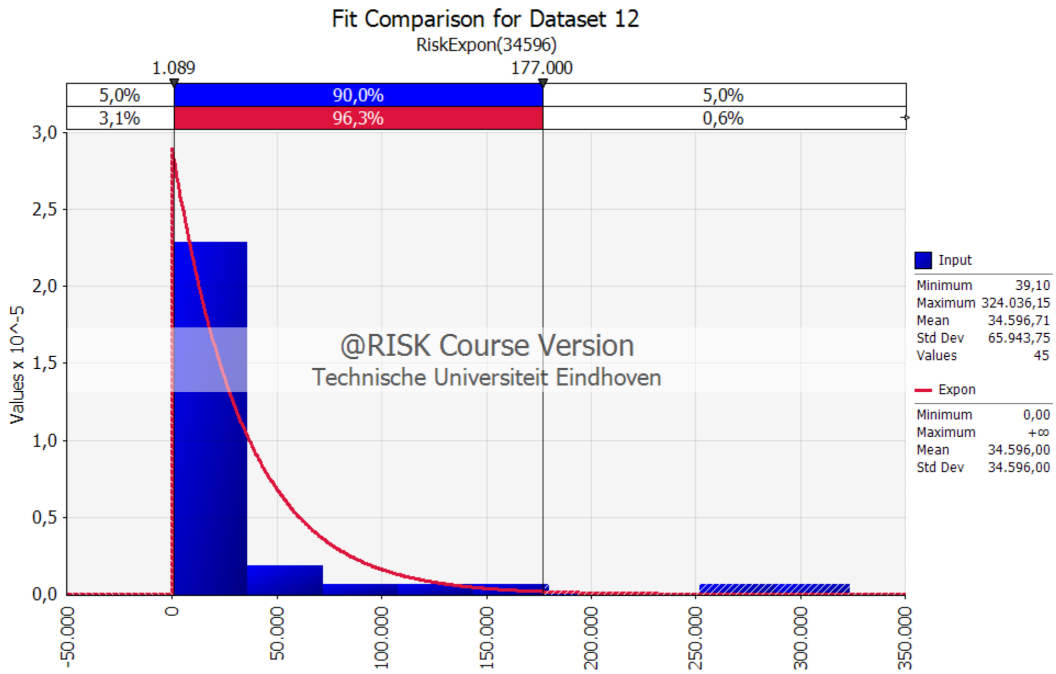


Figure E.1: Distribution fit on component price first indenture; Exponential with parameter $\lambda = 34.596$ and a goodness of fit $\mathcal{X}^2 = 18.11$

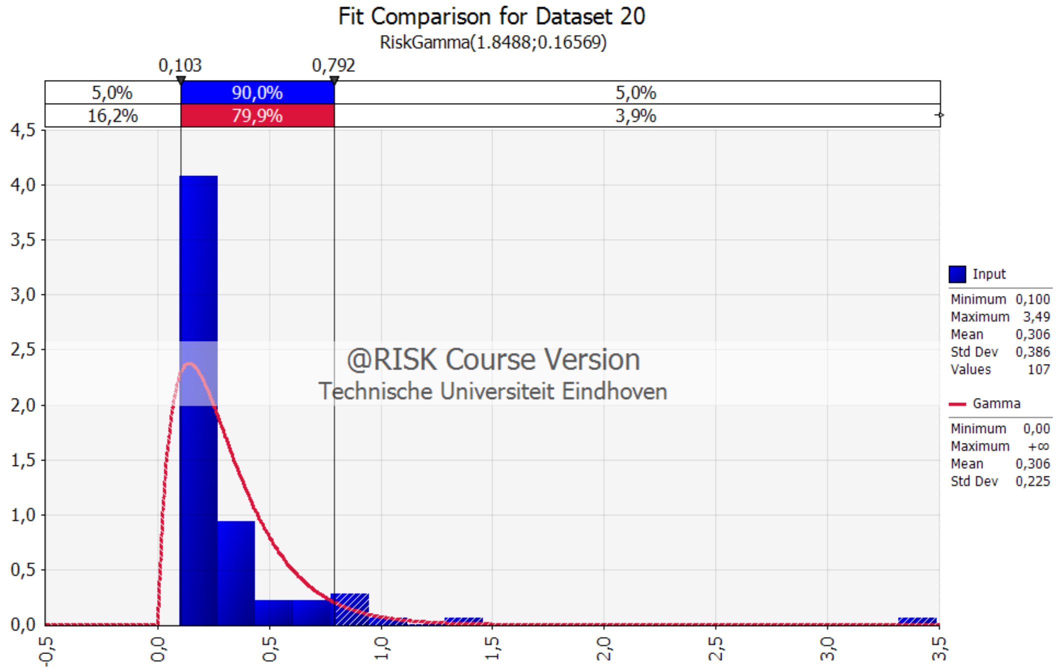


Figure E.2: Distribution fit on the annual failure rate; Gamma distribution with parameters: $\Gamma(1.85; 0.17)$ and a goodness of fit $\mathcal{X}^2 = 63.6$

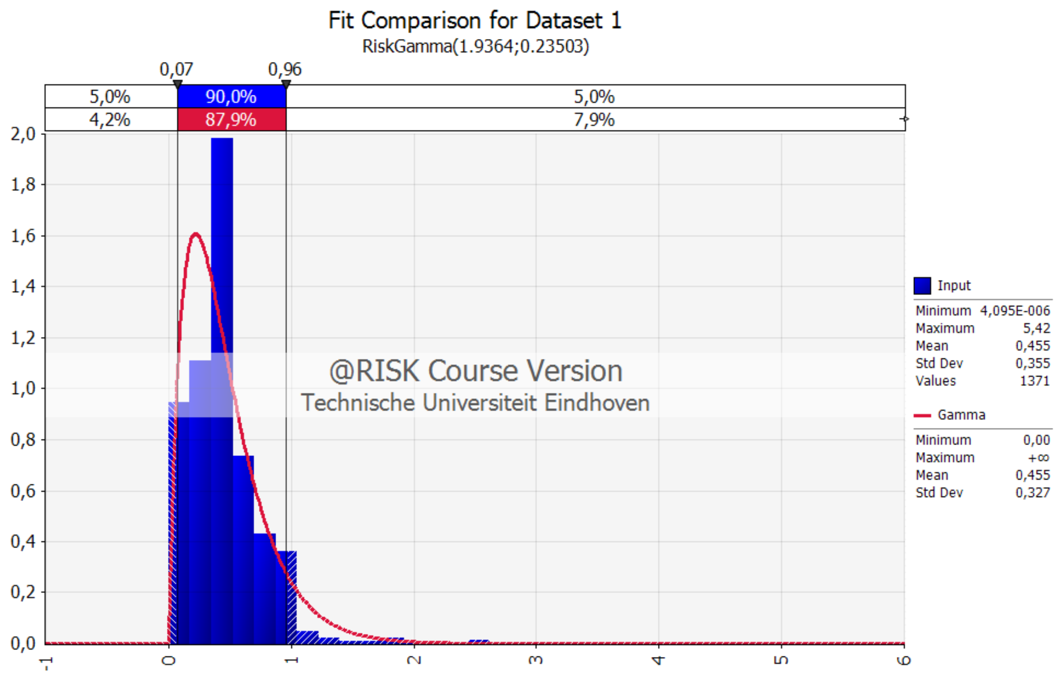


Figure E.3: Distribution fit on the fraction of repair costs divided by the new price; Gamma distribution with parameters: $\Gamma(1.94; 0.24)$ and a goodness of fit $\mathcal{X}^2 = 1639.3$

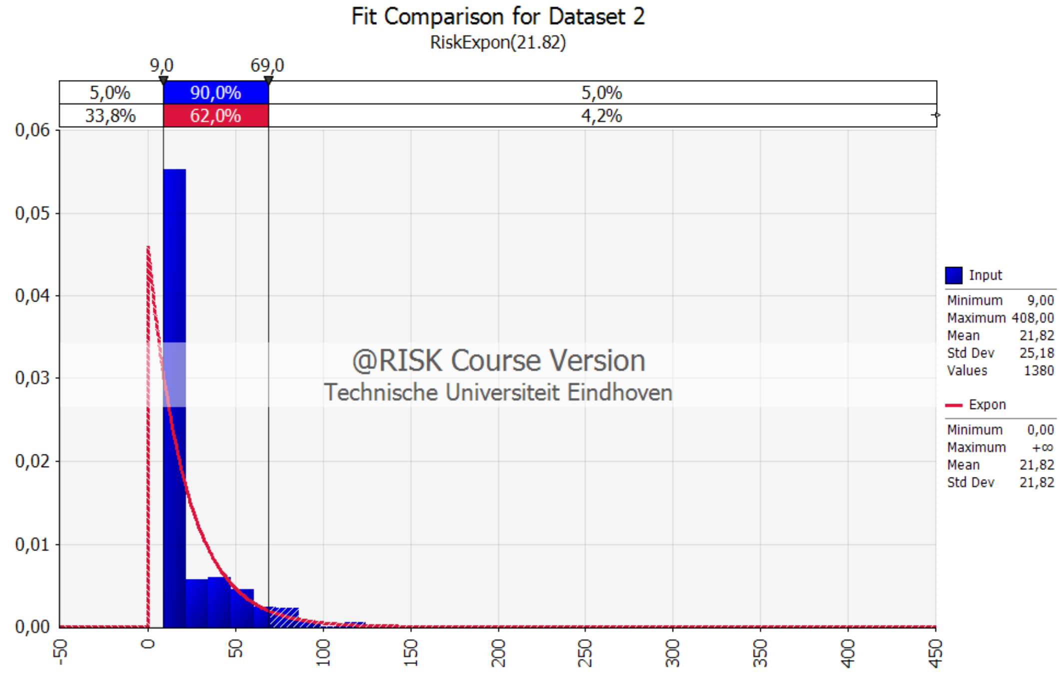


Figure E.4: Distribution fit on the repair lead time; Exponential distribution with parameter $\lambda = 21.82$ and a goodness of fit $\mathcal{X}^2 = 15307.1$

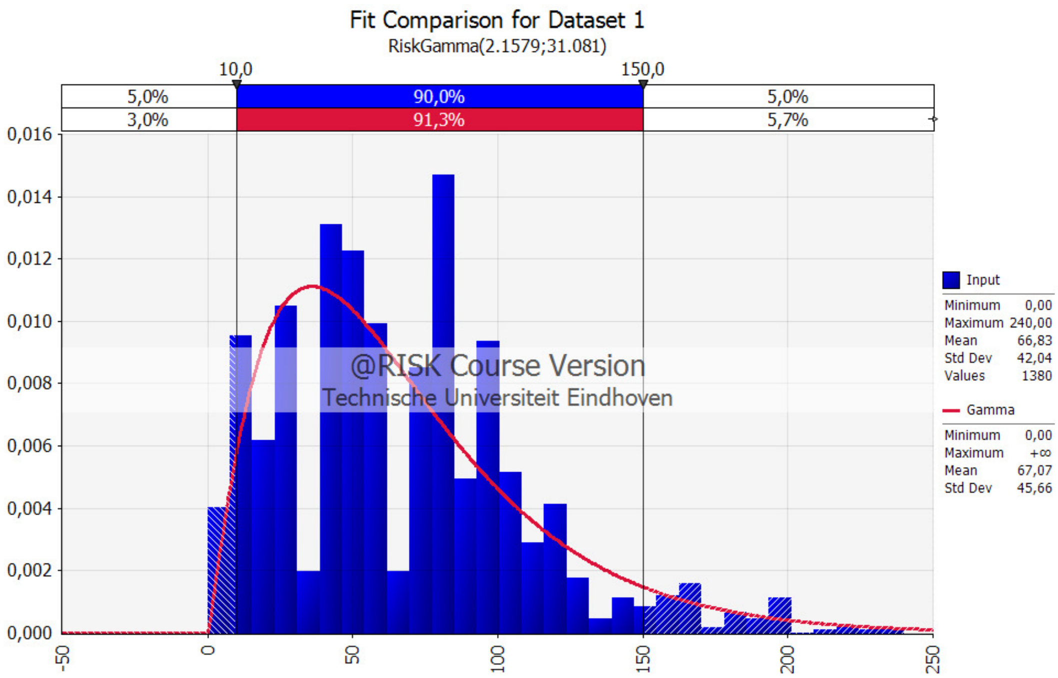


Figure E.5: Distribution fit on lead time suppliers; Gamma distribution with parameters $\Gamma(2.16; 31.08)$ and $\mathcal{X}^2 = 1158.2$

Bibliography

P. Alfredsson. Optimization of multi-echelon repairable item inventory systems with simultaneous location of repair facilities. *European Journal of Operational Research*, 99:584–595, 1997.

J. Arts and M. Driessen. Case study: Nedtrain B.V. 2011. Working paper.

Z.M. Avşar and W.H.M. Zijm. Resource-constrained two-echelon inventory models for repairable item systems. 2000. University of Twente Faculty of Mathematical Sciences.

L. Barros. The optimization of repair decisions using life-cycle cost parameters. *IMA Journal of Mathematics Applied in Business & Industry*, (9):40–413, 1998.

L. Barros and M. Riley. European journal of operational research. *IMA Journal of Mathematics Applied in Business & Industry*, (129):242–251, 2001.

R.J.I. Basten. *Designing logistics support systems, Level of repair analysis and spare parts inventories.* PhD thesis, University of Twente, Enschede, the Netherlands, 2009.

R.J.I. Basten, M.C. Van der Heijden, and J.M.J Schutten. An iterative method for the simultaneous optimization of repair decisions and spare parts stocks. *Beta working paper 295*, 2009a.

R.J.I. Basten, E. Kutanoglu, and M.C. Van der Heijden. An optimal approach for the joint problem of level of repair analysis and spare parts stocking. *Beta Working paper 298*, 2009b. submitted for publication.

R.J.I. Basten, J.M.J. Schutten, and M.C. Van der Heijden. An efficient model formulation for level of repair analysis. *Annals of Operation research*, 72, 2009c.

R.J.I. Basten, M.C. Van der Heijden, and J.M.J Schutten. A minimum cost flow model for level of repair analysis. *International Journal of Production Economics*, 133:233–242, 2011a.

R.J.I. Basten, M.C. Van der Heijden, and J.M.J Schutten. Practical extensions to a minimum cost flow model for level of repair analysis. *European Journal of Operational Research*, 211: 333–342, 2011b.

E. S. Brick and E. Uchoa. A facility location and installation of resources model for level of repair analysis. *European Journal of Operational Research*, 192(2):479 – 486, 2009.

K.S. de Smidt-Destombes, N.P. van Elst, A.I. Barros, and H. Mulder. A spareparts model with cold-standby redundancy on system level. *Computers and Operations Research*, 2010.

S. C. Graves. A multi-echelon inventory model for a repairable item with one-for-one replenishment. *Management Science*, 31(10):pp. 1247–1256, 1985.

J. V. Jones. *Integrated Logistics Support Handbook.* McGraw-Hill, 2006.

E. Kalvelagen. CPLEX mixed integer programs and time limits. `http://yetanothermathprogrammingconsultant.blogspot.com/2011/09/cplex-mip-and-time-limits.html`, 2011. last checked on 10 October 2011.

I.I. Mitroff, L.R. Pondy, and F. R. Sagasti. On managing science in the system age: two schemas for the study of science as a whole system phenomenon. *Interfaces*, 1974.

J.A. Muckstadt. A model for a multi-item, multi-indenture inventory system. *The International Journal of Management Science*, 20:472–481, 1973.

J.A. Muckstadt. *Analysis and Algorithms for Service Parts Supply Chains.* Springer, New York (NY), 2005.

E. Ozkan. New control mechanisms for the repairables in NEDTRAIN. Master's thesis, University of Technology Eindhoven, Netherlands, 2010.

J.W. Rustenburg, G.J van Houtum, and W.H.M. Zijm. *Exact and Approximate Analysis of Multi-Echelon, Multi-Indenture Spare Parts Systems with Commonality*, volume 63. Springer US, 2003.

F.R. Sagasti. Operations research from the viewpoint of general system theory. *The international Journal of Management Science*, 1(6):695–709, 1973.

H. Saranga and D. Dinesh Kumar. Optimization of aircraft maintenance/support infrastructure using genetic algorithms-level of repair analysis. *Annals of Operation Research*, (143): 91–106, 2006.

C. C. Sherbrooke. VARI-METRIC: Improved approximations for multi-indenture, multi-echelon availability models. *Operations Research*, 34(2):pp. 311–319, 1986.

C.C. Sherbrooke. METRIC: A multi-echelon technique for recoverable item control. *Operation Research*, 16(1):122–141, 1968.

C.C. Sherbrooke. *Optimal inventory modelling of systems. Multi-echelon techniques.* Kluwer, Dordrecht (The Netherlands), second edition, 2004.

M. Slay. VARI-METRIC: An approach to modelling multi-echelon resupply when the demand process is poisson with a gamma prior. Working paper, Logistics Management Institute, Washington D.C., 1980.

A. Sleptchenko, M.C Van der Heijden, and A. Harten. Effects of finite repair capacity in multi-echelon, multi-indenture service part supply systems. *International Journal of Production Economics*, 79:209–230, 2002.

NS. NS annual report. `http://www.ns.nl/binaries/content/assets/NS/over-ns/jaarverslag-2010/ns_jaarverslag_2010.pdf`, 2010. last checked on 12 October 2011.

United States Department of Defense. MIL-PRF-49506: Performance specification logistic managment information. Technical report, 1996.

H. Wong, B. Kranenburg, G.J van Houtum, and D. Cattrysse. Efficient heuristics for two-echelon spare parts inventory systems with an aggregate mean waiting time constraint per local warehouse. *OR Spectrum*, 29:699–722, 2007.