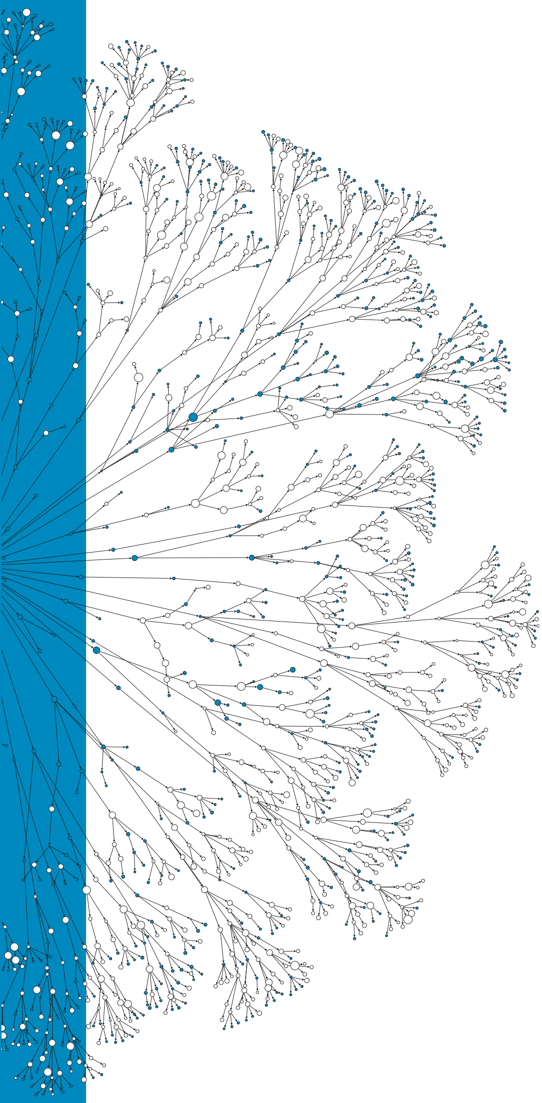
SERVICEABILITY OF PASSENGER TRAINS
DURING ACQUISITION PROJECTS



Jorge Eduardo Parada Puig

SERVICEABILITY OF PASSENGER TRAINS DURING ACQUISITION PROJECTS

DISSERTATION

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Jorge Eduardo Parada Puig

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The image of the front cover is a graphical representation of the indenture structure of a train, and its optimal line replaceable unit definitions.

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Summary

This thesis studies the role of serviceability of capital assets in the practices of large acquisition projects. Serviceability is here defined as the joint ability of technical system and its technical service system to afford both the supply and the demand for technical services; these services are ultimately destined to sustain a required capability of the technical system throughout its life cycle at a reasonable cost. It studies how serviceability is considered during acquisition projects in practice, and explores means to support decisions that intend to improve serviceability during such projects.

Capital assets are important for the welfare of developed society. These technical systems —such as trains, airplanes, power plants or MRI scanners— are core components of larger industrial systems and public services. They deliver services in the form of, for example, transportation, power generation or health care. Because of their societal and economic importance, a large effort is made to maintain capital assets.

Technical services, such as maintenance, are provided to capital assets over the life cycle. The main goal of maintenance is to ensure that capital assets be available for use. Inadequate maintenance can lead to failures or system breakdown. This causes safety risks and undesirable economic consequences, such as loss of quality or loss of production output. However, providing the proper maintenance represents an investment that not everyone is willing to make. The importance of maintenance is only visible when problems arise.

Billions of euros are invested in acquiring capital assets every year. However, most of the expenditure occurs during their operation and maintenance. Acquiring assets that can be serviced cost effectively is a fundamental goal during large acquisition projects. This is also the case during acquisition projects at the NS Group, the largest railway company in the Netherlands. Buying passenger trains and providing their required services requires important strategic decisions involving both the trains and their technical service system. Trains are expensive, they are bought in large quantities and have long life cycles. The service system requires investments in facilities, equipment and people. Design of passenger trains determines the service system needed. Design of the service system determines in turn the operational performance of the train. During acquisition of passenger trains, managers must specify requirements and make design decisions for both the trains and their support services.

We use a mixed methods approach in order to research the incorporation of serviceability in practice. This thesis presents the research as follows.

Chapter 1 provides an introduction. Next, Chapter 2 explores the conceptual definition of serviceability. Based on the affordance theory of design, the chapter defines serviceability as an affordance, a relational property. The chapter finds the related terminology, a relevant operational definition, and also provides the theoretical background of the research. Many attributes are used in the literature to describe an artifact from the perspective of the ease of doing maintenance. Serviceability, maintainability and supportability are researched.

Chapters 3 to 6 describe how NS acquires serviceable assets in practice. They each give a unique view on a single case study of NedTrain, the largest service provider for passenger trains in the Netherlands. Chapters 3 and 4 contrast technical design attributes of the passenger trains of NS and the plants of NedTrain that impact serviceability. Next, Chapters 5 and 6 contrast decisions that intend to improve serviceability. Chapter 5 describes decisions made during NedTrain's own improvement projects. Chapter 6 describes decisions made within acquisition projects for new passenger trains.

The most important factors that were found to condition service performance are: modularity and commonality of new passenger train platforms, organizational changes such as the speed of adaptation to service demands, and decoupling of service capabilities. However, it appears that these factors cannot be included in the performance requirements that are defined before contracting. It also appears that, in line with best practices, the organization fits new trains to the existing service system by maximizing the use of the previously developed service system. Meanwhile, improvement projects are carried out mostly independent of acquisitions of new trains. This leads to a premature reduction of the service design space during acquisitions. Serviceability of new materiel is addressed in the performance requirements in the form of a RAMS/LCC plan that includes the description of the existing service system. Solution dependent requirements constrain the creative expertise of suppliers. Intensive communication with the suppliers before contracting ensures that the supplier understands the existing infrastructure and processes. It is the relationship with the supplier that creates success.

Chapters 7 and 8 build on the insights obtained in Chapters 3 to 6 and provide further insights about supporting practice. It is found useful to distinguish between support that can be used before and after contracting. We develop support for each of these two epochs. Chapter 7 presents the development and initial testing of *The Logistic Support Game* to support service design before contracting. During this early stage of acquisitions, more effort is needed for service concept development. The game supports exploration of the design space of technical services. It is found that the game can provide improvements in this process, and its associated decisions. Chapter 8 presents support for the LRU-definition problem after contracting. This is the problem of selecting which items to replace upon failure within the indenture structure of the asset. To obtain a good LRU-definition, input is required from both the service provider and the system supplier. The chapter presents the LRU definition problem from the perspective of current practice, and provides a model to support experts in the definition of LRUs. Our model leads to a better LRU-definition, and can lead to important cost savings when compared to heuristics found in practice.

Chapter 9 draws the research conclusions. The attributes that influence serviceability according to the literature can be identified in practice at NedTrain. A best practice approach for acquiring serviceable capital assets remains elusive. For a company such as NedTrain, it appears that acquisition of serviceable capital assets is successful when the focus is on relationships with suppliers. Collaboration and partnerships are more important than the predictability of performance to produce a successful acquisition project. Before contracting, a dialog with the technical system owner and the system integrator, including the subsystem suppliers, helps NedTrain to mitigate risks and uncertainties. After contracting, close cooperation and communication are fundamental for the successful completion of a project.

Interested audience

This thesis can be an interesting source of knowledge for four main audiences.

1. *MS or other graduate students in the fields of industrial engineering, maintenance engineering, mechanical engineering, or operations management:* in a core maintenance planning course. All Chapters, and specially chapter 2 contain a wealth of literature for further reference. Chapters 3 to 6 give an in-depth look at technical design attributes and management decisions from the perspective of theory and practice.

2. *OR & OM researcher:* for practical as well as theoretical insights that may help to develop further research. Especially Chapters 7 and 8 provide relevant insights for further development of models and support to aid decision making.

3. *Acquisition managers:* for use as a reference. Interesting insights about theory and practice are provided in Chapter 6.

4. *Original Equipment Manufacturer (OEM) & Business to Business (B2B) suppliers:* for interesting insights and general reference.

Samenvatting

Dit proefschrift beschrijft de rol van *servicebaarheid* in grote aankoopprojecten van kapitaalgoederen. Servicebaarheid is daarin gedefinieerd als het gezamenlijk vermogen van een technisch systeem met het bijbehorende technische servicesysteem om zowel technische services te leveren als te ontvangen; deze technische services zijn bedoeld om uiteindelijk een vereiste capaciteit van het technische systeem te leveren gedurende zijn levenscyclus tegen redelijke kosten. In de studie beschreven in dit proefschrift is onderzocht hoe deze servicebaarheid wordt meegenomen in aankoopprojecten in de praktijk en is een verkenning gemaakt van de middelen om het maken van beslissingen met betrekking tot servicebaarheid te ondersteunen.

Kapitaalgoederen zijn belangrijk voor de welvaart van een ontwikkelde samenleving. Deze technische systemen —zoals treinen, vliegtuigen, energiecentrales of MRI scanners— vormen de kern van grote industriële systemen en publieke diensten. Zij vervullen een rol in het verzorgen van transport, het opwekken van energie en het leveren van gezondheidszorg. Vanwege hun maatschappelijk en economisch belang wordt er veel inspanning geleverd om kapitaalgoederen te onderhouden, zodat ze hun rol op een hoogwaardig niveau kunnen blijven vervullen.

Technische services, zoals onderhoud, worden uitgevoerd gedurende de gehele levenscyclus van kapitaalgoederen. Deze hebben als belangrijkste doel het kapitaalgoed beschikbaar te laten zijn voor gebruik. Het niet goed onderhouden van deze systemen kan uiteindelijk leiden tot een storing, of zelfs uitval van het systeem. Dit veroorzaakt veiligheidsrisico's en heeft ongewenste economische gevolgen, zoals een verminderde productiekwaliteit en een verminderde productiviteit. Echter, goed onderhoud vergt investeringen die niet iedereen bereid is om te maken. Het belang van onderhoud wordt pas zichtbaar wanneer zich daadwerkelijk problemen voordoen.

Ieder jaar worden er miljarden euro's geïnvesteerd in de aankoop van kapitaalgoederen. Echter, tijdens de levenscyclus van deze systemen zijn gebruik

en onderhoud de grootste kostenposten. De aankoop van kapitaalgoederen die kosteneffectief onderhouden kunnen worden is daarom een fundamentele doelstelling in grote aankoopprojecten; zo ook voor Nederlandse Spoorwegen (NS), de grootste spoorwegmaatschappij van Nederland. Met het kopen van passagierstreinen en het leveren van de nodige onderhoudsservices gaan een aantal belangrijke strategische beslissingen gepaard voor zowel de treinen als het servicesysteem. Treinen zijn duur, worden ze in grote hoeveelheden gekocht en hebben ze een lange levensduur. Het servicesysteem vergt investeringen in faciliteiten, gereedschappen en mensen. Welke kenmerken het servicesysteem moet hebben, wordt bepaald door het ontwerp van de aan te kopen treinen. Het ontwerp van het servicesysteem bepaalt op zijn beurt uiteindelijk de haalbare operationele prestaties van het technische systeem. Gedurende aankoopprojecten moeten managers daarom eisen specificeren voor en ontwerpbeslissingen nemen over zowel het ontwerp van de trein als de ondersteunende services.

Om integratie van servicebaarheid te onderzoeken in de praktijk is gebruik gemaakt van gemengde methoden. Het onderzoek is als volgt in dit proefschrift beschreven.

Hoofdstuk 1 geeft een introductie. Vervolgens wordt in hoofdstuk 2 de gebruikte conceptuele definitie van servicebaarheid beschreven. Deze is gebaseerd op de relationele eigenschappen vanuit de *affordance theory of design*. Tevens beschrijft dit hoofdstuk de bijbehorende terminologie, een operationele definitie, en het theoretisch kader van het onderzoek. Specifiek zijn *serviceability*, *maintainability* en *supportability* onderzocht.

Hoofdstukken 3 tot en met 6 beschrijven hoe NS servicebaarheid meeneemt tijdens de acquisitie van kapitaalgoederen in de praktijk. Deze hoofdstukken geven een unieke kijk op een *single case study* bij NedTrain, de grootste serviceverlener voor passagierstreinen in Nederland. De hoofdstukken 3 en 4 vergelijken technische ontwerpkenmerken van passagierstreinen van NS en van de servicefaciliteiten van NedTrain die van invloed zijn op de servicebaarheid. Vervolgens worden in hoofdstukken 5 en 6 beslissingen vergeleken die als doel hebben om de servicebaarheid te verbeteren. Hoofdstuk 5 gaat in op beslissingen in de eigen verbeteringsprojecten van NedTrain. Hoofdstuk 6 behandelt beslissingen in acquisitieprojecten van nieuwe passagierstreinen.

De belangrijkste gevonden factoren die serviceprestaties bevorderen zijn: modulariteit en standaardisatie van nieuwe treinsystemen, organisatorische veranderingen zoals de snelheid van de organisatie om te reageren op veranderende service-eisen, en het ontkoppelen van de servicesysteemarchitectuur en het technische systeem. Echter deze factoren kunnen niet in de prestatie-eisen worden verwerkt die worden opgesteld voor het moment van contractering. Tevens blijkt dat, in overeenstemming met *best-practices*, de organisatie nieuw aangekochte treinen aanpast aan het bestaande servicesysteem door het gebruik van eerder ontwikkelde servicesystemen te maximaliseren. Tegelijkertijd worden verbeteringsprojecten meestal onafhankelijk uitgevoerd van acquisitie van nieuwe treinen. Dit heeft als gevolg dat de ontwerpruimte voor het servicesysteem bij de aankoop van nieuwe treinen beperkt is. Servicebaarheid van nieuw materieel wordt namelijk geïntegreerd in prestatie-eisen door middel van een RAMS/LCC-plan. Deze oplossingsafhankelijke eisen beperken de mogelijkheid om creatieve expertise van leveranciers optimaal te benutten. Door middel van intensieve communicatie met de leveranciers voor contractering wordt garandeert dat de leverancier de bestaande infrastructuur en processen begrijpt. De relatie met de leverancier is daarom bepalend voor succes.

Hoofdstukken 7 en 8 bouwen voort op de inzichten verkregen in de hoofdstukken 3 tot en met 6 en leveren verdere inzichten in mogelijkheden voor beslissingsondersteuning in de praktijk. Het blijkt dat het nuttig is onderscheid te maken tussen de ondersteuning die gebruikt kan worden voor het moment van contractering en daarna. Voor beide momenten is beslissingsondersteuning ontwikkeld. Hoofdstuk 7 beschrijft de ontwikkeling en een eerste test van *"The Logistic Support Game"* voor ondersteuning van het malen van servicesysteemontwerp voor contractering. In deze eerste fasen van het aankooptraject is veel inspanning nodig voor serviceconceptontwikkeling. Het spel helpt het verkennen van verschillende concepten hiervoor. Er is aangetoond dat het spel de potentie heeft voor het verbeteren van dit proces en de beslissingen die daarin een rol spelen. Hoofdstuk 8 gaat in op beslissingsondersteuning na contractering voor het LRU-definitie-probleem. Dit is het vraagstuk omtrent welke componenten in de hiërarchie van het systeem samen vervangen worden wanneer er een storing plaatsvindt. Om tot een goede LRU-definitie te komen is input vereist van zowel de leverancier van het technische systeem als van de serviceverlener. Het hoofdstuk beschrijft het LRU-definitie-probleem vanuit de huidige praktijk en biedt een model om experts te ondersteunen bij het definiëren van deze LRUs. Het model leidt tot een betere LRU-definitie, die kan leiden tot belangrijke kostenbesparingen in vergelijking met bestaande heuristieken.

Hoofdstuk 9 geeft de conclusies van het onderzoek. De kenmerken die volgens de literatuur servicebaarheid beïnvloeden, kunnen in de praktijk bij NedTrain worden geïdentificeerd. Een *best-practice* benadering voor het verwerven van kapitaalgoederen met een hoge servicebaarheid blijft moeilijk haalbaar. Voor een bedrijf als NedTrain blijkt dat het meenemen van servicebaarheid tijdens acquisitie van kapitaalgoederen succesvol kan worden gedaan wanneer de nadruk ligt op het bewerkstelligen van een goede relatie met de leverancier. Voor een succesvol aankoopproject zijn samenwerking en partnerschap belangrijker dan de voorspelbaarheid van prestaties. Voor contractering zou een dialoog met de eigenaar en leverancier van het technische systeem, met inbegrip van leveranciers van subsystemen, voor NedTrain een goed middel zijn om risico's en onzekerheden te verminderen. Na contractering zijn een nauwe samenwerking en goede communicatie van fundamenteel belang voor een goede afronding van het acquisitieproject.

Contents

Acronyms

B2B Business to Business

COTS Comercial Off-The-Shelf

CRF Component Revision Facility

DBD Decision Based Design

DRM Design Research Methodology

DS-I Descriptive Study I

DS-II Descriptive Study II

FMECA failure modes, effects and criticality analysis

FRACAS Failure Analysis Reporting and Corrective Action System

FTA Fault Tree Analysis

GDP Gross Domestic Product

ILS Integrated Logistics Support

IPS^2 Industrial Product-Service System

LCC Life Cycle Cost

LORA Level Of Repair Analysis

LRU Line Replaceable Unit

LSA Logistic Support Analysis

MF Maintenance Facility

MRO Maintenance, Repair and Overhaul

MTA Maintenance Task Analysis

MTTS Mean Time To Support

NDI Non-Developmental Item

NS Nederlandse Spoorwegen

NSD New Service Development

OEM Original Equipment Manufacturer

PS Prescriptive Study

PSS Product-Service System

RAMS Reliability, Availability, Maintainability and Supportability

RC Research Clarification

RCM Reliability Centered Maintenance

RCMA Reliability Centered Maintenance Analysis

ROF Refurbishment and Overhaul Facility

SF Service Facility

SMED Single-Minute Exchange of Die

SSF Specialized Service Facility

TCF Technical Center Facility

TCO Total Cost of Ownership

TES Through-life Engineering Services

TOP Theory of Properties

TPM Total Productive Maintenance

TRIZ "the theory of inventive problem solving"

TTS Theory of Technical Systems

UOA Unit of Analysis

VE value engineering

Chapter 1

Introduction[1]

This thesis is about maintenance, specifically about the maintenance of trains, and the role of the maintenance organization in the acquisition process of new trains. This chapter gives an introductory overview of the research in this thesis, especially of its scope and focus. This introduction is divided into six sections. It first raises awareness about the importance of maintenance in Section 1.1. Next, Section 1.2 introduces the railway industry and the specific case of the largest maintenance service provider for passenger trains in the Netherlands: NedTrain. This case study will be central to the thesis. Then, Section 1.3 discusses the motivation for this research. After that, Section 1.4 gives the research problem. Section 1.5 shows the methodology, followed finally by the thesis outline in Section 1.6.

1.1 Capital assets, their acquisition and their maintenance

Mankind has relied on machines as a means of economic development for many centuries. However, since the industrial revolution many complex man-made machines –such as trains, airplanes, power plants or MRI scanners– have become central to the functioning of society. These machines are complex systems, also called capital assets, capital goods, or physical infrastructure assets[2]. Many other terms are used to refer to the same kind of machines, and/or the services they provide. Terms include large-scale systems (Asiedu and Gu, 1998), Industrial Product-Service System (IPS[2]) (Meier et al., 2010), capital assets (Department of

[1] Parts of this chapter are adapted from Parada Puig (2011) and Parada Puig et al. (2011).

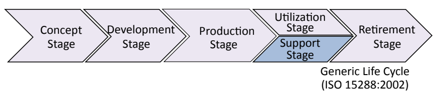
[2] Hereinafter we refer to them as (capital) asset(s) or technical system interchangeably. They are the core assets described in BSI (2004)

Defense, 2009), complex systems (Murthy and Kobbacy, 2008) and integrated solutions (Davies et al., 2001). Capital assets are used everywhere in industrialized societies. They deliver services in the form of transportation, power generation or health care. They are also used in the production of other goods by industrial processing or manufacturing.

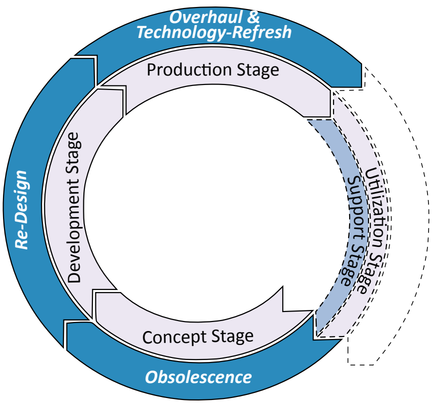
Capital assets are core components of industrial systems and public services. There are many common characteristics between land, marine or air transportation systems, energy plants, distribution grids, oil refineries and chemical plants. Firstly, they have a life span of 30+ years, from acquisition to the end-of-life. Secondly, assets are critical to the provision of services, where downtime –the period of time that the assets are not able to provide a service– may have devastating consequences to life, safety or the economy. Thirdly, billions of euros are invested in acquiring these systems every year, but most of the expenditure occurs during their operation and maintenance. Each of those characteristics is discussed in the sections 1.1.1 to 1.1.3, respectively.

1.1.1 Long life cycles

A typical (consumer) product has a characteristic life cycle: it is designed, produced and used/supported until it reaches its retirement age (ISO/IEC, 2008). Figure 1.1(a) shows the generic life cycle of these types of products. The concept of the asset life cycle is shown in the spiral model of Figure 1.1(b). This life cycle concept is inspired on the spiral model of software development proposed by Boehm (1988).



(a)



(b)

Figure 1.1: (a) *Generic life cycle of a product and* (b) *the spiral model of the life cycle of a capital asset.*

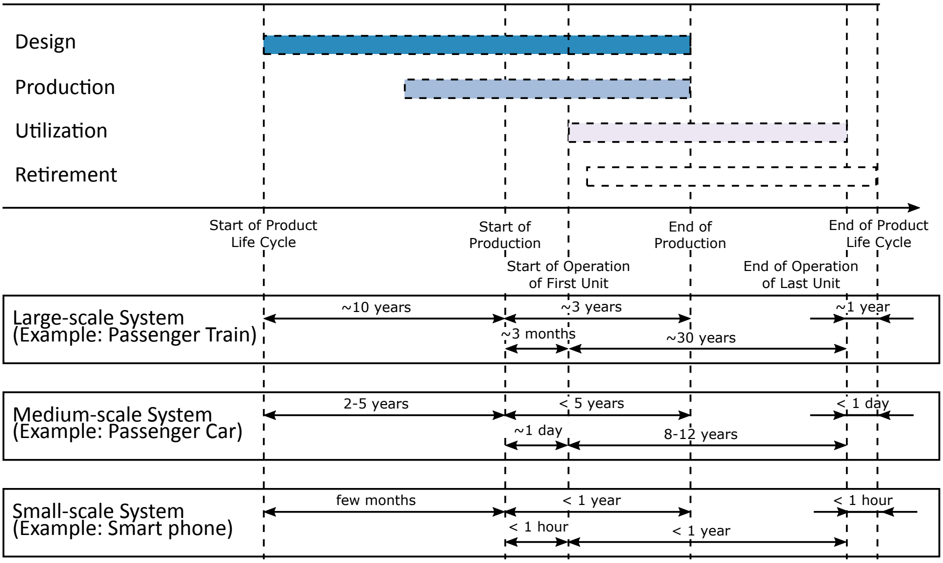


Figure 1.2: *The life cycle of a capital asset compared to other products (Adapted from Fixson, 2006).*

Capital assets have longer life cycles because asset obsolescence may be followed by multiple re-design, overhaul and technology refreshment projects. Often, when assets reach their planned end-of-life, life extension projects prolong the time until decommissioning. This warrants a life of 30+ years. This means that while a typical product can last from days or months to a few years –in the case of consumer goods or cars, for example– capital assets have characteristic life in the range of decades.

Figure 1.2 compares the simplified model of the life cycles of capital assets to other products. Unlike typical consumer products, which are mass produced, capital assets tend to be constructed under unique project and contractual circumstances. Design and development may require several years, and the period of production is likewise long. Over the whole life cycle, many stakeholders and organizations are involved.

The functioning of capital assets is generally taken for granted, and public awareness is only raised when disruptions occur, when there are safety-threatening accidents, when there are natural catastrophes or when public investment issues are debated by politicians, policy makers or stakeholder organizations (van Dongen, 2011).

1.1.2 Uptime is important

Uptime is the term that is used in industry to describe the time when an asset is *up and running*. Conversely, downtime is the term used to describe the period of time when an asset is not able to provide its function. Downtime typically costs money, but it usually has other negative impacts too, e.g., on safety.

Murthy et al. (2002) reports that lost revenues from downtime *per day* can amount to US $ 0,5 - 1,0 million for mining equipment, and roughly US $ 0,5 million for a commercial 747 airliner. Given these figures, it is not surprising that maintenance was considered a factory cost center for a long time (Marais and Saleh, 2009). Unplanned stoppages and other maintenance related problems produce losses that impact a company's return on investment (Alsyouf, 2009).

The primary goal of an asset is to be available for use. Without the proper care, failures eventually disrupt its operation. Such disruptions can mean that the whole system or a system component will cease to provide its intended function. This causes safety risks and undesirable economic consequences, such as loss of quality or loss of production output. Therefore, many technical services are supplied in order to sustain the required functioning of assets.

These technical services may include maintenance, engineering, spare parts, spare part repair, technical documentation management and technology refreshment. Service organizations[3] are typically entrusted with providing these services. These organizations must deal with service processes and all the necessary logistics that ensure smooth operation of the assets.

1.1.3 Maintenance costs are significant

Maintenance costs represent very large sums of money. In Europe for example, the volume of spending in maintenance-related activity amounts to approximately 1,500 billion Euros per year (Altmannshoffer, 2006). These costs represent a significant proportion of a country's Gross Domestic Product (GDP). In the Netherlands, the estimate of spending in maintenance is reported to be between €30-35 billion, a sector employing of 260-300 thousand professionals (NVDO, 2014). Estimated figures of the total maintenance spending were of about £15 billion a year in the UK alone by 1988 (Cross, 1988). Tables 1.1 and 1.2 give indications of maintenance expenditures for some countries in Europe.

For individual organizations, maintenance costs are a significant portion of the production costs. Based on data from previous studies, Simões et al. (2011) reports a ratio of up to 25% for manufacturing, 20-50% for the mining industry. In process industry maintenance costs can exceed the operating costs (Ben-Daya et al., 2009; Simões et al., 2011). Cross (1988) reports that the manufacturing sector in the UK spends 12 - 13% of the total factory operating expenses in maintenance. Komonen (2002) reports that maintenance costs can represent 0,5 to 25 % of company turnover in Finland.

[3]We will use the term maintenance organization and service organization interchangeably.

Table 1.1: *Examples of approximate maintenance expenditure (billions) in several locations (Adapted from Ahlmann, 2002; Altmannshoffer, 2006; Cross, 1988; NVDO, 2014; Willmott and McCarthy, 2000).*

Location	Exp. (year)	Exp. (€)†
Europe	€1,500 (2006)	1,734
Sweden	€20 (2002)	25
Netherlands	€30-35 (2013)	30-35
UK	£14 (1991)	44

†Relative economic power in 2013 euros

Table 1.2: *Maintenance expenditure as a percentage of turnover in European countries, (Adapted from Komonen, 2002; Willmott and McCarthy, 2000).*

Finland	5.5%
France	4.0%
Ireland	5.1%
Italy	5.1%
Netherlands	5.0%
Spain	3.6%
UK	5.0%

1.2 Passenger railways transport

This thesis is mainly focused on the transportation industry, and more specifically, on passenger railways transportation. Passenger railways transportation is an important economic activity. In many countries, railway companies were technology drivers of the industrial revolution. They fueled the manufacturing industry. The subsequent growth of service sectors around the railways became a force driving local economies. Rolling stock is the technical term for the vehicles that move on a railway, i.e., trains. These artifacts are the technical systems of this study.

1.2.1 Passenger service rolling stock

Manufacturing of rolling stock is a multi-billion euro industry. In 2010, rolling stock represented a worldwide market volume of more than €70 billion, and was expected to grow by more than 4% by 2015 (Leenen and Wolf, 2010). Rolling stock is considered both a focal point of customer experience and of the operational performance of the railways. Rolling stock is also an important contributor to the cost of travel. In the UK, for example, the annual cost of rolling stock represented approximately 15% of the total railways operating costs, amounting to £1.9 billion (in 2009/10) (Atkins, 2011).

The market for passenger service rolling stock is dominated by a small group of companies. Figure 1.3 shows the top ten rolling stock manufacturers by turnover, based on estimations by SCI/Verkehr (2010). Emerging practices in the rolling stock market are reported by Davies et al. (2007); Kawasaki (2008); Lacôte (2005); Mochida et al. (2010) and Sato (2005).

1.2.2 Rolling stock maintenance

Maintenance is a fundamental part of supporting rolling stock through-life. It is important for safety, quality and convenience of railways transportation, and it is required to set the conditions for high operational performance. Also, maintenance costs are a significant proportion of the life cycle costs of rolling stock.

The performance of rolling stock during the life cycle has only been the concern of manufacturers for the past two decades (Durand, 2001). Today, most of the worldwide Maintenance, Repair and Overhaul (MRO) market for rolling stock is still dominated by in-house service providers of domestic railways companies (SCI/VERKEHR, 2013). In those companies, intervention of the manufacturers is limited to the guarantee period, a period of up to five years. This is a small period, considering that rolling stock is operated by railway companies for at least three decades.

Rolling stock suppliers have short-lived knowledge about rolling stock maintenance and support. Nevertheless, as it is the case in other manufacturing sectors (Neely, 2009), rolling stock manufacturers are entering competition in the after sales market (Kawasaki, 2008; Mochida et al., 2010; SCI/VERKEHR, 2013). This threat of new entrants as technical service providers is certainly reshaping the industry. The market of through life services for rolling stock is only beginning to expand (SCI/VERKEHR, 2013).

1.2.3 Nederlandse Spoorwegen (NS) and NedTrain

The NS Group –we will use NS to refer to the company based on the Dutch name Nederlandse Spoorwegen (NS)– is the main railway company in the Netherlands.

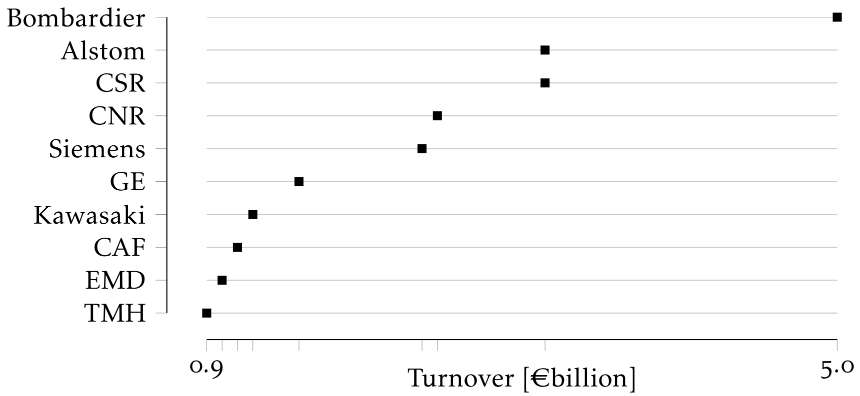


Figure 1.3: *Top 10 rolling stock manufacturers by turnover (Adapted from SCI/Verkehr, 2010).*

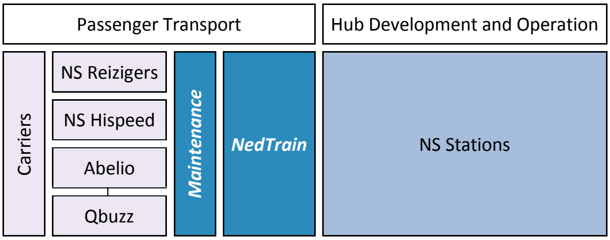


Figure 1.4: *NS Group Subsidiaries, (Adapted from NS Groep NV, 2013).*

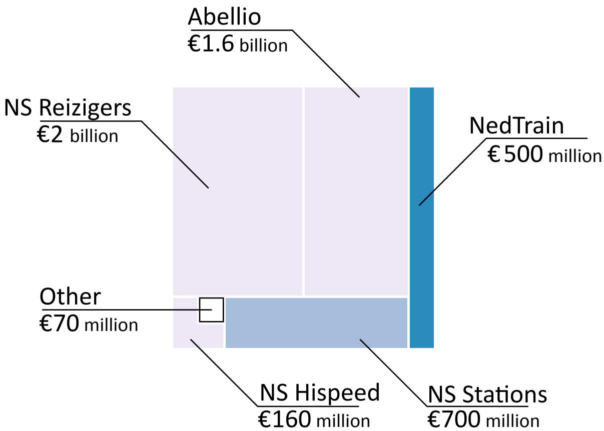


Figure 1.5: *Revenues of the NS Group and NedTrain (Adapted from NS Groep NV, 2013).*

Figure 1.4 shows the structure of the NS Group with all its subsidiaries in 2013: the operators NS Reizigers, NS High-Speed, Abellio and Qbuzz;the service company NedTrain; the hub development and operations company NS Stations. NS Reizigers is the main operator of intercity and commuter services within the Netherlands. NS High-Speed (now NS International) focuses on international travel and Abellio/Qbuzz handle several other transport operations outside the Netherlands.

The railways sector in the Netherlands presents similar spending characteristics as other industry sectors reported in the literature. Figure 1.5 shows the revenues for the different companies in the NS Group. Notice that for NS Reizigers, the revenues of the domestic passenger transport amount to €2 billion (NS Groep NV, 2013). Approximately 12% of this annual budget is invested in rolling stock acquisitions. Overhaul of rolling stock represents an approximate 7% of the annual operating costs, while regular maintenance, at 20%, almost double the costs of new rolling stock. The cost of ownership of rolling stock is relevant, and NS needs to find the correct balance between the investment costs and the other operating costs (van Dongen, 2011).

NedTrain is a maintenance organization. It is a full MRO service provider for the passenger trains of the NS Group in the Netherlands. It is a subsidiary of NS. This company, its maintenance operations, its experts and decision making processes are the central cases of this research. Within NedTrain, four operating units provide the required technical services. Namely, the service company, the maintenance company, the component repair company and the revision and overhaul company.

NedTrain services 2.850 coaches (trains & locomotives) on a 24/7 basis at thirty five service facilities, four maintenance facilities, one overhaul and refurbishment facility and one component repair facility. Figure 1.6 shows the service network of NedTrain in the Netherlands.

The service company has three types of facilities that perform maintenance: Service Facilities (SFs), Specialized Service Facilities (SSFs) and Technical Center Facilities (TCFs). Trains make daily visits to the service company's facilities for cleaning, simple repairs and fault finding tasks. These facilities also provide parking spaces and a shunting area. The maintenance company provides short cycle maintenance at the Maintenance Facilities (MFs). Short cycle maintenance currently happens on a three-month interval. Activities at MFs include opportunity maintenance, fault finding, replacement and minor repair of parts. Reparable parts are exchanged by the service or the maintenance company. These parts are sent for repair to the component repair company's Component Revision Facility (CRF). Refurbishment and overhaul projects for entire trains are carried out by the revision and overhaul company at the Refurbishment and Overhaul Facility (ROF).

1.3 Research motivation

Organizations buy capital assets to enhance their operations. The process of purchasing, also called acquisition process, is complex, and is of strategic importance. The process involves a series of activities that begin with the definition of requirements for the use of the asset. Next, organizations search the market for suppliers that are willing to provide the required capabilities, or the required performance. Typically, once a supplier is found and selected by the client, a contract is signed in order to enforce an agreement between the client and the supplier. After the contract, many activities may take place during a period of several years. These activities may include finishing the design, building, deploying and/or fielding the new asset(s). Organizations manage this process by means of an acquisition project.

The primary goal of an acquisitions project is to generate new opportunities and value to an organization. A new asset can create opportunities by opening new markets, improving current processes and providing better means of production –for example by reducing the environmental impact of operations. Acquisition processes are agreement processes that provide the means to conduct business

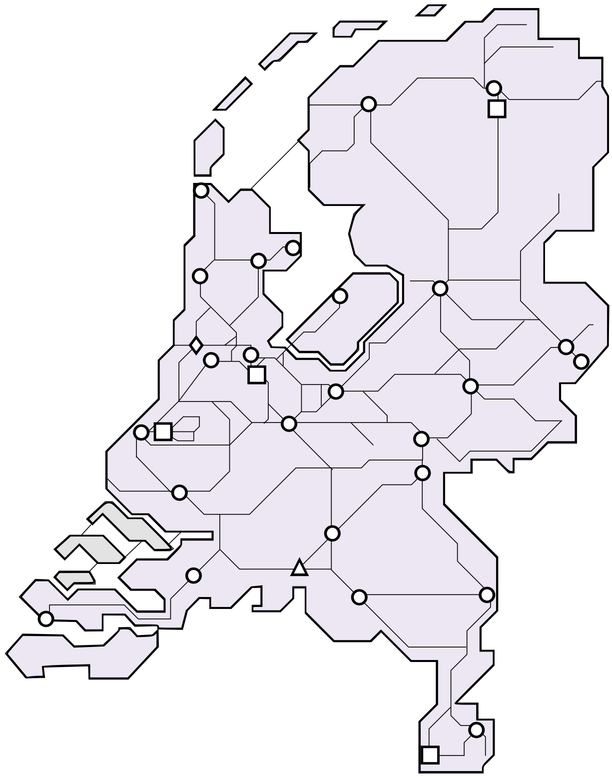


Figure 1.6: *The location of NedTrain's facilities (Adapted from NedTrain B.V.).* □ *Maintenance Facility (MF);* △ *Component Revision Facility (CRF);* ○ *Service Facility (SF);* ◊ *Refurbishment and Overhaul Facility (ROF).*

with a supplier. Suppliers can provide *(i)* products for use as an operational system, *(ii)* services in support of operational activities, *(iii)* elements of a system being developed by a project, or *(iv)* combinations of these products and services, also called Product-Service System (PSS).

People face several challenges when making decisions during acquisition projects. Acquisition projects are costly, they involve complex strategic decisions, and they determine operational performance for many years. Decision support can help improve the decision making process to be more effective (do the right things) and efficient (do things right), helping to make better decisions. Better decisions during acquisition result in assets that will be serviceable through-life. This will help organizations to improve the services and therefore obtain better performance at lower cost.

Achieving the potential benefits is an important driver for this research. However, acquiring serviceable assets is challenging. Motivation for this research comes from both science and practice. We first provide the scientific motivation for the research in Section 1.3.1. Next, the motivation from practice is presented in Section 1.3.2.

1.3.1 Scientific motivation

Best practice indicates that serviceability of capital assets is important to address in the context of acquisition projects (Department of Defense, 1986, 1997a; INCOSE, 2010; Jones, 2006a,b; Ministry of Defence, 2010). However, it is unclear whether existing analysis methods and tools are used or are useful in practice. There is limited knowledge about how serviceability is addressed in acquisition projects in practice. There is dispersed knowledge about equipment design aspects affecting serviceability. No useful framework linking these aspects to decisions and to acquisition decisions in particular has been found.

Existing methods and tools

For client organizations –those who buy capital assets– the relationship with the systems integrator is changing. Some organizations face a dilemma if they look to expand their capacity by acquiring new assets. Should they look to influence the supplier's design process? Alternatively, should they change their utilization/support processes and their supply chain? Literature suggests that best practice is to buy assets that best fit the existing support organization and processes. The underlying reason is that this approach would reduce the uncertainty concerning the performance of product, process and supply chain during the support stage. In addition, this would minimize the organizational changes required to support new technology. Research has focused on developing several methods and tools to support this best practices paradigm, but their adoption in practice is unclear. This will be discussed further in Chapter 2.

Limited knowledge about practice

Research into IPS²s –integrated product and service offerings delivering value in a B2B environment– focuses strongly on the manufacturer moving to the service business, and thereby capturing the increased revenues of the after sales services market (Baines et al., 2007; Meier et al., 2010; Neely, 2009). Recent research reports on the so-called service triad of the supplier, the buyer and the customer, where services are purchased by one organization from another, but delivered to a third party (Finne and Holmström, 2013; Li and Choi, 2009; Wynstra et al., 2014). The relationships developed in such context are fundamentally different from the traditional linear supply chains of Operations and Supply Chain Management research.

The case presented by Finne and Holmström (2013) emphasizes the effect of triadic cooperation when a subsystem supplier provides a service directly to the customer, where the buyer is the systems integrator. The contingent nature of the service capabilities of the provider are moderated by a fundamental factor: the relationship with the supplier. This factor will be a recurrent theme in the empirical data of this thesis.

There are some insights from the literature that suggest interesting research into the practices of acquiring serviceable assets in the railway industry. Also reflecting the trend on PSSs, research has mostly followed the manufacturer of rolling stock moving into servitization (Durand, 2001; Ivory et al., 2001; Kawasaki, 2008; Mochida et al., 2010; Sato, 2005).

Most of the insights from literature come from the manufacturer's perspective. A view of the acquisition process for capital assets from the perspective of the service organization is needed to better understand the process of service development and delivery. In the Netherlands, NS acquires rolling stock on a regular basis. This allows to match demand for passenger service, withdrawal for maintenance and obsolescence. Each acquisition project lasts for many years and requires investments of hundreds of millions of euros. It is understandable that rolling stock acquisition is a fundamental activity for NS.

During acquisition, NS must determine the performance requirements for the new rolling stock so that manufacturers make an offering to supply a system that meets these requirements. Rolling stock manufacturers have developed general rolling stock platforms which they use to make these offerings. Platforms enable them to accommodate the differences that exist in the rolling stock infrastructure of each country. After contract award, a specific model is engineered based on that platform which was selected by the client. This means that detail design is carried out after contract award.

As the maintenance service provider for the NS, NedTrain is in a strategic position to bring balance to rolling stock acquisitions. This maintenance organization possesses specific knowledge from many years of experience working with the NS fleet, and this is a very valuable advantage (Caniëls and Roeleveld, 2009).

Limited knowledge about design aspects

Design aspects impact serviceability. This will also be discussed further in Chapter 2. In order to make estimations on performance (the type particularly impacted by serviceability), the literature suggests to base the estimates on the performance of existing assets. This process is known as functional supportability analysis, and is related to case-based decision analysis tools. The highest potential of this process lies in the ability of the maintenance organization to make its estimates based on system architecture analysis. However, it is challenging for the service provider to identify which design attributes of a new asset are relevant for maintenance, and what level of detail is required to elicit them during acquisitions.

1.3.2 Motivation from practice

Service organizations are increasingly responsible for performance of capital assets over the life cycle. This means that serviceability of capital assets should be clear before contracting, and the influence of asset design on serviceability should be well understood. However, acquisition projects last several years, they take up considerable resources and there are many stakeholder interests. Dispersed efforts, competing importance of stakeholders and not enough resources limit the amount of attention to serviceability aspects in practice. Serviceability should be addressed efficiently and effectively, but what/how could companies learn from past experiences? What could the scientific community learn from practice? (see Section 1.3.1).

Performance based contracting

Service contractors are increasingly being paid for asset performance, not for the time spent on work or the spare parts bought (Kim et al., 2007). This drives increase in maintenance efficiency. Figure 1.7 shows the position of the result oriented value proposition: high complexity and high responsibility for the service provider in the context of manufacturing firms moving to the service business.

As servitization increases in developed markets, manufacturing industry shifts attention to the economic prospect of long-term support for their products –see for example transportation, defense and IT (McFarlane and Cuthbert, 2012). Furthermore, when competition saturates these developed markets, industrial suppliers will have to look for opportunities in developing economies. As product support extends to a global supply chain, the links between product, process and supply chain become relevant beyond manufacturing and into the support stage of the product life cycle. The support operations and the service supply chain

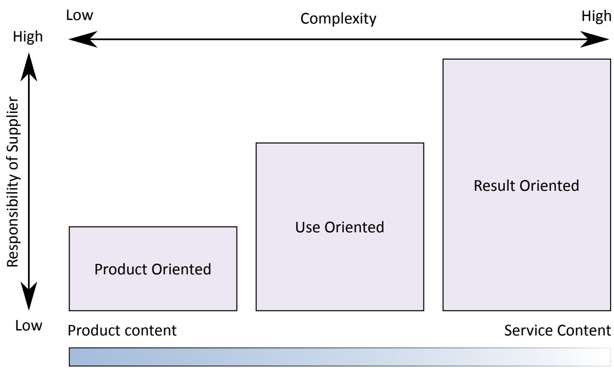


Figure 1.7: *Comparison across IPS² value propositions (Adapted from Erkoyuncu et al., 2013b).*

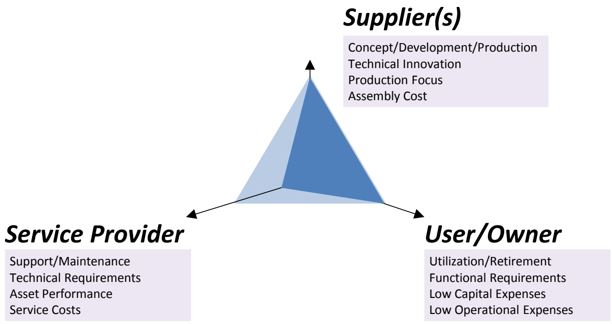


Figure 1.8: *The designer-user-service triad (Adapted from van Dongen, 2011).*

become increasingly important.

Serviceability before contracting

The challenged old views of the maintenance function have given way to the image of the modern asset management function: a competitive advantage and a means for performing at *World Class* level. It is agreed today by many research initiatives that maintenance can be a source of added value to organizations (Cross, 1988; Liyanage and Kumar, 2003; Marais and Saleh, 2009). It is a means of improving Reliability, Availability, Maintainability and Supportability (RAMS) given the implementation of adequate programmes. It can also be regarded as a key in the improvement of public Health and Environmental sustainability, i.e. RAMS-HE. Maintenance is therefore a value-adding function, providing uptime in industries that experience high downtime costs.

Despite what maintenance costs represent to organizations, and to society in general, the role of the maintainer has been undermined. Still today, we see acquisition decisions that can only result from short-term thinking. In the modern context, the acknowledgement of the maintenance function and its prominent role in design and acquisition projects is a fundamental step for improvement. It is therefore fundamental to integrate maintenance knowledge in the process of asset acquisitions, bringing balance to the position of the supplier, the user (owner) and the maintainer.

This balance is shown in Figure 1.8. While the user/owner is concerned with sustaining effective, low cost operations and providing functional requirements, the supplier can focus on technical innovation and low production costs. The asset management function is the only one in the position to provide knowledge about (i) technical requirements, (ii) installation performance, (iii) RAMS –especially maintainability– and (iv) maintenance costs that balance the total life cycle of the asset.

Difficult projects

Organizations use an acquisition process to specify, select, contract, develop and field capital assets. Also, the technical services required to provide support for the asset throughout its life cycle are determined during this process. Therefore, acquisition decisions involve decisions about the asset and about the maintenance that it requires.

Maintenance costs are known to be a significant portion of the Life Cycle Cost (LCC) for capital assets (Márquez et al., 2012). While acquisition investments can range from 12-35% of the Total Cost of Ownership (TCO), the costs for maintenance generally range from 50-75% of the total cost (Ellram, 1993; Jones, 2006b; Wise et al., 2005). This means that the cost of the use/support stage of the life cycle can be several times the purchasing price, normally amounting to billions of euros in maintenance, as shown in Figure 1.9. The figure displays several man-made artifacts such as cars, trains and airplanes, so that they can be compared with respect to the purchasing price and the maintenance costs over the life cycle.

Jones (2006b) suggests that capital invested in acquisitions can represent as little as 12% of the LCC for capital assets, while operations and maintenance (together) can account for up to 85% of the LCCs. For production equipment the initial purchase price can represent up to 35% of the TCO, while the costs

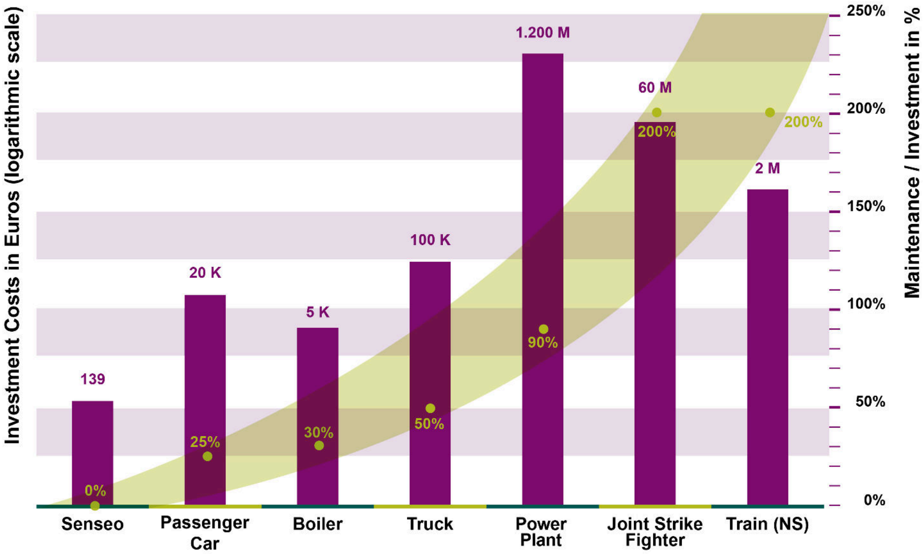


Figure 1.9: *The cost of maintenance and acquisition cost for several types of man-made artifacts (Adapted from van Dongen, 2011).*

after the asset is in use amount to around 50% of the TCO (Ellram, 1993). Other systems such as an aircraft engine, require maintenance and support that usually ranges from 60 to 75% of overall LCCs (Wise et al., 2005).

However, capital intensive industries, defence and public utilities before the 1980s traditionally relied on the purchase price to select their assets. A common criterion for selecting suppliers was to choose the lowest bidder (Ellram and Siferd, 1993). Considering the important contribution of operating and maintenance costs, different organizations are increasingly aware of the importance of purchasing under the umbrella of LCC or TCO concepts.

While these costs do not explain in themselves any of the underlying phenomena, they point to the need of strengthening research in maintenance and to use existing maintenance knowledge in strategic decision-making. The TCO concept was established to consider acquisition, use, and maintenance of an item, *not just* the purchase price. The essence of the TCO concept is long-term thinking, and it is is not the only concept in the literature. Similar concepts related to TCO are total cost, life cycle costing, and product LCC. For further reference the reader may refer to (Durairaj et al., 2002; Ellram, 1993, 1994; Ellram and Siferd, 1993; Ferrin and Plank, 2002).

Research points out the importance of the TCO of capital assets. However, consideration of the LCC during acquisition is difficult. Most of the cost of complex artifacts is incurred during operation and maintenance. These costs are difficult to estimate because of the uncertainty involved. Methodologies using expert judgement for identifying uncertainties and estimating service costs have been developed but they demand a lot of effort, they are data intensive and they are also limited by available information, expert knowledge, project/operations constraints and importance, and the budgetary allocation applied in the analysis (Erkoyuncu et al., 2013a,b). For long-term thinking to prevail, organizations must examine acquisition decisions considering the important contribution of operating and maintenance costs (Márquez et al., 2012).

Acquisitions involve many criteria, and also require a lot of effort, time and knowledge from the organizations involved. Decisions made during acquisition have a strong strategic impact on operational performance of capital assets. Therefore, performance outcomes are only visible in the long term, making it difficult to assess good decisions. There are opportunities to exploit because it seems that during acquisitions there is much more flexibility to make maintenance decisions than in the operating stage of the life cycle. The impact of decision support can be much larger, and research can help determine suitable support.

The uncertainty involved in acquisition projects makes the development and acquisition of capital assets particularly risky for the user/owner/maintainer. In such setting, collaboration and cooperation through long term partnerships could have a fundamental role.

Today, lack of collaboration makes knowledge transfer difficult. There are many uncertainties for acquisition projects, either when the product ownership is transferred to the user/owner, or when contracting places responsibility of through life support on the supplier. In this context, collaboration between supplier organizations and support organizations can lead to important shared benefits.

1.3.3 Other challenges for service organizations

This section discusses two challenges that maintenance organizations currently face. Firstly, an increasingly competitive labor market for talent. Secondly, the increasing technical complexity of capital assets (more software components, more interacting interfaces, more hardware items).

Increasingly competitive labor market

Availability of key skills is one of the top concerns of CEOs and supply chain executives, according to recent surveys (ManpowerGroup, 2014; Sodhi and Tang, 2014). According to a recent survey, 36% of employers report difficulties in filling jobs. Skilled trade workers, engineers, and technicians (production, operations, maintenance and other roles) list as the top three talents that employers are having difficulty in filling (ManpowerGroup, 2014). Increasingly, competition spans to global markets for labour and talent, resulting in rising wage rates (Sodhi and Tang, 2014).

The average age of the maintenance professionals is over 40. Forums of professional associations repeatedly report that younger generations do not find attractive career paths in maintenance, and increasingly choose white collar professions. In the Dutch maintenance industry there is a growing concern for the growing number of retirements of recent years –the so called baby boomers. A study in the Netherlands estimated that with 20% of the maintenance repair and overhaul (MRO) workforce over 50 years of age would lead to some 20,000 vacancies over the following ten years (Blok et al., 2009). Zandvliet et al. (2011) gives an indicative estimation, displayed in Figure 1.10.

Increasing technical complexity

Modern assets are becoming increasingly complex. An increase in complexity produces longer repair lead times, more difficult testing procedures, increase in No-Fault-Found, and an overall decrease in maintenance quality (as measured in recurring failures or mean time between unscheduled repairs). Paradoxically, increasing mechanization and automation has shifted the balance of production personnel towards maintenance personnel (Dekker, 1996). Increasing complexity of assets also accounts for labor intensive characteristics of the maintenance tasks, and the aging equipment in many sectors all contribute to rising maintenance costs (Parida and Kumar, 2006).

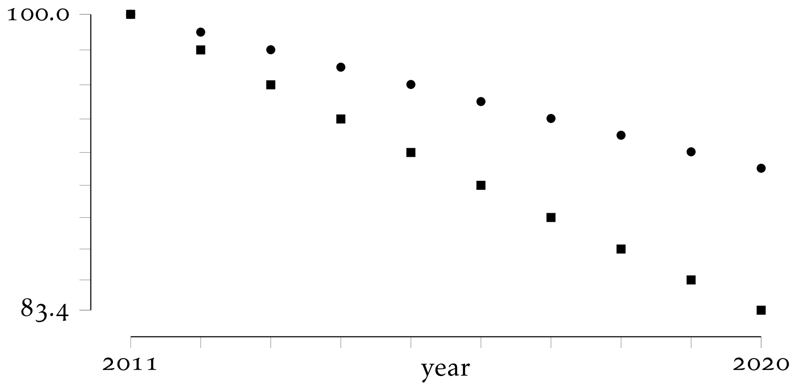


Figure 1.10: *Indicative trends of supply (■) and demand (●) for maintenance professionals in the Netherlands (Adapted from Zandvliet et al., 2011).*

1.4 Research problem

The goal of this research is to support maintenance decision making during acquisition projects of new rolling stock. The research objectives and the research questions are aimed to achieve this goal.

1.4.1 Research objectives

This thesis presents the problem of selecting both a capital asset and a suitable service strategy for the asset that ensures the serviceability throughout the asset life cycle. The three research objectives (ROs) are:

RO1 Explain the meaning of serviceability.

RO2 Provide insights about the acquisition of serviceable assets.

RO3 Support decision makers in their efforts to address serviceability in large acquisition projects.

The three research objectives are focussed on clarification, description and prescription, respectively. The focus of each objective is partly based on the research methodology of Blessing and Chakrabarti (2009). The methodological approach will be discussed further in Section 1.5.

1.4.2 Research questions

The topic of serviceability of capital assets in the practices of large acquisition projects requires a fundamental clarification about the exact meaning of serviceability. Therefore, the following question is aligned with the first research objective, RO1.

RQ1 What is serviceability?

Answering RQ1 gives a new angle for analyzing practice by positioning the concept of serviceability within existing design theory. The definition will also help position acquisition of serviceable assets in the context of management theory. Once the theory, the terminology and the constructs are clarified, the next research objective, RO2, can be addressed. The next research question is aligned with RO2.

RQ2 How do (capital intensive) organizations acquire serviceable assets in practice?

Answering RQ2 shows why serviceable assets can only be acquired successfully when there is a partnership developed between the organizations, and communication channels remain direct and open throughout the project. The study will provide a model connecting technical system design aspects, serviceability aspects, improvement projects and acquisition projects, suggesting that the main contingency factors found at NedTrain go beyond the technical aspects of the rolling stock.

To answer this research question we formulate two subquestions. Firstly, to gain insights from practice about the acquisition of serviceable assets, one must identify the relevant design aspects both of the technical system and of the technical service. Secondly, one must investigate acquisition practices. These insights will be obtained by answering subquestions RQ2a and RQ2b, respectively.

RQ2a What serviceability aspects are considered to be important to address during acquisitions?

Answering RQ2a provides an overview of serviceability aspects to address in acquisitions, as well as the reasons why. The impact of design aspects on serviceability is especially important in the context of acquisition projects. These aspects include the perspective of both the technical system design and the technical service design. The connection is made between design aspects and serviceability, providing insights that help understand the links between design properties. These insights allow decision makers to better analyze and evaluate design alternatives during acquisition projects. The next subquestion targets these projects by asking:

RQ2b How is serviceability addressed in acquisition projects in practice?

Answering RQ2b gives an overview of maintenance decision making, and of strategic maintenance decisions made at NedTrain. Additionally, it gives an overview of acquisition activities. The connection is made with technical service and technical system aspects, plus importance of addressing them during acquisitions. This brings us to RO3, which is addressed by the following question:

RQ3 How can decision makers be supported in acquiring serviceable assets in practice?

Answering RQ3 will involve developing and testing two possible ways to support practice: *(i)* a serious gaming tool and *(ii)* a mathematical model. The two types of support are targeted to acquisition projects before and after the contract period, respectively. Firstly, the serious gaming tool is designed to generate insight and awareness about improving serviceability during acquisition projects (before contracting). Secondly, the mathematical model provides insights about a replacement decision problem that is crucial for improving the serviceability of capital assets (after contract). Two subquestions will address each of the two types of support. The first subquestion is:

RQ3a What is a suitable way to support the early stages of an acquisition project (before contracting)?

To answer this question, a serious gaming tool is developed. The tool allows experts to make design tradeoffs explicitly, creating an opportunity to provide participants with awareness and insights about RQ2a and RQ2b. Answering this question reveals that serious games can be useful in the early stages of an acquisition project. The second subquestion is:

RQ3b What is a suitable way to support the late stages of an acquisition project (after contracting)?

Detailed engineering of capital assets often takes place after contracting. Methods for analysis of detail design are well developed, and different types of support are available. However, these methods often overlook the important interface between asset design and service design: the definition of the spare parts called Line Replaceable Units (LRUs). The selection of LRUs impacts downtime directly, and creates resource demand. This has direct consequences on cost and operational performance of the asset. The problem of defining what item should be line replaceable is not found in the literature. However, we see in practice that a lot of effort is placed in making this decision by the technical service provider. A mathematical model to support the LRU definition decisions is deemed as a suitable support. Answering RQ3 fills an important gap in the literature and gives insights for further research.

1.5 Methodology

This section details the overview of our research approach, the scope of our research and our research design. The research objectives involve *(i)* exploration, *(ii)* developing explanations and insight, and *(iii)* finding suitable ways to support practice. Therefore, the methodological approach used in this research is the

Design Research Methodology (DRM) of Blessing and Chakrabarti (2009). Design research is a mixed methods approach that uses a combination of exploratory, descriptive, and prescriptive research, as shown in Figure 1.11.

1.5.1 Overview of approach

Figure 1.12 shows the outline of the thesis and the research methodology. The general approach of this thesis is partly based on a so-called Type 5 study (Blessing and Chakrabarti, 2009, p. 62). The particular approach to DRM used in this research is shown below. Firstly, the Research Clarification (RC) aims to investigate the state of the art. Secondly, the Descriptive Study I (DS-I) is used to investigate acquisition projects in industry. Thirdly, the Prescriptive Study (PS) develops support. Finally, the Descriptive Study II (DS-II) validates the support.

Research Clarification (RC) gives an initial description of the state of the art and the relevant theoretical framework. The aims of the research and the research goals are clarified. The research design consists of a literature review. The research approach is depicted in Figure 1.13.

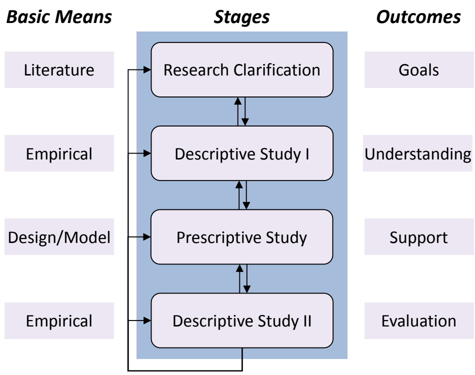


Figure 1.11: *Design research methodology framework (Adapted from Blessing and Chakrabarti, 2009).*

Chapter 1	Chapter 2	Chapters 3-6	Chapter 7	Chapter 8	Chapter 9
Research Clarification		Descriptive Study I	Prescriptive Study/Descriptive Study II		Conclusions
Review	Review	Comprehensive	Comprehensive/Initial	Comprehensive/Initial	
Research plan and literature review	*Literature review and definitions*	*Literature review and case study with four embedded units of analysis*	*Design science approach*	*Operations Research General Systems Theory approach*	

Figure 1.12: *Outline of this thesis and its research methodology.*

Descriptive Study I (DS-I) aims at increasing the understanding of the acquisition process. The research design for DS-I combines a literature review with an in-depth case study. This design is used in Chapters 3, 4, 5 and 6 to answer RQ2. The research approach for RQ2a and RQ2b is depicted in Figure 1.14. The case is a single in-depth case study with four embedded Units of Analysis (UOAs) (Yin, 2009). For answering RQ2a and RQ2b, each chapter will look at a different perspective within the case. The selected units are presented in Figure 1.15. The figure also shows that two subquestions will be asked of each individual UOA. Chapters 3 and 4 study the influence of design of technical systems (UOA is the fleet) and the technical service system (UOA is the plant) on serviceability, respectively. Chapters 5 and 6 study decision making in the service organization outside (UOA is the improvement project) and within acquisitions (UOA is the acquisition project) addressing serviceability, respectively. More detail on the methodology for Chapters 3-6 is given in Section 3.2.

Prescriptive Study (PS)/Descriptive Study II (DS-II) are combined to develop support and subsequently validate the support in current practice. Chapter 7 combines the PS and DS-II to answer RQ3a. That chapter uses a research design based on the Design Science approach of Holmström et al. (2009), as shown in Figure 1.16(a). Following Chapter 7, Chapter 8 combines the PS and DS-II to answer RQ3b. The chapter uses the Operations Research General Systems Theory research design of Mitroff et al. (1974), as shown in Figure 1.16(b).

The research design is adapted to the particular type of support that is developed. Each design presents different ways to identify whether the support can be used for the intended purpose. Initial evaluation of support is performed in a case project for RQ3a and by means of simulation for RQ3b.

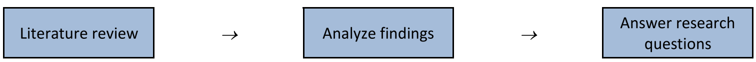


Figure 1.13: *Research approach for RQ1 in Chapter 2.*

Figure 1.14: *Research approach for RQ2a and RQ2b in Chapters 3 to 6.*

	Chapter 3	Chapter 4	Chapters 5	Chapter 6
UOA	***Fleet***	***Plant***	***Improvement projects***	***Acquisition projects***
RQ	RQ2a: What serviceability aspects are considered to be important to address during acquisitions?		RQ2b: How is serviceability addressed in acquisition projects in practice?	
Questions asked of individual UOAs	- What design aspects (of technical systems) are considered to play an important role in the acquisition of serviceable assets? -How do these design aspects influence serviceability?		-What decisions are made to improve serviceability during acquisitions? -How do these decisions influence serviceability?	

Figure 1.15: *Units of analysis used for answering RQ2.*

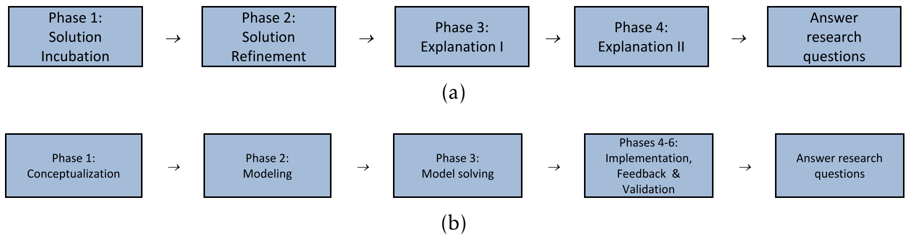


Figure 1.16: *Research approach for* (a) *RQ3a in Chapter 7 and* (b) *RQ3b in Chapter 8.*

1.6 Outline of the thesis

Figure 1.17 shows the outline of this thesis and links to the research methodology. The chapters offer both theoretical and practical insights to the reader. Below, we give more detail about the contents of each chapter.

Chapter 1 has introduced the problem of acquiring serviceable assets in practice. It focuses on the case of the main service provider for passenger rolling stock of the NS: NedTrain. We show the difficulties inherent in decision making during acquisitions, and describe the goals of the research: to provide insights about acquiring serviceable assets in practice, and to support practice.

Chapter 2 reviews the literature on serviceability and gives the theoretical framework. The chapter defines serviceability as an affordance: the joint ability of an item and its technical service system to afford both the supply and the demand for the technical services. We arrive at this definition after an in-depth review of the literature, though which we also operationalize the construct. We posit that the factors that impact serviceability can be identified in practice.

Chapter 3 gives insights about what design aspects (of technical systems) play an important role in the acquisition of serviceable assets, and how these design aspects influence serviceability. It uses the rolling stock fleet of the NS as an embedded unit of analysis. Eight rolling stock platforms are included in the study. Results show that commonality and modularity have important effects on serviceability. These factors affect the type, content, efficiency and progress of maintenance.

Chapter 4 gives insights about what design aspects (of technical service systems) play an important role in the acquisition of serviceable assets. Also, how these design aspects influence serviceability. It uses the maintenance facilities of NedTrain as an embedded unit of analysis. Four plants in the

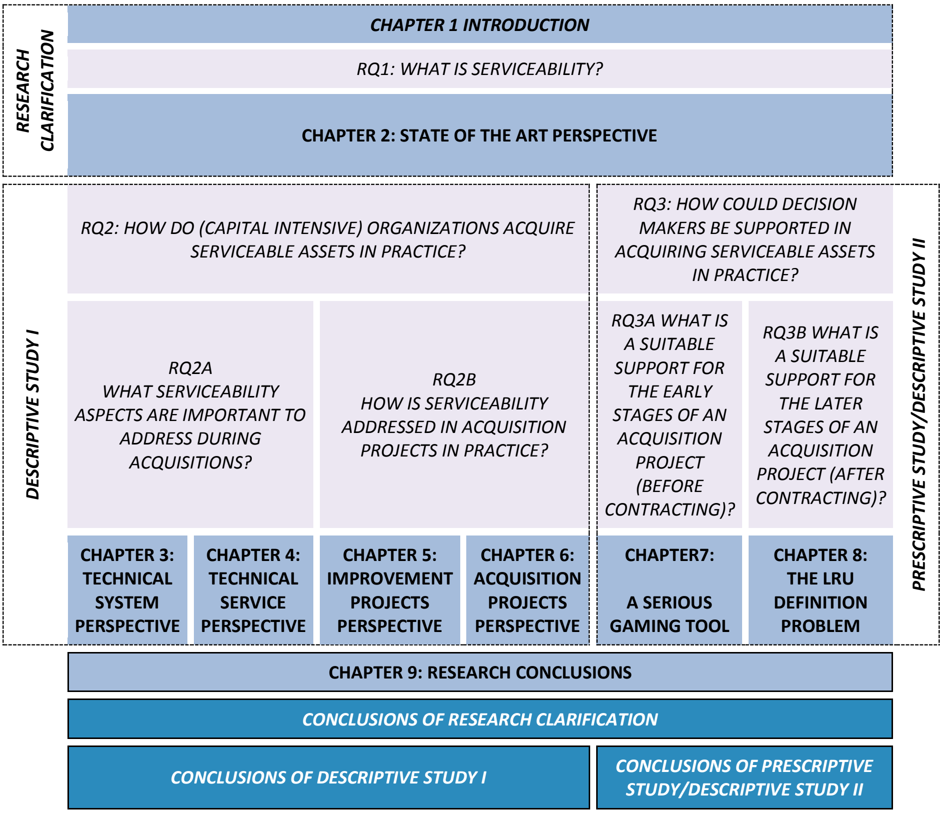


Figure 1.17: *Outline of this thesis and its research methodology.*

NedTrain supply chain structure are included in the study. We find that serviceability is contingent on mechanisms of organizational change as well as service modularity aspects, namely, decoupling of capabilities.

Chapter 5 investigates the decisions made to improve serviceability within improvement projects, and how these decisions influence serviceability. It uses improvement projects at NedTrain as an embedded unit of analysis. Ten improvement projects are included in the study. The organization fits new assets to existing service package while improvement projects are carried out mostly independent of asset acquisitions until after contracting. Strategic maintenance decisions are not concurrent to most rolling stock design decisions. The chapter exposes a need for methods and tools to support strategic maintenance decision making during early stages of acquisition, especially before contracting. We therefore develop such support in Chapter 7.

Chapter 6 investigates the decisions made to improve serviceability within acquisition projects, and how these decisions influence serviceability. It uses acquisition projects of the NS as an embedded unit of analysis. Four acquisition projects are included in the study. Results show that decisions are mostly left to the supplier before the tender by explicitly describing the maintenance (landscape) infrastructure and concept. Recent projects show a clear increase in the collaboration with first and second tier suppliers. New assets are merged to an existing fleet.

Chapter 7 develops the intended support for the early stages of an acquisition project (before contracting). This chapter shows a serious gaming tool developed as a service design experiment. Four game sessions are used to support design of the tool, produce the necessary improvements and evaluate its benefits and weaknesses. As it turns out, the game has several insightful applications. Validity is further tested in one case implementation for the early stage of acquisitions in practice. The game is shown to provide a collaborative decision making environment, and insights and awareness about the relationships between decisions.

Chapter 8 develops the intended support for the later stages of an acquisition project (after contracting). It presents the Line Replaceable Unit (LRU) definition problem using two cases from practice. An initial literature review shows that many maintenance repair decisions, such as the Level of Repair Analysis decisions, assume the LRU definitions implicitly. A gap is further examined in practice, where the LRU definition decision is usually made ad-hoc, or based only on engineering/technical criteria. A model is given for the LRU definitions problem. Finally, we show that significant cost reductions can be achieved when compared to two heuristics commonly used in practice.

Chapter 9 draws the conclusions of the research in this thesis. Firstly, by answering the research questions, it summarizes the most important insights that the research contributes, for both theory and practice. Next, the limitations of the research are addressed. Finally, it identifies several directions of further research.

Chapter 2

Defining serviceability: literature, theoretical background and analysis

This chapter reviews the literature on serviceability and gives the theoretical background of the research. It explains the meaning of serviceability by reviewing the literature, determining if the concept of serviceability might be explained by a currently existing theory. After a brief introduction in Section 2.1, Section 2.2 presents the methodology followed in this part of the research. Section 2.3 presents six key findings of our review: (1) serviceability, maintainability and supportability are often used interchangeably, (2) the terms have been around for decades, (3) their scope is often ambiguous, (4) they are measured both qualitatively and quantitatively but (5) mostly focus on time by correlation or regression, and finally (6) they are associated with design properties, and to an item's quality. Next, Section 2.4 defines serviceability: the joint ability of an item and its technical service system to afford both the supply and the demand for the technical services that are ultimately destined to sustain a required function of the item throughout its life cycle. That section also discusses serviceability measurement and analysis, as it will be used throughout the thesis, giving an indirect operational definition based on the constructs of maintainability and supportability. Finally, Section 2.5 draws conclusions on this part of the research.

2.1 Introduction

Popular use associates the term serviceability as synonymous to maintainability or supportability. However, while maintainability is often directly linked to the service activity itself, supportability seems more closely associated to the provision of resources to that activity (see, e.g., Blanchard et al., 1995; Smith and Knezevic, 1996a,b). This chapter aims to clarify *(i)* our current understanding, *(ii)* the scope and *(iii)* the meaning of the term serviceability. Research is necessary to gain deeper understanding both about how serviceability can be measured and about how it relates to existing concepts, e.g., maintainability, supportability.

Serviceability is a term often used to qualify a technical system as being fit for service. It is recognized as an important aspect related to the design of a technical system that also enables a service provider to supply the required technical services effectively and efficiently. For acquisition projects, serviceability of a technical system is seen as a fundamental factor of achieving operational performance at an affordable cost. However, an artifacts serviceability is bound to the technical service system that supports it, and therefore it is context dependent.

The discussion that is put forward in this chapter is firstly, that serviceability is a property that results from the design of both the technical system and the associated technical services. Secondly, that understanding serviceability is fundamental to understand *under what conditions an artifact will be useable*. Thirdly, that serviceability will determine to a large extent the cost and effort involved in operating technical systems throughout their useful life.

This chapter reviews the literature to understand how serviceability is defined and used in the research. Next, it explores how existing theory explains the concept of serviceability. The chapter uses product design theory to provide this theoretical framework. Design theory is a fundamental part of design research and methodology that addresses design, as well as designing. We begin with the science of design, because in the words of Herbert Simon, artificial objects can and should be studied scientifically. The seminal work of Simon is considered by many the start of the formalization of design science, or the science of artifacts. Since its early years many contributions have been made to the study of the process of designing, to study designers, to study artifacts, or to study the many interactions possible between designers, users and artifacts.

2.2 Methodology

This chapter is an exploratory study, and part of the Research Clarification (RC) described in Section 1.5. The main objective is to explain the meaning of serviceability, as stated in the research objective RO1 in Section 1.4. This section begins explaining the aim, scope and research questions. Next, it presents the research approach: a systematic review of the literature is conducted following the scheme of Figure 2.1. Finally, it describes how we analyze the results.

2.2.1 Aim, scope and research questions

The aim of this chapter is to study existing literature on serviceability to clarify its conceptual definition, its constructs and to ground the research of the following chapters on existing theory. The scope of the review will be the serviceability of capital assets and those concepts typically associated with serviceability, e.g., maintainability, supportability or technical services. These terms are often used to characterize some quality aspect of the in-service stage of the life cycle of technical systems (see, e.g., Neely et al., 1995). Section 2.3 will further clarify how these terms are related.

The main research question is RQ1 of Chapter 1: What is serviceability? To clarify the meaning of serviceability, this chapter addresses two additional sub-questions, namely, *What is the related terminology?* and *How is it operationalized?*

2.2.2 Approach

The research approach is based on a comprehensive review of the literature. Figure 1.13 shows the general approach: we review the literature, analyze the findings and answer the research question.

Approach to literature review

Figure 2.1 shows the scheme used to sample the books and articles in the literature review. This scheme is generally followed in this thesis (for RQ1, RQ2 and parts of RQ3). Sampling the literature begins with the selection of relevant sources in the field of study. This is done by selecting journals or proceedings from database services such as Scopus, Web of Science and Google Scholar. Books are selected ad-hoc based on their known relevance in the field. Next, a first selection removes any unsuitable sources, such as book reviews or editorials. In the next step one filters the data set searching for the relevant keywords in the title, abstract or keywords. After a set of articles (and books) have been found containing the relevant keywords, the remaining articles or books in the sample are analyzed in more detail. Relevant criteria in Chapter 2 are, for example, if the authors provide explicit definitions; or if operational measures are given; or if they mention attributes that may be linked to those measures.

The included areas in the field of study of this chapter are design research, maintenance engineering, maintenance management, supportability engineering and operations management. The main sources are found through Scopus, Google Scholar and open web search, the latter being applicable to find specific references. Keywords included are service(ability), support(ability), maintain(ability), maintenance, technical services, (architectural) attributes and (design) properties. Typical examples are those publications explicitly defining terms such as supportability (Matthews et al., 1994), serviceability (Sherif and Kheir, 1982), or maintainability (Department of Defense, 1997b).

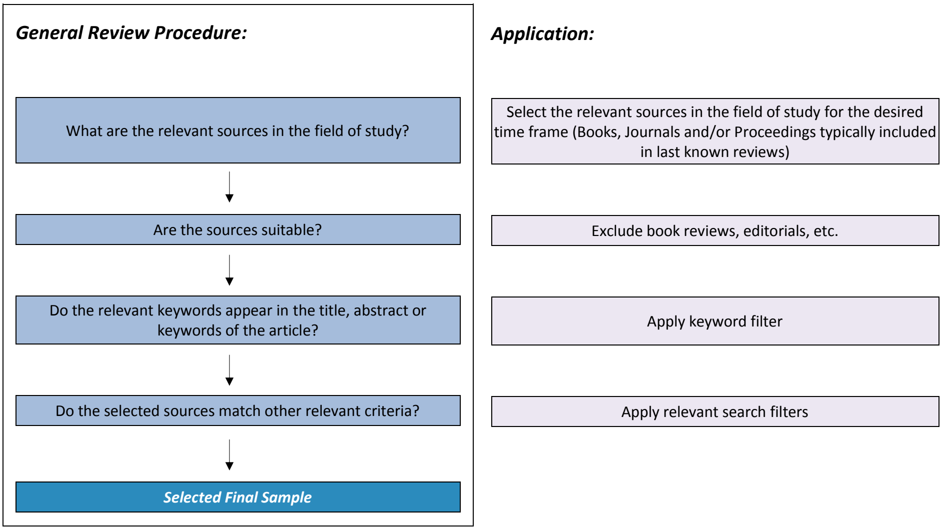


Figure 2.1: *Sampling approach for the literature reviews in this thesis.*

Finally, only those publications that either (1) define the concept of serviceability or (2) define its measures are included. These two additional relevant criteria are applied to filter the sample. The analysis of the sample focuses on clarification of the popular uses and definitions of the terms. This analysis continues to identify the possible theoretical underpinnings of the concept of serviceability. Relevant areas of theory considered include design theory, management theory and background related to best practices in acquisitions. After analyzing the findings we answer the research questions.

2.2.3 Results and analysis

At first, a broad search collected a database of 244 publications containing at least one of the relevant terms in the areas specified. Next, the database was reduced to those publications specifically useful for answering the research questions: to the definitions, the terminology or the operational measures. The final sample contains 54 publications. Initial analysis is carried out using reference manager software. Next, definitions were analyzed using mindmapping software to identify common definitions, overlaps in meanings and popular beliefs about their use. Six general themes emerged during this process. They are displayed as a mindmap in Figure 2.2. The review of these six general themes is then summarized into six key findings in Section 2.3.

Once the key findings are presented it becomes clear that the construct of serviceability is strongly linked to maintainability and supportability. Therefore, our analysis continues to propose a conceptual definition for serviceability in

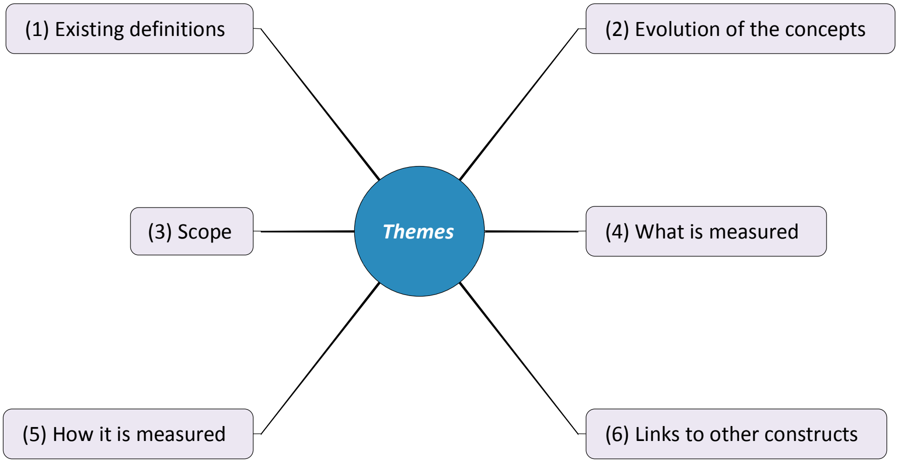


Figure 2.2: *Six key themes identified in the review.*

Section 2.4. In that section we provide theoretical support to the construct so that it is sufficiently general, yet rigorous.

2.3 Key literature findings

The following parts of this section summarize the results of the literature review into six key findings. Our first finding is that serviceability, maintainability and supportability are terms which are very closely related but inconsistently used in the literature. Surprisingly, the three terms have been used in the research for decades (second finding). Our third finding is that the scope of the definition of serviceability, in terms of the activity involving a technical service, is often entangled with the scope of maintainability and supportability. In our fourth finding we discuss that measures used for the construct of serviceability –again, similar to those used for maintainability and supportability– are dominantly time and cost-based. However, both qualitative and quantitative measures are used to assess the serviceability performance with a variety of methods (fifth finding). Our sixth finding is that factors that influence these time and cost-based performances can be broadly categorized into technical system design aspects, and technical service design aspects.

2.3.1 Existing definitions

There are three terms which are very closely related but inconsistently used in the literature: serviceability, maintainability and supportability. The term serviceable is an adjective that defines when something is suitable to be used (OALD, 2010).

The common uses of the word refer to both the provision and the acceptance of a service. This chapter explores the latter. Serviceability states the quality of *how able something is for service*, i.e., *how fit for service*.

Analysis of the literature reveals some similarities between the terms serviceability, maintainability and supportability. For example, the literature equates all three terms with speed and ease of maintenance. In some cases, serviceability and supportability are used interchangeably (see, e.g., INCOSE, 2010; Tinga, 2013). Tables 2.1 to 2.3 summarize the popular definitions found in the literature sample for the terms serviceability, maintainability and supportability, respectively.

Table 2.1: *Definitions of serviceability.*

Author	Serviceability is
ARINC (1964)	The degree of ease or difficulty with which a piece of equipment can be repaired
Department of Defense (1981b)	A measure of the degree to which servicing of an item will be accomplished within a given time under specified conditions
Di Marco et al. (1995)	The measure of how easy it is to perform all service-related operations on a product during its life-cycle
Dhillon (1999)	Degree of difficulty or ease with which a product can be restored to its operable state
Takata et al. (2004)	The ability of a product to be maintained
Giudice (2010)	The degree of facility with which the system is capable of being retained in, or restored to, serviceable operation

Finding 1

The concepts of serviceability, maintainability and supportability have a close meaning in the literature. The popular definition of serviceability states that it is a design characteristic representing the degree of ease or difficulty with which a system can be repaired or maintained. Authors use the terms interchangeably, but with varying scopes, measures and meanings depending to some extent on the research domain of the publication (OR, OM, ME, etc.).

2.3.2 Evolution of the concepts

The concepts of serviceability, maintainability and supportability have been used in the literature for decades. Maintainability has been the concern of engineering for more than one hundred years. Figure 2.3 displays a historical evolution of the concepts based on background provided by Dhillon (1999) and Jones (2006b).

Table 2.2: *Definitions of maintainability.*

Author	Maintainability is
Department of Defense (1981a)	The measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair
Gershenson and Ishii (1993)	The ease with which regular or routine maintenance can be performed
Kusiak and Lee (1997)	The ability of an item to be maintained
Department of Defense (1997b)	The relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair
Coulibaly et al. (2008)	The characteristics of equipment design and installation that provides the ability for this equipment to be repaired easily and efficiently
CEN/TC 319 (2010)	The ability of an item under given conditions of use, to be retained in or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources

Many developments of the 1950's and 1960's were the result of cross-fertilization of best practices from commercial industry and defense. Serviceability has been an especially important consideration for developing complex systems since the 1960's (Carter et al., 1964).

As a result, several specifications surfaced in the 1960s. Many of the standards were adopted and developed by the defence sector, aimed for their application in acquisition programs. An example of such developments include maintainability program requirements (MIL-STD-470), maintainability demonstration (MIL-STD-471), maintainability prediction (MIL-STD-472) and definitions (MIL-STD-721B). Within the DoD, Integrated Logistics Support (ILS) was developed as a management approach to address supportability from the beginning of a program.

An increased awareness about the importance of maintenance and support

Table 2.3: *Definitions of supportability.*

Author	Supportability is
Judge (1981)	A measure of the degree to which a ship can be maintained at an acceptable level of operational readiness and material condition
Matthews et al. (1994)	The ability of the system to support mission objectives
Department of Defense (1997a)	The degree to which system design characteristics and planned logistics resources meet system requirements
Blanchard (2004)	The degree to which a system can be effectively supported
Jones (2006b)	A prediction or measure of the characteristics of an item that facilitate the ability to support and sustain mission capability within a predefined environment and usage profile
Department of the Army (2009)	That characteristic of a system and its support system design that provides for sustained system performance at a required readiness level when supported in accordance with specified concepts and procedures
ASD (2009)	The measure of the degree to which all resources required to operate and maintain the product are provided in sufficient quantity

was made explicit later in the 1980s with the introduction of DoD Directive 5000.40. The Directive indicates objectives, policies and responsibilities "for addressing maintainability issues in the procurement process". The goal was to lower demand for maintenance and logistic support as early as possible in the program. More recently, similar standards have been developed in other countries (e.g., DEF-STAN-00-600).

Finding 2

The terms serviceability, maintainability and supportability have been used in the research for decades. Most definitions in the literature are an adaptation of definitions found in military standards or handbooks (e.g., Department of Defense, 1981a, 1983, 1988).

2.3.3 Scope

A careful study of the scope of serviceability reveals mixed popular beliefs. The scope of the definition of serviceability, in terms of the activity involving

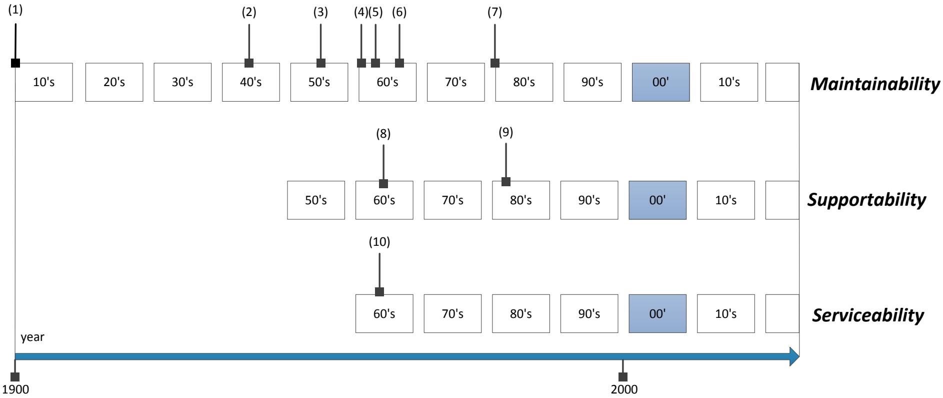


Figure 2.3: *Evolution of the concepts of maintainability, supportability and serviceability. Timeline milestones: (1) Army Signal Corps (Wright brothers' airplane); (2) Department of Defense (WWII); (3) Machine Design (1956); (4) MIL-M-26512 (1960); (5) Maintenance time specification (1963); (6) MIL-STD-470,471,472,721B; (7) DOD Directive 5000.40; (8) ILS (1965); (9) ILS standard (1984); (10) Serviceability features in computer systems (1964).*

a technical service, is often entangled with the scope of maintainability and supportability. Firstly, the scope of what is meant by technical service has evolved. Secondly, there are different views about the scope of the subject of measure when using the serviceability construct.

Table 2.4 shows the scope found in the research. Some authors do not constrain the scope of serviceability (service) to any particular type of activity (see, e.g., Kusiak and Lee, 1997), other sources (mainly from the defense sector) traditionally relate servicing to acts other than preventive or corrective maintenance (see, e.g., Department of Defense, 1988). The scope of maintainability is usually

Table 2.4: *Scope of definition.*

Serviceability	(1) regular maintenance; (2) routine maintenance (3) actions taken to restore or retain condition
Maintainability	(1) (malfunction) diagnosis; (2) maintenance (3) repair (4) replenishment of consumables (fueling, oiling, lubricating); (5) cleaning; (6) monitoring
Supportability	(1) installation; (2) training; (3) maintenance and repair services (generally termed services); (4) documentation; (5) availability of spares; (6) upgrades (enhanced functionality); (7) customer consulting; (8) warranty schemes

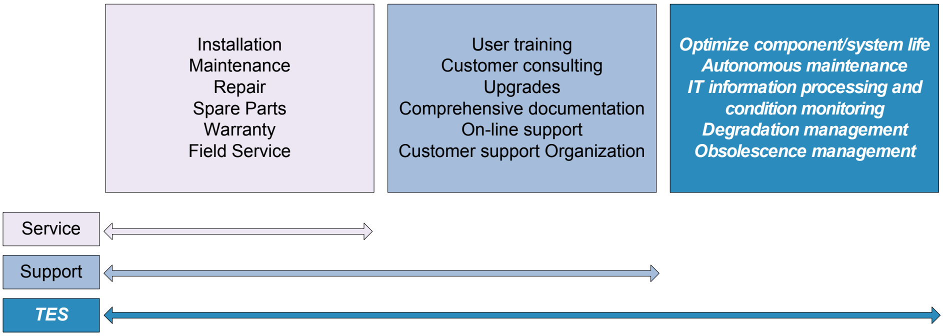


Figure 2.4: *Scope of service, support and Through-life Engineering Services (TES).*

related to many types of direct actions or tasks performed on equipment (e.g., replenishment of consumables).

Supportability refers to many types of tasks performed over the life cycle. However, no clear distinction exists between these tasks. Some authors use the term *support* referring to activities of resource *supply* that are external to the maintenance task. However, there is no consistency in the use of terminology. It is claimed, for example, that "some ships are more supportable than others –this means easier to maintain over the life cycle", and therefore "a ship is supportable if it can be maintained" (see, e.g., Judge, 1981). Others refer to supporting tasks as those that support the system, and maintenance and repair services (generally termed services) are also included in this scope (see, e.g., Goffin, 2000).

Figure 2.4 displays the scope of service, support and Through-life Engineering Services (TES) discussed in Goffin (2000); Roy et al. (2013). TES are a more recent extension to the provision of service or support.

Finding 3

The scope of what is meant by service, support or maintenance is not consistent in the literature. Through the years, the scope of the concepts has broadened. Serviceability was an issue of repairability (repair and replacement) and service in the 1960's (ARINC, 1964). In the 1970's, serviceability included maintainability and repairability (also a function of diagnostics) (Desai, 2006). More recent literature tends to use the concepts interchangeably. Recent developments in the research extend the scope of services to Through-life Engineering Services (TES) (see, e.g., Roy et al., 2013).

2.3.4 What is measured

The construct of serviceability is measured both qualitatively and quantitatively, and so are its related terms of maintainability and supportability. Quantification

Table 2.5: *The measures used in the construct definitions.*

Serviceability	Time; cost; ease of; facilitate; frequency
Maintainability	Time; cost; ease of; ability to be retained or restored; reduction of; efficiency of
Supportability	Time; cost; frequency; facilitate; degree of design and resources meeting requirements; measure if all requirements; ability to support objectives; sum of maintainability and logistics support; degree to which...

of their measure is referred to as a performance, e.g., maintainability performance (NEN-EN, 2010). Table 2.5 lists the many measures found in the literature to be associated with the construct definitions in this review.

Table 2.5 shows that operational measures for serviceability –and its related constructs: maintainability and supportability– are many. However, time measures appear to dominate the literature on quantitative assessments. The benefit of time based assessment is that they give insight that is useful for estimating availability of the technical system. The typical time based measure of maintainability is the lead time of repair tasks. Mean time to repair (MTTR) and maximum time to repair (MaxTTR) became very useful for the assessment of the maintenance burden for manual maintenance operations. However, many authors also give a probabilistic measure for the construct.

The typical time based measures of supportability are logistic delays. A logistic delay is the time during which no maintenance can be performed on a technical system because of waiting for resources (Department of Defense, 1991; Dhillon, 1999; NEN-EN, 2010). Normally these delays do not include administrative delays, which are actually "crated by some administrative constraint or priority" Dhillon (p. 37 1999). Jones (p. 9.7 2006b) identifies six delay types –e.g., travel to maintenance facilities, unsuitable weather conditions, waiting for facilities, equipment, service engineers, spare parts or information.

Qualitative metrics are most often used during the design of technical systems. Qualitative measures of serviceability often involve some index of task effort, complexity or difficulty (see, e.g., Di Marco et al., 1995; Ishii, 1998). Their measurement is discussed further in the next subsection.

Finding 4

Each of the three constructs is measured using similar metrics. Quantitative metrics such as lead time or cost are used. Qualitative metrics such as "ease of", or "ability to" are also associated with all three constructs.

2.3.5 How it is measured

We see both qualitative and quantitative measures for serviceability, maintainability and supportability. However, we also see a clear aim towards time and cost-based assessment. The field of maintenance has an abundance of theory, models, methods and tools that help engineers analyze, explain or predict maintenance performance of capital assets. Table 2.6 presents several models found in the literature.

Several tools have been developed to assist in the analysis and evaluation

Table 2.6: *The models, methods and tools: how it is measured.*

Serviceability	**Serviceability Cost Index** (Eubanks and Ishii, 1993; Gershenson and Ishii, 1993); **Petri net model** (Tiwari et al., 2002); **Fuzzy logic trained neural network** (Wang and Allada, 2000); **Service mode analysis (SMA)** (Di Marco et al., 1995; Gershenson and Ishii, 1991, 1993; Ishii et al., 1993)
Maintainability	*Statistical time distribution*: **Federal Electric (1960)** (Department of Defense, 1966; Smith et al., 1970); **Republic (1960)** (Department of Defense, 1966; Smith et al., 1970); **General Dynamics/Convair (1961)** (Smith et al., 1970); **ARINC (1962)** (ARINC, 1964; Department of Defense, 1966); **TEAM (1966)** (Bunger and Dibble, 1966) *Empirical correlation*: **RCA (1960)** (Department of Defense, 1966; Smith et al., 1970); **Bretby Index** (Mason, 1990); **Maintainability attributes digraph** (Wani and Gandhi, 1999); **Tribo-maintainability index** (Wani and Gandhi, 2002); **Vector projection Method** (Chen and Cai, 2003); **SAE index** (Desai and Mital, 2006; SAE, 2009); **Fuzzy evaluation** (Zhong and Youchao, 2007); **Desai & Mital Index** (Desai and Mital, 2010)
Supportability	*OR models*: **Spares** (Basten and van Houtum, 2014; Muckstadt, 2005; Sherbrooke, 2004); **Facilities and special equipment** (Kumar and Knezevic, 1998; Smith and Knezevic, 1996b); *Multi-criteria decision models*: **Attribute hierarchy to evaluate system architectures** (Johannesen and Verma, 2000; Verma et al., 2003)

of serviceability. The Serviceability Evaluation Chart plots for each module the frequency of service needs (SC) and service operation complexity (SD) (Ishii, 1998). Gershenson and Ishii (1991); Ishii et al. (1993) and Gershenson and Ishii (1993) develop service mode analysis to identify the major life-cycle service cost drivers early in the design process. Di Marco et al. (1995) continue this line of research proposing service modes and effects analysis.

Models for maintainability are the most common in the literature. Many of them are actually intended as models of maintenance time, so their scope overlaps with serviceability and supportability measures. Maintainability models have been categorized as time-synthesis models and correlational models (Smith et al., 1970). Time-synthesis models describe the maintenance burden in terms of statistical distribution of time required to complete a certain maintenance task. Correlational methods use checklists for determining maintenance burden in a qualitative fashion. The maintenance burden can be translated by correlation of the checklist scores with historical maintenance data. Statistical time distribution models are widespread in OR literature. The most common approach is to assume exponentially distributed repair times, with constant repair rate (Alfredsson and Verrijdt, 1999; Gupta et al., 2013; Mirzahosseinian and Piplani, 2011; Moreu De León et al., 2012; Wong et al., 2005).

Wani and Gandhi (1999) propose a an attributes digraph –a graphical representation of the maintainability attributes and their relations to each other– to relate design, logistics support and personnel. They later propose the inclusion of tribology in maintainability evaluation (Wani and Gandhi, 2002). Chen and Cai (2003) propose the vector projection method, based on the analytic hierarchy process (AHP). Their model was specifically developed for design reviews, and considers physical design, logistics support and ergonomics factors. Zhong and Youchao (2007) develop an index based on relative closeness to an idealized maintainable system, and propose the maintainability fuzzy evaluation method. Desai and Mital (2010) proposed a maintainability index based on checklists that incorporate design for assembly and disassembly criteria. Smith et al. (1970) and Desai and Mital (2006) review several other correlational models for maintainability.

Most quantitative models for supportability are applied to determine availability from the Mean Time To Support (MTTS). Supply support has certainly received the most attention (Basten and van Houtum, 2014; Muckstadt, 2005; Sherbrooke, 2004). Smith and Knezevic (1996b) develop two simple waiting time models. The models assume two systems are competing to use one repair facility and the models proposed are one for constant repair rate and one for distributed repair rate. Kumar and Knezevic (1998) extend these two models, developing Markov, semi-Markov and non-Markov models for multiple systems using multiple support facilities.

Finding 5

The literature shows a clear focus on lead time when analyzing serviceability. There has been increasing interest in quantifying repair time, maintenance time and delays. Qualitative expert-based assessments are used as an initial source of estimations in many indices, e.g., The Bretby index (Mason, 1990).

2.3.6 Links to other constructs

Many design aspects influence service performance, but we find that they can be broadly categorized into technical system design aspects, and technical service design aspects. Tables 2.7 and 2.8 list a series of factors found in the literature that either affect the quality of the concept (what influences it), or result from the quality of the concept (what it influences).

Influences and effects of serviceability, supportability and maintainability are a main concern for an acquisition project. Many of the factors presented in Tables 2.7 and 2.8 are explicitly addressed in acquisitions practices recommended in the literature. Many books and guidelines including Integrated Logistics Support (ILS) (Department of Defense, 1986; Jones, 2006a; Ministry of Defence, 2010),

Table 2.7: *Attributes that influence serviceability, maintainability and supportability performance (what it influences).*

Serviceability	Numerous failure modes with multiple effects and varying levels of predictability; Responsivity of the supply system; Modularity affects service performance; Reliability of components; Labor cost; Inventory cost; Accessibility of components or parts; Availability of materials and resources; Training; Customer preferences; Where the product is serviced; Length and coverage of warranty; Special resources (tools, equipment, facilities); Service requirements; Mean time of repairs; repair complexity (special skills)
Maintainability	Personnel having specified skills; Procedures; Resources; Level of maintenance; Level of repair; Interchangeability; Easy accessibility; Easy serviceability; Diagnostic and prognostic capabilities; Fault detection and isolation
Supportability	Highly complex network of totally interdependent relationships; parts obsolescence; paperwork processing; intermediate level turnaround time; depot level turnaround time; pipeline spares; participation; autonomy; reward and recognition; management information systems and performance measurement

Table 2.8: *The effects of serviceability, maintainability and supportability performance (what it influences).*

Serviceability	Reduced warranty cost; Enhanced customer appeal; Longer service life
Maintainability	Increase serviceability; increase repairability; increase cost effectiveness of maintenance; ensures meeting requirements
Supportability	Product downtime can be reduced; customer satisfaction; conceptual design; the program after design optimization; sustained system performance; sustained mission capability

Logistic Support Analysis (LSA) (ASD, 2009; Blanchard, 2004; Department of Defense, 1983; Hastings, 2010; Jones, 2006b), Systems Engineering (Blanchard and Fabrycky, 2011; INCOSE, 2010) and industry best practices recommend an explicit look at these attributes as fundamental factors of operational performance.

Finding 6

The literature presents a large number of factors that either influence or are influenced by the quality of serviceability, maintainability and supportability performance. Factors that influence these performances can be broadly categorized into technical system design aspects, and technical service design aspects. Factors that result from the quality of the performances tend to be associated with benefits for the client

2.4 Defining serviceability

This section provides our definition of serviceability as the joint ability of a technical system and its technical service system to afford both the supply and the demand for the technical services that are ultimately destined to sustain a required function of the technical system throughout its life cycle. Firstly, the section positions serviceability within a class of design attributes. Secondly, it borrows constructs from the literature on Single Minute Exchange of Dies (SMED) to make a direct link between the concept of serviceability, the service operation and the setups of the service operation. Lastly, it introduces our definition, and relates it to the concepts of maintainability and supportability explicitly.

2.4.1 Positioning serviceability within design attributes

Serviceability is a design property. It cannot be influenced directly by a designer, which means that designers must influence serviceability by means of controlling other technical system attributes. Table 2.9 shows the core of the different definitions of serviceability, maintainability and supportability found in the research. It is a popular consensus that all are attributes of design. However, a range of other definitions were found (see Table 2.9). This broad range of definitions makes it specially difficult to clearly understand what is meant by any of these terms.

At this point, it becomes beneficial to introduce a theoretical underpinning to clarify the meaning of the terms. Table 2.9 shows that all three concepts found in the literature are strongly linked to design. Several important contributions exist in the literature on Design Theory, but the overall mainstream is design based on functional thinking. The modern design theories based on functional thinking have their origins in the 1960s. The advent of General Systems Theory (Bertalanffy and Sutherland, 1969) and the work of Simon were foundational to this school of thought, mainly aimed at supporting designers. The work of Pahl et al. (2007, originally published in 1977) was key in developing methods to support functional modeling and the modeling of component interactions by flows of material, energy and information.

Since then, several design theories have emerged. Contributions include the theory of technical systems (Hubka and Eder, 1984), with its theory of properties and domain theory (Andreasen, 1980; Andreasen et al., 2014), the theory of dispositions (Olesen, 1992), FBS model of (Gero, 1990), axiomatic design theory (Suh, 1998), general design theory (Yoshikawa, 1981), extended general design theory (Tomiyama and Yoshikawa, 1987), C-K theory of design (Hatchuel and Weil, 2003, 2009), decision-based design (Hazelrigg, 1996) and affordance theory of design (Maier and Fadel, 2001, 2007, 2008). Andreasen (2011); Andreasen and McAloone (2008); Bayazit (2004); Chakrabarti and Blessing (2014); Eder (2008); Maier and Fadel (2008); Tomiyama et al. (2009) give a more detailed review of design theory and history.

Table 2.9: *The concept: what it is.*

Serviceability is a	characteristic of design; characteristic of installation; function of design; parameter of design; aspects of product; measures taken
Maintainability is a ...	characteristic of design; feature of design; dimension of quality; critical factor of performance; consideration of life cycle; element of design; sophisticated concept
Supportability is a	characteristic of design; characteristic of product; characteristic of a system and its support system design; function of system events; capability (of total system design); key component of performance; criteria of design requirements

We consider two main theoretical underpinnings that are good candidates for further analysis. Below, we discuss the Domain Theory/Theory of Technical Systems (TTS) and the Affordance Theory of Design. This allows a more detailed examination of the concept of serviceability from the looking glass of each of these contending theories.

Domain Theory/Theory of Technical Systems (TTS) the Theory of Technical Systems has been proposed as an approach to understand artifacts under a common framework. Its goal is to firstly classify and categorize knowledge about technical systems. Secondly, to provide a suitable terminology. Thirdly, to provide statements about the nature, conformation, origination, development and empirical observations on TTS. TTS defines the technical system as belonging to three domains: activities, organs and parts. Technical activities (activity domain) produce transformations of an operand, and are associated with the ultimate goal of the technical system. Organs (organ domain) are related to the function of a technical system, and TTS specifically addresses transformation functions. In technical systems, the different modes of action of a structure exhibit behaviours that provide the functions of the system. Parts (part domain) constitute the structure of a technical system. Parts are material entities that are assembled and interact through their assembly interfaces.

In each domain, an artifact can be described as producing a certain functionality, i.e., transforming its inputs into outputs. Hubka and Eder (1984) states that "every technical system ... has certain properties that belong to the system and define it. The terms property, attribute, quality and characteristic are all synonyms of aspects that define a technical system. (Hubka and Eder, 1984) recognized that there are many ways to classify a system's properties, that certain classes of properties had to be clearly differenciated. Based on TTS, Andreasen proposed his Theory of Properties to bring further clarification (Andreasen et al., 2014). The Theory of Properties defines attributes as a superclass that contains two main classes of properties. These two classes are (arbitrarily) named: structural characteristics and functional properties. On the one hand, characteristics define the anatomy of the technical system: its structure and relations within that structure. Characteristics can be controlled by designers directly. On the other hand, functional properties describe the behaviour of the artifact, and can only be determined indirectly. A special type of functional property is the relational property. Relational properties are carried in relation to a product life system. This type of relational property best defines the concept of serviceability.

The Theory of Affordances Affordance is what one system provides to another system (Gibson, 1979). This makes affordance a relational concept, and complementarity is entailed between two interactive systems. Gibson (1979) used affordance theory to explain how individuals in a group interacted with their environment. That work was initially adapted to design research in the 80's (Maier and Fadel, 2008). Since then, affordance theory has had a long trajectory in design research, branching into product semantics, interaction design and more recently received increasing attention as a fundamental concept of engineering design (Maier and Fadel, 2001).

The affordance theory of design is based on Gibson's concept. Maier and Fadel (2001, 2008) see designers, artifacts and users as a complex adaptive system. Designers design the artifact, users use the artifact and the designer determines how the user uses the artifact. However, the user also defines requirements about what the artifact must afford, and the artifact's embodiment affords certain behaviours by the user.

Serviceability could be clearly identified as an affordance of a system. As a non functional requirement, i.e., *the product shall afford servicing*. As a part of design analysis, i.e., *how well can this product afford servicing?* However, the relational aspect of the concept of affordance demands that such statements are made about the artifact *relative* to another system. The reference system is the technical service system. A statement of affordance requirements about maintenance could be "afford maintenance to service engineer". Dispositional thinking would trigger a designer to provide easy access to lubrication points, easy inspection of parts, easy replacement of parts, easy cleaning, etc.

There is a strong contextual character to the concept of serviceability. It does not result from design decisions of only one of the systems involved. It is perhaps for this reason that best practices dictate that early design decisions should involve development of a technical system together with the technical service system (Department of Defense, 1981a,a; Dowlatshahi, 1996; Jones, 2006a; Lee, 1996; Öner et al., 2007). Defining the scope is the next step in clarifying the conceptual definitions.

Therefore, based on domain theory we propose that serviceability is an attribute of a technical system belonging to the class of functional properties, and of the type of relational properties. Hubka and Eder (1984) suggests that these types of properties are difficult to measure, especially when technical systems are still in the design stage. It is not a characteristic that designers manipulate directly. Serviceability can also be expressed as an affordance, a relational property of the technical system and its technical service system. The main difference between the two views is that one defines properties based on the paradigm of function, i.e., a transformation taking place in the operand (Hubka and Eder, 1984). Affordances are not functionally defined (Maier and Fadel, 2001).

What this means for our research is that there are structural characteristics of a technical system that designers can control to improve the serviceability of technical systems. What these properties are, and how they impact serviceability will be discussed in Chapters 3 and 4.

2.4.2 Setups and service activities

As a relational property of a technical system, serviceability cannot be defined with knowledge of the technical system only. The relational nature of this attribute means that serviceability must also be determined by some external environment to the technical system. This environment is the technical service system. We believe that technical services and manufacturing have many things in common. To better illustrate the importance of the technical service system to the concept of serviceability, we refer to the concept of Single-Minute Exchange of Die (SMED), introduced by Shingo (1985) as a part of the Toyota Production System.

We find that as a relational property, serviceability must be influenced by the technical service activities. In manufacturing, Shingo (1985) describes three types of operations: essential operations, auxiliary operations and margin allowances. Two different setups help prepare an operation: those that can only be performed when the machine is stopped (internal setup), and those that can be conducted while the machine is in operation (external setup). By introducing this thinking about operations and setups, the SMED method accomplishes dramatic productivity improvements. The performance focus is on lead time improvements, but the changes introduced by the SMED have led to other improvements as well.

Under the assumption that technical services and manufacturing share many qualities, then we should find that serviceability must be impacted not just by the service activity, but by all (internal and external) setup processes of those activities. The concept of setups has been the concern of manufacturing for many decades. In manufacturing, a setup is any activity carried out to prepare an operation. Setups do not add direct value to the core activity. They introduce delays that prolong the lead time required to carry out an operation. Reducing setups was the core of the SMED method (Shingo, 1985). The fundamental insight in the SMED method is the clear distinction between what Shingo (1985) named internal and external setups.

Literature on maintainability, supportability or serviceability studies does not clearly make the distinctions between service activities and setups, despite the fact that performance measurement in many maintenance organizations is driven by a lead time mindset. Mechanical part replacement mostly deals with operations aspects of a technical service, but many internal setups are also mentioned in their metrics (see, e.g., Mason, 1990, where the author includes access factors such as (1) hatches and covers, (2) appertures and (3) location; and operations factors include preparation). This is apparently also the case in more recent literature, where technical system design factors are better distinguished from the service design factors, but no difference is made on what aspects of the lead time they influence. Appendix A shows maintenance times in relation to depot visits, operations and setups. Figure 2.5 shows the concept of serviceability and the related terminology, i.e., maintainability and supportability, as it will be used in this thesis. The term maintainability will be used in a more strict sense as a proxy to those internal properties of both the technical system and the technical service system that impact the essential operation, the auxiliary operation and the allowances. Supportability will be the proxy to those properties of both the technical system and the technical service system that influence all (internal and external) setup processes of the maintenance activity.

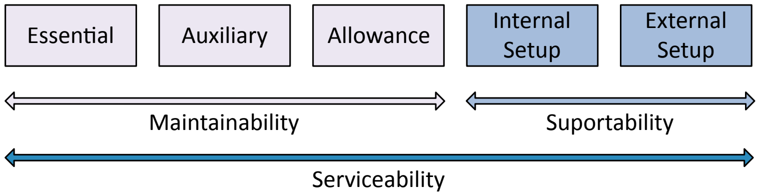


Figure 2.5: *The concept of serviceability.*

2.4.3 Serviceability definition

Figure 2.6 displays the conceptual definition of serviceability. Availability, and specifically the operational availability, is influenced by two performances: the reliability of the technical system, and the serviceability of the technical system in relation to the technical service system.

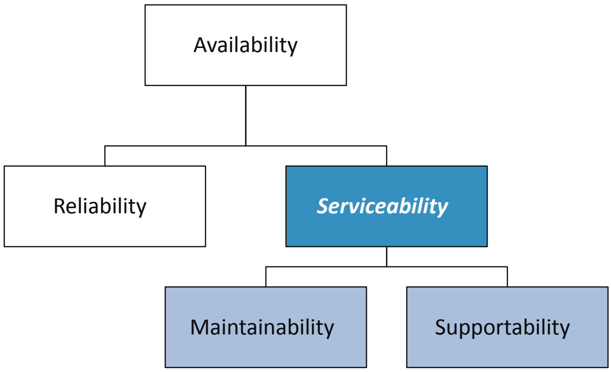


Figure 2.6: *Interpretation of serviceability.*

At this point we are ready to propose the following definition:

Definition. *Serviceability is the joint ability of a technical system and its technical service system to afford both the supply and the demand for the technical services that are ultimately destined to sustain a required capability of the technical system throughout its life cycle at a reasonable cost.*

The definition speaks of a technical system affording the supply of a technical service (it is able to receive a specific type of technical service). Also, it refers to a technical service system being able to supply the required service. Hence, both systems afford servicing.

2.5 Conclusions

This chapter defines serviceability as an affordance, a relational property of a technical system and its technical service system. Using the concept of affordance we defined serviceability the joint ability of a technical system and its technical service system to afford both the supply and the demand for the technical services that are ultimately destined to sustain a required function of the technical system throughout its life cycle at a reasonable cost.

The chapter further operationalized the construct of serviceability. The quality of serviceability influences system performance, as measured through the operational availability/cost ratio. Based on the concept of setups and service activity, we provide an indirect operational definition of serviceability: the combination of the construct of maintainability and supportability.

Chapter 3

Technical system perspective: serviceability in the fleet[1]

This chapter gives insights about what design aspects of technical systems play an important role in the acquisition of serviceable assets. Also, it provides insights about how these design aspects influence serviceability. It is the first part (out of four) of the company case, and it uses the rolling stock fleet of the NS as an embedded unit of analysis. Eight rolling stock platforms are included in the study. The literature tends to prescribe for acquisitions the selection of the best technical system architecture. Finding one best candidate proves to be difficult in practice, and contingent factors are commonality and modularity. These factors affect the type, content, efficiency and progress of technical services. Section 3.1 briefly introduces the research problem. Next, Section 3.2 presents the methodology, followed by the literature review in Section 3.3. The review shows that modularity and commonality are widely associated with serviceability, but their impacts are not clearly understood. Section 3.4 presents the case results from NedTrain, where the impacts of commonality and modularity are found in plant, people and processes, including the supply chain. The phenomenon of divergence, a decrease in commonality associated with acquisition and refurbishment of rolling stock, is identified in the fleet. Section 3.5 discusses the findings, and draws a conceptual model from both theory and practice to describe the design impacts on serviceability. Finally, Section 3.6 presents conclusions of the chapter.

[1] Parts of this chapter are adapted from Parada Puig et al. (2012a,b) and Parada Puig et al. (2013b).

3.1 Introduction

Technical system design impacts serviceability. High levels of serviceability are therefore related to a certain set of design attributes that influence serviceability performance most. Finding those attributes is challenging, and the literature identifies many of them. However, understanding how these attributes impact serviceability is not well understood. We conduct this research because it is unclear how these attributes impact serviceability. Determining those aspects that should play an important role in the acquisition of serviceable assets is relevant for practice.

The ultimate goal of decision makers during acquisitions of technical systems is to field a system that best fulfills all requirements throughout the life cycle. To achieve this goal the technical service provider usually looks for those qualities of a technical system that would render it serviceable, which is one of the important through-life requirements discussed in Section 1.3.

As it will be shown in this chapter, the difficulties arising during acquisitions of technical systems in identifying those design attributes that influence serviceability performance can be grouped into three categories. Firstly, there is a lack of a unifying framework linking the myriad of criteria and terminology associated with serviceability design attributes. Secondly, the stage(s) during the acquisition process in which these attributes can be controlled or influenced is unclear. Thirdly, and perhaps the most challenging, measuring those attributes of design impacting serviceability is very difficult. Outcomes of design attributes are only visible after long periods of operation. Therefore, decision makers must carefully study the technical system over long periods of time to draw conclusive knowledge about serviceability. We aim to learn from the experience of those decision makers by means of an in-depth case study.

This chapter is the first part of the company case. It describes how the design of technical systems impacts their serviceability performance. In the previous chapter, Chapter 2, we identified some terminology commonly used in design theory research to denote the attributes of a technical system. That terminology is used in this chapter. The remaining three parts of the company case are discussed in Chapters 4, 5 and 6.

The research in this chapter builds on the concept of architecture assessment to determine the serviceability of large-scale systems. In this chapter we assume that the architectures of capital assets are comparable. This comparison is made on the basis of the impact of design attributes to serviceability performance. This research discusses the attributes of modularity and commonality. The scientific relevance of this part of our research has been highlighted by past research where it is suggested that “studies that incorporate modularity and commonality’s multiple effects on various players along the supply chain, that combine multiple research methods, and that follow systems over time appear very promising” (Fixson, 2007a, p. 85).

There has been open research on the impact of design attributes over the life cycle stretching as far back as the 1970s. Rutenberg suggested that "modularity, commonality, and cannibalization should be analyzed simultaneously in a full theory of product design so as to reduce the total manufacturing, inventory, and maintenance cost of a line of products" (Rutenberg, 1971, p. 492). Assessing the impact of design attributes on serviceability performance is especially important during acquisitions of capital assets. The chapter contributes by reviewing research on design aspects that impact serviceability, providing an initial conceptual basis for analyzing practice. Next, we present findings of the company case on the effects of the technical system attributes on serviceability. The research uses novel operational definitions of the architecture and structure of the process and the supply chain.

3.2 Methodology

This chapter contributes to answering research subquestion RQ2a, as formulated in Section 1.4: What serviceability aspects are considered to be important to address during acquisitions? As we learn in Section 2.3, certain aspects of a technical system influence serviceability. Therefore, two questions are asked of the individual unit of analysis in this chapter. Firstly, what design aspects (of technical systems) are considered to play an important role in the acquisition of serviceable assets? Secondly, how do these design aspects influence serviceability? Answering these subquestions will give insights to help answer RQ2a. We answer RQ2a using a combination of literature review and a case study, as shown in Figure 1.14.

3.2.1 Approach to literature review

The first part of the research in this chapter consists of a systematic review of the literature. We review the literature to catalog design attributes of technical systems that are known to influence serviceability. These attributes have been mentioned across the fields of engineering design research, systems engineering, operations management, and operations research. We follow the scheme of Figure 2.1, in Section 2.2, and use the same fields of research in this chapter. We use the keywords *product*, *asset* or *artifact*. We also combine the terms *design property*, *design attribute*, and *design characteristic* with the keywords *serviceability*, *maintainability*, *supportability* and *availability*. Furthermore, we include *maintenance*, and several terms related to maintenance —*repair*, *replace* /*replacement*, *upkeep*, *mro*, *spare part*, *service*. We construct an initial conceptual model based on these preliminary findings.

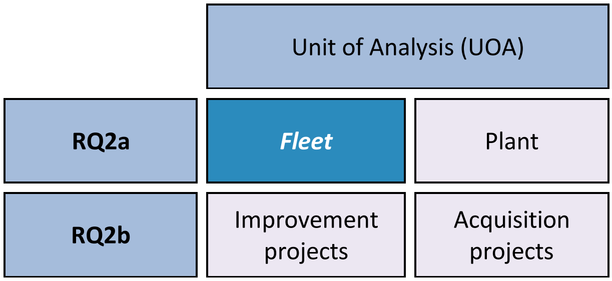


Figure 3.1: *Unit of analysis (UOA) of Chapter 3 within the broader case context.*

3.2.2 Approach to case study research

We conduct descriptive case research to understand whether the aspects identified in the literature are present within the unit of analysis, and if so, how they impact serviceability. As shown in Figure 1.12, Chapters 3 to 6 cover the DS-I part of the research. The research design is a single case study. Although other research methods exist, case studies provide a unique approach for investigating current operations within an organization. A case study is an objective, in-depth examination of a contemporary phenomenon where the investigator has little control over the events (Yin, 2009). The typical organizational scenario does not allow conditions to be controlled by the researcher, and variables cannot be manipulated. This makes case study research a very convenient approach for field research in the operations of a maintenance service provider such as NedTrain.

Case selection

The rationale for selecting the case of NedTrain, as discussed in Section 1.4, is that the case company presents a unique opportunity to observe and analyze modern acquisition practices for capital assets. This creates the expectation that the descriptive information alone will reveal important insights. Our single case study design uses four Units of Analysis (UOAs).

Figure 3.1 identifies the UOA in this chapter (UOA1): the fleet. The fleet is the transportation asset of the NS. Eight existing rolling stock platforms, shown in Figure 3.2, are included in the study. More details about the characteristics of UA1 can be found in Table 3.1.

Data collection

As with other empirical research in operations management literature, the validity and reliability of the results must be systematically addressed. The tactics used for the research are those recommended by Yin (Yin, 2009, p. 34). Quantitative and qualitative techniques are combined in this single case to attempt methodological triangulation, and therefore enhance the quality of results.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Figure 3.2: *Train series in our study.* (a) *SGM,* (b) *ICM,* (c) *ICR,* (d) *ICE,* (e) *DDM,* (f) *DM90,* (g) *VIRM,* (h) *SLT.*

Table 3.1: *Characteristics of UOA1: the fleet, in service as of 2014.*

Platform	Series name	Train Formula	First delivery	Supplier
A	SGM	ST	1975	Talbot
B	ICM	IC	1977	Talbot
C	ICR	IC	1980	Talbot
D	ICE	HS	1989	Siemens
E	DDM	IC,ST	1993	Talbot/De Dietrich/Adtranz
F	VIRM	IC	1994	Talbot/Bombardier
G	DM90	ST	1996	Talbot
H	SLT	ST	2008	Bombardier/Siemens

Table 3.2: *Research design characteristics.*

Research Design	Data collection methods	Data source
Single case study	Historical archive analysis	Management information systems
	Documents	Company documents
	Outside observation	Research notes
	Interviews	Semi-structured, in-depth interviews

Multiple sources of evidence (data triangulation) are used as a tactic to improve construct validity, and therefore help to establish correct operational measures for the concepts being studied. Table 3.2 shows the data collection methods with the sources for this data. Since the initial objectives of the case study are of descriptive nature, they pose minimal threat to internal validity. The tactic to deal with threats to internal validity will therefore attempt to address rival explanations (theory triangulation). Finally threats to reliability of the results are addressed by the refinement of the case study protocol, and developing the case study database.

This chapter mainly uses retrospective data collection methods. Data acquired consists of documents used for case history and archival analysis, product data, questionnaires, and semi-structured interviews, as well as reports by subjects. Table 3.3 gives an overview of the job descriptions of the interviewees consulted.

Table 3.3: *Overview of interviewees of UOA1.*

Job	Interviewees
Asset Manager/Project Manager	1
Manager Supply Chain	1
Component Manager	1
Head of Support	2
Technical Coordinator	1
Manager Acquisitions Project	1
Manager Component Life Cycles	1
Manager Train Formula	1
Program Manager	2
RAMS/LCC Manager	1
Senior Project Leader	1
Total	13

3.3 Literature review

Organizations acquiring capital assets are interested in high serviceability. The importance of this review lies in identifying known attributes of a technical system's design that may be important for acquiring serviceable assets. We begin providing some background and definitions from theory. Next, we identify the aspects of the design of technical systems that are commonly associated with serviceability in the literature. Once these aspects are identified, we summarize how these aspects impact serviceability according to the research. We then focus on the architecture of the technical system as a main driver of serviceability. Lessons for this review are a stepping stone to Section 3.4, below, where we look at the impact from the perspective of practice.

3.3.1 Definitions

The definitions used in our analysis are adopted from Hubka's Theory of Technical Systems (TTS Hubka and Eder, 1984) and Domain Theory (Andreasen et al., 2014). In the TTS, two main classes of attributes describe the nature of a technical system. The first class are called characteristics. These are constitutive/structural attributes. The second class are called properties. Properties are behavioral/relational attributes. It is a tradition of systems theory and systems engineering disciplines to distinguish between these two main classes (Chestnut, 1967; Klir and Valach, 1967, , cited in (Pedersen, 2010)).

A part of design theory research is concerned with finding approaches to reason about artifacts (technical systems are a type of artifact). Hubka and Eder (1984) articulate a Theory of Properties (TOP), making a fundamental distinction between three classes of properties. Firstly, those properties that designers manipulate in order to influence all other properties. Secondly, those properties that can be indirectly determined through the knowledge of the first type of properties. Thirdly, those properties that define the relationships between the technical system and its environment. TTS adopts arbitrary naming conventions for each of these classes, but the distinction between the different qualities of a technical system is very useful.

For convenience, we adopt the naming conventions proposed by Andreasen (1980), which are based on Hubka's original Theory of Properties published (Hubka, 1973). The naming convention has also been adopted by Weber (2005), and by several researchers from the "Copenhagen School" in the Technical University of Denmark (DTU) (Andreasen, 2011). Based on his original PhD research, Andreasen makes an arbitrary but useful distinction between classes of properties. The term *attribute* is reserved in the more general sense, meaning the set of both design properties and design characteristics. The term *characteristic* is used for those attributes that can be directly influenced by designers, namely, *structure*, *form*, *dimensions*, *material* and *surface quality*. The term *property* is used to describe the product's behavior. Properties can only be indirectly influenced

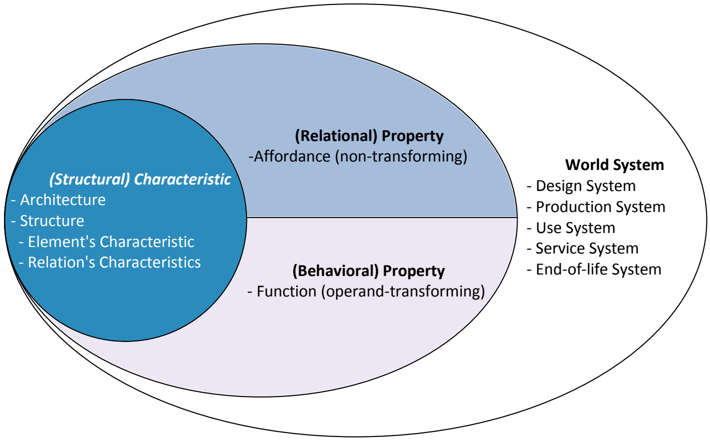


Figure 3.3: *Attributes of a technical system (i.e., characteristics and properties) based on our interpretation of the Theory of Properties (Andreasen, 1980; Hubka and Eder, 1984), and of affordance based design (Maier and Fadel, 2001).*

by the designer (see Gero's FBS model for a theory on how designers reason about behaviour (Gero, 1990; Gero and Kannengiesser, 2000)).

We agree with Weber (2005), who considers that characteristics in the framework of Andreasen (1980) are analogous to what Hubka (1973) called internal properties, and what Suh (1998) calls design parameters. Andreasen's definition of properties is analogous to what Hubka called external properties and to what Suh calls functional requirements (Weber, 2008). Andreasen further classifies properties as eigen properties, relational properties and allocated properties (Andreasen, 2011). Relational properties are a type of property that is similar to the concept of *affordance* proposed by Maier and Fadel (2001, 2009). See Brown and Blessing (2005) for a discussion on the relation between function (operand transforming) and affordance (non-transforming). Figure 3.3 shows the three main classes of design attributes.

TTS was foundational to a large amount of research about designs, and about designing. As discussed in Chapter 2, based on TTS, Andreasen (1980) developed domain theory. Domain theory provides a framework that helps us to reason about artifacts in terms of three main views or domains, namely, the part domain, the organ domain and the activity domain. Figure 3.4 shows the so-called Genetic Design Model System describing the parts of the theory. The part domain is analogous to the anatomy of the human body. In this view, parts are a material continuum. The organ domain is a higher level of abstraction than the part domain. Analogous to the organs of the human body, the organ domain is a view representing the main function carriers of the system. Finally, the activity domain is the view of interactions of the technical system with the use environment.

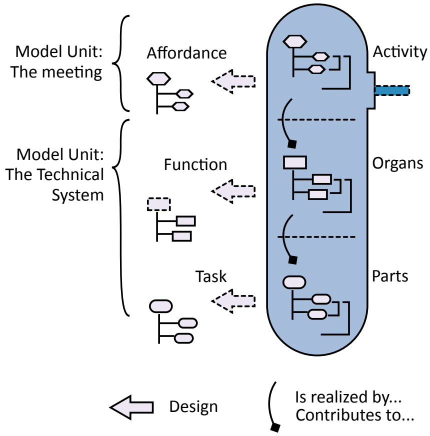


Figure 3.4: *The Genetic Design Model System (Adapted from Mortensen, 2000, cited in (Andreasen et al., 2014)).*

3.3.2 Design attributes in technical system

All properties of a technical system are achieved by means of a class of attributes that we call characteristics. Design characteristics are summarized in Table 3.4, namely, *structure*, *form*, *dimensions*, *material*, *surface quality* and *architecture*. Our objective is to find research that helps clarify which desirable characteristics may help achieve high levels of serviceability. We provide the relevant definitions below, mainly inspired by Hubka's Theory of Technical Systems (Hubka and Eder, 1984), and the Theory of Domains Andreasen et al. (2014). An example, below, introduces the related definitions.

Characteristics and properties

The terms attribute, property and characteristic are synonyms commonly linked to design aspects of an artifact. They are often used in systems engineering or product design literature with a broad interpretation. A property is any characteristic that belongs to a technical system and defines it. Serviceability, as defined in this thesis, is associated with the design of technical systems. As was discussed in Chapter 2, serviceability is often sought as a characteristic (Tillman et al., 1980) or attribute (Dowlatshahi, 1996) of design.

In Chapter 2 we described serviceability as a relational property. Relational properties are thus an important class of attribute for our research. Figure 3.3 shows our view on the three classes of attributes of a technical system: characteristics, behavioral properties and relational properties. A world system represents the external environment where the technical system may interact. In fact, the external environment will be our technical service system, and will be the focus of the next chapter, Chapter 4.

Table 3.4: *The characteristics of a product's three domains, based on Andreasen et al. (2014).*

Domain	Characteristics	Description
	Architecture	Mapping between domains
Activity	Structure	Set of activities and their relations. The relations are input and output state of operands (spacial, material, energy, information that is transformed by the main function), nature and state of operators, how operators are carried or lead into contact with the operands, or conditions necessary for a transformation to take place
Organ	Structure	Set of organs and their relations. The relations are active effects (Input/output)
Part	Structure Form Dimensions Surface Quality Material	Set of parts and their relations Shape, geometry of a part Physical sizes of parts (length, height, width, volume, etc) Color, texture of the external part interface Elementary composition of a part

Table 3.4 describes the design characteristics of the activity, organ and part domains. The structure of each domain describes the set of elements and their relations. The general layout, or mapping of these domain structures is determined by designers. The resulting attribute, the architecture, can therefore be classified as a technical system characteristic (not used here in the sense of the construction industry). The following example illustrates the technical system's characteristics.

Example. *A rolling stock unit is scheduled for maintenance. The trainset, built in 2008, belongs to a rolling stock platform that was originally introduced in the 1990s. The system has a four car formation as shown in Figure 3.5. The structure of the part domain consists of about 2000 parts (so-called maintenance significant items): about 500 critical items, 1200 non-critical items, and 300 items that have not been categorized according to their criticality. There are two main types of physical interfaces within the train: mechanical and electrical. The organ domain consists of 16 organs. These allow the entire range of train functions and affordances, for example, traction, braking, safety, access and heating, ventilation and air conditioning. The activity domain consists of the four activity elements that will be executed as scheduled: checks, inspections, cleaning and replacement.*

Fixson (2005) considers three categories that distinctively characterize the part interface, namely, their type, reversibility and standardization. The type of interface is characterized by the number and distribution of interfaces in the

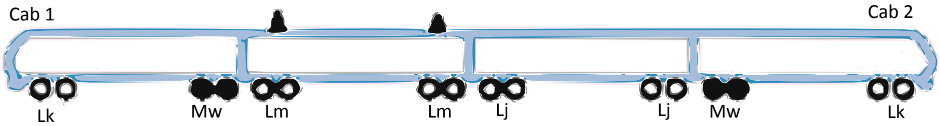


Figure 3.5: *A trainset with a four coach formation (Adapted from NedTrain B.V.).*

part assembly structure, and by their nature. Pimmler and Eppinger (1994) suggest that the interactions at the interface can be *(1)* spacial (physical space and alignment), and exchange of *(2)* energy, *(3)* information, *(4)* material.

The architecture of technical systems

Amdahl et al. (1964) was probably the first to use the term architecture in the context of systems design. It was originally employed in the development of the IBM System/360 "to describe the attributes of a system as seen by the programmer, i.e., the conceptual structure and functional behavior, as distinct from the organization of the data flow and controls, the logical design, and the physical implementation" (Amdahl et al., 1964, p. 87). Since then, architectures have been a fertile field of research in the multiple subdisciplines of engineering and management (Baldwin and Clark, 1997; Henderson and Clark, 1990; Ulrich, 1995; Ulrich and Eppinger, 2000; Wheelwright and Clark, 1992).

Perhaps one of the most cited definitions of a product architecture is provided by Ulrich, who defines it as follows:

Definition. *The architecture is "the scheme by which the function of a product is allocated to physical components"..."more precisely as: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components" (Ulrich, 1995, p. 419,420)*

This definition more or less agrees with the IBM's original use of the term (similar definitions are found in Ulrich and Eppinger (2000, p. 182), Fixson (2005); Hansen and Sun (2010); Mikkola and Gassmann (2003); Pimmler and Eppinger (1994)). Notice that the mapping between the functions and physical components can be translated by analogy in terms of domain theory to the mapping between the organ and part domains.

The term architecture is often used in relation with modularity, commonality and product platforms. According to Ulrich, modular-like architectures present a one-to-one mapping of functions and components, and decoupled interfaces between components. Conversely, in (complex) integral architectures, all functions are mapped to all components and every component contributes to every other function in the architecture, where interfaces are coupled between components (Ulrich, 1995, p. 422).

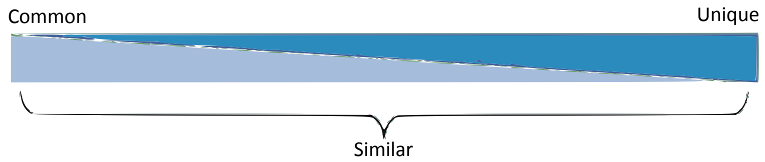


Figure 3.6: *Commonality spectrum from common to unique, where similar elements may present some degree of sharing attributes (Adapted from Boas, 2008, p. 21).*

Modularity is generally recognized as a key identity of an architecture. However, there is lack of agreement about what a module is, and what constitutes a modular architecture. Several reviews discuss existing concepts and measures of modularity (Fixson, 2007a,b; Gershenson et al., 2003, 2004; Salvador, 2007). Salvador (2007) classifies modularity research in two broad groups: those that focus on describing modularity (e.g., Salvador et al., 2002; Ulrich, 1995; Ulrich and Eppinger, 2000), and those that focus on understanding the system effects and the characteristics that such a system exhibits (see e.g., Fixson, 2007a, for a review of effects).

According to Gershenson and Prasad (1997), a modular design for serviceability implies that designers group "all attributes with similar service modes into a single module and decouple them from all other attributes and service modes". For a service engineer this means that the definition of module is probably linked to the service mode of interest (e.g., replacing, adjusting). Table A1 in Appendix A provides a non exhaustive list of typical operations in maintenance with manual labor. In our view, experts use the term modularity as a proxy for whatever they perceive to be a modular artifact. We focus on how they view or define a module in Section 3.4 whenever the definition needs a clarification.

Next to modularity, commonality is often used in relation to product architectures. Commonality refers to the sharing of *something* (emphasis is used to highlight the general scope of the term) within a given frame of reference. The term often used as synonym to standardization, interchangeability and parts similarity. Commonality can be represented as a continuum from *common* to *unique* elements, where the in-between range can be described as *similar*, as can be seen in Figure 3.6. It can also be defined depending on the unit of analysis, and exists within a product, among products, and among product generations If our focus is on the technical system, commonalities exist when there is sharing of an attribute, part, organ or technical activity within that reference frame (the technical system as described in domain theory).

3.3.3 Impact of design attributes

This section reviews existing research on the impact of design attributes on the serviceability of technical systems. Above, we discussed that product characteristics impact all the properties of a technical system. Technical system characteristics affect serviceability either by directly influencing the service activity or by affecting the setups to the service activity. Most of the effects that are associated with the service activity have to do with increase/decrease of cost or time (duration) of technical services.

Many authors tend to associate service aspects with many attributes of a design, i.e., the *what* impacts serviceability. Let us see two typical examples. Johannesen and Verma (2000) associates supportability with modularity, commonality, interfaces and RAMT –Reliability, Maintainability, Testability. Moreu De León et al. (2012) associate repair time with Simplicity, Identification, Modularity, Tribology, Standardization, Failure watch, Accessibility, Assembly/disassembly. Notice that both characteristics and properties are mentioned in the examples. This makes it difficult to understand the impacts, so we keep to our terminology below. Below we begin with technical system characteristics. The combination of form, dimensions and material are the most fundamental aspects of embodiment design of artifacts. It can be expected that these characteristics impact essential service operations directly.

Form

Element form –shape, topology, geometry in the part domain– is considered an important attribute in most maintainability analysis methods (Mason, 1990, see, e.g.,). The principal intervening phenomenon for manual service modes is human factors. Shape complexity normally affects handling of parts, and can be hazardous to service engineers.

Dimensions

Physical sizes of the embodiment such as length, height, width or volume have profound impact on service modes requiring handling and access. Service modes can become a costly endeavor due to dimensions outside of the anthropometric allowances. Large items may require more than one service engineer for handling, and dimensions may limit access through hatches or apertures. Very small or delicate items may require dexterous individuals and additional care to prevent quality mistakes.

Surface

Surface texture and quality tend to affect work preparation and handling. Surface texture impacts specific service modes like cleaning, but also general service conditions. Safety may be issue if work on a slippery surface of the artifact is required or personal protection is needed. Element surface allows identification of maintenance points or access panels.

Material

The elementary composition of a part, its density and physical state (solid, liquid, gas or other) affect handling and often constitute hazards to service engineers. Margin allowances and additional setup efforts may be needed to handle dangerous materials. This can be both costly and time consuming.

Structure (parts)

In the part domain, serviceability of maintenance significant items constitutes the core concern within the structure of technical systems. The number and complexity of components affects the frequency and cost of maintenance processes, (Dahmus et al., 2001; Dahmus and Otto, 2001, , cited by (Fixson, 2006)). Process complexity is the main intervening phenomenon.

Structure (relations)

Relations between elements in the part domain are dominated by component interfaces. Interface type has an important influence on reliability. Interface reversibility has a direct impact on the essential service operation such as removing/replacing, adjusting or slackening/tightening. Interface reversibility impacts disassembly in all its forms, and depends on the interface location, as well as the difficulty of physically detachment/disconnect one part from the rest.

Notice that the organ structure determines the mode of operation of the technical system. Relations in the organ structure determine functional complexity and interactions. Therefore, relations between elements in the organ domain have important impact of fault finding, fault isolation and condition monitoring.

Architecture (modularity)

Research points to the use of and benefit of modular design (Dahlgren et al., 2013). The support process complexity is affected by the function-component allocation scheme, by the reversibility of the interfaces and by the commonality of components in the product structure. The first two are causes related to product modularization, and are extensively considered in engineering literature with maintenance concerns. See for example Chen and Cai (2003); Verma et al. (2003); Wani and Gandhi (1999); Zhong and Youchao (2007). Groups of parts with similar expected lifetimes (FCA) minimize the required parts replacement processes, and likely to reduce the costs of repair and replacement (Dahmus and Otto, 2001). This grouping can also give module components identical service modes, which reduces the possibility of harming one component while servicing the other, and can actually decrease labor costs (Gershenson and Prasad, 1997).

Functional independence is characteristic of modular-like products and systems. Modules which are functionally independent can decrease downtime by increasing maintenance accessibility, testability and fault isolation (Tsai et al., 2003). Process complexity is decreased by reversible interfaces between components. Those components allowing easy and fast access for maintenance and repair tend to reduce maintenance time Chen and Cai (2003); Fixson (2006); Wani and Gandhi (1999); Zhong and Youchao (2007). Finally, commonality of components across members of the product family further influences process complexity by reduced set-up time, increasing productivity (Fixson, 2006).

External costs attributable to the support stage may include safety, health and environmental impact, for example of a catastrophic failure. The product architecture is linked to these costs because it is the source of human errors (e.g. slips and lapses). Integral and fragmented architectures make it difficult to determine the consequences of failure, and therefore complicate fault isolation and diagnostics.

Architecture (commonality)

In general, the literature suggests that commonality has profound impacts on serviceability. However, it is probably true that the literature shows an overreliance on the benefits of commonality. Outweighing the negative aspects is important (Boas, 2008, p. 15).

Commonality influences risk pooling. The benefits of component commonality for inventories have been part of academic research for a long time (Collier, 1981). Also, (Hillier, 2002) linked commonality to reduced costs in purchasing through order pooling. For the service supply chain, Kranenburg and van Houtum (2007) show that sharing stocks for different groups of machines can lead to a reduction in spare parts provisioning costs. If the product has multiple identical parts, fewer parts need to be stocked in inventory to provide the same level of availability, therefore lowering the spare parts inventory costs (Perera et al., 1999). Standardization facilitates part interchangeability, and reduces spare parts and tools required (Wani and Gandhi, 1999).

Commonality influences operator skills and learning. Increasing part commonality is known to reduce maintenance training and streamlines procedures, bringing significant cost savings to organizations (Airbus, 2013). In an example of the design of unmanned ground vehicles, Simpson et al. (2011) explain that low commonality is linked to increased training requirements and manpower, and explains the multiplicity in sets of spare parts, manuals and tools required to support the different machines (robots) of their study. Hastings also points out that commonality "...minimizes diversity in operation, training and maintenance, reduces total spares requirement by type and quantity; minimizes demands for tools, test equipment, range of know-how, and facilitates cannibalization" (Hastings, 2010, p. 182).

Commonality influences process complexity. Operations management literature has shown the performance effects of component commonality. Safizadeh et al. (1996) suggest that commonality allows sustaining high plant performance. Conversely, the increase in variety is known to decrease the performance of a production system (Hopp and Spearman, 2008). MacDuffie et al. (1996) used several measures of variety to describe process complexity, and used regression analysis to determine their impact on productivity and quality performance. The authors found however, that only the measure of parts complexity (a compound measure of variability), and not necessarily component commonality, revealed a significant negative impact on performance. Commonality of components across members of the product family further influences process complexity by reduced set-up time (Maimon et al., 1993).

Commonality is known to influence economies of scale, as found by (Garud and Kumaraswamy, 1995). Johnson and Kirchain (2010)showed that standardization is related to a host of cost effects. Jones (2006b) also associates commonality as a driver of supportability, and suggests an analysis of commonality for acquisition projects. There are several examples from industry practices of explicitly developing a fleet strategy in the commercial airline industry. Ryanair, for example, increased the commonality of its fleet with the purpose of reducing or controlling one of their primary expenses: aircraft equipment costs. Benefits point towards "limit the costs associated with personnel training, maintenance and the purchase and storage of spare parts, as well as affording greater flexibility in the scheduling of crews and equipment" (Ryanair, 2013).

3.3.4 Analysis of literature findings

We identify *(1)* design attributes that impact serviceability, *(2)* intervening phenomena and *(3)* the effect of the design attributes on serviceability. Table 3.5 summarizes these findings, and we explain them below. There appears to be a large body of research on modularity and commonality aiming to improve maintenance through design.

Design attributes

Characteristics and properties are generally not differentiated in the literature on technical services and maintenance. Modularity and commonality can influence the maintenance process lead-time and cost, as well as the service levels and the number of suppliers in the service supply chain. Assessing the impact of the product architecture on serviceability is especially important during acquisitions of large-scale systems.

Intervening phenomena

Five mechanisms have been identified in the literature by which the product architecture can influence the performance of the maintenance organization. These mechanisms are, namely, (i) process complexity, (ii) economies of scale and (iii) risk pooling (iv) human factors and (v) learning. Process complexity is an indication of cognitive or labor effort. It signals that jobs are more difficult to

Table 3.5: *Impact of design characteristics on serviceability.*

Characteristic	Intervening phenomena
Structure (assembly relations)	**Complexity**: part nesting, assembly depth, interface strength and reversibility difficult part replacement, disassembly effort, impacting time and cost of item replacement
Structure (parts)	**Complexity**: number and complexity of components affects the frequency and cost of maintenance processes. **Risk pooling**: number of identical parts in the assembly structure aids pooling demand for spare parts, impacting service level, cost and time. **Human factors**: Identical parts may enhance fault finding and isolation through repetition, impacting service cost and time
Structure (organs)	**Complexity**: relations between elements in the organ domain impact fault finding, fault isolation and condition monitoring
Shape	**Human factors**: part shape impacts handling difficulty
Dimensions	**Human factors**: part size impacts handling difficulty
Surface	**Human factors**: affect work preparation and handling, working conditions, specific service modes (e.g., cleaning) and identification of service points
Material	**Human factors**: hazardous materials, material phase (liquid/solid/gas phase) affect working conditions, safety and packaging, handling, storage and transportation of the item. This impacts service costs and effort
Architecture (modularity)	**Encapsulation**: hidden functions create difficulty of fault finding and isolation, impacting inspection time and cost; allow localization and confinement of failure modes affecting replacement time and cost
Architecture (commonality)	**Risk pooling**: reduced costs in purchasing through order pooling, sharing stocks for different groups of machines can lead to a reduction in spare parts provisioning costs, facilitates part interchangeability, and reduces spare parts and tools required. **Learning**: increased commonality reduces maintenance training, streamlines procedures, minimizes diversity in operation, maintenance, while low commonality increases training requirements and manpower. **Process complexity**: commonality of components across members of the product family further influences process complexity by reduced set-up time. **Economies of scale**: standardization is related to a host of cost effects

plan, organize, control or execute. Economies of scale produce beneficial cost advantages by lowering unit costs when standardization and commonality are present. Risk pooling allows reducing costs because of common, interchangeable or shared stock are used. Human factors are the group of factors that impact the ease or difficulty of safely performing manual labor. Learning reflects the improvement of speed and quality of performing maintenance jobs through repetition and training.

Effects of design attributes

There are two central performance effects of design attributes on serviceability performance. On the one hand, time effects are identified, and they have a major role in the availability of technical systems. This is especially important for capital assets. Characteristics such as material, form, dimensions, and surface texture of physical components impact essential operations, auxiliary operations and allowances of technical services.

On the other hand, we identify mixed results when it comes to the impact on the cost of services. Design characteristics such as commonality and modularity may impact service costs in different ways. Some point to the beneficial effects of commonality in inventory holding costs, or in reducing variety in disassembly/assembly processes. However, commonality has important drawbacks in the achievement of economies of scope, customization and development complexity.

3.4 Technical system: the fleet

This section shows the impact of design attributes of the NS fleet on serviceability. Analyzing the NS fleet is difficult for several reasons. Firstly, knowledge about specific design aspects is not easily available. Our main source of data comes from the configuration management department, the supply chain operations, and partly operations management at NedTrain. Secondly, one notices that the platforms listed in Table 3.1 have been built several years apart. Older fleets were developed in the dawn of CAD systems, and most maintenance configuration data is based on blueprints and design documents of assemblies, not the smallest maintenance significant items. Thirdly, given the complexity of rolling stock, knowledgeable experts would be qualified to give opinions on specific platforms. Impressions on the fleet level were more difficult to find.

3.4.1 Design characteristics of passenger service rolling stock

New technology impacts maintenance. Antilocking brake systems that protect the wheelsets from excessive wear, changing materials that produce lightweight structures and communication systems that increase customer value. All these new developments have an effect on the serviceability of rolling stock. This section discusses some those design characteristics such as form, dimensions, materials, structure and architecture, as they are seen in practice.

Form

As a first general treatment of design characteristics, we find that passenger trains –like cars, airplanes, ships or power plants– have evolved into a more or less stable topology. Trains have coaches with a conductor cabin at two extremes. Coaches are mounted on bogies –mechanical assemblies also called cars– that are mounted on metal rails. Space inside the train is reserved for passengers and operators while physical constraints and industry standards have forced most supporting equipment (supporting the main function of the train: transporting passengers) to the roof or to the undercarriage.

Dimensions

When compared to human size, train sets are large systems. A single trainset is configured by coupling smaller individual units called coaches or cars. Typical formations in the NS fleet consist of 2, 3, 4, 5, 6 and 8 passenger cars. That means that the total length of a trainset can vary from 52 to 200 meters. This means that a service engineer takes anywhere from (approximately) half a minute to just over two minutes to reach from one end to the other at average walking speed (average Dutch walking speed of $1.6 m/s$ from Levine and Norenzayan (1999)). This is an important impact on service time, specifically the setups required for (work order) changeovers.

Material

Energy efficiency is one of the biggest challenges facing modern transportation systems. A small improvement in energy efficiency has a huge potential contribution to the operator's bottom line. Passenger service rolling stock are no exception. New lightweight and resistant materials are being introduced regularly into rolling stock design (Kawasaki, 2008; Mochida et al., 2010). Introduction of new materials in an acquisition program has strong dispositional effects.

Structure (organs and parts)

NS designs passenger services by decomposing passenger classes. Customization of travel is a big part of the efforts of communication and train formula management at NS. An ideal situation is that passengers experience travel from door to door attending to their individual needs. The transport asset of NS is currently decomposed into the so-called train formulas. Train formulas constitute the organ structure of the fleet. Inter City (IC), Stop Train (ST) and High Speed (HS) are the three main organs (mapping to the part domain is discussed bellow). If one identifies the fleet of NS as the unit of analysis, the transport asset can be considered the highest level in the hierarchy of the technical system of NS. Parada Puig et al. (2011) study the performance of the fleet using this aggregate level.

A modern rolling stock platform accommodates 20 subsystems (organs). Each of these subsystems is in its own right a complex embodiment solution optimized for traction, heating, air conditioning, etc. In the parts domain, complexity arises from the sheer number of elements in the system.

Architecture (modularity)

Describing modularity of rolling stock has proven difficult. On the one hand, there is lack of specific configuration data regarding assembly structures to compare all trains. On the other hand, the inherent complexity in the enormous number of parts of a train makes it a daunting task to analyze any modularity metric. We therefore mainly rely on expert assessment about modularity effects, and do not explore the modularity characteristics in-depth.

Architecture (commonality)

NS has built capacity for passenger service over the years. Figure 3.7 shows the increase in capacity according to company data. The different shades of Figure 3.7 show different train series dedicated to passenger service. Notice that any particular series is commissioned and replaced over a long life cycle. Figure 3.8 shows the increasing variety that results from the capacity increases over time (measured by the number of train series operated in each period). This phenomenon is known as divergence, and it is pervasive in organizations like NedTrain.

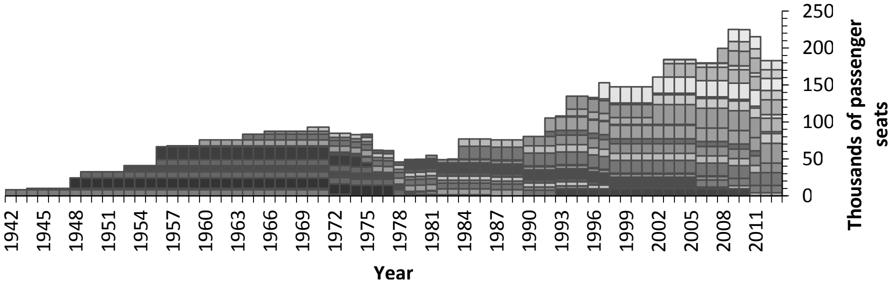


Figure 3.7: *Building capacity for passenger transport in The Netherlands.*

Figure 3.8 shows that while the transport capacity of the NS increased rapidly over the 1990s, the number of train families increased at a slower pace. This is the result of a policy of acquiring larger series. Train series are individual variants of a platform, and are therefore similar to other trains of the same platform; for example, they can be of different lengths, i.e. four cars vs. six-car train. However, train series can carry significant differences because their manufacturing can be offset by several years, as well as retrofits and overhauls.

Divergence is not only a phenomenon of lifecycle offsets. Train formulas are the primary source of divergence at NS. Train formulas are a way to increase customer value for NS, and their fundamental goal is in straight contrast with standardization. As the manager of train formulas comments "...in Schiphol you need different trains. There, other functionalities are more important. If you

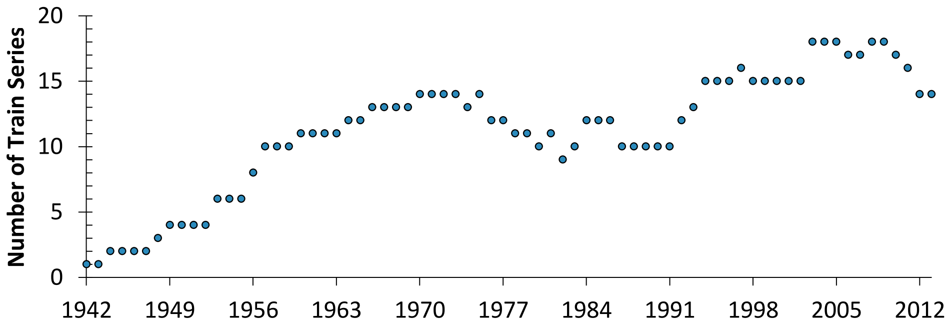


Figure 3.8: *Trend of increasing variety.*

take a train to the Randstad for work then you are there for a short while... then you need a lot of space for people standing. If we say I want one train formula, then you want everything in one train... that makes it much more complex in satisfying our clients with that product. If you have a long journey, and we have a standard train, one train for all, then that train will fulfill your needs less than a specific train". As a result, NS has three basic operational profiles. The so-called train formulas are Intercity (IC) such as the VIRM, Stop Train (ST) such as the SLT, and High Speed trains such as the ICE.

3.4.2 Impact of design characteristics in practice

This subsection explains how design characteristics affect serviceability.

Form

This first characteristic has an impact on manual labor, as access and location of maintenance points is generally either inside or outside the train, and therefore activities take place in the underfloor, overhead, or at body level, as shown in Figure 3.9. Van Dongen et al. (2011) discuss the life cycle impact of topology decisions at an early stage. Two design alternatives were presented where the unit could be installed either from the outside, on top of the roof, of from the inside, secured under the roof. They report savings of €4.2M over the lifecycle of the Inter City trains being upgraded. Mulder et al. (2013) provide another example case where design changes were implemented during acquisitions of the Sprinter Light Train (SLT). Setup time was eliminated and costs over the life cycle reduced by a change in the orientation of the compressor mount.

Dimensions

On the one hand, we see that trainset dimensions impact the fixed costs and technical service setups directly. Longer trains need larger workshops, more

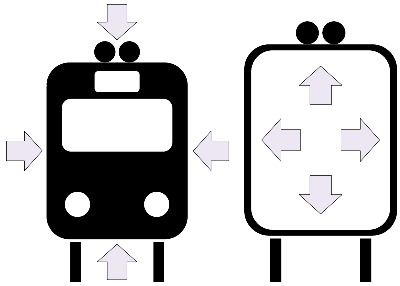


Figure 3.9: *Maintenance points in the basic layout of a passenger train.*

access points and impact service complexity. Compensation for this characteristic requires trading off fixed costs with service setups. It is not uncommon for crews and service engineers to move around the NedTrain workshops safely on bicycles, trolleys or other devices. On the other hand, part sizes impact essential operations directly. Rotables such as bogies, wheelsets or traction motors impose perhaps the biggest handling difficulty. These items are not replaced often, but their size and weight normally require special handling equipment and tooling. It becomes clear that those design characteristics that the service system is not designed to afford will become bottlenecks to serviceability performance (see Chapter 4 for further discussion).

Material

Newer train series such as the Sprinter Light Train (SLT) have aluminum bodies, a big change for NedTrain. The material properties impose new conditions for the assembly and disassembly of parts and body repairs. New specialties are needed, and service engineers are trained in MIG and TIG aluminum welding, as well as in the use of adhesive bonding not used before on the carbody –e.g., European Adhesive Bonder (EAB, vlgs DIN 6701). Structural cracks may be a common failure mode of aluminum structures. New service modes such as integrity inspections (e.g., using penetrant testing) are required, increasing the cost of service.

Structure (organs and parts)

Each train formula is differentiated by speed of travel, frequency of stops, and distance between destinations. The current notion of the train formula has allowed NS to set up distinctive functional requirements during acquisitions. And this has an impact on technical services provided by NedTrain. Industry practices are strongly driven by performance during the design stage. This means that each train formula has more or less evolved its own specifications into distinctive embodiment solutions.

Structure (relations)

Interfaces are important for acquisitions. As one expert assesses: "The most difficult is the interface. The intrinsic reliability of a system is mostly correct. An HVAC or a toilet system, these correspond (in the field). However, they are installed, and there is a cable, and the cable goes through the diagnostics, or it has to be connected through a switch somewhere... so these interfaces is where most of the criticality lies... and train manufacturers, suppliers also don't know".

Knowledge of the impact of interfaces on failure behaviour has inspired NedTrain to find new ways of collaborating with suppliers.

Architecture (integrality)

Experts at NedTrain typically deal with the increasing complexity of rolling stock (more software components, more interacting interfaces, more hardware items). Increasingly, maintenance jobs used to be demanding in terms of manual handling and dexterity. The mechatronics built into new rolling stock place large demand on knowledge intensive work, as shown in Figure 3.10.

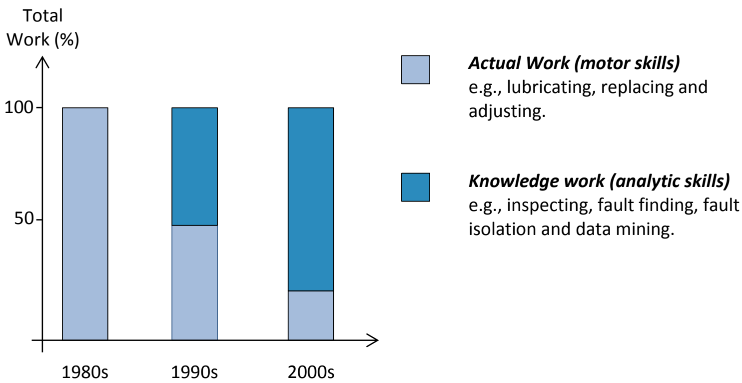


Figure 3.10: *Indication of the complexity effect of integrality.*

Architecture (commonality)

At NedTrain, fleet commonality has profound impacts on serviceability performance. We begin with a simple example: the case of retractable trays in the second-class passenger seats of platform F. A single coach has five different types of retractable trays, and this leads to large safety stocks and long delivery lead times. Standardization of such an item was estimated to save circa €115.000[2] in safety stock.

Commonality has profound influences on serviceability performance. It leverages mechanisms such as risk pooling, learning and economies of scale that according to experts would lead to important cost reductions. A senior project leader suggests that commonality "would provide huge cost reductions on your safety stocks, also on the number of specialists, you could handle much less knowledge workers, and the knowledge work that you have, you could allow to specialize much deeper. You would be able to establish clear links between failures and your maintenance concept, so you could optimize your maintenance concept, and do it faster. You would need less specialization on locations (locations would not handle a specific, different, type of train), so you would have a much more uniform training across plants. I think that would provide huge cost reductions".

However, experts further commented on the drawbacks, mainly in affecting customer value. In the words of a senior project leader: "I think the disadvantages (of a standard fleet) are to be found on the side of our clients. That is a large disadvantage because they have sprinters, they have intercities and they have high speed trains. In my opinion you cannot run those services with one type of train".

3.4.3 Analysis of case findings

Several design characteristics were identified in the case data affecting serviceability. Commonality has by far the largest impact according to experts. Divergence was identified between train series belonging to different train families, and to a lesser degree between rolling stock of different generations (life cycle offsets). Table 3.6 summarizes the main findings of the case.

Rolling stock design characteristics are mostly determined during the design stage of NS acquisitions. During that stage, after contracting, detail design is carried out, mostly consisting on systems integration. Design is intended to develop a specific platform based on the so-called functional requirements[3] that have been contracted with a supplier. The rolling stock series delivered to NS is a variant of the rolling stock platform of the supplier. This variant has specific characteristics that fit the rail network of the Netherlands (specific voltage, safety system, station height, etc.).

[2] Internal study by Gordian on spare parts management conducted in 2011

[3] Functional specifications, or functional requirements, are the set of design properties that describe the system in the parts, organ and activity domains.

Table 3.6: *Effects of design commonality and intervening phenomena impacting serviceability, technical system perspective. i: interview; o: observation; mf: maintenance facility.*

Characteristic	Phenomena	Supporting data (additional to quoted text (additional to quoted text)	Source
Commonality	Scheduling	Less effort for manual scheduling	o:mf W,Y
Commonality	Risk pooling	Shared pool of equipment and tools	o:mf W-Z
Commonality	Divergence	the problem is one series is made in 1990, the other one in 1998. There are eight years in between. Often there is no possibility of interchange, because there is a completely different system in the train	i:component manager
Commonality	Dependence	A collector from a different supplier is not compatible, and this lack of standardization difficults switching suppliers	i:component manager
Commonality	Dependence	A relay switch has a certain size, a certain connector housing, they are not exchangeable, so that prescribes what we are going to use the remainder of the life cycle.	i:component manager
Standard		What we don't do is specify standardization since the very beginning of a project.	i:manager component life cycles
Commonality	Divergence	Again, you have all types of variants of a non-motored bogie.	i:manager component life cycles
Commonality	Scale Economies	As benefit for standardization you get economies of scale, but also the certainty on performance, lower safety stocks, all those things. I think most of the benefits are there now, but well, if that leads to a specific type of material, to expensive parts; if you preffered a cheaper part then perhaps you are throwing money away.	i:manager component life cycles
Commonality (formula)	Customer value	you provide more value if on different main lines you have different train formulas	i:manager train formula
RAMS	Customer value	The performance of a train is more than the technical RAMS performance that we have in our contract.	i:program manager
Commonality (formula)		A type of train operable for all... the advantage is that you can train all your people once, everyone with the same knowledge; spare parts, common spares; interchangeability... now that is a large advantage	i:rams/lcc manager
Commonality	Divergence	A train is not a standard product. Perhaps the train-body, perhaps... but in the Netherlands: 1.5kV, different safety system, rail infrastructure is different. They are huge technical differences.	i:rams/lcc manager
Interfaces	Uncertainty	so these interfaces is where most of the criticality lies... and suppliers, they also don't know	i:rams/lcc manager
Standard	Flexibility	Interchangeable components are very important for us... The reason is that if we have to make a revision, then I cannot exchange the bogies, and then the train has a lead time of six weeks to get its bogies back.	i:rams/lcc manager

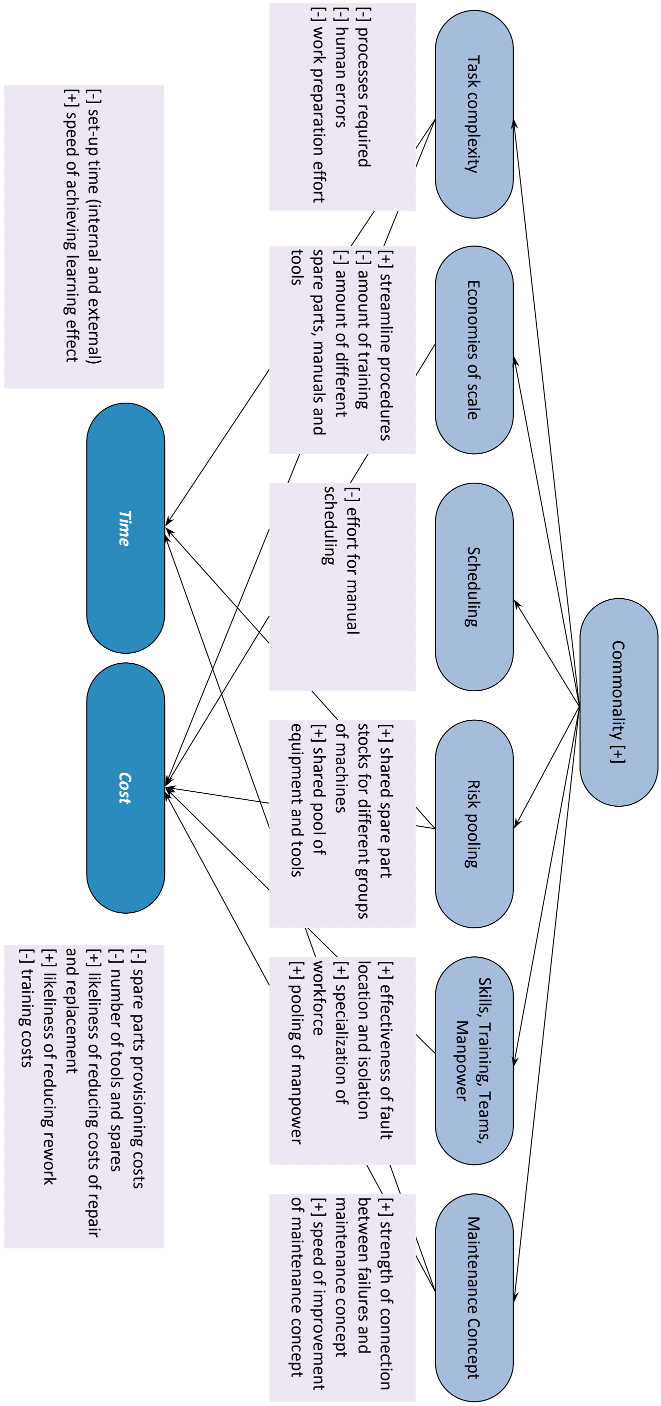


Figure 3.11: *Conceptual model of technical system architecture impacts on serviceability.*

Acquiring serviceable rolling stock is specified on the basis of design properties. For NedTrain, reliability, availability, maintainability and safety in conformance to CELENEC (1999), as well as Life Cycle Costs are the basis of serviceability specifications. Those design characteristics known to the organization to impact serviceability are incorporated in design evaluation. Expert teams evaluate design characteristics by means of checklists. The checklists are a qualitative review of an item's maintenance importance. Through the checklist, experts value standardization, interchangeability, abuse-proof, accessibility, special tools, dismounting/installing, mounting-proof, human factors, ease of performing a job, troubleshooting, testability, skill level and job type (e.g. test, exchange, overhaul).

3.5 Conceptual model

According to the literature, complexity, risk pooling, learning and human factors are the main mechanisms that impact serviceability performance, which is measured by its cost and time. Findings from practice show us that besides these phenomena, other important mechanisms exist: scheduling, supplier dependence, customer value and flexibility are affected by design characteristics, especially by commonality. The findings further show that impacts of commonality on serviceability are the most far reaching. Inspired on these insights we present a conceptual model, next.

Figure 3.11 shows a conceptual model that relates the effects that were found in the literature and in practice. It connects technical system design aspects and serviceability.

3.6 Conclusion

This chapter contributes by giving an overview of technical system design attributes that impact serviceability. It also explains how serviceability is impacted by identifying intervening mechanisms that influence either the time or cost of technical services. Also, it contributes with a model connecting technical system commonality and serviceability.

Results analysis of the first part (out of four) of the case shows difficulties in selecting one best technical system based on the system architecture. We found important contingent factors such as commonality and modularity (integrality), that have important impacts on serviceability performance. Implications for decision making are profound: commonality could be controlled during acquisition projects, and modularity of the technical system could be an important factor in technical system redesign.

Design characteristics that should be taken into account are the architecture, structure, form, dimensions, material and surface. A highly modular architecture seems to increase flexibility in the selection of the level of replacement (for a system that is repaired by replacement). The existence of modularity in the architecture of technical systems allows designers to group maintenance significant items into the separable units that can be replaced, called LRUs. The technical system structure reflects these LRUs, and the level of parts sharing and commonality. These insights about technical system design will be exploited further in Chapters 7 and 8.

Chapter 4

Technical service perspective: serviceability in the plant[1]

This chapter presents another side to the research presented in Chapter 3. The focus here is on the role of design aspects of the technical services in the acquisition of serviceable assets. Also, this chapter describes how these design aspects influence serviceability. It is the second part (out of four) of the company case, and uses the plant of NedTrain as an embedded unit of analysis. Four plants in the NedTrain supply chain structure are included in the study. Best practices highlight the elements that should exist in the technical service architecture for acquiring serviceable assets. Results show no support for one best technical service architecture. Contingent factors involve organizational change aspects as well as service modularity aspects, namely, decoupling of capabilities. These factors affect the ability of the service organization to adapt to new technical systems efficiently and effectively. After a brief introduction in Section 4.1, Section 4.2 gives the methodology details. Next, Section 4.3 reviews the literature. Literature suggest several attributes of a service design that impact serviceability, but it is not clear how exactly they impact practice. After that, Section 4.4 presents the case results from NedTrain, where the impacts are found on the performance of the fleet. Commonalities in existing support capabilities are not consistent at all levels of the supply chain. The agility of the organization in decoupling manpower capabilities is shown by means of an example from the case. Finally, Section 3.6 discusses the findings and draws the conclusions of the chapter.

[1] Parts of this chapter are adapted from Parada Puig (2011); Parada Puig et al. (2012b) and Parada Puig et al. (2013b).

4.1 Introduction

Chapter 3 provides insightful views about the serviceability of technical systems. Maintenance work at NedTrain carries a large burden in complexity and variability. Rolling stock used in the production of the transport services of NS can be very complex. A single type of rolling stock can have thousands of parts, many of which are prone to receive maintenance at some point of the life cycle. The full-scale transport asset, the fleet, has thousands of such machines. In addition, NedTrain deals with a mix of different types of rolling stock. This results either from differing functional requirements (train formulas) or from the sequential introduction of new technical systems over time (life cycle offsets).

The literature often illustrates the product architecture as a coordinating mechanism of decisions in other domains, such as the process or the supply chain (Baldwin and Clark, 1997; Fine, 1998; Fixson, 2005). As we discuss in Chapter 3 the train architecture certainly has an important role in the serviceability performance of the fleet at NS. However, we miss some fundamental insights. If we acknowledge that serviceability is a relational property of the technical system and its corresponding technical service system, then the service system must have a role in affording technical services.

The current chapter describes how the design attributes of a technical service system impacts serviceability performance. Service design has gained important momentum since the servitization of manufacturing. Since the 1990s many organizations that used to rely on manufacturing as a source of competitive advantage have made services their new weapon. Other organizations, those with a tradition in services, have been launched into a market with increasing stakes. NedTrain, with their expertise in designing technical services, show us insights into this special situation.

In Chapter 2, we identified some terminology commonly used in design theory research to denote the attributes of a technical system. The Theory of Technical Systems (TTS) defines maintenance as a relational property (Hubka and Eder, 1984). However, maintenance does not belong to the primary transformation activities described in TTS. The theory of domains lists the service activity as a function of the technical system in terms of *what we can do with the product*. However, we gain additional insight if we focus on the technical service system as a class of technical system in its own right.

The current chapter contributes firstly by giving a new angle to the theory of domains, positioning the role of the technical service system as a driver of serviceability. Borrowing the conceptual framework of domain theory Andreasen (1980); Andreasen et al. (2014), we pose that service systems can be equally decomposed into three fundamental views or domains: the activity domain, the operations domain, and the resource domain. Secondly, we contribute by reviewing the literature on service design to identify those that could be considered key attributes of a technical service system. Stemming from Hubka's theory of properties Andreasen (1980); Hubka and Eder (1984) we assume that a technical service system must have attributes that can be directly influenced by designers (characteristics) and attributes that a designer cannot influence directly (properties). With this looking glass, and once those key attributes are identified, we look at practice. This second part of the NedTrain case describes how the design of technical service system impacts NedTrain's serviceability performance.

4.2 Methodology

This chapter also contributes to answering research subquestion RQ2a, formulated in Section 1.4. Both the subquestions asked of this part of the case and the research methodology are the same as in the previous chapter (refer to Section 3.2). The focus of this chapter is on the technical service system. Below, we give our research approach.

4.2.1 Approach to literature review

A systematic review of the literature (as described in Figure 2.1) is conducted to describe what design aspects (of technical service systems) are considered to play an important role in the acquisition of serviceable assets. This review includes similar sources found for the previous chapter. We use keywords such as *(technical) service*, *service operation* or *service system*. We also combine the terms *architecture*, *attribute*, and *characteristic*. We also use the previous keywords in combination with the keywords *serviceability*, *maintainability*, *supportability* and *availability*. Furthermore, we include *maintenance*, and several synonyms for maintenance —*repair*, *replace /replacement*, *upkeep*, *mro*, *spare part*, *service*, for example.

4.2.2 Approach to case study research

The case study approach follows the same lines of the previous chapter. We wish to understand whether the design attributes identified in the literature are present within the unit of analysis, and if so, how they impact serviceability.

Case selection

Figure 4.1 displays the Unit of Analysis (UOA) in this chapter (UOA2): the plant. The plant –Maintenance Facility (MF)– is the place that provides the technical service capabilities of NedTrain. Four plants, displayed in Figure 4.2 are included in this study. More details about the characteristics of UOA2 can be found in Table 4.1. The allocated production is the population of clients that visit the plant at regular intervals, displayed as an average number of triansets. Plants W, X and Y (Onnen, Leidschendam and Maastricht) are the oldest plants, and service two train formulas: Inter City and Stop Train. Plant Z (Watergraafsmeer)

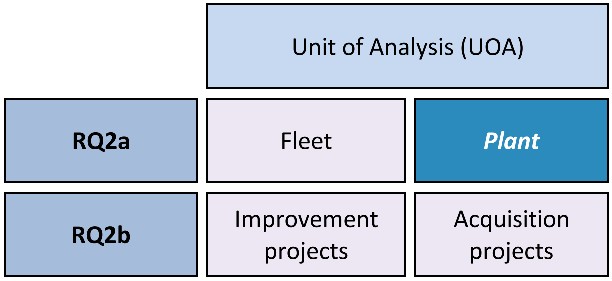


Figure 4.1: *Unit of analysis (UOA) of Chapter 4 within the broader case context.*

(a)

(b)

(c)

(d)

Figure 4.2: *Maintenance facilities included in this study.* (a) *Leidschendam,* (b) *Onnen,* (c) *Maastricht,* (d) *Watergraafsmeer.*

was designed and built more recently, and its purpose is to service the High Speed train formula for international travel. Section 4.4 will provide a more in-depth discussion on the characteristics of these facilities, and the technical service network of NedTrain.

Data collection

Data collection follows the same approach as in the previous chapter, Chapter 3. Maintenance performance data was gathered for the plants using the Management Information Systems (MIS). Some details are kept hidden to protect sensitive company information. Information about the processes, performance, roles of the organization and historical changes was either queried directly from databases

Table 4.1: *Characteristics of UOA2: the plant. Train formulas serviced are the Inter City (IC), Stop Train (ST), and the High Speed (HS) for international and domestic passenger routes. †Also services 41 locomotives*

Plant name	Plant	Built	Employees	Train formula	Allocated trainsets
Onnen	W	1985	230	IC	217
Leidschendam	X	1908	250	IC,ST	304
Maastricht	Y	1871	220	IC,ST	110†
Watergraafsmeer	Z	2007	135	HS	19

and documents, or gathered from current and retrospective, semi-structured, in-depth interviews. Table 4.2 lists the interviewees and their job description.

Table 4.2: *Overview of interviewees of UOA2*

Job	Interviewees
Asset Manager/Project Manager	1
Manager Supply Chain	1
Configuration Manager	2
Department Director	1
Head of Purchasing	1
Head of Support	2
Technical Coordinator	1
Manager Acquisitions Project	1
Project Leader	1
RAMS/LCC Manager	2
Senior Project Leader	1
Total	14

4.3 Literature review

Service organizations have a major role in improving serviceability. This section reviews the literature to identify attributes of service design that impact serviceability. We find, to the best of our knowledge, that a clear understanding of services is still lacking in the literature. Therefore, in order to reason about technical services we adapt the concepts of Domain Theory to technical service systems (we introduce Domain Theory in Section 2.3, and revisit those concepts in Section 3.3). We draw several analogies to Domain Theory in this section. We

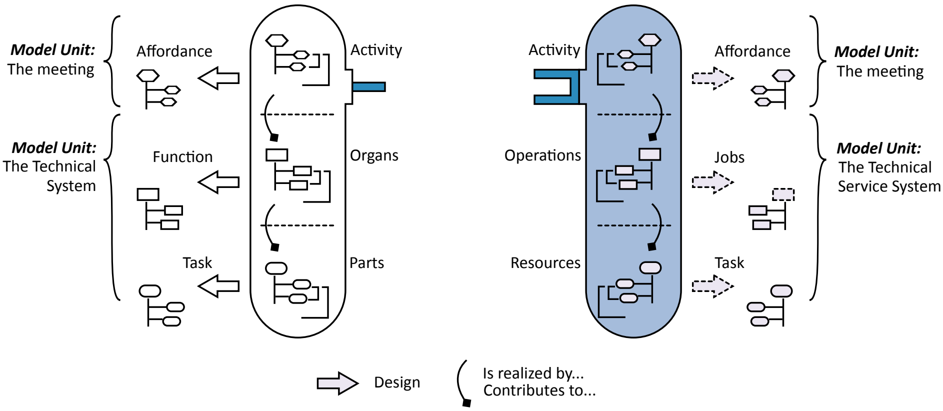


Figure 4.3: *Adaptation of the Genetic Design Model System (Adapted from Mortensen, 2000, cited in (Andreasen et al., 2014)).*

begin by identifying what constitutes a design attribute in the context of the technical service system. Next, some technical service system attributes that impact serviceability are identified in the research. Finally, we summarize our findings. As in the previous chapter, what we learn in the literature is our guide to understanding practice in Section 4.4.

4.3.1 Definitions

Technical service systems can be defined based on the Theory of Technical Systems (TTS), and Domain Theory. Domain Theory provides three views (domains) on a technical system: the part, organ and activity domains. We propose to adopt an analogy to that definition. We show in Figure 4.3 the three corresponding views on a technical service system, namely a resource domain, an operation domain and an activity domain. Resources are components of a service system, analogous to the parts of the technical system. They can be tangible like equipment, people, tools or technical documents; but they can also be intangible like information or software, for example. Operations are analogous to the organs of a technical system. Operations consist of interconnected jobs that provide the service system's function. Finally, activities provide the required outcomes of the service system, analogous to the activity domain of technical systems.

This analogy can be found to a degree in the process and service literature. Thus, we borrow concepts from the literature such as the dimensions of Hayes et al. (1988): *(i)* operations, *(ii)* resources and *(iii)* interactions. Bullinger et al. (2003) provide a similar description, suggesting services can be characterized by a structure dimension, a process dimension and an outcome dimension. We also find that this domain structure shown in the figure of the service system is

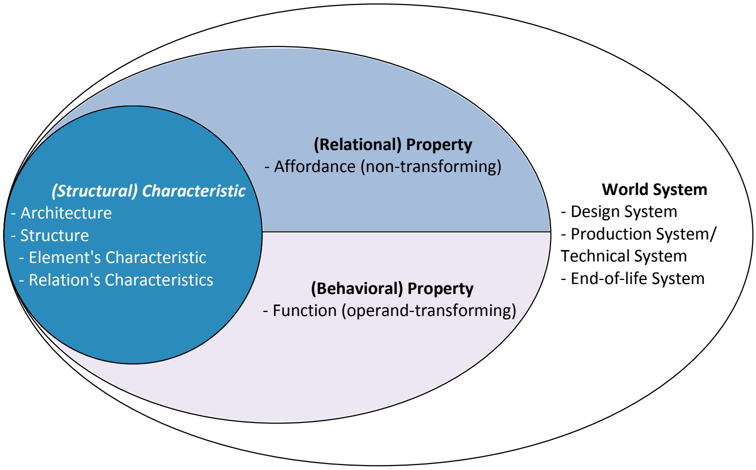


Figure 4.4: *Attributes of a technical service system (i.e., characteristics and properties) based on our interpretation of the Theory of Properties (Andreasen, 1980; Hubka and Eder, 1984), and of affordance based design (Maier and Fadel, 2001).*

similar to the flow model, scope model and view model of Sakao and Shimomura (2007). Respectively, these dimensions belong to the resource, operation and activity domains of Figure 4.3.

Figure 4.4 shows the three main classes of technical service system attributes that we adopt, namely, the (structural) characteristics, the relational properties and the behavioral properties. We propose definitions by analogy to the attributes of a technical system. The two main characteristics of a technical service system are its architecture and structure. As discussed in Chapter 3, the structure is the set of elements and their relations within each of the three domains –i.e., the resource, operation and activity domains. Also, we propose below that a service system has an *architecture* defined as the mapping between domains. The *form*, *dimensions*, *material* and *surface quality* are the element's characteristics of the resource domain in a technical service system.

4.3.2 Design attributes in technical service systems

Traditionally, design and engineering research has a focus on developing products (we call them technical systems). Increasingly, research is looking for better ways to reason about services. We need to develop a fundamental understanding about their nature. In this section we review service design attributes. We identify those key characteristics and properties that can help improve a technical service system's serviceability performance. Table 4.3 shows our proposed characteristics of a service system's three domains, analogous to those described in Section 3.3.

Table 4.3: *Our interpretation of the characteristics of a service system's three domains, inspired by Andreasen et al. (2014), and analogous to the characteristics of a technical system.*

Domain	Characteristics	Description
	Architecture	Mapping between domains
Activity	Structure	Set of activities and their relations
Operation	Structure	Set of jobs and their relations
Resource	Structure	Set of resources and their relations
	Form	Shape, geometry of a resource
	Dimensions	Physical sizes of resources (length, height, width, volume, etc)
	Surface	Color, texture of the external resource interface
	Material/Knowledge	Elementary composition of a resource

Service characteristics and properties

A service is an activity. The outcome of a service activity is a change of state of the service receiver to a desired state (Sakao and Shimomura, 2007). Services are typically associated with attributes that are considered unique when compared to physical products. There is debate about whether or not these attributes actually define a service, and several paradigms exist attempting to describe their nature. Classic descriptions of service delivery systems describe services by their degree of customer contact (low/high) and level of routinisation (rigid/fluid) (Wemmerlöv and Urban, 1990). Services are also described as intangible, heterogenous, inseparable (production and consumption are simultaneous) and perishable (they can't be stored or transported) –so called *IHIP* characteristics (Lovelock and Gummesson, 2004; Spring and Araujo, 2009; Voss and Hsuan, 2009; Yu et al., 2008). The "rental/access paradigm" states that in services ownership is not transferred, and that nonownership is a unique characteristic of a service (Lovelock and Gummesson, 2004). Unified Service Theory tells us that the defining characteristics of a service are the customer inputs and customer involvement (Sampson and Froehle, 2006).

Arguably, describing a service as unique has its drawbacks. The fact is that technical service operations and manufacturing operations may be identical. Spring and Araujo (2009, p. 449) provide an example, where "if a worker on a car assembly line fits a tyre to a wheel, it is considered to be a manufacturing operation, because what results is a "thing" –a completed car. If a garage worker fits a new tyre to a car brought in by its owner, it is considered to be a service operation". We believe this argument is strong enough for us to step back from the exploration of the characteristics of a service, and issue a new angle by firstly defining the types of services that we are concerned with, i.e., technical services, and subsequently discuss the characteristics and properties of the technical service systems that supply those technical services.

Thus, we provide the following definition:

Definition. *Technical services are activities that fulfill the purpose of transforming technical systems from an undesirable condition of operation to a desirable one.*

Table 4.3 lists the characteristics of technical service systems, analogous to Chapter 3. An example helps to introduce the related definitions:

Example. *According to the week plan of a rolling stock maintenance facility, a trainset is scheduled to arrive on Monday evening for short cycle maintenance. The facility hosts a set of stations that will execute eight services in a span of several days. Work preparation (e.g., inspections) starts upon work release, and continues to regular maintenance. Once the set of scheduled regular maintenance jobs a complete, a train safety check is executed. Next, the wheel machining station executes a batch of jobs (wheel grinding). Next, services are composed such that jobs resulting from inspections (which are scheduled but unplanned) are executed. Cleaning is produced and lastly quality control. Example interfaces are found throughout this service flow. Beginning with (a) the resource level of the technical service, we find interfaces between the machining station, a qualified service engineer and the machine tools, (b) the job level with the relevant jobs in the work order (e.g., replacement of parts), and (c) the activity level, where the traffic control department at NedTrain and the NS (client) agree and cooperate on service scheduling, delivery (including service arrivals) and composition (including scheduled but unplanned repairs).*

In Chapter 3 we defined two types of structural characteristics in each domain view. We adopt those definitions here to describe the nature of technical service systems. We propose that for the technical service system's resources have four characteristics: form, dimensions, surface and material. These are characteristics of a resource element such as a facility, equipment, tooling or people, where for the case of people, material may be more substituted by knowledge and skill. These resources are typical of technical service delivery, and like technical systems, they can exist in a hierarchy. Relation's characteristics describe the service network and the facility locations (supply chain structure), facility layout (process structure) or installation of resources (elements nested in the lowest part of the hierarchy). It is the resource-resource interfaces that determine the element's relations. People are the key element in technical service delivery, and the human machine interface could be considered the dominant interface in the resource domain.

We propose that the structure of the operations domain is analogous to the structure of the technical system's organ domain. The operations structure defines the set of jobs and their relations. Appendix A gives several examples of jobs that typically compose technical service operations. We define the relations between maintenance jobs as the interfaces in structure of the operations domain. These relations are active effects (input/output relations).

The service activity structure can be described in terms of activities and their relations. The set of activities involved in technical services can be very broad. Appendix A and Chapter 2 discuss the scope of these activities. The activity relations are the interfaces of service activities. These relations are input and output state of operands (spacial, material, energy, information that is transformed), nature and state of operators, how operators are carried or lead into contact with the operands, or conditions necessary for a transformation to take place.

The architecture of technical service systems

A service architecture can be defined as "the way that the functionalities of the service system are decomposed into individual functional elements to provide the overall services delivered by the system" (Voss and Hsuan, 2009, p. 546). Their definition is inspired by systems discipline. It speaks of function-decomposition similar to the treatment of architectures of technical systems. The architecture of services is generally founded on this notion that services flow through a network of service providers (nodes) (see, e.g., Sakao and Shimomura, 2007). The service providers are connected in this network (arcs) to produce the flow of services.

The technical service system architecture can be defined by analogy to the definition we used for the product architecture in the previous chapter:

Definition. *The technical service system's architecture is the scheme by which the operations of the service process are allocated to the service provider's resources.*

The concepts of modularity and commonality have a similar meaning in the context of the technical service system. However, in the field of services, modularity is a recent topic. A review by Dörbecker and Böhmann (2013) finds that most existing literature on service modularity was published between 2005 and 2012. Very few authors were found to address the subject before 2008, and a surprisingly small amount of articles (13) was found specifically treating service modularity until 2012.

A module in the service context will be defined as follows.

Definition. *"A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. Clearly there are degrees of connectivity, thus there are gradients of modularity" Baldwin and Clark (2000, p. 63).*

Voss and Hsuan (2009) propose that service modularity exists within different levels in a hierarchy of actors: the industry, the service company/service supply chain, the service bundle and the service package/component (Voss and Hsuan, 2009). Interfaces determine the relations and interactions between elements in each domain. As in the case of physical products, the nature of the interactions can be spacial, energy, information or material (Pimmler and Eppinger, 1994). Voss and Hsuan (2009) point out that in services, interfaces "can include people, information, and rules governing the flow of information" Voss and Hsuan (2009, p. 545). De Block et al. (2014) find empirical evidence of several types of interfaces in health care services. On the one hand, they find that interfaces exist between interacting entities in the service provision. They find interfaces between service components and between service providers in the care package. On the other hand, they find that those interfaces are aimed at providing either variety or coherence to the service offering.

A second key identity of the service architecture is commonality. Commonality in the context of technical services means that resources can be shared and reused across the service network. From a process perspective, commonality is regarded as the shared set of processing steps (Balakrishnan and Brown, 1996). Commonality is a characteristic of service composition, where a number of processes may be similar, or common to all customers. As in the case of products, commonality is characteristics of the service platform, which shares a number of common processes.

4.3.3 Impact of design attributes

In the previous subsection we have proposed to define the characteristics of a technical service system's design by analogy to product design literature. This appears to be a common approach in service research, from which researchers borrow concepts such as architecture, modularity and interfaces (De Block et al., 2014; Menor et al., 2002; Voss and Hsuan, 2009). According to the literature, the technical service system characteristics such as structure, topology and dimensions impact serviceability by either directly impacting the service activity or the setups required by the activity. The effect is mostly associated with service cost and time (duration). However, in the service context the outcome's value to the customer has a more important role.

Structure (resources)

The structure of the service network impacts service supply chain costs and customer service (Chopra, 2003). Customer service properties impacted include response time, product variety, product availability, customer experience, order visibility, returnability. Supply chain costs affected by the supply chain structure are the cost of inventories, transportation, facilities and handling and information (Chopra, 2003).

An example of interfaces in the resource domain exist in the supply chain. The supply chain´s connectivity is modulated by the choice of a transport mode for the delivery of spare parts. Increased supply lead time is often compensated by inventories. This results in increased inventory costs.

Architecture (modularity)

The most important effect of service modularity on serviceability appears to be in the lines of cost reduction, increased flexibility of the service offering. Dörbecker and Böhmann (2013) identify 12 effects of service modularity. There seems to be an agreement, or rather a common interest in the literature about the influence of service modularity on service design. Modularity of services is said to affect customization of services, reusability of service modules, redesign of existing services and design of new services.

For the customer of the service, service modularity is argued to increase flexibility (of the service offering) and to reduce costs. Fewer authors argue on the effects of service modularity for simplification of complex systems, standardization of services, substitution of service modules, increase in perceived service quality, standardization of interfaces and packaging of functionalities (Dörbecker and Böhmann, 2013).

Architecture (commonality)

A well-known law of factory physics states: "increasing variability degrades the performance of a production system". Therefore, organizations have a choice in buffering through a combination of inventory, capacity or time (Hopp and Spearman, 2008). Delivering a service package typically entails the execution of a number of jobs that the technical system requires. In the literature we find that "as the number of service packages increases in a given service system, combinatorial effects cause the system to become more complex, which increases the coordination effort" (Voss and Hsuan, 2009, p. 550). Unique services are difficult to copy. But this also means for the service provider that they will be difficult to replicate in multi-site organizations.

4.3.4 Analysis of literature findings

Our main finding from the literature is that the technical service process is arguably very similar to manufacturing. If one acknowledges the rental/access paradigm as the only key characteristic that differentiates services from typical products, then a large body of literature can be used from that analogy. We will provide an in-depth discussion in Chapter 5 about decisions made during design of technical service systems. Table 4.4 summarizes our findings from the literature. On the left column we identify those design attributes of technical service systems that impact serviceability according to the literature. Intervening phenomena are explained on the right column. They are the central mechanisms that are found to produce the effects.

Table 4.4: *Impact of technical service system design characteristics on serviceability.*

Characteristic	Intervening phenomena
Structure (Resources)	**Risk pooling**: the structure of the service network impacts service supply chain costs and customer service
Architecture (modularity)	**Flexibility**: modularity increases flexibility (of the service offering) and reduces costs
Architecture (commonality)	**Complexity**: as the number of service packages increases the coordination effort also increases **Variability**: increasing variability degrades the performance of a production system

Design Attributes

The structure and architecture of the technical service system impact serviceability. On the one hand, the structure of the service network, location, layout, and capacity of facilities are fundamental characteristics of the service system. On the other hand, service modularity and commonality are discussed in similar terms to the previous chapter. The research on service architecture is still in its infancy.

It seems probable that the hierarchy levels in Voss and Hsuan (2009) belong to different domains. The first two levels, namely, the industry and the service company/supply chain appear to be hierarchies of the *service provider*. However, the remaining two levels, defined as the service bundle and the service package/component seem to belong to a different domain. They are more closely related to what the service does, and what the clients can do with the service. The operation domain and activity domain appear more fitting to these last two levels of the hierarchy, respectively.

Intervening phenomena

We identify risk pooling, flexibility, complexity, and variability as dominant intervening phenomena, according to the research.

Effects of design attributes

Design attributes of technical service systems impact service cost, time and the customer perception of value.

4.4 Technical service: the plant

This section describes how design attributes of a technical system affect serviceability in practice. We first describe the general characteristics of rolling stock MFs. Next, we describe how these characteristics impact serviceability. Finally we discuss our main findings at NedTrain: (1) some resources (e.g., equipment, people) are not specific to train platforms; (2) facility locations are dispersed within the rail network, so that access and vehicle routing requires large effort in coordinating service delivery; (3) the maintenance concept and planning culture have the most profound impact on serviceability performance.

4.4.1 Design characteristics of rolling stock maintenance facilities

A facility is a place that provides a capability. The four MFs of NedTrain are located as shown in Figure 1.6. These facilities provide a depot level of maintenance within a large distributed service network. Each facility is allocated with a large set of resources that makes it technically complex. Turnaround time is usually longer for depot visits. MFs are largely decoupled from the SFs' daily services. At the plant level, services are composed centered on resources. A supply chain network is configured for spare parts supply based on two streams of demand: preventive and corrective maintenance.

Resource specificity at NedTrain

Each facility is allocated with a set of resources. The basic equipment are pit tracks, train washing installations, automatic train protection tracks, lifting track, level track, drop-table, ground wheel-lathe, cherry picker and other supporting equipment such as waste water treatment plants, washing/filling hydrants and service vans.

There is a large degree of commonality in the equipment within the workshop. The support manager's give us an example:

> If you look at the exchange of bogies, for example, you typically use the same equipment, it is one and the same track for the droptable. Tools are different for each train series

Differences in train platforms do not necessarily lead to different equipment or to additional setups of the equipment, but may lead to different tools. People are cross-trained, so that changeovers from one series to another do not impact the process flow. Work descriptions and documentation are specific to each train series. Therefore, training is specific for each type of train, but service engineers in any facility must be able to work on any of the trains allotted to that facility. At Onnen for example, service engineers are expected to work on ICM as well as on VIRM (PLatforms B and F of Chapter 3, respectively).

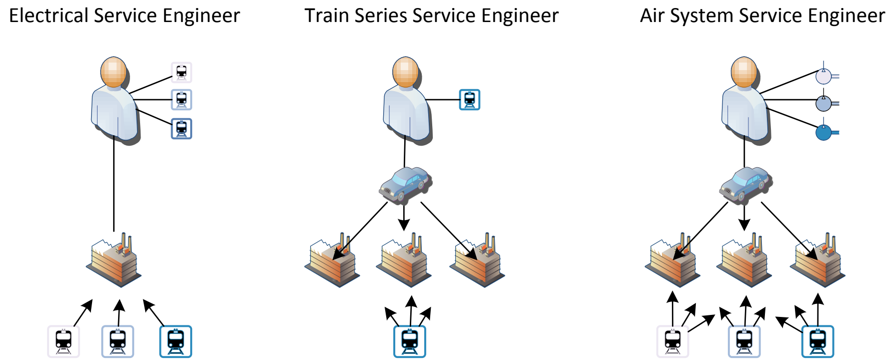


Figure 4.5: *Knowledge and specialization used as a means of increasing flexibility.*

Decoupled capabilities

Capabilities for the level of maintenance are decoupled in several levels. At the network level MFs are decoupled from the SFs' daily services. Some overlap exists, as MFs also do SFs' work and viceversa. At the plant level, services are composed centered on resources. However, the ability to disconnect locations, resources and allocation of jobs helped to test changes to the current maintenance concept.

That means that resources determine, to a large extent, the flexibility of composing service packages. Let us use Figure 4.5 as example. Currently, service engineers are organized by professional skills as electrical or mechanical service engineers. They were easily able to cope with demands of rolling stock, and a train series service engineer would be knowledgeable in one train series, to deal with difficult failure finding tasks and repairs.

Currently, NedTrain is busy with specialization. A trend to increase specialization may lead to service engineers that are knowledgeable in specific subsystems on the train, e.g., an air system service engineer. Decoupling the resources at the organ level of the asset, and therefore on the operation level of the technical service system, is a different paradigm of service composition. Instead of modularizing based on decoupling the resource domain, the service composition logic based on organs or activities can provide increased flexibility.

Service interfaces

Several interfaces were identified during our fieldwork and interviews with experts. Two of them are acknowledged by experts as having an important impact on serviceability. We describe those two interfaces next. The two interfaces exist between the providers of the technical services. The first interface aims at creating coherence (De Block et al. (2014, p. 185) describe coherence as "ensuring

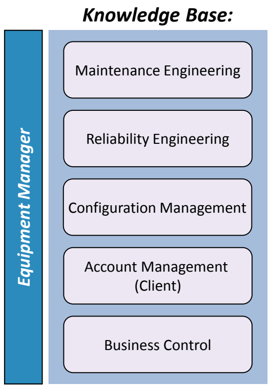


Figure 4.6: *An asset management team.*

that service providers acted in a prescribed and predictable manner"). Twice a day the maintenance schedule is discussed in a meeting with the maintenance crews at each of the four maintenance facilities. The meetings are a key moment of information exchange between planners and service engineers of a maintenance facility. Estimated task completion times are updated by the experts and communicated to the planning department.

The second of the two interfaces is the so-called asset management team's meetings. This interface aims at creating variety (De Block et al. (2014, p. 185) describe variety as "allowing choices to be made from the whole spectrum of care and service components offered"). The aim of this interface is to provide adaptation and continuous monitoring of the performance of the asset. The asset management team is a group of experts from several disciplines, as shown in Figure 4.6. With the client involved, the asset management team is responsible for the life cycle plan of the asset.

Supply chain network

Supply chain operations (SCO) is the department responsible for the Component Revision Facility (CRF), the Refurbishment and Overhaul Facility (ROF) and also other external parties providing repair capabilities. The supply chain network represented in Figure 4.7, is configured for spare parts supply and the reverse flows of repairable items based on two streams of demand that could be categorized as resulting from preventive and corrective maintenance. The maintenance concept has a profound impact on the performance of the supply chain. The maintenance concept modulates demand, and therefore influences demand variability. This variability limits responsiveness of the supply chain. According to one expert "the maintenance concept (that we have) has very little predictive character on the technical system". Arts (2013) gives more detail about spare parts planning and control at organizations like NedTrain.

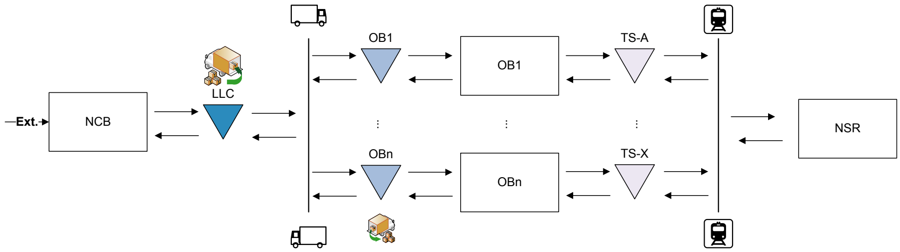


Figure 4.7: *Supply chain configuration.*

4.4.2 Impact of design characteristics in practice

Structure (resources)

There is a large degree of commonality in the resources of MFs, and according to one expert RAMS/LCC Manager, "approximately 85% of the parts are not dependent on workshop capabilities. For this 85% rule of thumb, the replacement action can take place in most workshops". The increased flexibility of commonalities across the service system is especially useful for planning new acquisition projects.

However, maintenance companies tend to specialize their manpower. Figure 4.5 shows an example of the trend of increasing specialization. As systems become more complex, the knowledge base of the maintenance workforce is concentrated in a specific type of component or subsystem. There seems to be a common agreement that for new rolling stock the training is the bottleneck. The demands of increasing mechatronics in the trains has changed the skills profiles in a number of ways. The head of support explains the impact as a sand clock model.

> "...we also have a new thinking. Mat64 has this kind of (pyramid) education. So you have a lot of people who do not have quite a lot of skills, but that are capable of basic abilities (base)... and this goes up ... then you get university... but with the SLT you see it isn't that simple. Maybe you need a... specially in the beginning... the analysis for what is the problem with the train is much more complex than before... So I think if you look in a few years you get more like a sort of sand clock. So you have a big overhead and then you still need the guys that fix the train. But then in the beginning you invest... and that's new to us. We didn't fully understand it until we started with the SLT".

Architecture (modularity)

For NedTrain, service modularity is increasingly important. Elements of service modularity are slowly changing the traditional maintenance concept at NedTrain. The maintenance concept is an abstract term often used in the maintenance literature referring to the set of maintenance policies followed for a technical system. A change of maintenance concept has far reaching implications for a maintenance organization. It promises increased flexibility of the service offering for the NS.

Two projects have been financed by NedTrain to develop the modular maintenance approach. They will be discussed in the next chapter. The maintenance concept has an impact on the planability of logistic processes. It was estimated that as a result of the maintenance and the operating concept, only about 20% of the spare parts demand can be planned[2].

Architecture (commonality)

At NedTrain, it seems that a lack of commonality in rolling stock platforms does not cascade, i.e., it does not seem to propagate variability within the workshop. In fact, there are many similarities in the available resources of the technical service system and people absorb variability through cross training. Impact of new asset introduction is more concerning for its obsolescence effect on resources, and specially on knowledge. Despite the fact that there is high commonality of resources between facilities, it is the knowledge of service engineers (that is specific to a train platform) that has a large influence on serviceability performance. A train cannot be repaired easily on any location without a knowledgeable expert. And likewise, this also increases pressure on the transport logistics. On an already highly utilized network, maintenance transport logistics are a major source of downtime. Specialization is seen by some experts as a means to increase flexibility.

4.4.3 Analysis of case findings

Table 4.5 summarizes the main findings of the case. We see that NedTrain compiles a list of existing resources, with a set of jobs that are common practice in the technical service, a kind of service concept. NedTrain supports system specification by providing a RAMS/LCC plan of seven main subsystems of the train. A supplier develops the NS-specific platform variant to fit the main systems to the jobs of the technical service system. System components are expected to fit the resources of the technical service system, but this is a responsibility that is allotted to the supplier.

We identify four leading mechanisms by which the technical service system design impacts serviceability: flexibility, learning, decoupling capabilities and

[2] study on spare parts management conducted in 2011

Table 4.5: *Design aspects and mechanisms impacting serviceability. Technical service perspective*

Characteristic	Phenomena	Supporting data (additional to quoted text)	Source
Commonality (resource)	Flexibility	Training is specific for each type of train, but service engineers in any facility must be able to work on any	i:head of support/technical coordinator
Resources	Shifting responsibility	They need to be sure that we can maintain it	i:head of purchasing
Commonality	Cascading	Differences in train platforms do not necessarily lead to different equipment or to additional setups of the equipment	i:head of support/technical coordinator
Interface		Estimated task completion times are updated and communicated to the planning department.	o:mf maastricht
Knowledge	Learning	I think if you look in a few years you get more like a sort of sand clock. So you have a big overhead and then you still need the guys that fix the train	i:head of support
Modularity (service)	Decoupling capabilities	The ability to disconnect locations, resources and allocation of jobs helped to change the maintenance concept.	i:manager acquisition project
Modularity (service)	Task complexity	The work demand for people was completely fluctuating. Now there is job A, then B, then it began again. Then the floors, then the windows. Finally we decided to go back to our old system	i:department director
Operating Concept	Flexibility	If I have trains around the entire country, then sometimes the train is here, sometimes it arrives there...	i:rams/lcc manager
Resources (spares)	Uncertainty	The supply chain organization's biggest problems appear with the introduction of new rolling stock, or when fielding modernized trains. At that moment, there are large changes in our assortment.	i:change manager sco
Resource	Obsolescence	When the new train arrived, our service engineers knew very little about the train.	i:rams/lcc manager

task complexity. Only flexibility and complexity were identified in the literature. While variability and risk pooling were not assessed as important mechanisms (by the experts that we interviewed). Instead, we find that changing knowledge profiles through learning, and the decoupling of capabilities are two fundamental mechanisms impacting serviceability, both within the structure and within the architecture of the technical service system.

4.5 Conclusion

This chapter contributes by giving an overview of technical service design aspects that impact serviceability and by reasoning why they do so. Also, it contributes by connecting technical service design aspects and serviceability. A set of element characteristics, namely *form*, *dimension* and *material/knowledge* provide compatibility between technical systems and technical service systems. That means for example, that the physical allocation or mapping of a train to a particular maintenance facility requires matching of technical system size and weight to those of the maintenance facility. NedTrain ensures that these characteristics are taken into account. On a high level, NedTrain openly communicates an inventory of resources available in their workshops. According to NedTrain experts, providing that information is important to the supplier "because they need to be sure that we can maintain it (new rolling stock)". This also signals a shift in responsibility to the supplier.

Results of the second (out of four) part of the case show no support for one best technical service architecture. However, contingent factors involve organizational change aspects as well as service modularity aspects, namely, decoupling of capabilities. The important implications for decision making reside in the knowledge that decoupling technical service capabilities is contingent on asset design aspects: modularity and commonality. The technical service design implications are important, because fixing the mismatch requires attention to technical service redesign during acquisitions. This is an important organizational change.

These insights about a technical service system's design will be exploited further in Chapters 7 and 8.

Chapter 5

Improvement projects perspective: improving serviceability [1]

This chapter investigates what decisions are made to improve serviceability during acquisition of capital assets. And, how these decisions do that. It is the third part (out of four) of the company case, and uses the improvement project as an embedded unit of analysis. Ten improvement projects are included in the study. Section 5.1 briefly introduces the research problem. Next, Section 5.2 presents the methodology, followed by the literature review on maintenance decision-making in Section 5.3. There we give attention to strategic decisions made before, during and after acquisition of capital assets, but we find that this literature focuses on existing assets after contract. The literature suggests that assets and their maintenance services should be developed concurrently. In contrast to this, Section 5.4 reports the findings of the case study conducted at NedTrain. Two important insights are as follows. Firstly, that the organization fits new assets to the existing service package. Secondly, improvement projects are carried out mostly independent of asset acquisitions. We find that although decisions about services should be made early, they are not made until after contracting, and often after fielding a new train series. That means that strategic maintenance decisions are often not concurrent to rolling stock design decisions. Chapter findings are presented in Section 5.5. There we present a framework that provides an organized overview of all those decisions that we identified in practice. Finally, Section 5.6 presents our conclusions. The chapter exposes a need to support strategic maintenance decision making during early stages of

[1] Parts of this chapter are adapted from Parada Puig et al. (2015) and Parada Puig et al. (2013a).

acquisition. Chapter 7 will later develop such support.

5.1 Introduction

Acquisitions of capital assets provide a wealth of opportunities for improvement of serviceability. It is often noted that decisions made at this stage of the life cycle of a capital asset have the largest potential to impact life cycle costs. Acquisition costs only represent around 40% of the Life Cycle Cost (LCC) of an asset, and upon contract award 85% of the cost of ownership decisions are made (Jones, 2006b). Choices begin with how contracting is done, e.g., material contracts, service contracts or Industrial Product-Service System (IPS^2).

Today, acquisitions of capital assets involve a complex contracting environment. The technical system that is involved in the contract, i.e., the capital asset, can originate as a new development project, as a partial development based on an existing platform, or it can be a commercial off the shelf system. The more of the design is fixed then there is less flexibility for decision making. Decisions that increase serviceability may target the technical system, the technical service system or both. This chapter discusses how maintenance decisions, centered on the technical service system, influence serviceability of rolling stock.

The maintenance function can play a key role by supporting decision making during rolling stock acquisition (Parada Puig et al., 2011). Research has pointed to the importance of considering maintenance in planning the product life cycle, (see, e.g., Umeda et al., 2012) but this emphasis has received limited attention (Takata, 2013; Takata et al., 2004). During asset acquisition, maintenance decision making helps to ensure that the asset can be properly supported, e.g., deciding on facilities, equipment or training of the workforce (Blanchard, 2004; Hastings, 2010; INCOSE, 2010; Jones, 2006b).

5.2 Methodology

This chapter aims at improving the understanding of maintenance decisions made during the acquisition of rolling stock. In Section 1.4 we formulated research subquestion RQ2b: How is serviceability addressed in acquisition projects in practice?

This chapter contributes to answer that research subquestion by asking, firstly, what decisions are made to improve serviceability during acquisitions? Secondly, how do these decisions influence serviceability? Our research combines a literature review and a part of the company case study, as shown in Figure 1.14. With this approach, we examine both academic research and practice. The research methodology is similar to the previous Chapters 3 and 4 (refer to Section 3.2).

5.2.1 Approach to literature review

The literature review includes research from several research disciplines in the fields of decision sciences and engineering. The systematic review follows the scheme of Figure 1.13. We review journal papers from the disciplines of operations research (OR), production and operations management (POM), maintenance engineering (ME), reliability engineering (RE) and systems engineering (SE). Relevant sources are queried using electronic database services such as Scopus, Science Direct, IEEE Xplorer and Web of Science. We use keywords such as *management*, *decision*, and *decision making*. Furthermore, we include *maintenance*, and several synonyms for maintenance —*repair*, *replace /replacement*, *upkeep*, *mro*, *spare part*, *service*, for example. Finally, we include in our search additional categories such as *strategic*, *tactical* and *operational* maintenance decisions. We explicitly focus on research on *maintenance decision frameworks* as additional set of search terms. However, we exclude most *conceptual frameworks*, because they are used in empirical papers for measuring operationalized constructs and give little guidance about decision making (e.g., Prasad Mishra et al., 2006). We include books known to discuss the topic of *maintenance decision making*, *maintenance management* or *logistics*.

5.2.2 Case selection

As a continuation of the company case, this chapter focuses on improvement projects as the Unit of Analysis (UOA): UOA3. This UOA is shown in Figure5.1 in the broader context of the company case.

Improvements to serviceability of rolling stock span from new facilities, equipment or technology to new methods, standards or policies for handling repair. The UOA described in Table 5.1 includes important projects, or project components that have been articulated by NedTrain during the past decade. Further descriptions can be found in EU-OSHA (2006); Mooren and van Dongen (2013); van Dongen (2008, 2015); van Uffelen and Busstra (2007).

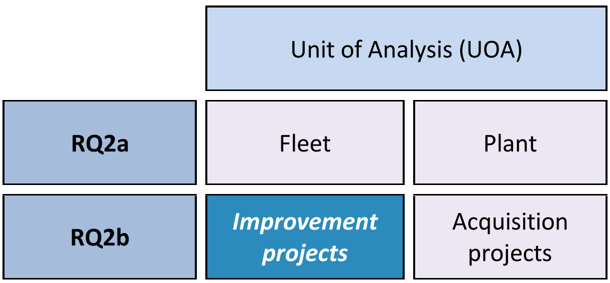


Figure 5.1: *Unit of analysis (UOA) of Chapter 5 within the broader case context.*

Table 5.1: *Characteristics of UOA3: improvement projects.*

Project	Start year	Description
Reliability Program	2007	Reduce maintenance withdrawals by reliability improvements
GOIDS/MOOD	2010/2014	Scheduling maintenance in shorter and more frequent intervals between peaks. No rush hour withdrawals (Geen Onttrekking In De Spits) and modular maintenance (MOdulair OnDehoud)
Technical Centers	2012	Facilities with extended capabilities specializing in failure repairs located at strategic railway junctions
Risk Based Maintenance	2013	Make transparent trade offs between performance, risk and costs
Remote Condition Monitoring	2013	Use condition of individual trains in planning maintenance withdrawals
Functional expansion of Leidschendam	2008	Improve capabilities of the maintenance facility to accommodate new rolling stock
Watergraafsmeer maintenance facility	2005	Maintenance facility for high-speed rolling stock
Refurbishment projects	2006/2009	Revision and modernization of rolling stock
K3 lead time reduction	2007	Reduce maintenance withdrawals by reducing production lead time
Maximo CMMS	2013	Implementation of new Computerized Maintenance Management System for process control

5.2.3 Data collection

For the case study we combine interviews, company documents and plant visits as primary sources of data. We analyze the case data and go back to the literature to clarify the decision making process, and to compare practice and theory. We focus on the maintainer. The case uses individual semi-structured interviews. The sample includes management —e.g., senior, acquisition, support, maintenance or fleet managers, mostly with an engineering background— and technical staff that has been involved or consulted for improvement projects, acquisition projects or maintenance assessment. In total, 18 experts have been interviewed. Ease of access to the organization also allowed for many informal conversations with key informants. Some experts in key positions have been interviewed several times. Interviews have been recorded, transcribed and analyzed to extract decisions mentioned by experts. We have carefully documented those decisions, giving special attention to when these decisions were made, who is either responsible or has a stake in the decision and what criteria are important to make the decision.

5.3 Literature review

This section reviews the literature on maintenance decision making. It explores what maintenance decisions are made to improve serviceability during acquisition of capital assets according to the literature. We begin in Section 5.3.1 describing the typical hierarchical decomposition of decisions found in the literature. There, we find that strategic maintenance decisions are most relevant during early stages of acquisition. Next, Section 5.3.2 reviews the strategic decisions. We find that according to the literature, assets and their maintenance services should be developed concurrently. We also find that existing research on strategic maintenance decision making is dedicated to later phases of acquisition, especially after contracting.

Maintenance decision making is an active research area. For generally useful books and reviews see, e.g., Ben-Daya et al. (2009); Garg and Deshmukh (2006); Murthy and Kobbacy (2008); Pintelon and Gelders (1992); Pintelon and van Puyvelde (2006). Operations research offers several reviews on maintenance decision making from the perspective of maintenance optimization (see, e.g., Horenbeek et al., 2011; Nicolai and Dekker, 2008). The research on strategic maintenance decisions is too broad to review individual decisions, and therefore we review papers that structure decisions in the form of frameworks. Frameworks are meta-models that structure the theory with its models, and typically outline the (i) connection between decisions, (ii) choices, (iii) decision areas, (iv) methods for making decisions and/or (v) tools for making decisions. We use these attributes to examine the research. As such, frameworks are commonly used in research to structure decision processes, and to position methods used to support decision making.

Before continuing with our review in the next section, we first give some definitions. We adopt the definitions of maintenance concept, policy and action from Pintelon and van Puyvelde (2006).

Definition. *A maintenance concept is the set of maintenance policies and actions of various types and the general decision structure in which these are planned and supported.*

Definition. *A maintenance policy is a rule or a set of rules describing the triggering mechanism for the different maintenance actions.*

Definition. *Maintenance actions are basic maintenance interventions, elementary tasks carried out by a technician.*

Definition. *The maintenance program documents the planned maintenance actions, and shows the schedule needed for the implementation of maintenance interventions.*

5.3.1 Strategic, tactical and operational decisions

Decomposing decisions into hierarchies of decisions has been widespread in the operations management, supply chain management and operations research literature (Driessen et al., 2014). It appears that strategic decisions have the largest impact during early stages of acquisitions. Table 5.2 shows the typical decision areas in maintenance decision making. The strategic decision areas of the table are drawn from operations management research (Hayes et al., 1988; Pinjala et al., 2006; Tsang, 2002), while tactical and operational decisions are inspired by Pintelon and Gelders (1992); Pyke and Cohen (1990).

Strategic decisions give shape to the *maintenance strategy*. The planning horizon for strategic decisions is typically two to five years (some spanning 10+ years). The maintenance strategy refers to the *structured pattern of decisions* made in specific *decision areas* to develop its maintenance *capabilities* (Pintelon and van Puyvelde, 2006). Strategic decisions typically have the highest level of associated uncertainty, and they involve the conceptual design of maintenance services, i.e., the conceptual design of the technical service system.

Tactical decisions are mostly policy decisions that are revised annually or bi-annually. These decisions are typical of the maintenance supply chain organization. Tactical decisions tend to prescribe information and material flows, throughput or inventory levels, and this includes repair (job) shop planning. Material flow decisions are typically decisions on (i) batch size, (ii) timing of a production or shipment request, (iii) setting dispatch or allocation rules, and (iv) the presence of interference mechanisms for expediting or handling of emergency orders (Pyke and Cohen, 1990). Operational decisions are weekly or daily decisions. They involve choices about task schedules and handling of work orders, e.g. arranging the sequence in which work orders are executed and by whom (Pintelon and Gelders, 1992).

In this chapter, we do not review tactical and operational decisions. We only present them shortly in our findings of section Section 5.4. We review those decisions in Chapter 8, where we also provide new insights and develop a model to support decision making on a strategical/tactical level.

5.3.2 Strategic maintenance decisions

In this section we learn that strategic decisions are made during design of technical service systems, and therefore draw links to our previous chapter. The literature discusses two phases of acquisition during which maintenance decisions for new capital assets are made: one phase during the functional phase of system development (first phase), and one phase focusing on developing support for the design solution (second phase)(Jones, 2006b). The first phase entitles the buyer with the role of developing requirements. Once requirements are issued in a Request For Proposals (RFP), it is expected that the original equipment manufacturer is responsible for developing support options that are submitted

Table 5.2: *Main decision areas involved in strategic, tactical and operational decisions.*

Planning level	Decision Areas
Strategic	(1) Capacity, (2) Facilities, (3) Technology, (4) Integration, (5) Organization, (6) Policy, (7) Human Resources, (8) Design, (9) Production Control, (10) Performance Measurement and Reward
Tactical	(1) Information flows, (2) Material flows, (3) Throughput, (4) Buffers
Operational	(1) Schedules, (2) Coordination (3) Task Grouping

with the proposals. Design decisions for the maintenance and the asset are made concurrently. The support options are decided upon when the buyer selects the best proposal (Blanchard, 2004; Jones, 2006b). Second phase decisions involve the detail design of the asset and the required services. To the best of our knowledge, existing research on strategic maintenance decision making is dedicated to the second phase.

Few papers give an overview with several decision areas in strategic maintenance decisions. Notable exceptions are Pinjala et al. (2006); Tsang (2002). Horenbeek et al. (2011) and Jardine and Tsang (2013) review maintenance optimization models and give an overview framework that illustrates the typical decision areas (output) of maintenance optimization models. These frameworks tend to explain the areas of strategic decision making, but they either do not show connections between decisions, or do not show the methods and tools required to make them. In contrast, Al-Turki (2011) uses a framework to describe the alignment to higher level corporate strategy for the selection of the appropriate strategies regarding service delivery mode, type of contracts for outsourcing, organization, work structure or maintenance management methodology.

Table 5.3: *Research papers proposing frameworks for strategic maintenance decisions.*

Decision areas	Literature sources
General/Asset Management	**Strategic Maintenance Management** (Murthy et al., 2002), **Maintenance Management Framework** (Crespo Márquez and Gupta, 2006; Crespo Márquez et al., 2009; López Campos and Crespo Márquez, 2011; Pintelon and Gelders, 1992), **Distribution Network Service Providers Framework** (Gómez Fernández and Crespo Márquez, 2009), **Life Cycle Maintenance Framework** (Takata, 2013; Takata et al., 2004), **Asset Management Framework** (Tam and Price, 2008; Tam et al., 2007)

Table 5.3: *(Continued).*

Decision areas	Literature sources
(1) Capacity	**Maintenance Resource Requirements** (Jardine and Tsang, 2013); **Maintenance manpower supply** (see, e.g., Yan et al., 2004)
(2) Facilities	**Maintenance Resource Requirements** (Jardine and Tsang, 2013), **Network Design** (see, e.g., Melo et al., 2009; Srivastava, 2008)
(3) Technology	**IT/IS Evaluation Framework** (Gunasekaran et al., 2006)
(4) Integration	**Maintenance Resource Requirements** (Jardine and Tsang, 2013), **Outsourcing** (see, e.g., Pintelon and van Puyvelde, 2006)
(5) Organization ..	**Network Design** (see, e.g., Melo et al., 2009; Srivastava, 2008)
(6a) Policy	**Risk Based Maintenance Policy Framework** (Dawotola et al., 2013), **Quantitative Framework** (Faccio et al., 2014), **Multi Criteria Decision Making Framework** (Ghosh and Roy, 2010)
(6b) Concept ...... Development	**Reliability Centered Maintenance Framework** (Rausand, 1998), **Total Productive Maintenance Framework** (Mckone and Weiss, 1998), **CIBOCOF** (Waeyenbergh and Pintelon, 2002, 2004, 2009), **Value Driven Maintenance Planning** (Rosqvist et al., 2009), **Individualising Maintenance Concept** (Naughton and Tiernan, 2012)
(7) Human .... Resources	**Training Program** (Gramopadhye et al., 1997)
(8) Design	**Integrated Logistics Support** (Blanchard, 2004; Hastings, 2010; Jones, 2006b)
(9) Production .... Control	**Spare Parts Planning** (Cavalieri et al., 2008; Driessen et al., 2014)
(10) Performance . Measurement	**Maintenance Performance Measurement Framework** (Kutucuoglu et al., 2001; Muchiri et al., 2011; Parida and Kumar, 2006)

Table 5.3 organizes the papers found in the literature according to the strategic decision areas of Table 5.2. We include the category of General/Asset Management in Table 5.3 for frameworks that give insight into the management system. The table shows that most papers provide frameworks for General/Asset Management, Maintenance Concept and Maintenance Policy decisions. The decision areas of Capacity, Facilities and Integration can be found in several reviews that include maintenance manpower (see, e.g., Yan et al., 2004), network design (see, e.g., Melo et al., 2009; Srivastava, 2008) or outsourcing decisions(see, e.g., Pintelon and van Puyvelde, 2006). We found only one framework in the area of Technology (Gunasekaran et al., 2006). Although it is not specific to maintenance, it gives insights that can be easily extended to the selection of Computerized Maintenance Management Systems.

Maintenance Policy selection frameworks tend to use quantitative approaches.

For example, Faccio et al. (2014) give a quantitative framework to develop maintenance policies. The authors use several cost models that include spare parts, labor, missing production costs, and other indirect costs. The proposed framework has three phases, (i) equipment analysis, (ii) survival data collection and analysis and (iii) decision making process. The general decision scope includes a mix of strategic and tactical decisions.

Frameworks for Concept Development give a general decision structure for planning/supporting the set of policy decisions for an asset or a group of assets. Maintenance concept development is the focal point of maintenance decision making. Reliability Centered Maintenance (RCM) and Total Productive Maintenance (TPM) are two classic approaches to prescriptive maintenance concept development (Mckone and Weiss, 1998; Rausand, 1998). Naughton and Tiernan (2012) challenge the notion of using resource intensive, non-generic and pre-existing frameworks for concept development. Based on their experience, these are often complex and specific to one particular industry. Some research has therefore focused on tailoring maintenance concepts for individual organizations (e.g., Naughton and Tiernan, 2012; Waeyenbergh and Pintelon, 2002).

We categorize the Integrated Logistics Support (ILS) framework in the area of Design. ILS is used in the defense sector for structuring decisions on the logistic support concept. The emphasis is that maintenance service design and asset design should go together, starting from the initial stages of asset design (Jones, 2006b). Production Control frameworks are mainly focused on tactical decisions. For example, in Cavalieri et al. (2008) authors propose five decision making steps for spare parts control of first line maintenance. Authors in Driessen et al. (2014) extend that framework by including the repair shop —second line maintenance— and its control.

We found only one framework in the area of Human Resources. Gramopadhye et al. (1997) give an overview framework about designing visual inspection training programs in aviation. Performance Measurement and Reward frameworks give insight into alignment of the maintenance function with operational and corporate goals, and they help position the performance management of maintenance services (e.g., Muchiri et al., 2011).

5.3.3 Literature findings

The literature on maintenance decision making gave us interesting insights about designing technical service systems. Consistent with our findings from the previous Chapter 4, we see that strategic decisions about maintenance (services) are drawn from the literature on manufacturing, mostly extended from production and operations management research, management science and operations research.

We find that the literature presents limited insights about decisions made before contracting. In fact, most of the strategic decision frameworks that we found are not intended for early service development, but rather for assets that are fielded and in operation. This means that the strategic decisions represented in frameworks are assuming that the asset has already been designed, and detail design decisions about the technical service systems follow. Decision making that is intended to improve serviceability during acquisitions seems lacking in this context.

5.4 Improvement projects at NedTrain

This section presents the results of the empirical case. It describes the practices of maintenance decision making in the context of NedTrain. Van Dongen (2015) gives insights about the maintenance strategy of NedTrain; Parada Puig et al. (2011) give more detail about its maintenance operations, which we also discuss in Chapters 1 to 4. This section organizes the results in a similar way as the literature review. Firstly, Section 5.4.1 discusses strategic, tactical and operational maintenance decisions at NedTrain. We find there that many maintenance decisions result in continuous improvement projects to manage the existing fleet. Secondly, Section 5.4.2 presents the case results about strategic maintenance decisions. There we show that improvement projects have helped develop the technical service system of NedTrain. We provide insights that show how these projects have developed independently of rolling stock acquisitions.

5.4.1 Strategic, tactical and operational decisions

Improvement decisions often follow from the results of industry benchmarks. Using the benchmarks, companies make an effort to follow industry leaders that outperform them in some dimension. Supported by BSL Management Consultants, NedTrain conducted such an industry benchmark in 2004. The focus was on costs and rolling stock performance: reliability, failure rates and availability (Bente and Roeleveld, 2006). As a follow up of that benchmark, an additional study was conducted in 2006 to produce a more detailed benchmark with the top performer. Those studies indicated routes for improvement that spanned different domains of the organization.

Following best practices, NedTrain began a long process of improvement supported by several projects. Some of these projects are included in this UOA, shown in Table 5.1. Table 5.4 shows the relation of improvement projects at NedTrain with the decision areas of Section 5.3.1. Decisions in these projects span strategic, tactical and operational levels. Below we discuss this further by means of an example.

Table 5.4 shows decision areas of Table 5.2 linked to improvement projects listed in Table 5.1. Many decisions are made to optimize the maintenance services. The sum of these decisions results in the configuration of the technical service system. We find that these decisions are not made during acquisitions, but to

Table 5.4: *Most important decision areas involved in improvement projects. (+) signals that 'project explicitly targets decision area';* ***GOIDS****: Geen Ontrekking In De Spits (No rush hour withdrawals);* ***MOOD****: MODulair OnDerhoud;* ***K3****: Korter, Korter, Korter;* ***CMMS****: Computerized Maintenance Management System.* ***Strategic decision areas****: (1) Capacity, (2) Facilities, (3) Technology, (4) Integration, (5) Organization, (6) Policy, (7) Human Resources, (8) Design, (9) Production Control, (10) Performance Measurement and Reward.* ***Tactical decision areas****: (1) Information flows, (2) Material flows, (3) Throughput, (4) Buffers.* ***Operational decision areas****: (1) Schedules, (2) Coordination (3) Task Grouping.*

Project	Strategic										Tactical				Operational		
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	1	2	3
Reliability Program					+	+	+	+		+							
GOIDS/MOOD		+			+	+			+		+	+	+	+	+	+	+
Technical Centers		+															
Risk Based Maintenance						+				+							
Remote Condition Monitoring																	
Functional expansion of Leidschendam	+																
Watergraafsmeer maintenance facility		+								+	+	+	+				
Refurbishment projects				+				+									
K3 lead time reduction										+	+		+	+	+		
Maximo CMMS			+						+								

manage the existing fleet. New train series are merged with the old ones and the complexity is managed by means of a so-called fleet life cycle plan. The fleet life cycle plan gives the insights that NedTrain managers use to choose improvement targets. The Reliability Program has a large content of strategic decisions (5/10), as shown in Table 5.4. We discuss that program next.

Reliability program

The Reliability program was one of the first large scale initiatives that resulted from the benchmarking efforts. The program had a duration of three years and was designed to target unscheduled withdrawals of rolling stock (van Uffelen and Busstra, 2007). The program selected 37 projects that would result in the reduction of unscheduled entries to the maintenance facilities by 50%. Figure 5.2 gives a simplified cognitive map of some of these improvements discussed with key informants.

The left part of Figure 5.2 shows the three performance problems identified in the initial situation: quality, withdrawals and costs. Quality problems were associated with recidivism, i.e., failures repeated on the same rolling stock after maintenance interventions. This often meant that withdrawals for unscheduled maintenance represented a considerable amount of the total maintenance withdrawals. Increased withdrawals impacted capital costs, as the fleet size must increase to compensate unavailable trains in order for the client to keep a required level of passenger service. Unresolved failures impacted costs as well.

Increased awareness was a result of the first phase of the program, shown in Figure 5.2. As one informant commented: “we made measurements on trains after leaving the maintenance facility. Then you saw that after maintenance you would get a surge in the number of failures... it would stop after two or three weeks”. Defective LRUs on the shelves of the shop floor were being used, undetected. “We made our own failures” said one expert. Design defects were also found in components that produced inconvenient failures, e.g., when exposed to harsh weather. Additionally, the maintenance concept had a share of influence on the quantity of unplanned work. It was recognized that at the time “...the maintenance concept hadn’t changed in 30 years”.

With the pressure to improve, the root causes were identified and improvements were proposed through problem solving sessions. Component management teams were organized in reliability sessions. Experts in these sessions were commissioned with the task of looking at which components were causing unplanned withdrawals, deciding on how to track and measure the problem items, and defining the repair approach. Design defects were identified in some of these components. This meant integrating the supply chain to the improvement process. Process quality problems were resolved through a method inspired by cross industry knowledge sharing.

First Time Right resulted as a quality improvement initiative using a systematic fault correction approach: “First time right is our solution to recidivism”, the

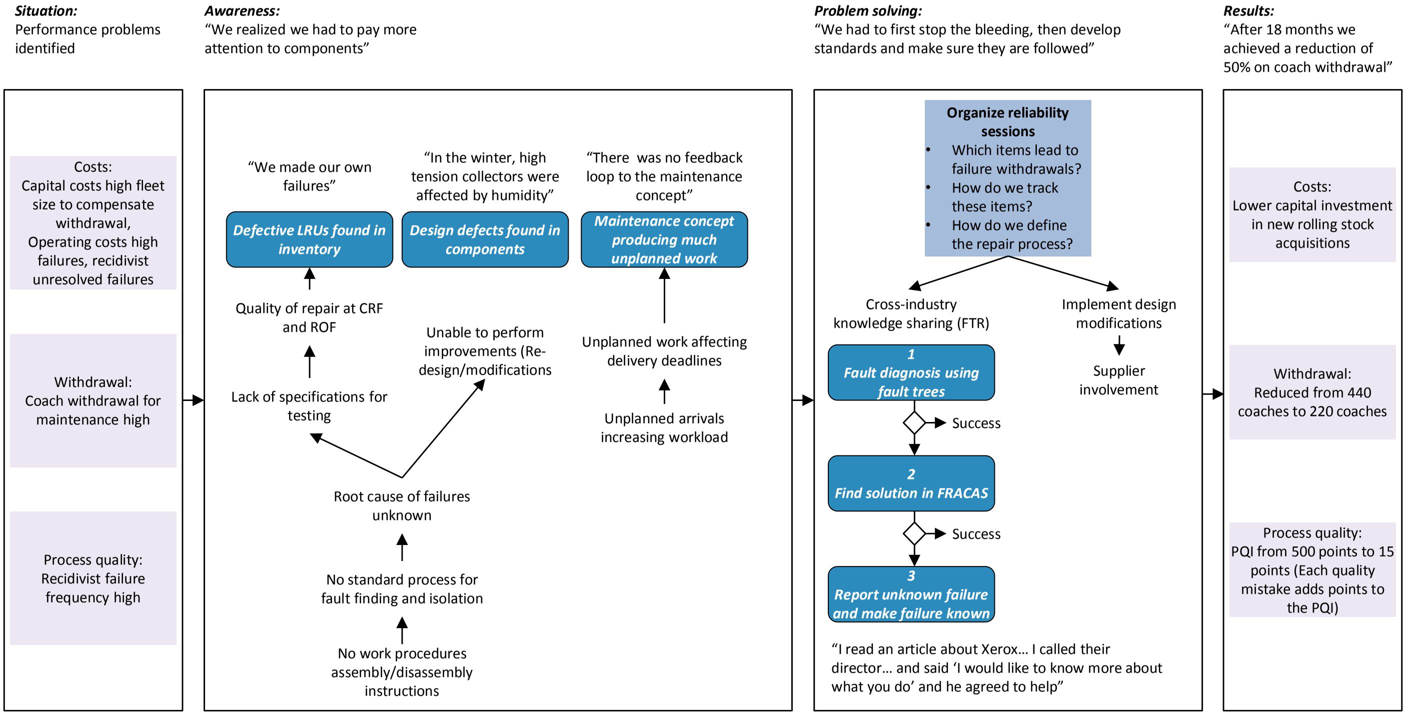


Figure 5.2: *Some key developments of the reliability program. PQI: Performance Quality Index; CRF: Component Repair Facility; ROF: Revision and Overhaul Facility; FTR: First Time Right.*

project leader commented. It consists of three basic steps. Firstly, upon a failure report, a service engineer visits the train with the required fault finding and isolation tools and documentation of the specific train type. The Service engineer assesses the failure and searches a for a solution in the standard documentation. Secondly, if a solution is not readily found in the standard documentation –e.g. fault tree of failure– then the service engineer searches for a solution in the Failure Analysis Reporting and Corrective Action System (FRACAS). This system holds a shared knowledge base of how other service engineers may have dealt with similar problems. Thirdly, if the failure is not found in the system, then it is an unknown failure. The service engineer then calls in a service specialist. The service specialist has the task of making the failure known and of reporting it in the system.

The first time right method has been adopted as standard practice by the organization. However, success appears to have many influencing factors. Changes in technology brought about by modernization projects and new rolling stock acquisitions are increasingly challenging the traditional maintenance concept. Additionally, the allocation and specialization of the workforce has an increasingly important impact. "... that a service engineer sees a failure more often. Routine! A surgeon may only operate if he has practice so how can we make for the [newer train series], a computer on wheels, how can we create routine?". Learning from these more recent challenges has led to other changes. Some of these changes involve training and building of teams of service engineers, to the construction of new technical centers specialized in failure repair and to the deeper understanding of failure behaviour by component management teams.

Finally, an important part of the improvements initially derived from the reliability program is *how do we improve the maintenance concept?* Figure 5.3 shows NedTrain's improvement cycle centered in the plan-do-check-act cycle. Planning is the responsibility of maintenance engineers (ME). Maintenance engineering is a function of asset management responsible for drawing up the maintenance tasks, the maintenance program and the maintenance concept. Implementation and execution of the maintenance concept is the "do", in the lower part of Figure 5.3; this becomes the responsibility of Operations Management. Reliability engineers (RE) have a leading role in the "check" part of the cycle. This role includes measuring performance against contract parameters, analyzing train behavior and drawing-up improvement proposals. Finally, in the "act" part of the cycle, asset management together with operations is responsible for determining improvement actions.

Figure 5.4 shows in more detail the process of developing the maintenance concept. There are five phases within the decision process, namely the (i) inventorying technical maintenance tasks, (ii) task clustering, (iii) forecasting or estimating, (iv) concept evaluation and (v) detail planning. The first three phases are the responsibility of Fleet Management. Task inventorying produces the maintenance management inventory. The KPIs safety, reliability and quality are used in this decision. The clustering decision is dependent on skills, tools/equipment,

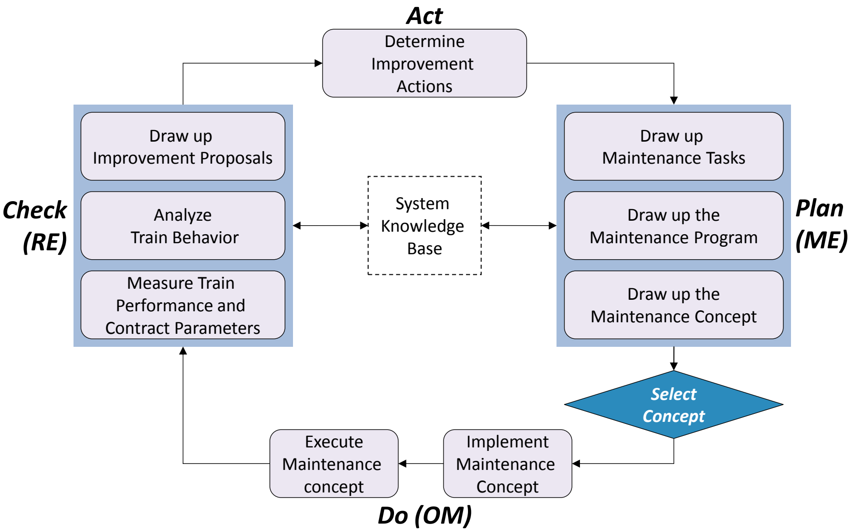


Figure 5.3: *Plan-do-check-act cycle to design/approve a maintenance concept. Reliability Engineering (RE), Maintenance Engineering (ME) and Operations Management (OM) roles.*

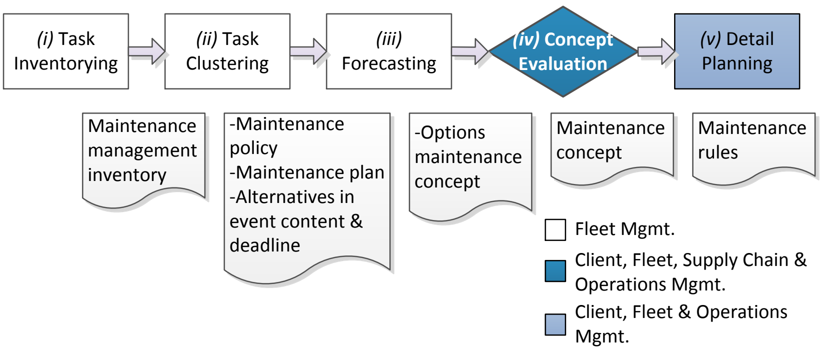


Figure 5.4: *NedTrain's maintenance concept development.*

resulting task frequency and build of the train. The performances of the alternatives are measured in costs per hour, material costs and downtime.

The rolling stock asset management team (from the Dutch name "*materieel team*"), is responsible for the fourth phase: concept evaluation. This requires group decisions and agreements between Operations Management, Supply Chain Management and the client, NS. The team is normally composed of at least six experts: a rolling stock (equipment) manager, a maintenance engineer, a reliability engineer, a configuration manager, an account manager (NS) and a business controller. Therefore, this decision takes into account cross-functional

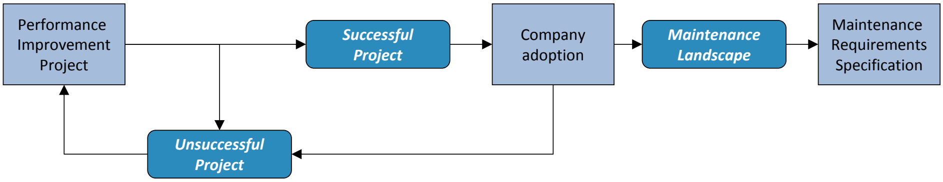


Figure 5.5: *Improvement projects as contributors to maintenance requirements specifications.*

and cross-hierarchical aspects. Concept evaluation has a focus on costs and availability. Upon approval of the improved maintenance concept, detailed operational planning will follow. Maintenance operations has to determine the task allocation approach, the best routing policy (maintenance routing of trains) and the required documentation —work orders and work descriptions, for example.

5.4.2 Strategic decisions

Most strategic decisions at NedTrain are made in the context of improvement projects. These decisions improve the serviceability of the NS fleet. As an example from the reliability program, unscheduled withdrawals have been halved, process quality problems have been resolved to a large degree and costs have decreased for NedTrain. Figure 5.5 shows how the long term adoption of projects with high strategic content influence acquisitions. While those improvement projects that result in long term adoption are improving the performance of the fleet, and of the organization, changes are slowly absorbed in what one expert called the maintenance landscape.

This landscape is the configuration of the technical service system of NedTrain. It is the main input for acquisitions. The technical service system's specification becomes a part of the Maintenance Requirements Specification used in the acquisition requirements documents during a tender. What we see in practice is that maintenance decisions are made after contracting, mainly focused on tactical decisions that help fine tune or optimize the maintenance supply chain.

Figure 5.6 sketches strategic/tactical decisions made after contracting new rolling stock. Firstly, a fundamental decision for NedTrain is the definition of Line Replaceable Unit (LRU) items. LRUs are items that are replaced directly from the technical system upon a maintenance intervention, in order to restore the system's operational capability. Knowledge of what items must be replaced often depends on operational experience of the technical service provider. This decision will be discussed in more detail in Chapter 8.

Once the preliminary list of LRUs is agreed, the initial assortment is defined. Decisions on maintenance policy optimization and level of repair help allocate and install resources for supporting new rolling stock. Next, sparing analysis

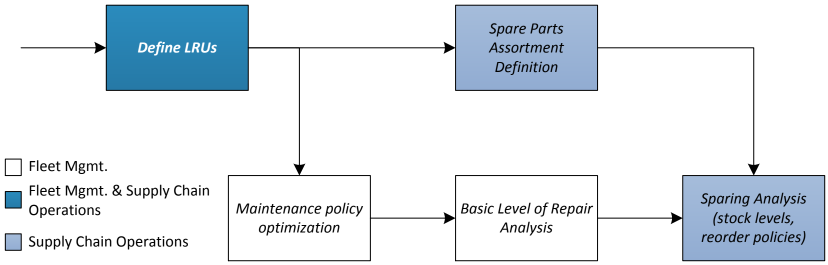


Figure 5.6: *Strategic/tactical decisions made after contracting.*

determines stocking levels, material flows and so on.

5.4.3 Analysis of case findings

We find that in practice, few strategic decisions are included in the acquisition agenda. We showed in Figure 5.6 that strategical/tactical decisions are made after contract. We also found that defining LRUs is a key decision for NedTrain. Support seems to be lacking in the literature. Further research on this topic is presented in Chapter 8.

We see that those interventions that seek improvements across the entire scope of technical services are transferred to a know-how that experts usually call the "NedTrain way", or the maintenance landscape. Because these decisions are assumed to work for new and all trains, the so-called landscape in built into the requirements. This practice is consistent with the recommendations of Jones (2006b). However, it also leads service engineers to a premature reduction of the design space.

From practice we identified a wealth of decisions made by the organization to improve maintenance services. These decisions, made in the context of improvement projects, appear to be cherry picked in an emergent way, to conform to improvements suggested by management, consultants or benchmarks with the industry. We attempt to organize these findings in a meaningful way as shown in our framework of Figure 5.7, below.

5.5 Chapter findings

The review in Section 5.3 results in the organization of the research as shown in Table 5.3. In Section 5.3.1 we find the focus on strategic decisions. The research is too broad to review individual decisions. Therefore, in Section 5.3.2 we review papers that structure decisions in the form of frameworks. These papers refer to managing built and in-use assets, and are not specific to decisions made during the acquisition. Few papers give an overview of all relevant decisions. Most papers discuss strategic maintenance decisions of a single decision area from Table 5.2, e.g., maintenance *policy* selection.

The case results in Sections 5.4.1 and 5.4.2 show decisions about continuous improvement of the maintenance services. Improvement projects at NedTrain combine several functional domains of the organization. Most projects involve decisions combining several hierarchical levels. Our interviews and case data from NedTrain, described in Section 5.4, show little evidence of strategic maintenance decision making during acquisition of rolling stock. This finding will be contrasted with specific acquisition projects in the next chapter, Chapter 6.

Improving serviceability during acquisitions appears to require more support for strategic decisions made early and concurrently, before contract. After contract, LRU decisions appear to play a pivotal role in configuring the technical service system, adapting new rolling stock to existing processes. Supporting this crucial decision after contracting may provide new opportunities for improving serviceability.

5.5.1 Decisions framework for technical service system

Figure 5.7 shows our proposed framework of strategic decisions. Many of the decisions identified at NedTrain are shown. The framework is inspired by strategic decisions found in the prescriptive approach of Logistic Support Analysis. The flow of decisions is intentional. Our impression from the company case is that decisions on the upper part of the figure tend to cascade on decisions of the lower part. At the top, performance measurement and reward decisions create an opportunity for change at all levels of the organization. At the bottom of the figure, production control decisions are generally addressed after other decisions have been made. Inside this block, many of the tactical and operational decisions will follow.

5.6 Conclusion

This chapter has presented research that improves our understanding of the theory and practice of maintenance decisions made during acquisition of rolling stock, a special type of capital asset. Firstly, we have reviewed the literature on maintenance decision making. Secondly, we have presented the third (out of four) part of the NedTrain case. The review resulted in an overview of maintenance decision making (strategic, tactical and operational levels), and then has focused on strategic maintenance decisions. The papers providing frameworks to structure maintenance decisions were organized into decision areas. The case provides insights about strategic maintenance decisions made in practice at NedTrain. The

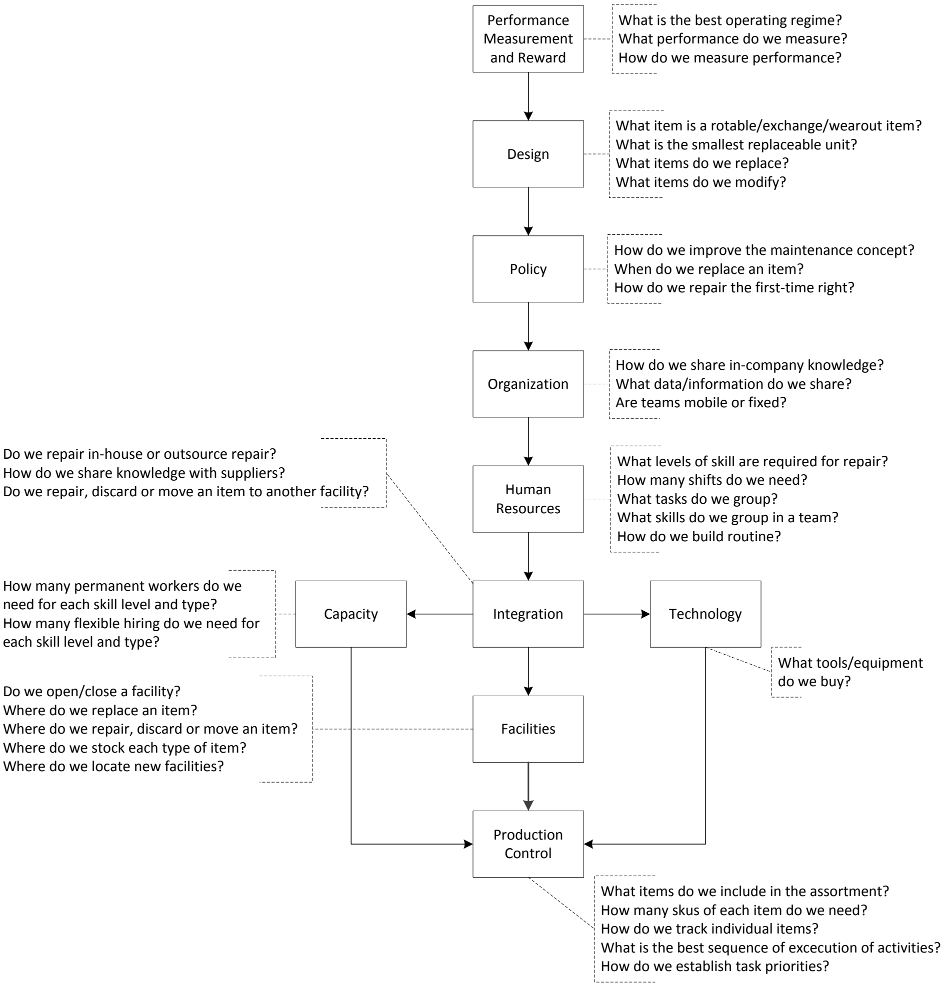


Figure 5.7: *Strategic decisions framework for developing technical service systems.*

main insight is that improvement projects are carried out mostly independent of asset acquisitions.

Strategic maintenance decisions have the highest potential for serviceability improvements. According to the literature, maintenance should be an integral part of systems engineering. The maintenance concept should be developed with the asset, and most maintenance decisions could be made at an early stage of development. In practice, however, strategic maintenance decisions are not made during acquisition of rolling stock by the maintenance organization. This means that the system of NedTrain is not designed concurrently with new rolling stock being acquired. The technical service system system evolves through gradual process improvements.

These insights about a strategic maintenance decision-making will be exploited further in Chapters 7 and 8.

Chapter 6

Acquisition projects perspective: addressing serviceability[1]

This chapter contributes with an overview of acquisition approaches from the literature, and of activities followed in practice within four rolling stock acquisition projects. Also, how these decisions influence serviceability. It is the fourth part (out of four) of the company case, and uses the acquisition project as an embedded unit of analysis. Four acquisition projects are included in the study. Section 6.1 introduces the research problem, followed by the methodology in Section 6.2. After that, the literature review of Section 6.3 shows that many acquisition paradigms exist in the literature. Further, acquisition practices described in many books, military guidelines and standards are prescriptive, and their recommendations tend to be context independent. This implicitly declares the universality of these practices for acquiring serviceable capital assets. Section 6.4 reports the findings of the case study conducted at NedTrain. Results show that decisions are mostly left to the supplier before the tender by explicitly describing the maintenance (landscape) infrastructure and concept. This suggests an adaptation slightly deviating from practices reported in literature. Recent projects show a clear increase in the collaboration with first and second tier suppliers. New assets are merged to the existing fleet through the fleet life cycle plan. Section 6.6 draws conclusions for this part of the case.

[1] Parts of this chapter are adapted from Parada Puig et al. (2015) and Parada Puig et al. (2013a).

6.1 Introduction

Organizations acquiring technical systems and their associated services have many choices to make. For organizations such as NedTrain, each acquisition has the potential to impact the life cycle cost of the entire fleet. It is important to consider services during acquisitions. Serviceability is to be addressed through design, as both maintainability and supportability issues can be resolved. Best practices suggest that a cost effective technical service system results from integrating support considerations during technical system design (Blanchard and Fabrycky, 2011; Blanchard et al., 1995). Verma et al. (1995) suggest that introduction of supportability issues should take place during the requirements definition process and continue through design.

This chapter is the fourth part of the company case, which focuses on specific rolling stock acquisition projects at NedTrain. Chapter 5 showed how maintenance decisions were made by NedTrain to improve the technical services offered to NS. These improvements were shown to result in a technical service system –so called maintenance landscape– that is fully disclosed in the requirements documents of new acquisition projects. However, the description of maintenance decisions only clarifies one side of the design decisions made during acquisitions: those involving the technical service system. This chapter gives a complementary view by introducing the technical system decisions made to improve serviceability during acquisitions.

This chapter contributes by showing how maintenance decisions and the acquisition projects of the recent past have been decoupled. It also contributes by describing how acquisition practices have shifted from a transaction focus to a relationship focus, where partnerships are key to success. It provides details about the evolution of acquisition practices that have increasingly involved suppliers as a means of transferring and retaining valuable knowledge.

6.2 Methodology

This chapter continues to contribute to answering the research subquestion RQ2b: How is serviceability addressed in acquisition projects in practice? As was the case in the previous chapter, two additional subquestions are asked, aiming at exploring, as well as describing theory and practice: What decisions are made to improve serviceability during acquisitions? and How do these decisions influence serviceability?

We use an identical approach as Chapters 3 to 5, shown in Figure 1.14. The research methodology is also similar to those chapters (refer to Section 3.2).

Table 6.1: *Characteristics of UOA4: the acquisition projects.*

Project	Name	Built	Park Size (coaches)
AP1	VIRM-4	2008-2009	205
AP2	SLT	2009-2012	648
AP3	Hi-Speed	2009-2011	152
AP4	SNG	2016-2017	404

6.2.1 Case selection

Figure 6.1 shows the UOA of this chapter, UOA4, within the broader company case. Table 6.1 presents four acquisition projects (AP1-AP4) that constitute the unit of analysis in this chapter. The selection of these projects ensures a consistent time-frame with the improvement projects in Chapter 5. Additionally, these more recent acquisitions have presented easier access to decision makers involved, as well as readily available documentation.

6.2.2 Data collection

This part of the company case relies on interviews and company documents. Semi-structured interviews were conducted with the four managers of each of the four rolling stock series. Additionally, key informants involved in the decision making process of these projects were interviewed on several occasions. Interviews were recorded and later transcribed for analysis. Additionally, notes were taken directly after each interview. This helped the researcher clarify the themes and main findings of the interview.

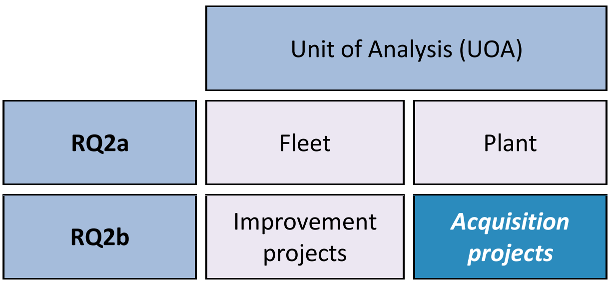


Figure 6.1: *Unit of analysis (UOA) of Chapter 6 within the broader case context.*

6.3 Literature review

Acquisition processes are agreement processes that provide the means to conduct business with a supplier: of products that are supplied for use as an operational system, of services in support of operational activities, or of elements of a system being developed by a project (ISO/IEC, 2008). An acquisition is initiated when the organization *(i)* detects a need that cannot be satisfied in-house without assistance, and *(ii)* can commit resources to satisfy this need. However, acquisition processes can also result when it is economically attractive and suppliers are able to meet specific needs of the organization in a reduced amount of time (INCOSE, 2010).

The primary goal of an acquisitions project is to generate new opportunities and value to an organization. A new asset can create opportunities by opening new markets, improving current processes and providing better means of production –for example by reducing the environmental impact of operations. Acquiring a new asset will add value to the organization if it is purchased with the aim of cost-effectiveness. A cost effective asset is the one that provides the best possible performance at an affordable life cycle cost (Jones, 2006b; Stapelberg, 2009).

Acquisition projects can be clearly differentiated in the government, defence and commercial industry. In government, procurement is the word often used to refer to acquisition of goods and services. Government acquisition projects have the longest history (Thai, 2001). Documented contributions to the acquisitions projects in the defence sector appeared after WWII. With the pressure of decreasing budget, it became evident that the cost of support of military materiel needed more attention. Finally, commercial industry has been a major contributor to the systematic development of acquisition know-how. Industry contribution is far more documented, and the business-to-business transactions are studied in industrial marketing literature.

6.3.1 Types of contracts

Roy and Cheruvu (2009) provide a typology of types of contracts used in business to business environments. Figure 6.2 displays the so called Industrial Product-Service System (IPS^2) contracts. IPS^2, a combination of product and services, can be purchased through incentive contract, cost-reimbursement contracts, fixed-price contracts, spiral contracts, time-and-materials, labor-hour, and letter contracts or spiral contracts. Generally, any of these acquisition contracting schemes can be positioned in a continuum between material contracts and performance contracts. Material contracts are designed to purchase the physical system. In performance-type contracts the client buys the system's function, not the physical system itself. Therefore, the contracting scheme is based on some agreed service level.

At NS, material contracts are still the dominant approach to acquisitions, and the service component is usually entrusted to the supply of spare parts and/or training. Material contracts can be distinguished by the amount of design activity

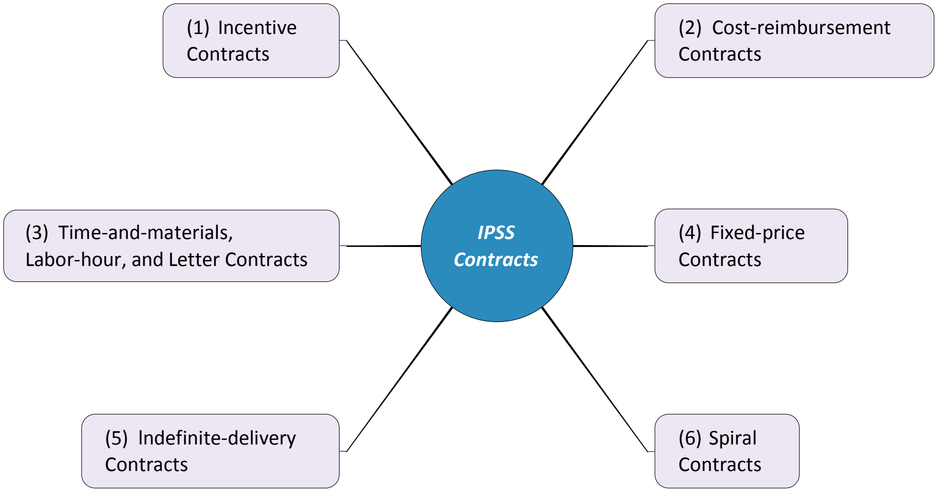


Figure 6.2: *Types of contracts used in IPS² (Adapted from Roy and Cheruvu, 2009).*

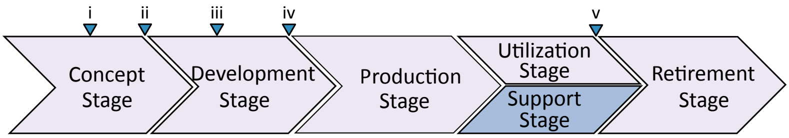


Figure 6.3: *Generic Life Cycle (ISO/IEC 15288:2008) and types of acquisitions (Adapted from Parada Puig et al., 2011).*

that must be realized to complete the total system. In these acquisition projects the client can decide to (i) upgrade or modernize an existing system, (ii) purchase a commercial system —Comercial Off-The-Shelf (COTS), (iii) modify an off the shelf system, (iv) acquire a Non-Developmental Item (NDI) or opt for (v) full scale design and development (Department of Defense, 1997a; Jones, 2006b). This traditional categories for acquisition projects have their roots in the technical system life cycle, as exemplified in the life cycle view of Figure 6.3.

Upgrading or modernizing an existing asset is the core business of many organizations in the maintenance, repair and overhaul (MRO) industry. Equipment or plant turnaround management projects are executed to extend the life of equipment through major overhauls that can improve their performance, incorporate new technology or add new functions to the old asset platform (Ben-Daya et al., 2009).

The next option, procurement of a commercial asset —Commercial-Off-The-Shelf (COTS)— has been a mayor goal of many procuring agencies (Verma, 1997). A COTS system has normally been developed for the requirements of other organizations, and may or may not fulfil the entirety of the requirements of the acquisition programme. An alternative is to modify such a commercial item, and adapt it to the particular operating/infrastructure conditions of the client. The third option, modifying a COTS system involves some extent of design and engineering, and therefore the acquisition program will require more effort.

The fourth option for material contracts is acquiring non-developmental items. Such contracts generally involve a larger effort in systems integration. Contracting is based on suppliers for components which are built by Original Equipment Manufacturer (OEM). These components will provide the necessary functions that have to be integrated to the overall system.

The fifth and last option is full scale design and development. This is the type of procurement approach that is traditionally followed when none of the other alternatives is found to be viable. It also applies when the specific needs of the programme are not fulfilled by other alternatives because no commercial item exists or a NDI solution is found infeasible.

6.3.2 The dynamic railways market

Today, the market for passenger service trains is changing rapidly. Asset acquisitions and the provision of through life engineering services are high on the agenda. The main drivers for change are globalization, deregulation of markets, behavior of the organization (core competence problem), and the evolution of information technologies (Cova and Salle, 2007).

Globalization is a force driving railway markets. Not long ago, manufacturers had market niches within their own domestic railway companies. Today, they have become global players, and are overflowing their domestic markets, especially in Asia and Europe. Increasing pressure to deregulate markets worldwide promises faster changes to come. But this is not new in this dynamic market.

The market for passenger trains has already seen its share of deregulation. In 1991, the European Council produced the Directive 91/440, which emphasized that European countries give domestic support for liberalizing the railways. The directive was also seen as an opportunity –within countries like the UK, The Netherlands and Germany– to create more support for European policies (Knill and Lehmkuhl, 2000). This marked the beginning of a long process of change within the whole industry in Europe.

Traditionally, railways operators specified the technical and design features of trains in order to suit their local market. Before 1991, European railway operators were state-owned. Acquisition projects traditionally consisted of a strong engineering department within the domestic railway companies (Alderman et al., 2005; Ivory et al., 2001, 2003). Manufacturing was outsourced, and the system was integrated in-house.

The role of the national railways as systems integrators is depicted in Figure 6.4(a). One of the problems that arise from this way of doing business, is that manufacturers have minimal customer feedback. Little or no motivation is given for rolling stock improvement towards technical services (Durand, 2001).

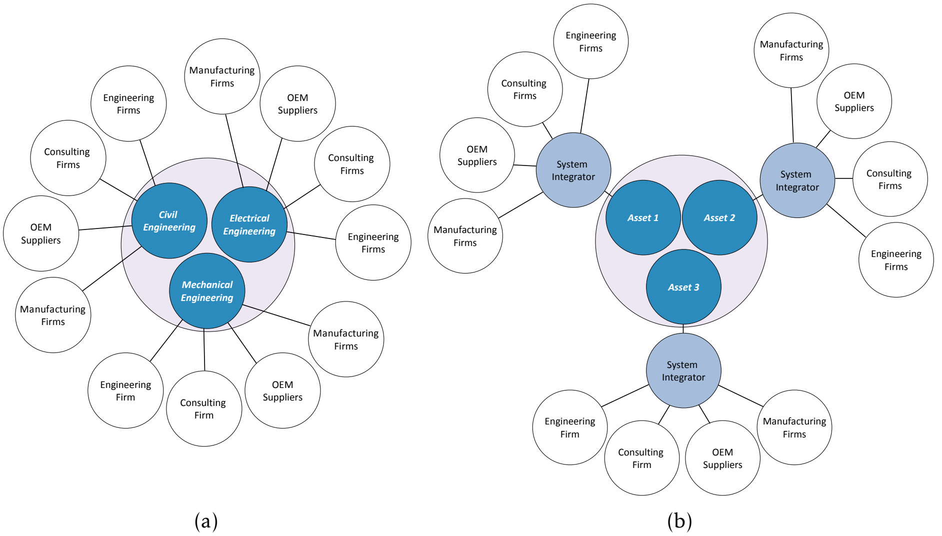


Figure 6.4: *Evolution of the role of large utilities (now the client) in the acquisitions process* (a) *Client as system integrator, and* (b) *client as asset manager (Adapted from Parada Puig et al., 2012b).*

After 1991, the traditional passenger train development projects gave way to new forms of acquisitions. Operators focused on performance, and assumed the new role of asset manager. While domestic railways moved away from their technical background to focus on transportation and service (core competence), manufacturers began to lead in train design. As second tier suppliers became evermore specialized, manufacturers evolved into the role of system integrators. Commercial components now provide the functions for the rolling stock systems, as shown in Figure 6.4(b).

Competition in this industry reflects the modular marketplace described by Baldwin and Clark (1997, p. 88) “A company can compete as an architect, creating the visible information, or design rules, for a product made up of modules. Or it can compete as a designer of modules that conform to the architecture, interfaces, and test protocols of others”.

6.4 Acquisition projects at NedTrain

Since its founding in 1992, NedTrain has been involved in the acquisition projects of NS. The degree of involvement has changed over time. This section describes the way in which NedTrain plans the maintenance for new rolling stock in the specific context of the acquisition projects, UOA4. Table 6.2 contrasts the different

Table 6.2: *Acquisition project timelines. †According to project plan.*

Project platform	Acquisition Project	Duration (months)
VIRM	AP1	32
SLT	AP2	111
Hi-Speed	AP3	120
SNG	AP4†	64

projects according to their total duration. This section shows how NedTrain fits new rolling stock to their existing maintenance system.

6.4.1 Acquisition programs and maintenance decisions

Acquisition of rolling stock and service design decisions are recognized by the organization as decisions having strong strategic impact. However, these decisions are not made concurrently, as explained in Chapter 5, Section 5.5. Table 6.3 positions strategic decisions made at NedTrain in relation to the four most recent acquisition processes included in our case data. The reliability program and project K_3 are not included in the table, but to the best of our knowledge they were both unrelated to any particular acquisition project. Chapter 5 gives more details about these decisions. The table shows that two thirds of those strategic decisions made during an acquisition program are decisions dealing with capacity, facilities, and technology of the technical service system. Not surprisingly, they are decisions that intend to make the new technical system compatible with the technical service system. To the best of our knowledge, none of the decisions listed were concurrent to technical system design, and they were also not considered before contracting.

Serviceability aspects have been developed in projects where there are varying degrees of involvement of the service organization. Project AP1 is marked by the evolving design of previously existing train series. For this project, the lead time from initial proposal to the first trainsets in operational service was less than 18 months. We discuss the evolution of the rolling stock platform of AP1 in Section 6.4.3 below. For AP1 the first important maintenance decision in the project was the selection of maintenance facilities amongst those available in the NedTrain repair network. The design stage covered most of the planning items involving long term maintenance decisions. These focused on identifying long lead time items, producing the tool and equipment delivery plan and adopting the maintenance concept of NedTrain by optimizing the maintenance policies.

Project AP2 was signed by the decision not to involve NedTrain at early stages in the project. As a result, little or no support information was given in the initial phases of the project. Only information relevant to system performance was given in these descriptions. Failure to incorporate this information left out a key

Table 6.3: *Three acquisition projects and past decisions at NedTrain. GOIDS: 'No Withdrawals During Rush Hour'. RBM: Risk Based Maintenance. CMMS: Computerized Maintenance Management System. RBM: Risk-Based Maintenance.*

Decision areas	Acquisition Project				Impr.	Impr. Projects
	AP1	AP2	AP3	AP4	Dec.	
(1) Capacity	-	++	-	-	++	Functional Expansion of Leidschendam
(2) Facilities	-	-	++	-	++	Watergraafsmeer maintenance facility
	-	++	-	-	++	New Technical Centers
	++	++	-	-	++	GOIDS
(3) Technology .	-	-	++	-	++	CMMS
(4) Integration .	-	-	-	-	++	Refurbishment projects
(5) Organization	-	-	-	-	++	Material teams
(6) Policy	-	-	-	-	++	GOIDS, RBM
(7) Human Res.	-	++	-	-	++	Fault repair teams, specialization
(8) Design	++	-	-	-	++	Refurbishment projects
(9) Prod. Ctrl. ..	-	-	-	-	++	GOIDS, CMMS
(10) Performance	-	-	-	++	++	RBM

- 'no relation between decision and acquisition project'
++ 'acquisition project influenced the decision'

item which later delayed the procurement process. The tender was made for suppliers that would not comply with the technical service system of NedTrain, e.g. infrastructure, strategy and so on. Several decisions made late in the project had a major impact on the schedule. See Mulder et al. (2013) for an example of design decisions made to adapt the replacement of compressors to the NedTrain facilities.

Project AP3 was in the words of one informant "...only on paper, so not really focused on content because each deviation had a risk over planning and costs". This project was heavily influenced by a business approach that established a mindset of "we have a contract, and you shall comply, or else: penalty" according to an expert, "...and that doesn't work!", continued. The lesson is that "...you cannot put absolutely 100% of what you want (in the requirements)... the supplier does not always know how you will commission and operate the system".

Project AP4, the most recent project has gathered a considerable amount of knowledge from recent acquisition experiences. According to the manager, success can be described as the smooth introduction of the train series into the field: "I think that a program is successful if we arrive with the supplier to the train that we had specified, and that we, on our side, have prepared both the operator and the maintenance organization. By prepared I mean on-time and competent for the new train". The main lessons learned from AP2 and AP3 are incorporated in AP4. This gave the acquisition team more room to focus on the suppliers. Some key elements in this new approach are discussed in the next section below.

Table 6.4: *Role of the service provider in the project.*

Project	Requirements/RFP/BAFO
AP1	Engineering
AP2	NedTrain not involved
AP3	Risk focus
AP4	Close cooperation

6.4.2 New approach to planning maintenance during acquisition projects

The most recent approach to acquisition at the Netherlands Railways (NS) involves NedTrain as collaborator during acquisition. With knowledge collected from past projects, the maintainer is now seen as an important stakeholder in the life cycle of rolling stock. NedTrain now supports decision making during the entire acquisition process, starting with maintenance requirements definition. To fit the new trains to the maintenance services of NedTrain, the decision process follows a so-called *maintenance assessment*. We find that these decisions intend to fit new rolling stock to an existing maintenance infrastructure.

There are multiple stakeholders involved in active collaboration during the life cycle of rolling stock. Within NedTrain, three departments have a leading role in decision making. Fleet Services is accountable for (i) equipment performance monitoring, (ii) management functions —maintenance, configuration, RAMS/LCC management—, (iii) maintenance development and (iv) engineering —maintenance, reliability and systems engineering—. Operations Management is in charge of the production workshops. Supply Chain Management handles acquisition and logistics of the maintenance supply chain, i.e. supply chain operations.

NedTrain has knowledge that can help NS to select the best candidate from a maintenance point of view. For this reason, NedTrain collaborates with suppliers and the NS during acquisition by performing maintenance assessment. Figure 6.5 shows the place of maintenance assessment in acquisition projects of NS. We focus on the decisions made during maintenance assessment, as they are most influential in making a good fit of new assets to NedTrain.

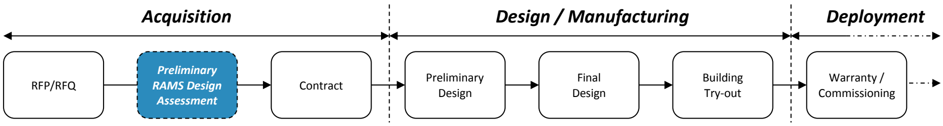


Figure 6.5: *Maintenance assessment in acquisition projects (Adapted from Parada Puig et al., 2015). RFP/RFQ: Request For Proposals/Request For Quotations. RAMS: Reliability, Availability Maintainability and Supportability.*

Suppliers receive a detailed description of NedTrain's maintenance strategy. This is a part of the maintenance requirements definitions. These requirements are made during the tender, and they are included in a Request For Proposals/Request For Quotations (RFP/RFQ). RFP/RFQ is an opportunity for the supplier to provide an offering that fits the maintenance concept of NedTrain. NedTrain then gives a preliminary design assessment focused on asset and subsystem level. For NedTrain, this would allow decision making for the design of the maintenance services before contract. For NS this would give a more realistic RAMS/LCC commitment, both from the suppliers and the maintainer of the asset.

The decisions made during maintenance assessment can be described by: *given the (forecasted) demand associated with the new train series, allocate resources —of the existing maintenance infrastructure— to support the new trains*. The method of analysis consists of decisions about maintenance manpower —the *who*—, content —the *what*—, interval —the *when*—, maintenance level —the *where*—-, RAMS/LCC and quality —the *why*— and the procedures —the *how*. It is desirable for NedTrain to adapt the original manufacturer's maintenance program with the goal of obtaining a smooth demand pattern for the resources of its workshops.

The initial *asset life cycle plan* is the key result from the decision making process during acquisitions. It contains, for example, information on asset configuration, the maintenance program, technical KPIs, obsolescence management and technology refreshment plans. Van Dongen (2015) offers more detail. After (commissioning) fielding the new train series, the individual life cycle plan is coupled to the life cycle plan of the entire fleet. RAMS/LCC are the most important performance criteria for maintenance assessment. However, RAMS/LCC performance data has a level of aggregation that makes operational costs difficult to estimate before contracting. Therefore, many of the strategic decisions of designing the maintenance services are being shifted to the initial fielding of the train, when the contract is already signed and there is less room for change. Table 6.5 shows the decision areas covered in the RAMS/LCC.

6.4.3 Timing of new rolling stock introduction

The size of the fleet has grown considerably since the 90s and newer train series have a larger installed base than those of two decades ago. This is thought

Table 6.5: *The maintenance landscape in the RAMS/LCC plan of NedTrain.*

Decision area	Description
Facilities	Network of repair sites, equipment and tools
Organization	Levels of maintenance and installation of resources
Technology	Information systems
Human Resources	Disciplines, competences and training

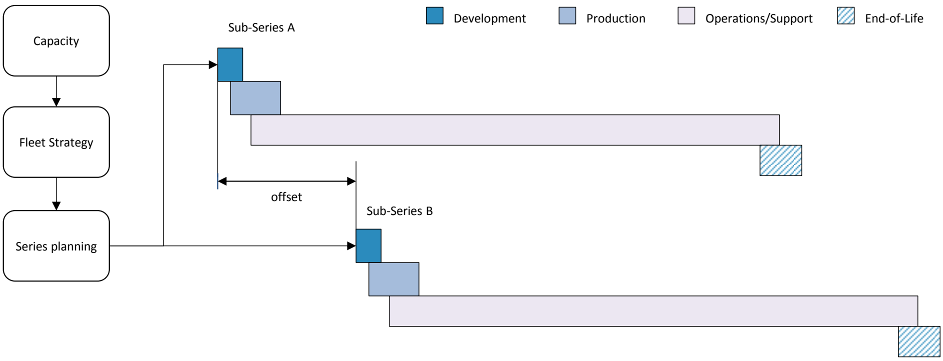


Figure 6.6: *Life cycle offsets (Adapted from Boas et al., 2013).*

by experts to partly mitigate some of the negative effects of divergence of the fleet. However, due to the complexities inherent in manufacturing rolling stock, production lasts for several years. Timing of new rolling stock introduction is sequential, and therefore the life cycle of rolling stock platforms are offset, as shown in Figure 6.6. Life cycle offsets mean that, over time, maintenance organizations deal with increasing variety of equipment. This represents a fundamental cause of a commonality decrease while the development of rolling stock platforms progresses over time (see, e.g., Boas et al., 2013).

Significant technical differences in the rail infra prevent COTS acquisitions. The main constraints are platform dimensions, power grid specs and safety system specs. The acquisition process has shifted from design projects to non-developmental items (NDI). In addition to offsets, each new rolling stock is introduced and the life cycle of new platforms is merged with that of the existing fleet, as shown in Figure 6.7. Planning is made considering the stage in the life cycle of each of the train series, but this also means that strategic decisions cannot be adopted for the entire fleet. This makes (some) improvement projects unique to (some) specific series, and increases the difficulty in adoption of programs across rolling stock platforms.

Introduction of larger series is supported as a means to increase commonality.

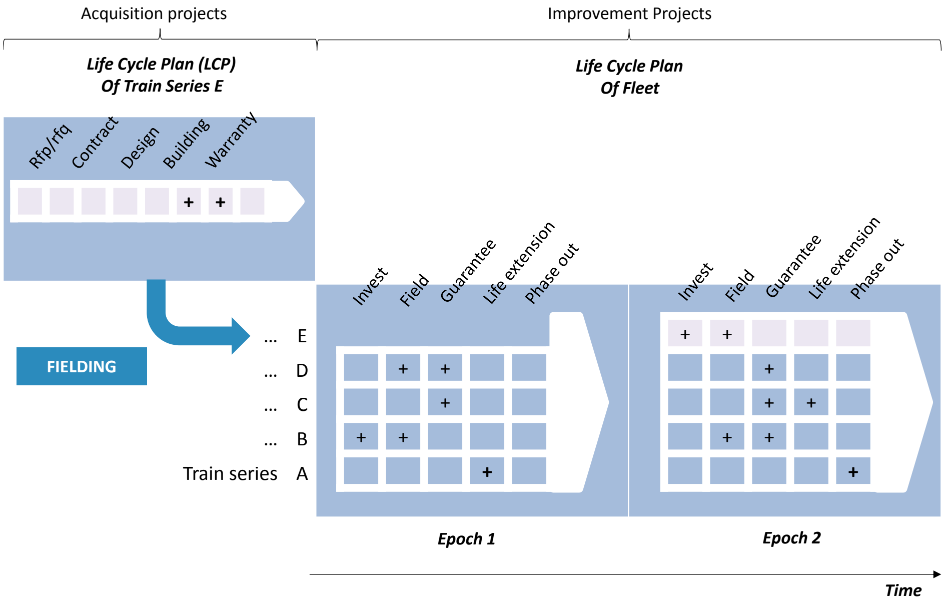


Figure 6.7: *The fleet life cycle plan.*

However, commonality is not actively targeted during acquisition projects. There is the general feeling that even if commonality was actively targeted it would be difficult to attain with the way contracting is made today. For example, one informant suggested:

> "But on the basis what is being done in the [current] project ... we want our requirements on a functional level. So we are not going to tell the manufacturer: you should use that compressor, that seat, that module... the only thing we want is a train that performs its job with that level of reliability, that level of availability... In specifying it like that, the chance of commonality is pretty low, because that manufacturer will go into the market and say ok: who can supply me with an airco, a climate control system, or a traction system, or a low voltage system, or a compressor that will perform this task, at the lowest price levels. That will possibly be a different component than we already have. So where commonality may help you in decreasing lead time and increasing reliability and quality of the performance, the chance of writing it down in the specifications and actually getting it done is very low".

In a similar example regarding acquisition projects, another informant suggested that

> "... with leasing companies implementing a new way of acquisitions,

> technical details are not as important as the purchasing price. We can expect commonality at the component level to drop if we are no longer designing our trains, but purchasing them every time from a different manufacturer. The pantographs in the [train X], for example, are different than the ones that had been traditionally used. That will no longer be a common component in the system".

It becomes clear from the feedback provided by experts that collaboration is increasingly important. "Collaborating, better product", as he himself synthesized his view. "Success is to bring your supplier into what your organization and your processes are, and then not only the running of the train but also how we will maintain it in the initial stage, already before there is a contract. Let them see, this is us, we want (that) performance, because that is what we agreed with the government. And by jointly with the supplier, also during design, steering...".

The general vision of the experts is similar. "smooth introduction" means that "we are busy with the train supplier to make the train that we required in the contract, and that we, on our side, prepare the transport organization and the maintenance organization, on-time and competent for the new train".

6.4.4 Analysis of case findings

Table 6.3 positioned several strategic decisions of NedTrain, showing that these decisions are mostly independent of acquisition projects. Section 6.4.2 show a process that intends to fit new assets to existing services. Decisions in Section 6.4.2 focus mainly on optimizing maintenance before fielding, not before contracting, as was also shown in Section 5.4.2. Maintenance assessment is the principal role of NedTrain before contracting. This analysis and evaluation of proposals has the goal of providing an initial RAMS/LCC assessment on the main subsystems of the train.

In Section 6.4.3 we find that characteristics of design have a minimal role both in the requirements and in the contract specifications during acquisitions. Instead, we find that the organization is focused on building relationships with suppliers and sub-suppliers. Making sure that communication channels stay open throughout the project helps NedTrain manage some of the uncertainties arising in the projects.

6.5 Chapter findings

The approach of NedTrain to maintenance assessment has elements of the framework of Logistics Support Analysis (see, e.g., Blanchard, 2004; Hastings, 2010; Jones, 2006b). Such analysis may influence the choice of equipment as well as the nature and structure of supporting services (Hastings, 2010). Jones (2006b) provides rules for the selection of the comparison system. The new system and the comparison system must have similar performance functions, operational environment and support environment. This can hardly be met if any changes are to be implemented, either in the new asset itself or on the way it is maintained compared to older systems. Because of the importance of the early design decisions in this functional phase, the maintenance organization has an important role in decision making.

However, most of the effort of decision making is currently invested in the second stage of decisions involving detailed design. During the phase of functional design, decision makers are steered into a premature reduction of the design space. The attempt seems to be oriented to compensate by collaboration and supplier involvement.

6.6 Conclusion

This chapter has provided insights about the practices that help improve serviceability of rolling stock from within the acquisition projects. The chapter contributes with an overview of acquisition approaches from the literature, and of activities from within four projects in practice. Also, it provides an overview and connection with technical system aspects, highlighting the importance of addressing them during acquisitions. The main insight is that decisions are mostly left to the supplier before the tender by explicitly describing the maintenance (landscape) infrastructure and concept. New assets are merged to fleet by means of an explicit fleet life cycle plan. We find a clear trend to collaboration with suppliers, and subsuppliers moving up the stream are becoming integrated since before the contract.

The unique circumstances of the research allowed access to both retrospective and real-time data, from old and current projects. In practice, logistic support design decisions are delegated to the original equipment manufacturer. The maintenance system of NedTrain is not designed concurrently with new rolling stock being acquired: the supplier optimizes rolling stock locally; the rolling stock maintenance company optimizes services locally. New rolling stock is fitted to the existing maintenance system, and the maintenance system is gradually improved.

These insights about acquisition decisions will be exploited further in Chapters 7 and 8.

Chapter 7

A Serious gaming tool[1]

This chapter contributes by developing The Logistic Support Game, a serious gaming tool. It is the intended support developed for the early stages of an acquisition project (before contracting). Section 7.1 introduces the chapter and the methodology follows in Section 7.2. Next, Section 7.3 shows the relevant literature. After that, Section 7.4 summarizes the problem description for the support. From the problem description, the chapter shows a serious gaming tool developed as a service design experiment. Sections 7.5 and 7.6 present the development process, from solution incubation to solution refinement, respectively. Four game sessions are used to test the tool, produce the necessary improvements and evaluate its benefits and weaknesses. As it turns out, the game has several insightful applications. Validity is further tested in one case implementation of the intended support. This case is an application of the game to the early stage of acquisitions in practice, and is discussed in Section 7.7. The game is shown to provide a collaborative decision making environment, insights and awareness about the relationships between decisions.

7.1 Introduction

Chapters 3 and 4 have shown that design attributes of a technical system, and of its technical service system, have profound impacts on serviceability. Decisions made to modify those design attributes were further described in Chapters 5 and 6. Each chapter discussed how decisions about improvements to serviceability are made by either changing the technical services (Chapter 5) or by influencing design of the technical system within the acquisition projects (Chapter 6). This chapter goes further, trying to find ways to support experts in exploring the

[1] Research in this chapter was presented in Parada Puig et al. (2014)

design space of technical services during acquisitions. We do so by helping make decisions about both the technical services and the technical system.

Making decisions at early stages of the design process is advised by many researchers. Early design decisions are known to have significant impacts on manufacturing and logistical activities (Dowlatshahi, 1996). Markeset and Kumar (2004, p. 568) conclude that "that it is essential to integrate RAMS issues early into design work processes to arrive at the best possible cost effective product support strategy for industrial products". It has been mentioned in the research that integrating development processes of products and their required services poses an innovative research area (Luczak et al., 2007). Methods are needed for incorporating maintenance considerations early in the product design process (Hernandez et al., 2002).

Service development is especially important during acquisition of new capital assets. During acquisition, 85% of the decisions that impact the life cycle cost of assets will be made before the contract is signed (Jones, 2006b). Many of them are strategic maintenance decisions, and making these decisions is challenging. Strategic maintenance decisions are knowledge intensive; they involve many stakeholders and their effects on operational performance are only visible in the long term. Decision support can help improve the decision making process to be more effective (do the right things) and efficient (do things right), helping to make better decisions. A suitable way to support service development is needed.

This chapter explores the application of serious games as a tool to support decisions made within the acquisition process. It contributes with a novel approach to service development based on existing design methodology. Design decisions that tend to make most impact to serviceability improvements require collaboration. To support the acquisition of serviceable assets we propose that experts explore the design space via gaming. Using serious games is suggested here as a means to sustain collaboration. This chapter discusses how using serious gaming lowers the barriers to communication. Serious games are also shown to raise awareness and provide insights about the relevant design decisions to each stakeholder in the process.

7.2 Methodology

This chapter is the first part of the Prescriptive Study (PS) and Descriptive Study II (DS-II) of the thesis. It answers research subquestion RQ3a: What is a suitable way to support the early stages of an acquisition project (before contracting)? The aim of this chapter is exploring decision support alternatives, and thereby finding one that is suitable for the problem at hand: supporting decision making during the acquisition process that may help increase the serviceability of newly acquired assets. To achieve this aim, we use a research methodology that is inspired by that of Holmström et al. (2009). Therefore, this research design is based on the Design Science approach, as shown above in Figure 1.16(a).

This research uses a prescriptive problem solving approach. Decision support is required that can help the maintenance organization analyse both the train, and the required services, to make decisions and observe outcomes. Such decisions made at an early stage in acquisitions can raise awareness and focus efforts on the maintenance of new rolling stock. We conduct our research as shown in Chapter 1. In the first phase we incubate a solution. We accomplish this by determining which solutions exist in the literature for concept design of a technical system and its technical service system (product/service). Next, we determine which of those can be useful for service development at an early (concept) stage. We research those tools that are employed within the existing methods. Based on existing methods and tools we select a serious gaming approach, and develop a tool that fits the needs of NedTrain.

In the second phase of the process we refine the solution. This is accomplished by evolving the initial serious gaming tool. Four test sessions and design reviews are used while we improve the prototype game. The test sessions gather feedback from research colleagues and company experts. Each test session is recorded by video. Additional feedback is received using the questionnaire shown in Appendix B.5. The results from each session were translated into design changes that impacted game dynamics or the prototype embodiment. Most changes were implemented into a new game prototype before the following session.

In the third and fourth phases of the process we conduct a case session within one high profile acquisition project. The main goal of this case session is to test the suitability of the serious gaming approach within a real life scenario. The case presented a unique opportunity to test supporting decisions made during early stages of the acquisition of new rolling stock at NedTrain. The specific aim of the session was agreed with the main project stakeholders and will be discussed further in Section 7.7 below. To understand the suitability of the tool, validity is checked using the criteria of table 7.1. The four initial test sessions also gathered a rich source of complimentary data that helped to explain and understand the validity and suitability of the serious gaming approach, and The Logistic Support Game tool.

The main issue for validation of an instrument lies in the achievement of the goals. Namely, does it measure what it is intended to measure? Does it fulfill its intended purpose? The criteria regarded as best evidence for validation are adopted from Graafland et al. (2012); Peters et al. (1998). Tool validation is addressed as follows. During each session the participants were asked for feedback about the decisions made during the game. Typical questions were *(i)* why did you make (this/that) decision? *(ii)* what aspects did you consider? and *(iii)* what did you expect as outcome to this decision? Data analysis is performed in a similar way to previous empirical chapters. The videos are transcribed and coded using the same approach of Chapter 3 to 6.

Table 7.1: *Validity types used for evaluation of the game sessions (Adapted from Graafland et al., 2012; Peters et al., 1998).*

Validity	Description	Criteria
Content	Game content adequately covers the decisions made during early stage acquisitions.	Uniform and positive evaluation of game content and associated decisions by experts and colleagues.
Face	Degree of resemblance between game play and reality, as assessed by participants.	Uniform and positive evaluation of the game as a valuable support for exploring service concepts.
Construct	Inherent difference in outcome amongst sessions of experts and non-experts.	Outcome differences between participants of different level of skill.
Concurrent	Concordance of session results using the game and the results of the traditional approach used in the project.	Expert qualitative assessment of the differences between the existing approach and the case session results.
Predictive	The degree of concordance of a decision's outcome and the expected outcomes in reality.	Experts assessment of the game outcomes in contrast to the expected outcomes of a real life situation.

7.3 State of the art review

This section summarizes the current state of the art for supporting early design decisions of technical systems and their required services. Chapter 4 gave some interesting insights about several aspects of service design research. Firstly, despite the fact that services represent important value to developed economies, the research on service development is limited (Luczak et al., 2007).

The literature shows that service development has proven to be difficult. We know relatively little about designing services, especially about the design and delivery of complex engineered services (Neely, 2009). Services are generally under-designed and inefficiently developed, especially if compared to physical products: skills, tools and methodologies are lacking (Rapaccini et al., 2013). The research agenda on developing service design goes back more than a decade. Menor et al. (2002) propose in their research agenda that New Service Development (NSD) should be investigated to understand how existing tools are applicable or can be modifies to be applicable. (Morelli, 2002). Still today the research seems fragmented into different areas. An important area of research is devoted to service optimization (e.g., Kuo and Wang, 2012), and approach the problem with the algorithmic paradigm of decision-based design (Hazelrigg, 1996). The product service system and industrial product service system literature have also provided several initiatives. Cavalieri and Pezzotta (2012) review the state of the art in product-service systems engineering, and find that only service engineering (see, e.g., Bullinger et al., 2003) approach service design in a systematic way. The methods found in the research for concept development and evaluation are reproduced in Table 7.2. Only "the theory of inventive problem solving" (TRIZ) was identified in the research dealing with concept development or exploration, our core problem.

TRIZ was a method originally developed for inventive problem solving (Altshuller, 1984), but it is not oriented to collaboration. Other tools such as serious games have been successfully used in service development with health care applications (Garde, 2013). Serious games are useful tools for learning (Graafland et al., 2012), to study decision making (Axsäter, 2006; Mintzberg et al., 1976; Narayanan et al., 2009) and designing (Brandt, 2006; Finger and Dixon, 1989; Garde, 2013; Thalen, 2013). Games can be used as a form of participatory design (Brandt, 2006). Artifacts such as card games enhance communication and collaboration between stakeholders (Thalen, 2013).

Our research into the state of the art of serious gaming applications is summarized in Table 7.3. The table shows that several companies in the Netherlands are involved in serious games that target decisions in maintenance and asset management. The state of the art on gaming applied to maintenance decisions in industry suggests the usefulness of games for insight and awareness of industrial practices. At NedTrain, serious games have also been developed.

NedTrain has also developed serious gaming applications, for example, the so-called "chain game" (translated from the original dutch name Ketenspel). This board game brings elements of operational and tactical decisions made within NedTrain's supply chain. A game session brings together several stakeholders

Table 7.2: *Concept development methods in the PSS Engineering literature (Adapted from Cavalieri and Pezzotta, 2012).*

Method	Purpose of application
TRIZ	To identify, generate and evaluate possible solutions to service problems in the engineering process To optimise the idea generation process to support the shift from "intuition" to "formal development" To reduce the risk in the service development phase to deliver breakthrough sustainability concepts To predict what are the most likely improvements that can be made to a given PSS

Table 7.3: *Existing gaming tools with application to the fields of maintenance and asset management.*

Game	Company	Type	Model	Asset type	Goal
In-Service Support (ISS) Game	Thales	B	Low-Fi	Naval ship	Setup and control logistics for ships with two systems (radar and command & control)
VALID Game	AMC T&T	B	Low-Fi	Offshore wind park	Give insights about building asset management information system and aligning data needs
Asset Pouwer Game	Asset Pouwer	B	Low-Fi	Port & naval fleet	Give insights about asset management strategy, investments, information and risks
Asset Dynamics Game	Copernicos Groep	S	Hi-Fi	Any	Give insights about trade-offs between asset condition and lifetime costs using system dynamics and brainstorming sessions supported by a computer modeling and simulation tool
Den Ooievaar	Stork	P/C	Hi-Fi	Model furnace	Give insight about bottlenecks between operation and maintenance
DGAME1	Amico Services	C/W	Hi-Fi	Offshore wind park	Give insights about best asset management during the exploitation stage
DGAME2	Amico Services	C/W	Hi-Fi	Offshore wind park	Optimize the use and maintenance of the assets

B: Board game; C/W: Computer/Webgame; S: Simulation; DGAME: Dynamic Gathering Asset Management Enhancement; AMC: Asset Management Control.

from within the organization to gain insight and awareness about the bullwhip effects in the reverse supply chain of repairable items. This game delivers many lessons to participants including insights into the entire supply chain of NedTrain: its stock levels, information handling and the effects of uncertainty on component repair shops. This game is a recent development and is currently being tested by the Supply Chain Organization with several experts from different departments.

7.4 Problem description

There is a need to support design of technical service at NedTrain. Designing services requires many strategic decisions. These decisions involve large risks, a full causal model is not understood, and the range of possible outcomes for operational performance cannot be predicted. A specific issue that has been identified is the need to broaden the decision tradespace: exploring more maintenance concept options during acquisition. However, complexity of rolling stock, and the limited detail information about final design that exists during acquisition calls for alternative implementation of the traditional maintenance decision models found in the literature and discussed in Chapter 5 and the typical acquisition projects discussed in 6.

Our aim is to enhance collaborative decision making during design of service concepts. Case-based decision analysis using rigorous analogies or quantitative multiple scenario tools could be very useful to support decision makers in this context. Design games have shown to be a useful methodology in several contexts. Therefore, we shall explore the suitability of supporting early design decisions by means of a serious game. Combining participatory design and decision-based design principles, the two general requirements for the development of the support are:

- The tool shall clearly communicate different design attributes of rolling stock and its maintenance system.

Development of the game focuses on embodiment of two of the design attributes discussed in Chapters 3 and 4, namely, modularity and commonality. We learned in those chapters that design decisions affect serviceability, and that modularity and commonality analyses may help decision makers to evaluate and rank proposals from the perspective of serviceability. Embodiment of design properties in the game environment helps to deepen our understanding about how experts use of design attributes in acquisition projects. Introducing this level of detail into the game model strengthens face validity of the support (see Table 7.1).

- The tool shall clearly introduce elements of decision making that involve selecting a technical system and the technical service system.

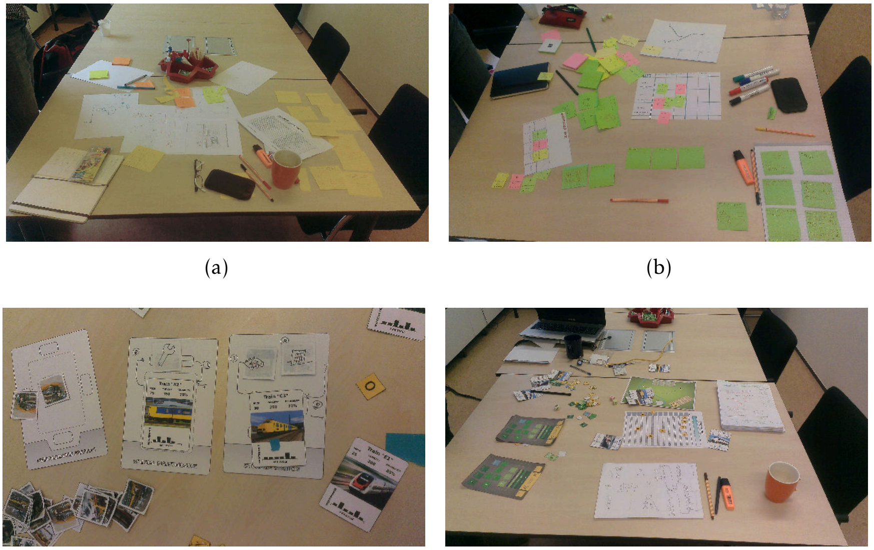
The game design introduces the trade offs involved in making decisions about the asset and its services concurrently. Change the train, change the organization, or change both. Chapters 5 and 6 discussed how many of the decisions about the technical service system are actually made prior to new rolling stock acquisition projects. The impact of making late decisions about changes to the service system may be severe. Delays to the acquisition program, late adaptation to new technology and supplier dependence could be avoided if service decisions are made early in the acquisition project.

Our approach combines the paradigm of decision-based design (Lewis et al., 2006) with participatory design (Garde, 2013; Thalen, 2013). We use serious gaming as a tool to allow participation of stakeholders in the design process. Serious games are a form of scenario based decision process (Courtney et al., 2013). Games are an engaging way to allow stakeholders with different backgrounds to explore, develop, and reflect on future situations, while also lowering the barriers that inhibit communication of tacit knowledge. Participation of stakeholders gives them the opportunity to self-determine their work, taps into their knowledge and expertise, and fosters commitment for change (Garde, 2013; Thalen, 2013)(other sources). Our aim is to enhance collaborative decision making during design of service concepts. This is an important contribution for organizations like NedTrain, as discussed in Chapters 5 and 6. Our approach can support strategic maintenance decision making at an early stage of rolling stock acquisitions, namely, before contracting new rolling stock.

7.5 Solution incubation

Solution incubation begins with the choice of the model of the real life phenomenon. This choice is inexorably linked to the choice of implementation approach. The initial choice is between a computer game, a board game or a combination of both. All have benefits and drawbacks. Generally speaking, board games are limited to a low fidelity model, while computer games can implement a much broader range of models, from low to high fidelity. The combination of both types of implementation may balance the benefits of both, but development is much more difficult and costly.

This research opted for a board game implementation for several reasons, namely, development costs, effort and suitability. Development costs and effort for a high fidelity implementation was until recently considered high because traditionally the technology required was complex, expensive and time consuming to deploy (Thalen, 2013, p. 21). Although this has changed dramatically in recent years, and tools such as virtual reality have been shown to be suitable for supporting design (Thalen, 2013), use of computer implementation requires expertise that raised the bar to access this type of development within our time-frame. We have observed from serious gaming experiences in practice (for example from the games of Table 7.3) that board games promise engagement of participants in a design exploration exercise by offering a lower threshold to participation. Similar



(a) (b) (c) (d)

Figure 7.1: *Game design iterations.*

findings are shown in literature (see, e.g. Garde, 2013). Board games appear to be suitable for concept exploration, and we intend to research this further. Our solution incubation process is depicted in snapshots in Figure 7.1. Until the first prototype is built, each initial design iteration is followed by design a review session. Each design review helped to clarify the game goals, mechanics and embodiment details.

On the one hand, computer games usually allow the construction of a high fidelity model. Digital game implementations shown in Table 7.3 usually have a fine grained model of real life, and can potentially use a large volume of data from a company. However, not all computer games allow the same level of participation. While digital games allow scaling of contact through internet, the scale benefits fade when more collaboration and communication is required from a session. The level of engagement of participants in collaborative digital games is strongly influenced by the facilitator and by the game setting –e.g., participants using separate computers, playing individually versus participants sharing a computer and playing in teams. Benefits of digital games usually come at the expense of a much more rigid gaming environment. The underlying model often remains obscure, and the lack of a clear understanding of this model may impair the player's confidence in the results of a session.

On the other hand, board games only allow a low fidelity representation of a real life phenomenon. This may distance the real life phenomenon from the

Figure 7.2: *Initial prototype of The Logistic Support Game.*

gaming environment. In that situation, the role of the facilitator in mapping the game situation to a real life problem becomes much more important. Board games also have important benefits. The game development process is much simpler, and much more affordable. This allows rapid development of the gaming tool as well as the easy introduction of design changes. Two additional important benefits comes from participant engagement and interaction between participants. Having things that participants can touch and manipulate creates a connection to the game environment. Participants can benefit from this because they can easily communicate ideas and arguments during a session by touching or moving objects in the game. Our experience with analog (board game) tools is that participants engage in much more active communication during the game, as compared to digital implementations.

The game design required input of approximately 120 man-hours over a 15 week period. A rapid development process is carried out by translating initial requirements into a succession of embodiment design, game mechanics design, test sessions and design reviews. The initial prototype is displayed in Figure 7.2. The game allows the choice of train architecture with the goal of explicitly eliciting the preferred level of modularity/commonality. The strategic decisions discussed in Chapters 5 and 6 are incorporated in a low fidelity model of the maintenance system. The architecture attributes are built into the game.

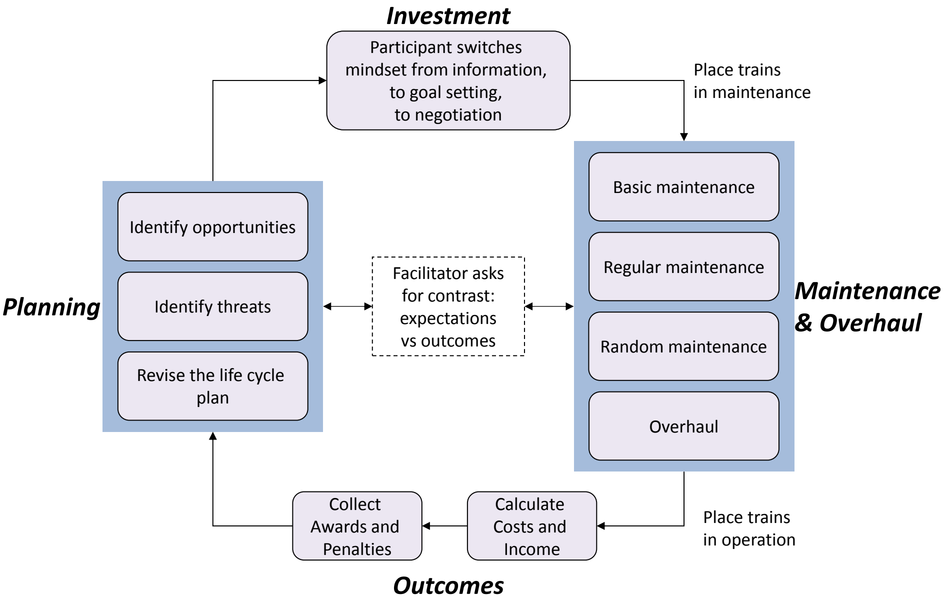


Figure 7.3: *General Structure of a game round in The Logistic Support Game.*

7.5.1 Gamification

In our research, gamification is understood as the embodiment of a real life problem into the design of a game. The aim of gamification is to induce participants into problem solving connected to the real life (non-gaming) situation by synthesizing the main elements of the problem into the game scenario. The game designer uses game mechanics –points, levels, challenges, rewards and so on– in order to engage participants into the game problem. In turn, the participant inherits a set of behaviors, decisions, and actions triggered by the game through the design of its game mechanics.

Our process of gamification is carried out based on extensive empirical research discussed in Chapters 3 to 6. One of the most challenging decisions is the choice of the content of a game round. Figure 7.3 shows the general structure of a game round. More detail is explained in Appendix B. The possibility to introduce random and planned events, selecting a time frame, control over information content and difficulty, as well as balancing challenges and rewards all play an important role. Initial design accommodates a number of scenarios to focus participants on different problems or roles. The performance goals may be set depending on that choice of a problem for the session. Therefore, several game mechanics are included in the initial game definition. Game mechanics evolve throughout the design process, and several appealing alternatives are implemented and tested as shown in Section 7.6, below.

7.5.2 Participants and facilitators

The game is designed to be played in groups. This game mode leverages the most advantages from a gaming session. However, individuals can play the game, in which case the game has an effect on the individual as a learning or training tool. Participants have to fulfill the tasks of fleet manager(s), rolling stock operations manager(s), financial manager(s) and maintenance operations manager(s). Each of these functions can be delegated to the group. The game session demands that participants in the team must switch their mindset several times from information, to goal setting, to negotiation.

A session facilitator helps to provide the necessary guidance and support during the session. The prime tasks of the facilitator are *(i)* to teach the game rules, *(ii)* to provide the initial game scenario for the session, and *(iii)* to promote open communication of the participants. This last element means that the facilitator acts as the moderator of group dynamics.

7.5.3 Expected strengths and weaknesses

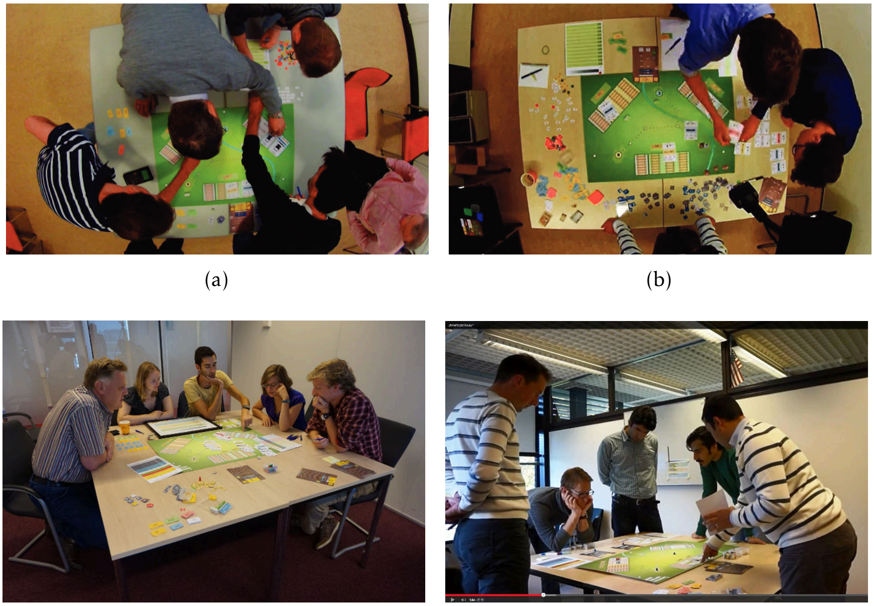
The selected gaming approach has several weaknesses. Firstly, the serious gaming tool represents a non-realistic decision environment. This affects the participants, who may fail to appreciate how problems discussed in the game world relate to real life. Secondly, the game session itself may be labour intensive. Preparing and doing the gaming sessions requires a considerable amount of man-hours.

Strengths of the tool are expected to be similar to other gaming environments. Design games have been shown to improve communication by contextualizing the design problem and diminishing the power relations between participant stakeholders. It is also expected that the tangible nature of the game objects also lowers the bar to test and experiment new concepts, resulting in the design space being extended at an early stage. This aspect is important for service development, because it creates a tangible environment to discuss abstract concepts.

7.6 Solution refinement

A group of initial workshops were used for prototype testing, design review and design improvement. Appendix B gives more detail about The Logistic Support Game. Figure 7.4 displays frames extracted from the videos of each session. Design feedback is extracted for the phase of solution refinement by means of field notes, jottings, and video analysis. All respondents would play again if changes are made, with a shorter session, a clear goal/problem and a different group.

Appendix B.5 shows a survey instrument used to measure individual perceptions on the game session. Participants fill in the survey during the final minutes of a test session, as shown in Figure 7.5. Collecting participant feedback also



(a) (b) (c) (d)

Figure 7.4: *The Logistic Support Game test sessions.*

happens during the game session. This real time feedback is video recorded for later analysis.

7.6.1 General assessment of the tool

Results of initial workshops show that sessions were found useful, nice, interesting and insightful. In general every participant thought positively about the game experience. The survey instruments were used to register the perceived cognitive strain as proxies for game difficulty rating. Based on cognitive strain scale of 1 to 7 (7 being very difficult) the resulting value of 4,2 was measured, representing a moderate difficulty level. 80% of the participants found the initial workshops to be a useful learning or study tool.

Several improvements were suggested: (i) improve balance between incomes and expenditures, (ii) perhaps take a look at other functions, (iii) Allow trains during use to be placed in maintenance; possibility to exchange trains so as it happens in practice; reserve trains available for all services, not just one station. (iv) shorter sessions, for example, two short sessions instead of one.

Figure 7.5: *A survey instrument is used to measure individual perceptions of the game sessions.*

7.6.2 Improvements to the session

Feedback from these sessions was very useful for improving the game mechanics, content and goals. Also, session lengths were adjusted thanks to participant feedback. The initial four hour sessions were found to be too long by all respondents. Therefore, the session length was gradually cut to three, and then to only a couple of hours. Different suggestions for repeating game sessions were proposed. Repeating sessions once or twice a year, once every four months or once every three months was suggested by participants.

Following recommendations from participants, training sessions were modified. The initial training scenario has a huge impact on the perceived complexity of decision making. Our initial approach to training was to provide a greenfield scenario in which players had all the freedom to make decisions and reach the common goal. This proved to be ineffective for training, yet very insightful for investigating decision making. Initial decisions in the greenfield scenario were often reached after about 45 minutes. In this situation, experts and non-experts in the area of maintenance and acquisitions approach the problem very differently. Non-experts quickly attend to the game rules, and make a decision. However, in this greenfield scenario experts are very attentive to evaluate all the possible options and make several iterations before reaching a choice.

Streamlining the training session was a major contributor to reducing the session duration. A group of 3 to 6 participants is found positive by all respondents of the survey.

7.6.3 Improvements in decision making

Feedback from initial test sessions was also used to enhance decisions. Random costs and reserve trains were incorporated as a result. Participants generally found a good balance between decision making and the game dynamics. One respondent did assess that the game was still far from practice. This is expected, as only a low fidelity model is implemented. This means that only the most elementary factors are included in the trade-offs. All respondents found that they better understand how they came to a decision.

All respondents found the goal clear and understandable, and additionally commented on the complexity and having clarified the goal better towards the end of the session. Regarding the level of modularity, respondents generally found this a good level in the system to make the decisions clear. One respondent found it particularly good for generating discussion.

7.7 Implementation

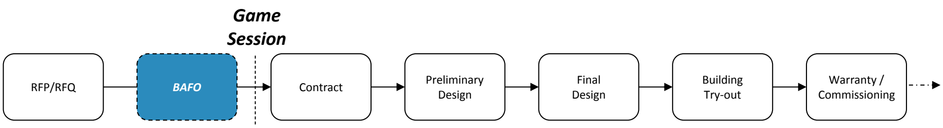
Table 7.4 lists the results of our game evaluation. For convenience we include the evaluation of the initial test sessions as well as the evaluation of the implementation session. We discuss the implementation session below.

Game implementation follows the four initial test sessions. Finding the case scenario was one of the first challenges. Several communications, interviews and small clarification sessions paved the way for an evaluation session with

Table 7.4: *Game evaluation.*

Validity	Case session
Content	Game components were enough to create a discussion, saw no need to make changes to the data on the game cards to fit values of the acquisition program. Found the game very insightful. The current game format allows to have a discussion about (a specific) problem, bringing the decision of functional commonality to the test.
Face	Game is not generally valued as support for exploring service concepts, but to generate insights that can lead to focused problem-solving.
Construct	Decisions with experts take longer, and the results were better decisions.
Concurrent	Item very difficult for experts to asses. New service concepts are not discussed normally by acquisition teams.
Predictive	Expectations on the outcomes of the game were difficult to manage initially. Outcomes of a real life situation are not really known for such projects in advance.

(a)



(b)

Figure 7.6: *The Logistic Support Game case session.* (a) *Session snapshot and* (b) Stage of the case project within the acquisition process.

experts from a concurrent acquisition project. Finally, one case application of the intended support is used to study *(i)* the correctness/validity of the intended support and *(ii)* the use of the intended support in a real life project setting.

Figure 7.6 displays the positioning of the case within the acquisition process of the case project (Acquisition Project 4 (AP4) of Unit of Analysis (UOA) 4 (UOA4) discussed in Chapter 6, above). The opportunity to test the serious game tool at this stage presented itself when the project team had already received the Best and Final Offers (BAFO) from the relevant suppliers. Three experts from the project team, including the team leader, participated in the case session.

During the case session, participants clarify their requirements. One participant confirmed the need to explore design options, and stated that '...what we are looking for are the means and activities to reach our goal. So how can I come to find the specific activities and means to reach that goal? We can formulate the goals' he continued, 'the art is to find what activities we need to do. After that, you can think about the consequences'.

Session Step 1: Mindset for problem solving Participants receive by email a problem solving questionnaire, shown in Appendix B.5.

Session Step 2: Training Setup The problem solving session begins with a training scenario. This scenario is setup by the facilitator, and includes an pre-defined technical service system, unbalanced demands between lines, and a rogue fleet.

Session Step 3: Scenario Setup After the training round, participants are asked to share their views on the problem. The facilitator asks them to try to contextualize the problem to the game world by thinking in terms of the expected outcomes. The debriefing question asked is: What is your expectation of the outcome if such an idea would be implemented? The scenario in the session helps to test changes in the technical service system to reduce basic, regular and random maintenance costs.

Session Step 4: Discussion/Debriefing Participants are asked to discuss how an alternative scenario could be adapted to the game. The facilitator asks, for example: What investment can you make, in the technical service system of the game world, that can help you reach your goal?

Session Step 5: Tool Evaluation Participants are asked to assess the usefulness of the game tool for the application at hand.

The case session gave us insights about changing mindsets about the service design space. In the words of one participant '. . . there are many things that we do traditionally, and we can step back from that. . . '.

During step 5, and referring to the discussion, the team leader issued a remark: 'from the standpoint of the project for Planning of the Maintenance Concept (new series) we have a train and its technical capabilities and limitations are central. It must be maintained in a functioning organization, and that tension that exists should be interesting to see. We could set up a game starting from the perspective of the (existing) functioning organization, or allow the train with its opportunities and limitations take the lead. Where do you find conflicts? and how can you use the game as a tool to enhance your understanding of the project?'.

7.8 Discussion

Now we are ready to discuss the usability of the game. The game exceeded the expectations in several respects. The level of engagement and the level of the discussion generated during the session was very satisfactory. Important decisions were carefully negotiated, information was shared accordingly and the feeling of collaboration was latent during game play. Sessions used to test game development actually served a dual purpose: providing insights for the group, and experience for the facilitators. Although the level of engagement was not initially moderated by the facilitator, as complexity in the game increased, the facilitator's role was crucial. The skill of the individual was determinant in creating moments to retrieve information, focus, and moments to make decisions.

Gaming sessions have been found to be useful for exploring service design options and their possible outcomes. As it turned out, managing expectations of participants is a very important part of preparing for a serious game session. One participant commented: "I feel that you should not have the illusion that I had before. I had the illusion that a game has an answer to a question. A game has to trigger a good discussion by means of involving the right players and having them look at a problem from the same angle, I think that is the added value...".

7.9 Conclusion

This chapter developed The Logistic Support Game, a serious gaming tool as support for acquisitions in the early stages, before contracting. As a part of the DS-II phase, the support is evaluated for validity (content, face, construct) and reliability. The chapter provides an overview of the method used for expert sessions.

Literature suggests that serious games are useful tools for learning, decision making, training and designing. They help participants develop awareness and insight. State of the art shows the usefulness of games in asset management (industrial) practice for awareness and insight. Initial tests suggest the game is fit for the intended use. However, concurrent validity (comparison with other tools for the same end) and predictive validity (ability to predict outcomes) was not shown, nor tested, given the low-fidelity characteristic of the game.

This chapter provides several contributions to research by presenting the problem, the literature, developing support and performing initial testing of the support. The game has several insightful applications. Firstly, to study decision makers' preferences and negociation of trade-offs in a controlled environment. Secondly, as a part of an agreement process, to reach consensus on important aspects of a service design decision. Thirdly, to help experts communicate their preferences more effectively and efficiently. Lastly, as a training and learning tool for service design.

The serious game was tested in a real case scenario to help explore solutions to a decision problem. Initial tests show that serious games could be a suitable support for early stages of an acquisition project. We conclude (1) that service development is important during acquisitions of capital assets, (2) that gaming can increase the speed of reasoning about the service design space, and (3) that the method has the potential to increase both efficiency and effectiveness of the decision making process during service design. In this chapter we have shown that gaming can be a useful tool to improve communication and broaden the service design tradespace. The design of a gaming tool has been shown to provide a collaborative decision making environment.

Additional research and development would be needed to add rotable spares (central or distributed) to the decision making process. This particular decision was pointed out by one participant. Indeed, introducing this decision would make the gaming experience closer to the real life situation. However, we also expect this addition to increase game complexity.

Chapter 8

Practice and theory of defining line replaceable units[1]

This chapter presents the Line Replaceable Unit (LRU) definition problem using two cases from practice. It supports LRU definitions by using a mathematical model to include factors not currently used in practice. This is the intended support developed for the later stages of an acquisition project (after contracting). The chapter is introduced in Section 8.1. Next, the methodology is presented in Section 8.2. Section 8.3 shows that many maintenance repair decisions in the literature, such as the Level of Repair Analysis decisions, assume the LRU definitions implicitly. In Section 8.4 a gap is further examined in practice, where the LRU definition decision is usually made ad-hoc, or based only on engineering/technical criteria. Section 8.5 gives a model for the LRU definitions problem, presenting the notation, assumptions, and the mathematical formulation. The model is validated in simulation experiments in Section 8.6. Finally, Section 8.7 draws conclusions. Insights about the LRU definition problem are, namely, (1) technical aspects dominate the decision in practice, (2) Appendix C.3 shows that it is NP-hard and (3) it can be optimized using a MILP model for instances that are realistic in practice, and in a reasonable amount of time, (4) it can lead to important cost savings compared to heuristics found in practice. Finally, significant cost reductions can be achieved when compared to two heuristics commonly used in practice. Model development appears to be a suitable support for the later stages of an acquisition project.

[1] Most parts of this chapter are adapted from Parada Puig and Basten (2014), and have also been submitted to the European Journal of Operational Research (currently under review)

8.1 Introduction

The design of the capital asset is a complex process. Original equipment manufacturers are systems integrators. Original Equipment Manufacturers (OEMs) design a system platform that allows them to supply different markets by combining existing technology and subsystems into their platform. During this process, the maintenance significant items from the different subsystems are integrated into a spare parts package.

To maintain capital assets, a typical maintenance organization repairs them by replacing failed items (repair-by-replacement). A physical item that is replaced is called a *line replaceable unit* (LRU; see, e.g., Department of Defense, 1996). The LRU definition problem is a maintenance policy decision that should be considered as a part of strategic or tactical maintenance planning: the exchange of LRUs produces downtime, and therefore the selection of items that should be defined as LRUs is a critical decision. Downtime can be compensated for with spare assets, and this means that the LRU decision should be considered from the outset of a capital asset acquisition program.

Traditionally, non-economic criteria are used to define LRUs. For example: Is it possible to know (test) that the item requires maintenance? Can the failed item be disassembled, and a spare reassembled to the asset without destruction or damage to other parts? Are there special adjustment and calibration needs? These technical criteria help engineers fit the LRU definition to existing practices and available resources of the maintenance organization. While these non-economic criteria are of key importance, inclusion of economic criteria can lead to a more cost effective LRU definition. The aim of this chapter is to take a step in that direction.

We first link the problem to the scientific literature. Three relevant literature streams are reviewed: *(i)* maintenance task analysis, *(ii)* maintenance optimization, and *(iii)* level of repair analysis. The setup of this review is based on the Logistics Support Analysis framework (see, e.g., Jones, 2006b). We find that the LRU decision is implicit in existing models for maintenance planning, and thus has not received the attention that it requires.

We next show how the problem is treated in practice by gathering insights from two organizations: a system developer, Thales Nederland BV, and a maintenance service provider, NedTrain BV. We show how LRU decisions are made at these organizations, giving insights about when they make the decision, who makes the decision, and what criteria are used. Also here, we find that the LRU definition decision is often made implicitly.

We propose to model the LRU definition problem explicitly. Using insights from the literature and from practice we come up with a *mixed integer linear programming* (MILP) formulation to find the optimal LRU definition. We perform a numerical experiment using typical problem sizes and parameters as they appear at NedTrain. Our theoretical contribution is as follows:

1. We link the problem to multi-component maintenance optimization and frame

it in the literature as a decision that should be made after maintenance task analysis, and before level of repair;
2. We improve the LRU definition decision that is traditionally technical, by explicitly modeling the trade-off between downtime and cost, including replacement lead time, spare assets and the cost of replacement;
3. In multi-component maintenance optimization, the interactions between components are modelled. We explicitly incorporate one type of interaction called structural dependence, in which defining *what* to replace depends on the assembly structure of the capital asset.

From a practical point of view, we contribute by examining the cost savings that could be achieved compared to ad-hoc decisions made by experts. We do this in an extensive numerical experiment. We thus show that it is important to make the LRU definition decision explicitly in practice, and we give a model that can be used to do this.

8.2 Methodology

This chapter presents research that aims to answer research subquestion RQ3b: What is a suitable way to support the late stages of an acquisition project (after contracting)? Our approach follows closely the operations research process presented in Figure 8.1. Firstly, the process of conceptualization is adopted by means of a literature review and a two example cases from practice. Next, in step 2 of the process we follow a mathematical modeling approach using linear programming formulations that are commonly found in the literature on similar problems. In step 3, model solving is performed via the MatLab software environment using

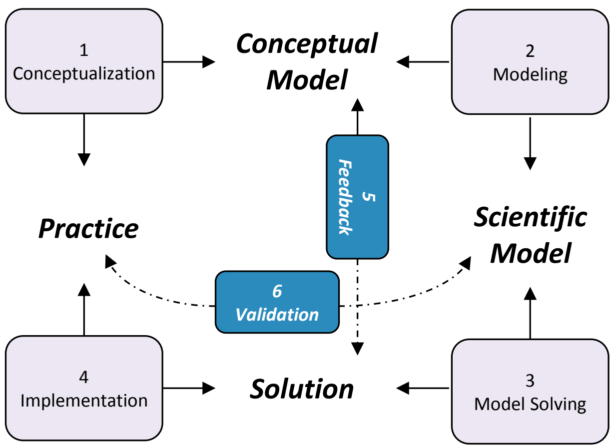


Figure 8.1: *The operations research process, adopted from Mitroff et al. (1974); Sagasti and Mitroff (1973).*

CPLEX, as described in Section 8.6 below. In that section, we implement our model (step 4) and present a numerical simulation using problem instances that are drawn from practice. This last step completes our methodological approach and provides insights for further research, discussed further in the next chapter, Chapter 9.

8.3 Literature

We use the framework of LSA to structure our review of the literature. The LSA framework is shown in Figure 8.2. It structures the decisions needed to produce the maintenance program for an asset, including the required (amounts of) resources. This enables us to position the LRU definition problem in the literature.

We first explain the LSA framework in Section 8.3.1. We then focus on three topics in detail; on maintenance task analysis in Section 8.3.2, on maintenance optimization, which covers the LRU definition problem, in Section 8.3.3, and on level of repair analysis in Section 8.3.4.

8.3.1 Logistic support analysis

Jones (2006b) and Blanchard and Fabrycky (2011) provide good overviews of the LSA framework. It begins with the analysis of possible failure events. *Reliability predictions* are made for the failure of asset components. Next, maintenance significant items (and their failure effects and criticalities) are identified with the help of Fault Tree Analysis (FTA) and failure modes, effects and criticality analysis (FMECA). The analysis results are combined in the Reliability Centered Maintenance Analysis (RCMA) to establish the set of feasible maintenance policies for the capital asset, e.g., time based maintenance or run-to-failure (see, e.g., Moubray, 1997; Tinga, 2010). At this point in the LSA framework, engineers have thus determined which items may fail, how often that is expected to happen,

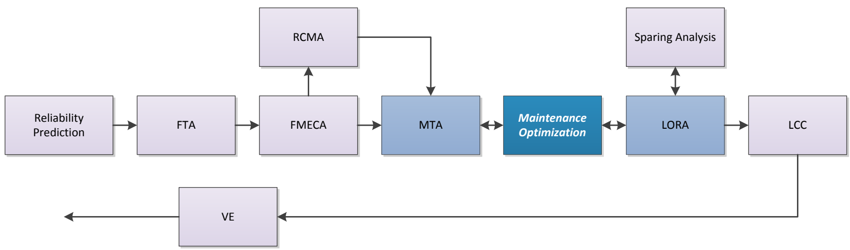


Figure 8.2: *The Logistics Support Analysis framework (Adapted from Jones, 2006b, page 11.23, Figure 11-16).*

what effect and criticality such failure may have, and what preventive measures (if any) to take.

The next three analyses, Maintenance Task Analysis (MTA), *maintenance optimization* and Level Of Repair Analysis (LORA), are discussed in detail in the next three sections. MTA helps to identify and quantify the required maintenance resources, such as manpower or support equipment. Maintenance optimization models are mainly used to determine the optimal preventive maintenance intervals and task clustering. LORA supports repair or discard decisions, and determines where in the repair network to carry out these activities.

Sparing analysis, which follows after LORA, helps determine the spare parts package (see, e.g., Basten and van Houtum, 2014; Muckstadt, 2005; Sherbrooke, 2004, for an overview of the literature on spare parts inventory control models). Life Cycle Cost (LCC) is determined next. Finally, value engineering (VE) highlights asset functions that add cost but do not add significant value and feedback is given to design.

8.3.2 Maintenance task analysis

Maintenance task analysis is the detailed, step-by-step analysis of a maintenance task to determine how it should be performed, who will be required to perform it, and what physical resources are needed to complete it. Most maintenance tasks involve manual disassembly and (re)assembly operations. To find the best task procedure for maintenance, engineers use human factors analysis, path/motion planning and assembly/disassembly sequencing.

Human factors analysis helps to asses the effort to access the maintenance point and the risks involved, given a proceduralized task (see, e.g., Dhillon and Liu, 2006). Together with human factors, path and motion planing helps to reveal the best way for a service engineer to reach and route a part into or out of an assembly. Next, optimal sequencing helps to establish the optimal order of assembly and disassembly (see, e.g., Lambert, 2003).

Once the task procedure is established, maintainability analysis is used to estimate (or measure) the required time and resources. The literature on maintainability analysis has mostly concentrated on estimating the (mean) time to repair, using either statistical methods or expert-based assessment (see, e.g., Barabadi et al., 2011; Moreu De León et al., 2012). A quantification of both resource demand and task time are very useful for decision making. The data could be used as input of maintenance optimization models. We will need the results from MTA for solving LRU definition problem.

8.3.3 Multi-component maintenance optimization

Most literature on maintenance optimization focuses on defining the best policy for *when* to replace a particular item. However, for multi-component assets it is important to define not only when, but also *what* to replace. This derives from the fact that in capital assets with many items, interaction between items influences the maintenance action that should be chosen. Nicolai and Dekker (2008) review the literature on multi-component maintenance optimization and they distinguish between economic, stochastic and structural dependence as a result of interaction between items.

Economic dependence exists when costs decrease or increase by grouping maintenance tasks. Stochastic dependence exists when items present failure interactions, i.e., states of items can affect the states of other items and their failure rate. Finally, structural dependence exists when items have to be replaced, or at least dismantled, before failed components can be replaced or repaired.

The term structural dependence was coined by Thomas (1986), who was one of the first to review the problems in multi-component maintenance optimization with structural dependence, i.e., where, "... the question is whether one should replace the whole car, the engine or just the piston rings when the piston rings need to be replaced". With structural dependence, the disassembly precedence relations are important, which follow from MTA. We see the LRU definition problem as a multi-item maintenance optimization problem with structural dependence.

This problem has been a recurring problem in the literature on maintenance optimization for several decades, starting with the seminal paper by Sasieni (1956) (see e.g. Marais et al., 2013; Nicolai and Dekker, 2008). Moreover, while typically the focus has been on the decision about the optimal maintenance interval, i.e., *when* to replace, the key decision for the LRU definition problem is at what level within the indenture structure of a physical asset to define the LRU, i.e., the decision on *what* to replace.

8.3.4 Level of repair analysis

The level of repair analysis problem is a cost minimization problem that involves two decisions. Firstly, determining whether a maintenance significant item should be repaired or discarded upon failure. Secondly, determining where to allocate this repair/discard task in the repair network. The LORA problem has been addressed in the literature as a MILP model by several authors (see, e.g., Barros and Riley, 2001; Basten et al., 2011). Recently, LORA models have been extended to consider availability by incorporating the amount of spare parts to stock (the sparing decision) (see, e.g., Basten et al., 2012). We find that the literature on LORA takes the LRU decision as a given.

To the best of our knowledge, the importance of optimally determining line replaceable units was brought to attention only by Jensen (1975), in the context of level of repair analysis. Jensen states that the LRU definition is implicit in his LORA formulation. However, one of the inputs of his model is the explicit definition of which item is replaced directly from the asset, and which items (if any), are used to repair the failed LRU. Therefore, the LRU definition decision must be made *before* his LORA model can be used.

8.4 Defining LRUs in practice

We show insights about how organizations make the LRU definition decision in practice based on two exploratory cases. Interviews were conducted following the methodology in Schotborgh et al. (2012). This means that we begin by asking experts to compare performance of different LRUs, and next focus on what performances they consider, e.g. time to replace, resources needed, task difficulty. We thus determine *(i)* when LRU definition decisions are made, *(ii)* who makes them, and *(iii)* what criteria are considered.

In Sections 8.4.1 and 8.4.2, we present our findings at a high-tech system developer and a maintenance service provider, respectively. For each case, we give a short company overview, followed by a description of the LRU definition process. Next, we discuss the criteria used by experts, and we give individual case conclusions. Finally, in Section 8.4.4 we draw more general conclusions from practice.

8.4.1 High-tech systems developer

Thales Nederland B.V. (Thales) is the largest defence company in the Netherlands. Thales designs and manufactures naval command and control, sensor, and communications systems. As a high tech systems developer, Thales is involved in maintenance by providing training, supplying service parts (LRUs), overhaul, upgrades, and modifications to its clients, and by performing repairs according to support contracts.

At Thales, design tasks are partitioned according to the type of technology used, and engineers are grouped into Technical Units with expertise in each type of technology, e.g., processing or microwaves. Figure 8.3 shows how the LRU definition process is organized at Thales, according to the V-model of systems engineering. Through the process of system requirements analysis, engineers translate the client's capability requirements into system performance. Maintenance performance is allocated at system level in the form of *Reliability, Availability, Maintainability, Testability* (RAMT) requirements.

Next, each Technical Unit must allocate the system level RAMT requirements to individual LRUs, thereby making the LRU definition decision. They use for this the *(i)* LRU requirements and the *(ii)* Integrated Logistic Support (ILS) Guidelines that have been developed by the ILS department. The Technical Unit communicates the LRU definition decisions to individual design teams. Design Teams will then develop the LRUs (parts) complying with the requirements and the logistics guidelines. For completeness, we include a summary of the LRU requirements in Appendix C.5.

The ILS Guidelines are used to give an overview of supportability aspects to be considered by designers, as well as performance targets for design. Their goal is to improve system supportability and lower life cycle cost. Improving LRU definitions at Thales often involves redesign, and this is a considerable effort.

Thales outsources manufacturing of some of its components, and this means that redesign has to involve the suppliers. Engineers can use the guidelines to trade-off manufacturability with supportability, i.e., a trade-off between manufacturing and operating costs.

The LRU requirements describe two types of criteria used by design teams when developing LRUs. Firstly, an LRU has to satisfy four *mandatory criteria*. If this is impossible, then the next higher assembly/equipment is defined to be the LRU. Otherwise, the maintenance concept is changed to direct repair of the hardware item while installed in the asset, i.e., no repair by replacement and no definition of LRU.

Secondly, there are a number of *preferred criteria* for selection of LRUs. For example, there exist requirements for the maximum weight and dimensions. These allow the LRU to be handled by one service engineer only. If the design team has a good reason not to fulfill the requirement, then the preferred criteria may be waived. However, there is a constraint on the total number of waivers. Waivers are controlled during design review.

In summary, we have found that LRU definitions at Thales are made during the early stages of design. Engineers within technical units make the LRU definition decisions, and criteria for defining LRUs are based on compliance to standard LRU requirements. These requirements do not explicitly mention economic trade-offs.

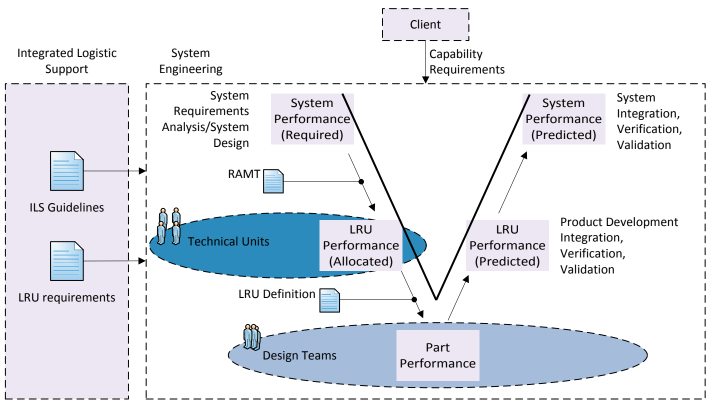


Figure 8.3: *LRU decisions in the workflow of Thales B.V.: from Functional Requirements (FR) to Design Solution (DS). Allocation of performance —Reliability, Availability, Maintainability, Testability (RAMT)— from system Level to LRU Level.*

8.4.2 Rolling stock maintenance service provider

NedTrain B.V. (NedTrain) is a full maintenance, repair and overhaul (MRO) service provider for trains. It is a subsidiary of NS, the main passenger railway operator in the Netherlands. NedTrain provides 24/7 service involving regular maintenance, repair, overhaul, modernization and life extension. Four types of facilities provide the required services, spanning from first line service to component repair and overhaul.

For NedTrain, the supportability of new trains depends on the level in the indenture structure at which LRUs are defined. The LRU level is initially defined during acquisitions of new trains, resulting in a preliminary list of LRUs. The preliminary list of LRUs may change throughout a train's life cycle when new knowledge about item performance becomes available. The actual LRU decision is made at the operational level. In practice, the LRU level is changed ad-hoc by service engineers during repair.

Figure 8.4 shows how the LRU definition process takes place during acquisition of new trains to produce the preliminary list of LRUs. A similar process is followed to change the list later in the life cycle. The LRU level is initially defined by the supplier during acquisitions, and it is communicated to NedTrain as a recommended spare parts assortment. For each of the suggested LRUs, NedTrain must decide to accept or revise this LRU level.

If NedTrain decides to revise the suggested list of LRUs, then experts will try to find an LRU level that gives a better fit to existing resources and to the maintenance concept. The whole process involves frequent communication with the suppliers. A team of experts begins the LRU research. This is typically done by looking deeper in the indenture structure to try to find smaller LRU candidate than the one proposed by the supplier. Next, they determine whether or not there are parts in this new level that *can* be exchanged. This is the most important technical aspect considered for defining LRUs. If there is no feasible disassembly sequence to remove the LRU candidate item directly, then the item is non-LRU. In this case the team shifts focus to the parent (assembly) item and repeats the analysis.

For some LRU candidates, direct replacement is possible only when the proper tools or equipment are available. If resources facilitate replacement and they are available, then the item is selected as an LRU. Some of the aspects considered for this decision include task frequency, skill level and effort required, for example. It is a rule of thumb that approximately 85% of the parts can be replaced in any maintenance workshop of NedTrain. However, the problem of limited availability of skills and manpower was noted by several experts.

If the required resources are not readily available in the workshop, then there is a cost trade-off. The expert team filters out those items that require expensive tools or equipment. If the cost of installing the additional resource is unacceptable, the expert team begins negotiations with the supplier to outsource replacement. If an agreement is reached with the supplier, the item is defined as

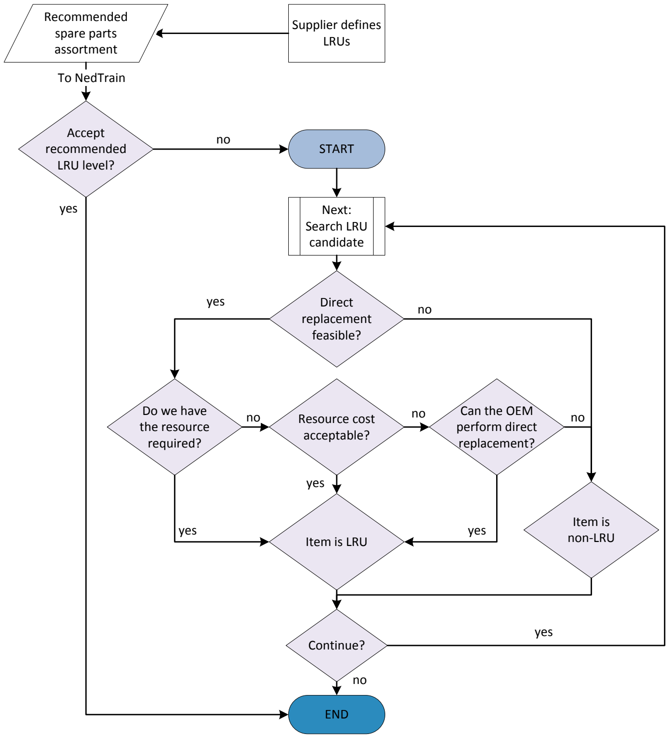


Figure 8.4: *First LRU decisions at NedTrain B.V..*

LRU. In this case a service contract is signed and the supplier will perform direct replacement on the train. Otherwise, the item is defined as non-LRU.

The preliminary list of LRUs lends the operational LRU decision to service engineers in the workshops. Once the trains are fielded, there is a lot of freedom for service engineers at NedTrain to decide how a particular failure is repaired. LRU definitions are changed ad-hoc, i.e., the decision of what component is replaced. Often, if a service engineer decides to correct the failure by replacing an O-ring, (s)he can. If otherwise (s)he decides to replace the entire (assembled) unit, then that may also be allowed.

Service engineers find it is easier to replace a small part instead of a large assembly. This is because typically less interfaces have to be taken apart by replacing smaller items. Also, large and heavy components need more handling effort. However, some experts suggest that while replacing a small component is cheap, the train often remains waiting longer. The behavior of service engineers may come in conflict with this point of view. Our conclusion is that the LRU definitions should be a strategic/tactical decision. This is also the position of management.

Summarizing, we have found that LRU definitions decisions at NedTrain are made during acquisition and during the operating life of passenger trains. The goal during acquisitions is to analyze the preliminary list of LRUs of the supplier to create an initial spare parts assortment that better fits the maintenance concept of NedTrain. Therefore, the objective is not the specific choice amongst replacement alternatives. This LRU definitions are made by an expert team of engineers, in agreement with the suppliers, to fit the resources of NedTrain. In practice, during the operating life of the train the service engineers may make the replacement decision ad-hoc, and the LRU level within the indenture structure may change.

8.4.3 Case findings

The LRU decision has non economic criteria. Experts use these criteria in a different way to the non economic LORA decisions. Table 8.1 summarizes the approach to non-economic LORA versus non-economic LRU definitions. As shown in Chapter 5, both decisions are core strategic/tactical decisions that are made after contracting technical systems.

8.4.4 Case conclusions

Our research shows that LRU definitions require considerable efforts, that costs are not always incorporated and that supplier involvement is required. At NedTrain, performing the LRU definition decision for a new train series requires one year of an expert team's efforts. In practice, RAMS/RAMT influence LRU definitions, and LCC calculations have a limited influence in the decision. Both for Thales and for NedTrain, increasing collaboration with suppliers has led to improved LRU definitions, e.g., higher availability and lower LCC.

To help Thales and NedTrain, we propose to use model-based decision support. We use an optimization approach in Section 8.5 of this chapter which will probably be more useful for companies like NedTrain, though we expect it will also give insights that help designers at Thales. NedTrain can benefit from reduced downtime and increased standardization of repair. At Thales, helping designers make logistic trade-offs is required to support the system engineering efforts. This could be subject of future research.

8.5 Modeling

In Section 8.5.1, we explain the relevant notation and assumptions, and in Section 8.5.2, we present a mixed integer linear programming formulation for the

Table 8.1: *Non-economic LORA (Adopted from Basten (2009)) vs. non-economic LRU definitions*

Non economic LORA	Non Economic LRU definitions
Is the component prone to failure?	Is the component a maintenance significant item?
Does the customer prescribe the maintenance policy for the component?	Does the supplier define the maintenance significant item as LRU?
Does the value of the component exceed a certain threshold? (if beyond a threshold it's not worth repairing)	Is direct replacement technically feasible?
Are intellectual property rights involved that prohibit the customer from performing repairs? (if so the OEM can repair it, or it should be discarded)	Do we have the resource required?
Is the component procurable, and will it be procurable in the future? (i.e. should it not be discarded)	Is the resource cost acceptable? (if beyond a certain budget it won't be installed)
Does the component have any handling constraints? (e.g. restricted to special facilities)	Can the OEM perform direct replacement?

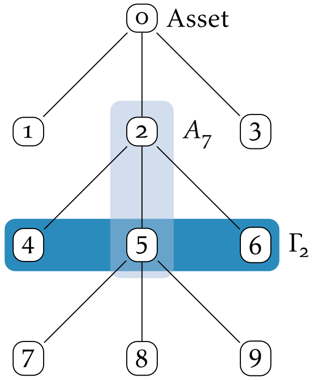
LRU definition problem. Appendix C.3 shows that the resulting LRU definition problem is NP-hard.

8.5.1 Notation and assumptions

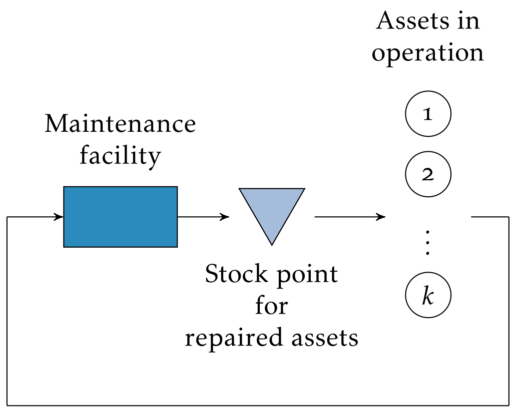
Consider a capital asset with several indenture levels. Such a multi-indenture structure is a rooted ordered tree. Figure 8.5(a) shows an example three-indenture asset with the notation that we use. Let I be the set of all maintenance significant items, and $|I| \in \mathbb{N}$, with $|I|$ denoting the cardinality of I. For convenience we denote $I = \{1, 2, \ldots, |I|\}$. Let Γ_i be the subset of items that are direct descendants of item $i \in I$. Notice that $\Gamma_i = \emptyset$ if and only if item $i \in I$ is a leaf (i.e., has no descendants). We denote by the set A_i the set of all ascendants of item $i \in I$, i.e., all assemblies that contain, at some indenture level, item i.

Consider the maintenance system in Figure 8.5(b). An operator requires k assets to be operational on average, i.e., the target average availability is k. Each of the k assets will remain in operation until a corrective maintenance action or preventive maintenance is required. When a maintenance event is required, the asset is removed from service and taken to a maintenance facility. After maintenance, the asset is sent to an inventory stock point.

We make some assumptions in order to keep our model simple, allowing us



(a)



(b)

Figure 8.5: (a) *Example indenture structure (e.g., $I = \{1, \ldots, 9\}$, $\Gamma_2 = \{4, 5, 6\}$, and $A_7 = A_8 = A_9 = \{2, 5\}$), and* (b) *A maintenance system for capital assets.*

to focus on the insights that we can get. We assume that there is ample repair capacity (i.e., uncapacitated resources) and that item replacement times are deterministic with lead time $r_i > 0$ for LRU $i \in I$. The item replacement time is the total time required for failure detection, isolation, repair and checkout/calibration. We assume that the asset behaves as a series of critical items: if one fails, then the asset fails. Finally, we assume that failures happen individually.

Let m_i be the *individual* failure rate (yearly number of failures) of item $i \in I$.

This means that if $m_i > 0$, then failures occur in item i that are *not* due to failures in any of its descendants. Without loss of generality it holds that $m_i > 0$ for all leaf items, i.e., items $i \in I$ with $\Gamma_i = \emptyset$. We assume m_i over k operational assets. There may be moments when there are less than k assets operational, but given a high service level, this does not happen often and the number of operational assets will not be far below k (for a more extensive discussion of why such a constant failure rate is realistic to assume, see Sherbrooke, 2004, p.24, or Basten and van Houtum, 2014, p.40).

Let λ_i be the *cumulative* failure rate of item $i \in I$. λ_i is the sum of the cumulative failure rates of those child items $j \in \Gamma_i$ that are not defined as LRU. λ_i is thus an auxiliary variable and we show our recursive approach for calculating λ_i in Section 8.5.2. By definition, $\lambda_i \geq m_i$, for all $i \in I$, and $\lambda_i = m_i$ if item i is a leaf item, i.e., if $\Gamma_i = \emptyset$.

We define the following decision variables:

- $X_i = \begin{cases} 1, & \text{if component } i \in I \text{ is defined as LRU,} \\ 0, & \text{otherwise;} \end{cases}$
- $N \in \mathbb{N}$ is the total number of assets to acquire.

The cost function contains two cost factors. Firstly, the annual holding cost, c_0, of the assets (this includes interest, depreciation, etc). Secondly, the cost of replacement of an LRU $i \in I$, c_i. Replacement costs include labor and material costs.

8.5.2 Mixed integer linear programming formulation

Our objective is to determine which items out of the total set of items I to define as LRU, plus the total number of assets N to acquire, such that the total costs are minimized while the availability constraint is met. We state the LRU-definition problem as a mixed integer linear program below. The linearization of the objective function and Constraints 8.2–8.4 can be found in Appendix C.2.

$$\min \quad c_0 N + \sum_{i \in I} c_i \lambda_i X_i \tag{8.1}$$

$$\text{s.t.} \quad N - \sum_{i \in I} r_i \lambda_i X_i \geq k \tag{8.2}$$

$$\lambda_i = m_i + \sum_{j \in \Gamma_i} \lambda_j (1 - X_j), \ \forall\, i \in I \tag{8.3}$$

$$\lambda_i \leq \lambda_i X_i + \sum_{j \in A_i} \lambda_j X_j, \ \forall\, i \in I \tag{8.4}$$

$$N \in \mathbb{N} \tag{8.5}$$

$$X_i \in \{0, 1\}, \ \forall\, i \in I \tag{8.6}$$

Constraint 8.2 is a constraint on the number of assets that must be available for operation. Constraint 8.3 is the recursion stating that an item $i \in I$ is replaced both when failing individually (m_i), and upon failure of one of its child items that have not been defined as LRU. Finally, Constraint 8.4 assures that a child non-LRU that fails must have an LRU ascendant. If $\lambda_i = 0$ or if $X_i = 1$, the constraint is always satisfied. If $X_i = 0$ and $\lambda_i > 0$, then some parent item must be defined as LRU, i.e., $\sum_{j \in A_i} X_j \geq 1$, and thus $\lambda_i \leq \sum_{j \in A_i} \lambda_j X_j$.

8.6 Numerical Experiment

This section explains our numerical experiment. We first give the setup of our numerical experiment in Section 8.6.1; a detailed description of how we generate some parts of the problem instances can be found in Appendix C.4. We show the results in Section 8.6.2. The LRU definition problem is implemented using the CPLEX 12.6 Class API for MATLAB R2013a on an Intel Core i5 M540@2,53GHz, with 4GB RAM running 64-bit Windows 7. All instances are solved to optimality; we do not use a time limit.

8.6.1 Instance generator

We use a problem instances generator that is inspired by that of Basten et al. (2012). We define three *problem sets* (PS): PS1, PS2 and PS3. Table 8.2 lists the settings used to modify the asset structures for each of the three sets, and Table 8.3 lists the settings for the other parameters. Typical values found at NedTrain are in between the low and high values used in the problem sets. We use a full factorial design per PS, and generate ten problem instances per parameter setting to avoid basing conclusions on one unique instance only.

Table 8.2: *Asset structure settings: numbers of components per indenture level.*

PS	Parameter			Indenture level					
	$\lvert\Gamma_0\rvert$	$\overline{\lvert\Gamma_i\rvert}$	$\lvert L\rvert$	1	2	3	4	5	6
1,3	50	2	3	50	100	200	-	-	-
	100	2	3	100	200	400	-	-	-
	50	4	3	50	200	800	-	-	-
	100	4	3	100	400	1,600	-	-	-
2	50	2	3	50	100	200	-	-	-
	50	2	4	50	100	200	400	-	-
	50	2	5	50	100	200	400	800	-
	50	2	6	50	100	200	400	800	1,600

Table 8.3: *Parameters settings or sampling range for PS1, PS2 and PS3.*

Parameter		Setting	
		1	2
Item failure rate per asset (1/*year*) .	m_i/k	[0.01; 0.1]	[0.01; 1]
Item replacement lead time (hour)†	r_i	[0.25; 2]	[0.5; 4]
Item replacement cost (€×1,000) . .	$^{\dagger\dagger}c'_i$	[1; 10]	[10; 100]
Parent-child cost factor	f_c	[0.5; 1.5]	[1; 3]
# required operational assets†	k	10	100
Asset cost (€×1,000)	c_0	[200; 400]	[1,000; 2,000]
Wage (€/hour)	w	5.5	55

† For PS3 r_i and k are fixed at Setting 1.
†† For leaf items $i \in I \mid \Gamma_i = \emptyset$.

Since maintenance is a labor intensive service, in our experiments we explicitly consider the effect of wages on the LRU definitions. We define the labor cost as the product of the yearly wage, w, and the direct labor time, r_i. This means that the cost of replacement of an LRU $i \in I$ is: $c_i = c'_i + wr_i$, with c'_i covering material and indirect labor cost.

We use three parameters to produce the asset structures used in each of the three problem sets: *(i)* the number of items in the first indenture level, denoted by $|\Gamma_0|$, the *(ii)* average number of items per parent, denoted by $\overline{|\Gamma_i|}$ and *(iii)* the number of indenture levels, denoted by $|L|$.

In PS1 and PS2 we explore the effect of different indenture structure combinations (see Table 8.2). In PS1 we fixate the number of indenture levels while varying the average number of items per parent, $\overline{|\Gamma_i|}$, and the number of items in the first indenture, $|\Gamma_0|$. In PS2 we vary the number of indenture levels, $|L|$, while keeping constant $|\Gamma_0|$ and $\overline{|\Gamma_i|}$. Besides the different indenture structure combinations, each problem instance in PS1 and PS2 takes one value or range for each of the seven parameters from Table 8.3. This means that we generate a total of $10 \times 2^7 \times 4 = 5{,}120$ problem instances per PS.

Based on the results of PS1 and PS2, PS3 has been designed to focus on the effect of changes in the parent cost, $c'_i \mid \Gamma_i \neq \emptyset$, as a function of the costs of its children. Therefore, the setup is identical to that of PS1, with the exception of two parameters that remain fixated at setting 1 (see Table 8.3) because they were found not to influence the results in PS1 or PS2. This means that for PS3 we generate $10 \times 2^5 \times 3 \times 4 = 3{,}840$ problem instances.

We give more details on the parent-child cost factor, f_c, and the parent cost,

$c'_i \mid \Gamma_i \neq \emptyset$, because this helps to explain the results in Section 8.6.2. A detailed explanation of the other parameters is given in Appendix C.4. For PS1 and PS2 the cost of a parent assembly is proportional to the cost of its most expensive child item, i.e., $c'_i = f_c \max c'_j \mid j \in \Gamma_i$, for $i \in I \mid \Gamma_i \neq \emptyset$. In addition to this setting, in PS3, we also consider $c'_i = \frac{f_c}{|\Gamma_i|} \sum_{j \in \Gamma_i} c'_j$ and $c'_i = f_c \sum_{j \in \Gamma_i} c'_j$. The former setting means that a parent assembly has the average cost of the child items, $j \in \Gamma_i$, multiplied by a cost factor. In the latter setting, the cost of a parent is the sum of the cost of the child items multiplied by the cost factor.

8.6.2 Results

Computation times are mainly driven by the changes in the asset structure settings of Table 8.2. Therefore, Table 8.4 shows the minimum, mean and maximum computation times for each subset of problem instances that share the same asset structure settings. The computation times are typically low, so we do not further focus on them. The remainder of this section discusses the results by answering the following questions:

1. What cost increases result when we compare the optimal LRU definition with defining *(i)* the first indenture (largest) items as LRU and *(ii)* the highest indenture (smallest) items as LRUs?
2. Which model parameters influence the cost increases in the above cases?

Table 8.4: *Computation times of our experiments (in seconds).*

PS	Parameter			Computation time		
	$\lvert\Gamma_0\rvert$	$\overline{\lvert\Gamma_i\rvert}$	$\lvert L\rvert$	min	mean	max
1	50	2	3	0.01	0.03	0.20
	100	2	3	0.03	0.05	0.21
	50	4	3	0.04	0.07	0.26
	100	4	3	0.12	0.18	0.46
2	50	2	3	0.01	0.03	0.24
	50	2	4	0.03	0.06	0.33
	50	2	5	0.07	0.15	0.48
	50	2	6	0.20	0.33	18.37
3	50	2	3	0.03	0.04	0.22
	100	2	3	0.03	0.05	0.08
	50	4	3	0.05	0.06	0.07
	100	4	3	0.11	0.16	0.39

To answer these questions, we solve each problem instance to find the optimal LRU definition, and we apply two heuristics that are based on what we have seen in practice. We call the first heuristic the *large heuristic* (make LRUs as large as possible, i.e., all first indenture items), and denote the resulting costs by C^l. We call the second heuristic the *small heuristic* (make LRUs as small as possible, i.e., all leaf items), and the resulting costs are denoted by C^s. The optimal costs are denoted by C^*. Notice that both heuristics represent a naive approach, because they are generally not followed for all items when defining LRUs in practice. However, we believe that it is a good reference point for contrasting extreme cost results.

We answer Question 1 by showing the cost increases that appear when comparing C^*, with the cost of the two heuristic solutions: C^l and C^s. The percentage increase that we show is calculated as $\frac{C^{l/s}-C^*}{C^*}$. Question 2 addresses the influence of model parameters on the possible cost increases. Answering this question gives managerial insights about the relevant cost drivers in the model. We use an n-way analysis of variance to test the significance of the results for different parameter settings.

To answer Question 1, Table 8.5 summarizes the cost increases over all problem instances. We see that for all PSs, using the heuristics results in huge cost increases compared to the optimal solution, with the small heuristic performing better than the large heuristic. The cost increase for all problem instances is at least 4% (shown in Appendix C.6). These results show that solving the LRU definition problem considering technical aspects only, as is currently common in practice (see Section 8.4), typically leads to high additional costs. Optimization incorporating economic criteria is required.

We next answer Question 2. We discuss only those parameters that have a significant effect on the achieved cost increase. Item replacement time, r_i, and the target number of assets, k, had no significant effect on the cost increase in any of the PSs. Figure 8.6 shows the main effects plot of the cost increase in PS1 for those parameters that have a significant effect (p-values less than 0.05 in the n-way analysis of variance of the cost increase). We discuss each of these effects below. Appendix C.6 shows the minimum (*min*), average (*mean*) and maximum (*max*) cost increase for parameter settings of PS1, PS2 and PS3.

Table 8.5: *Average cost increase between optimal and heuristic solution for PS1-PS3.*

Problem Set	# Instances	Cost increase	
		C^l vs C^*	C^s vs C^*
PS1	5120	62%	33%
PS2	5120	80%	54%
PS3	3840	112%	33%

The largest cost increases result from increasing the number of items per parent ($\overline{|\Gamma_i|}$ from 2 to 4) and the cost factor (f_c from the range [0.5; 1.5] to the range [1; 3]). Both increases mean that costs of leaf items remain the same while parent items become more expensive. As a result, it becomes more costly to make a suboptimal LRU definition. Furthermore, in the optimal solution, the number of LRUs doubles and LRUs are smaller than before. Therefore, we see that the percentage cost increase of the large heuristic compared with the optimal solution becomes much higher, while this effect is much smaller ($\overline{|\Gamma_i|}$) or even reversed (f_c) for the small heuristic.

Increasing the item replacement cost, $c_i' \mid \Gamma_i = \emptyset$, or the item failure rate, m_i, leads to a slightly higher cost increase. While these setting changes do not significantly influence the number of LRUs in the optimal solution, the LRU replacement costs increase with increases in c_i or λ_i. Therefore, the relative contribution of the costs of the fleet to the total optimal costs becomes much smaller: it becomes more costly to make a suboptimal LRU definition.

With increasing asset price, c_0, we found an average reduction in the cost increase for both heuristics. Increasing c_0 has the inverse effect of c_i or λ_i. The reduction in the cost increase results because for more expensive assets the costs of the fleet are higher, and the relative weight of the LRU replacement costs becomes smaller. Finally, changes in w do not lead to large cost increases. The reason is that wages represent a relatively small contribution to the total costs.

Figure 8.7 shows the main effects plot of the cost increase due to an increase in the number of indenture levels, $|L|$, from three to six indentures (settings 1-4) for PS2. Increasing $|L|$ creates more opportunity for allocating cheaper repair options in the optimal solution. We find that the number of LRUs in the optimal solution has large variations within each setting, while remaining almost unchanged for

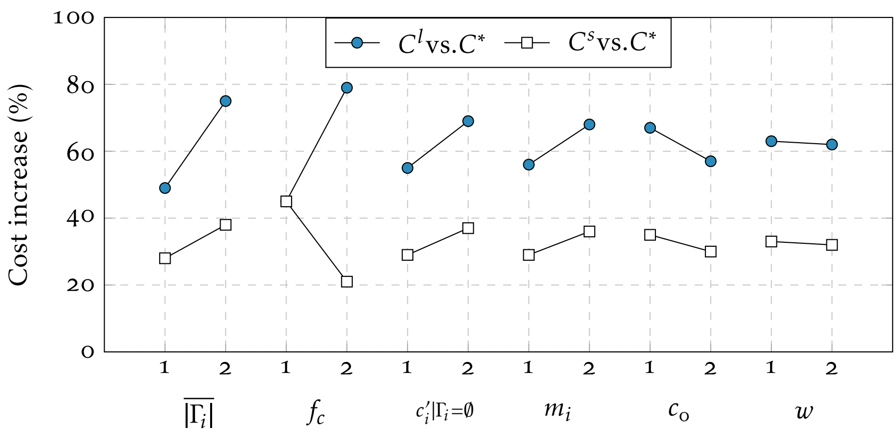


Figure 8.6: *Percentage cost increase for settings (1 or 2) of model parameters for PS1.*

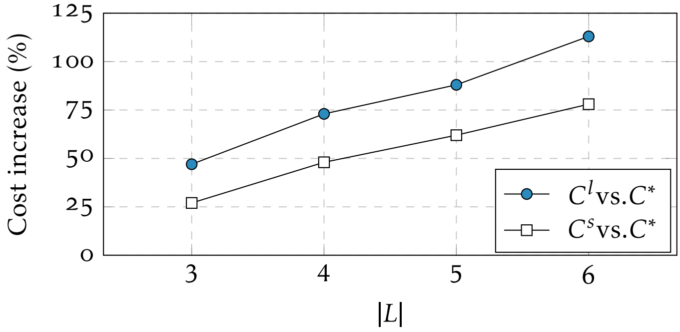


Figure 8.7: *Average percentage cost increase for increasing indenture levels of PS2.*

both heuristics, e.g., for $|L| = 6$, problem instances range from 478 LRUs (closer to the large heuristic) to 1476 LRUs (closer to the small heuristic). Both heuristics result in increased costs.

Figure 8.8 shows the main effects plot of the cost increase given the parent item cost settings for PS3. The differences between the average cost of the parent between settings $\frac{\sum_{j\in\Gamma_i} c_j}{|\Gamma_i|}$ and $\max c_j$ is very small, which explains why they result in very similar cost increases. With $\sum_{j\in\Gamma_i} c'_j$, more small items are defined as LRU in the optimal solution. This makes a small cost increase for the small heuristic, but makes a huge cost increase for the large heuristic.

Summarizing, the cost of parent assemblies relative to child items can have a huge influence on the cost increases. Therefore, if parents become more expensive compared to their children, there is more to gain by making optimal LRU definitions, and these optimal definitions include smaller items.

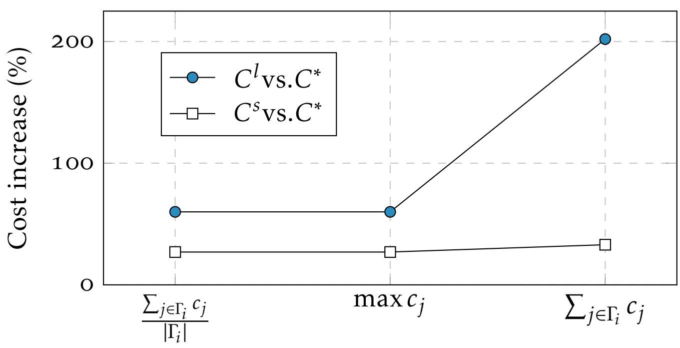


Figure 8.8: *Median percentage cost increase for settings of parent cost, $c'_i \mid \Gamma_i \neq \emptyset$, for PS3.*

8.7 Conclusion

This chapter contributes to the conceptualization of a decision problem. This is done by gathering insights from two cases positioned at two sides of the lifecycle: a system developer and a technical service provider. The selection of the LRUs differs considerably between both cases. In general, the decision is made based on technical aspects. Cost and downtime are not considered together. We model the problem and show important insights through simulation, namely, that cost reductions are possible compared to heuristics currently used in practice.

LRU decisions are not found in the literature. However, we see in practice that a lot of effort is placed in making this decision by the technical service provider. According to the literature, replacement decisions can be modelled using three types of dependencies: stochastic, structural and economic. Chapters 3 and 4 showed that LRU decisions depend on the product properties, especially modularity. Incorporating structural interactions is therefore deemed important, and the artifact is modelled as a rooted ordered tree.

Model development is a suitable support for the later stages of an acquisition project. This chapter supports LRU definitions by using a mathematical model to include factors not currently used in practice. Insights about the LRU definition problem are, namely, (1) technical aspects dominate the decision in practice, (2) it is NP hard and (3) it can lead to important cost savings compared to heuristics found in practice.

Chapter 9

Conclusions and further research

This final chapter draws the conclusions of the research in this thesis. Firstly, it summarizes in Section 9.1 the most important insights that the research contributes, for both theory and practice. This is done by answering the research questions formulated in Section 1.4. Next, the limitations of the research are addressed in Section 9.2. Finally, in Section 9.3 it identifies several directions of further research.

9.1 Conclusions

This section provides detailed conclusions on each of the three main research questions, as well as their respective subquestions. This section also discusses the extent to which we have achieved our research objectives.

RQ1: What is serviceability?

In Chapter 2 we define serviceability as the joint ability of a technical system and its technical service system to afford both the supply and the demand for the technical services that are ultimately destined to sustain a required capability of the technical system throughout its life cycle at a reasonable cost. The quality of the serviceability affordance influences system performance, as measured through the operational availability/cost ratio. This performance ratio has three fundamental constituents, namely, (1) reliability, (2) maintainability and (3) supportability. Reliability and maintainability are not our core focus, they are mostly under full control of the system integrator. Supportability is a property of a technical system that influences all (internal and external) setup processes of the maintenance activities. Given the strong relational component of this property, we argue in the lines of contingency theory that there is no best way to acquire serviceable assets, but the factors for the contingent nature of serviceability can be identified in practice.

RQ2: How do (capital intensive) organizations acquire serviceable assets in practice?

This research question was answered in Chapters 3 to 6. We formulated two subquestions in order to answer RQ2. To understand how organizations acquire serviceable assets, we first need to understand what aspects need to be addressed during acquisitions, and then understand how these are in fact addressed in practice. The first subquestion is:

RQ2a: What serviceability aspects are considered to be important to address during acquisitions?

The empirical case in Chapters 3 and 4 yielded little evidence for one best architecture for the technical system or the technical services. Contingent factors are commonality, modularity and organizational change aspects. We found that the technical service experts at various levels in the organization highlighted the need for flexibility of allocating capabilities across the supply chain in a way that absorbs the uncertainty in demand. This decoupling of capabilities was found to be a primary factor in the service concept. However, this decoupling is contingent on the modularity and commonality of the technical system. This raises important questions about the applicability of the best practices paradigm from the literature for acquisition of serviceable assets.

RQ2b: How is serviceability addressed in acquisition projects in practice?

Continuation of the empirical case in Chapters 5 and 6 showed that decisions that may impact serviceability are mostly left to the supplier before the tender. This is done by explicitly describing the so called maintenance landscape: the service network, infrastructure and maintenance concept of NedTrain. The organization fits new assets to a previously existing service package while improvement projects are carried out mostly independent of asset acquisitions. New assets are merged to an existing fleet's life cycle plan, which introduces a considerable offset in the life cycles of a mixed fleet. These life cycle offsets create additional complexity in balancing the service demand and supply of the installed base. The phenomenon of divergence –a decrease in commonality over the duration of a project– is also present in the case for the acquisition projects. One concludes that commonality should be considered and managed from the start of the project.

After answering both subquestions we can draw conclusions to answer RQ2. Modularity and commonality of new rolling stock platforms, organizational change (e.g., speed of adaptation to service demands of IT and mechatronics), and decoupling of service capabilities are found to be important factors conditioning service performance. However, these factors are not, and cannot be used in contracts using performance requirements. The organization fits new assets to the existing service package while improvement projects are carried out mostly independent of asset acquisitions. In line with best practices, service developers use the previously developed service concepts during acquisitions leading to a premature reduction of the service design space. Serviceability is addressed in the form of a RAMS/LCC plan embedded in the requirements. Solution dependent requirements constrain the creative expertise of suppliers. Intensive communication with the suppliers before contracting ensures that the supplier understands the existing infrastructure and processes. It is the relationship with the supplier that creates success. These insights are used further in the thesis to answer the following research question.

RQ3: How can decision makers be supported in acquiring serviceable assets in practice?

The degree of maturity of rolling stock design before and after contracting is quite different. Before contracting, rolling stock platforms are not currently designed in detail. There is limited information about the subsystems that will be integrated into the platform and the suppliers may not fully disclose the information available to them. After contract, there is enough certainty about suppliers, and detail design information begins to become available. For this reason, developing support should be differentiated between these two epochs in the acquisition project. Two subquestions address the needs before and after contracting, respectively.

RQ3a: What is a suitable way to support the early stages of an acquisition project (before contracting)?

Initial tests show that serious games can be a suitable support for early stages of an acquisition project. In Chapter 7 we developed The Logistic Support Game, a serious gaming tool used to support collaboration and stakeholder involvement. The game was designed to incorporate some of the important design aspects described in Chapter 3 and Chapter 4, as well as some of the decisions described in Chapter 5 and Chapter 6. It helps stakeholders select assets and design their technical services concurrently during early concept development, broadening the service design space. Serious gaming tools could help increase awareness and develop insights about (possible improvements to) the technical services before contracting. By increasing the number and quality of new service concepts, serious gaming can improve the efficiency and effectiveness of the decision making process. This may result in a more successful acquisition project.

RQ3b: What is a suitable way to support the late stages of an acquisition project (after contracting)?

Model development can be a suitable support for the later stages of an acquisition project. In Chapter 8 we developed support for the LRU definitions by using a mathematical model. We included factors not currently used in practice. Insights about the LRU definition problem are, namely, (1) technical aspects dominate the decision in practice, (2) it is NP-hard and (3) it can lead to important cost savings compared to heuristics found in practice.

Chapters 7 and 8 provided insights to answer RQ3. It is found useful to distinguish between support used before and after contracting. Before contracting more effort was needed in concept development, and serious games have shown to provide important benefits in this process. After contracting, we found an interesting problem at the interface of the supplier and the technical service provider. The problem is that of selecting which items to replace upon failure within the indenture structure of the asset. Solving this problem fills an important gap in the literature. We called this problem the LRU definition problem. Both types of support showed promising results.

General conclusions and research objectives

There are four important assumptions that have led to the research described in this thesis. Firstly, that by improving methods for design analysis we are better able to assess the serviceability of new capital assets, as well as the life cycle costs involved in providing the required services. Secondly, that the design properties of a technical system, and of the technical services that support it, can provide the required and sufficient insights to support acquisitions in practice. Thirdly, that structured decision processes during the procurement of capital assets will result in a successful acquisition program. Fourthly, that an equally structured decision process will result in the best possible design of the technical services that fit both the requirements and the capabilities of the service organization.

The general conclusion is that there is no best way to acquire serviceable assets, but the factors that influence the contingent nature of serviceability can be identified in practice. For a company such as Nedtrain, it appears that acquisition of serviceable capital assets is successful when the focus is on relationships, not on transactions. Collaboration and partnerships are more important than the predictability of performance to produce a successful acquisition project. At Ned-Train, a dialog between the technical system owner, the technical service provider and the system integrator including the second tier suppliers (of subsystems) helps mitigate risks and uncertainties before contracting, but close cooperation and communication throughout the project are fundamental after contract.

In Section 1.4 we provided three research objectives:

RO1 Explain the meaning of serviceability.

RO2 Provide insights about the acquisition of serviceable assets.

RO3 Support decision makers in their efforts to address serviceability in large acquisition projects.

We have explained the concept of serviceability in Chapter 2. Subsequently, we used this concept to analyze our case data from Chapter 3 to Chapter 6. In those chapters, we provided insights about the acquisitions of rolling stock and the required technical services at NS. We provided two suitable ways to support decision makers in their efforts to address serviceability during rolling stock acquisitions. Firstly, in Chapter 7 we presented The Logistic Support Game. This was our attempt to bridge the gap between technical service design and technical system selection during acquisition. Secondly, in Chapter 8 we provided a mathematical model to support LRU definition decisions.

9.2 Limitations of the research

The research in this thesis used a combination of research methods, namely, literature reviews, case studies, tool design, modeling and simulation. Data was also collected from a rich mix of data sources. Below, we discuss the data, the case study approach, the game design and the mathematical model.

The data The large majority of the data in this research was collected by the author (principal investigator). At some points in the research, data availability proved problematic, especially availability of detail configuration data for old train series. This of course limited our ability to provide an in-depth comparison of design attributes between different train platforms. Both real-time data and retrospective data was gathered at different times during a four year period. The real-time data collection methods included in this research were mainly observation and simultaneous verbalization. Observation included (i) taking field notes, (ii) counting occurrences and contents of an event and (iii) measuring values and occurrences. Simultaneous verbalization was mainly used in Chapter 7, and focused on recording team discussions and interviewing participants during the actual process. Retrospective data collection methods included documents used for case history and archival analysis, product data, questionnaires, and semi-structured interviews, as well as reports by subjects.

The case study approach The case study is a very powerful research method. It can be used to study real-life phenomena where the context is important.

The real-life setting allows the researcher to gather a wealth of qualitative information that can be used to explore, describe or explain the phenomena. However, the research design of the case study in this thesis was mainly focused on one industry (railway transportation), and one company within this industry: NS. This resolve was made, given the time-span of this research project and the complexity of the phenomena involved in the research. The appeal of a revelatory case was accepted, but developing case studies on other industries could prove to be beneficial. The research can be adapted to other industries, but not without considerable effort. Finally, it has involved the very particular rolling stock maintenance operations in The Netherlands, but further analysis is required when considering other countries and cultures. The extension of such studies is left for further research.

The game design There may be several threats to validity from this approach. Firstly, selection of subjects that participated in the game sessions was non-representative. The participants involved in the first game sessions had a very limited stake in the actual decision process, but were the main contributors to feedback game design. Secondly, the experimental setting has an effect on participants making decisions. Controls may be provided, but were not in place during the expert sessions for several reasons: the game sessions took place at the company, in some cases the facilitator had the dual role of the researcher. This sometimes meant a choice between observing and introducing controls, in which case observation was preferred. Thirdly, the point in time has an effect on participants. Scheduling, location and timing were found by participants to be an important aspect of the session. Fourthly, the current game is highly customized for a specific organization, with an industry specific context.

The mathematical model This thesis used a deterministic modelling approach in Chapter 8. Maintenance events, however, are not always predictable, as also shown in the empirical research. This limits the scope of our model for a practical situation, and further research is required to have such a model implemented in practice.

9.3 Further research

This section gives directions for further research. Firstly, we provide some research directions to improve current understanding of technical systems and their required services. Secondly, we give directions for further research into the use of serious gaming for service design. Thirdly, we provide research directions for improving the LRU definition model.

9.3.1 Industrial Product-Service Systems research

The findings presented in Chapters 3 to 6 describe the acquisition of serviceable assets in the context of the railway industry. The Industrial Product-Service System (IPS^2) literature has pointed to the need to answer additional questions that have not been answered in our research (Baines et al., 2007):

The design of IPS^2 This thesis showed the perspective of a service provider strongly tied to the user/operator, where the external party is the system integrator and the second tier suppliers. We described their approach to designing technical services together with technical systems during acquisitions. How IPS^2 are designed when both the technical services and the technical system fall within the full responsibility of one organization remains an open question (see, e.g., Baines et al., 2007). Further research is required to understand the practices in the railway industry, and in other industry as well.

IPS^2 delivery This thesis described how technical systems (and their services) are acquired (and provided) by one organization. We provided insights into the relationship and collaboration required to manage such complex projects. How this manufacturing and delivery takes place in other industry has been described to a limited extent in the literature, and requires further research (see, e.g., Wynstra et al., 2014).

Uncertainty during acquisitions Uncertainty modeling has not been a focal point of this thesis. However, further research is needed on models, methods and tools to identify, mitigate and manage uncertainties during acquisition projects. The work of Erkoyuncu et al. (2013a,b) has made interesting contributions in this direction, but more research is required in improving their tools.

9.3.2 Serious games and service design

The serious gaming approach presented in Chapter 7 could be improved in several ways. This leads to interesting further research that I will group into five broad categories, namely, design exploration, gaming and design space methods, a service design space exploration method, the game development process and using serious games as a research method.

Design exploration A specific issue identified in this thesis is a need to broaden the design space to make service design decisions: exploring more maintenance concept options during asset acquisitions. Other existing tools for case-based decision analysis using rigorous analogies or quantitative multiple scenario tools could also prove to be useful, and could be researched further.

Links between gaming and design space methods Research is needed to improve the transition between the low fidelity, physical game implementation, and high fidelity computer simulation tools. Improving this transition from games –and the design concepts resulting from such games– to detail design could provide an important contribution to existing research. This research direction would improve existing decision support tools for service design.

Developing a method to explore the service design space Design space exploration is a promising direction of research for service development. However, such methods require a transition from the low fidelity methods –discussed in this thesis– to high fidelity models and tools. Again, from existing product development and systems engineering one can envision several paths for research.

Improving the game development process Gaming has shown several paths for further research. A design method to develop service design games could be useful to shorten this game development process. The development effort should be reduced so that games can be customized in a shorter amount of time. This requirements stems directly from our case experiences. Once participants understand the value of the method as a communication tool, demand for new functionality immediately increases. The effort required to prepare a case situation may limit the usefulness of gamification. Therefore, a method for shorter time to market is required.

Serious games as research method A serious gaming tool could be used as a means to validate conceptual models. We have attempted this in this research but it has proven difficult. Test sessions for the Logistic Support Game were planned to provide contrasting scenarios to participants. These scenarios were aimed to trigger discussions about design aspects influencing rolling stock serviceability. We found a main limitation in the time available to participants. We could not entirely fulfill our model validation objectives. Nevertheless, the idea of using a serious game as a controlled experimental setup to study stakeholder preferences, preference compromising and value frames remains appealing to us. Adapting the serious gaming tool to elicit project uncertainties would also be an interesting approach.

9.3.3 LRU model

The LRU model presented in Chapter 8 can be improved in several research directions. The model assumptions may be relaxed, the model can be extended, and the model can be combined with other existing models. We discuss these directions next.

Model assumptions Some of the assumptions in the current model of the LRU definition problem may be relaxed, especially that of sequential maintenance.

Model extensions The model can also be extended by incorporating limited labor capacity. We have seen that wage differences do not significantly influence in LRU definitions. However, we have also seen in practice a growing concern for labor scarcity in the maintenance industry. Limited manpower (working hours per skill sets) could be an additional constraint in the model. Increasing task frequency builds routine, and helps prevent costly mistakes in maintenance work. A lower bound on replacement frequency can be added as constraint.

Combining with existing models Proceeding in the direction of combining the LRU definition problem with other problems would be useful to support the joint maintenance and logistics decisions for re-defining LRUs, for example at NedTrain. One way would be to combine it with LORA, e.g., the work by Basten et al. (2011). This means combining the MILP model for the LRU definition problem with the MILP model for the LORA problem. It may also be beneficial to help maintenance assessment by combining the LRU definition problem with the joint optimization of level of repair analysis (LORA) and spare parts stocking (see Section 8.3.4). One way would be by extending the work by Basten et al. (2012). This means combining the MILP model for the LRU definition problem with the MILP model for the LORA problem. Solving that MILP first and then a spare parts stocking model. Using a feedback loop to the MILP model leads to an iterative heuristic to solve the joint problem.

Appendix A

Scope and measure of serviceability

A.1 Serviceability scope

Table A1 shows the scope of operations and setups typically considered in the manual labor of technical system maintenance. Serviceability includes a broad scope of activities including installation, maintenance, repair, field service, upgrades, IT information processing and condition monitoring, degradation

Table A1: *Examples of operations and setups in our definition of serviceability of Section 2.4.*

Type	Examples
Essential operations	**Mechanical manual repairing**: replacing, removing/installing, dismounting/mounting, disassembling/assembling, dettaching/attaching, slackening/tightening, unsecuring/securing, unlocking/locking, disconnecting/connecting, carrying, lifting, loading, inspecting, testing, verifying, fluid compartment checking, component checking, adjusting, lubricating (oiling, greasing), modifying, draining, filling, replenishing, cleaning, correcting, controller tuning, calibrating, software upgrading, debugging.
Auxiliary operations	Quality control, work approval.
Margin allowances .	Energy expenditure, posture, head room, visual demand, multiple operator coordination.
Internal setup	Field transportation, access hatches and covers, condition data management.
External setup	Online support, documentation release, work order release, spare parts supply, manpower supply, facilities/equipment release, equipment calibration, tool-kits preparation, close work order.

management, obsolescence management and autonomous maintenance.

A.2 Maintenance time

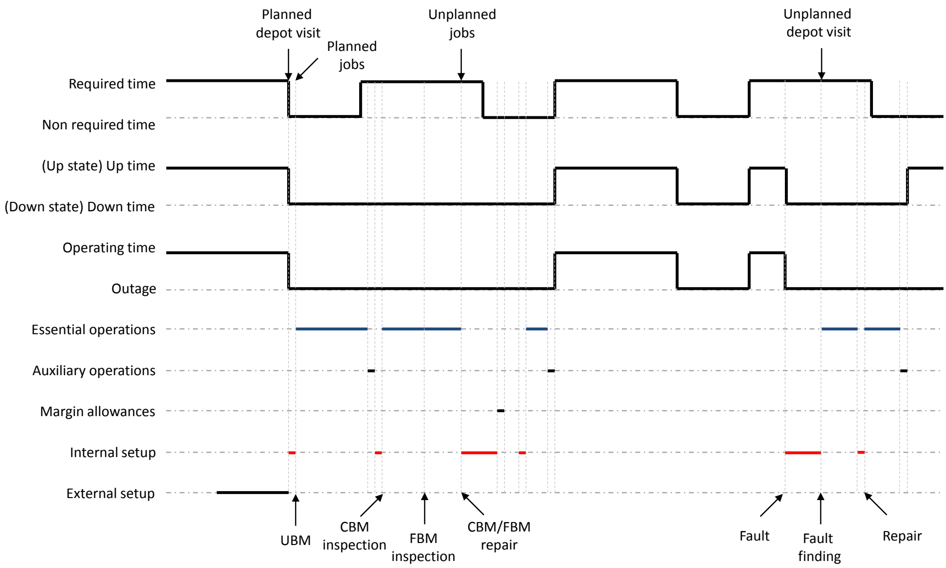


Figure A.1: *Maintenance time and the concept of operations and setups, inspired by Huisman (2014); NEN-EN (2010). CBM: condition based maintenance; FBM: failure based maintenance; UBM: use based maintenance*

Appendix B

The Logistic Support Game

This appendix gives additional detail about The Logistic Support Game presented in Chapter 7. It presents the different decisions available to game participants. Next, it explains the different maintenance events. Finally it presents the questionnaires used for collecting participant feedback.

B.1 Game material

The basic material used in the game session is shown in Figure 7.6(a) of Chapter 7, above. The main parts of the game are the game board, train cards, maintenance cards, fleet management cards and overview cards. The game board has a simple layout of a rail network consisting of three lines connecting three main locations (cities), labeled A through C. A total of 8 intermediate locations are available within the network. Each of the three lines is allocated a number of slots for train cards, and demand for passenger service is indicated to participants through visual cues. Development of the tool includes additional material, for example, game coin and visual cues. These cues are physical objects that help to identify and visually link locations to maintenance cards.

Train cards represent a rolling stock series that can be purchased to provide transport capacity. Train cards allow the participants to choose between Inter City (IC), Stop Train (ST), High Speed (HS) and HYbriD (HYD) train formulas. This choice synthesises commonality at the fleet level. Many different options of train cards may be provided to trigger a specific discussion about a design attribute of a train. One side of the train card shows the type of train formula, the platform name, the capacity, the cost and the life cycle plan (regular maintenance and overhaul epochs). This is the operations side of the train card. The reverse of the train card is the maintenance side of the card. This side displays special maintenance, random maintenance, LRU replacement level and type of main parts.

Maintenance cards are a bundle of cards that may be purchased to provide capabilities. These cards are the maintenance facility card, special resource cards and tool/equipment cards. The maintenance facility card is a placeholder for a maintenance facility, and is linked to a specific location on the game board via visual cues. To expand capabilities, participants can choose to install additional resources on the maintenance facility card, while linking these resources to different locations on the network. This allows the maintenance facility card to embody a maintenance concept's resources, while actually decoupling the capabilities from a specific facility location.

Fleet management cards consist of a set of visual cues that help keep track of the operational (and non-operational) fleet. Firstly, a fleet management board keeps track of the game rounds and assists participants in keeping track of the life cycle of each individual train series, as represented in the operations side of the train card. Secondly, a set of small cards allows the reproduction of the train card's life cycle on the fleet management card. A train series identifier provides visual cues to help identify a particular train card. This links the train cards, the game board, and the fleet management board.

Game overview cards are provided to help players communicate information. The steps of the game round are shown in the game round card. The details of the different train cards are summarized in the train characteristics card. Maintenance resource installation costs, use costs and withdrawal are summarized in the maintenance components & costs card.

B.2 Decisions

The service design decisions included in the game are the decisions from areas covered in Chapter 5. These decisions include: facilities, facility location, repair capacity, installation of resources, maintenance policy and concepts and, of course, asset selection. Facilities can be purchased to provide a basic maintenance capability. The facility location decision is linked to the decision to purchase a facility. Once a basic facility is located, the decision to install additional resources can be made. All of these decisions are allowed in a specific moment of a game round. Players decide on the amount of resources required for repair, as well as the type of resources. The capacity decision is designed into the game so that players have to trade off investing in maintenance capacity and providing the necessary transport capacity for passenger service.

Installation of capabilities include installation of tools, roof access, overhaul or fault diagnosis. Tools may be purchased and are specific to the train, or to particular modules of the train, namely, boogies or wheelsets. Roof access is a special capability required by specific train types in the game world. Overhaul capability allows players to extend the life of a train card for an additional period, as indicated in a train card's life cycle plan. Finally, fault diagnosis can be installed to facilitate dealing with random maintenance events. These events are explained below. Additional capabilities may be installed and linked to a specific location, but this location need not be the location of a basic facility. At an additional cost, resource capabilities may be introduced at a different location than the original facility. This embodies the concept of decoupling.

Decisions on maintenance policy and concept are linked to the lifecycle plan of the fleet in the game world. This is tied to the asset selection decision. Several train series have to be purchased during a game session in order to provide enough transport capacity, as required by the session scenario. Transport capacity is provided by making three decisions: selection of a train type, chosing the amount of trains to buy, and allocating the train to a particular train line.

B.3 Maintenance events

Three types of maintenance events are considered, namely, *basic maintenance*, *regular maintenance* and *random maintenance*. Maintenance events are included in the lifecycle plan of a particular train type, as issued in a train card.

Basic maintenance identifies minor maintenance, namely cleaning, basic inspections or minor repairs. This has no consequence for train withdrawal as long as the required capability has been installed. The *use capability* cost is the cost of using basic maintenance, and is a recurrent cost in each round. Basic maintenance pays transport costs whenever the maintenance facility is not located on the origin of a line.

Regular maintenance identifies planned maintenance of the train, bogie or wheelset. This may have a consequence on train withdrawal depending on the level of replacement selected in the maintenance concept. Regular maintenance can only be produced if the *install capability* cost has been paid, i.e., the resource is installed. The *use capability* cost is paid for each event occurrence. Regular maintenance can be necessary for the train level, the bogie level or the wheelset level depending on the specification of the train card. Regular maintenance pays transport costs whenever the maintenance facility is not located on the origin of a line.

Random maintenance identifies unplanned maintenance of the train, bogie or wheelset. This may have a consequence on train withdrawal depending on the outcome of the fault diagnosis event. Random maintenance can only be produced if the *install capability* cost has been paid for the required repair level or above, i.e., the resource is installed for that level. Random maintenance can be necessary for a train, a bogie or a wheelset. The *use capability* cost is paid for each event occurrence. Random maintenance pays transport costs whenever the maintenance facility is not located on the origin of a line. Dices are thrown for each train per round. If no diagnostics exist, and the random repair event appears, the train card must be allocated to the train workflow of a maintenance card.

B.4 Game scenarios

Different game scenarios are possible using The Logistic Support Game. The initial scenario used for the test sessions consists of a greenfield approach. The game in this scenario has the goal of an initial investment to develop a rail network that is under a tender. Players are instructed to invest in such a way that they can keep operating the network for a specific number of rounds, earning profits and providing the required transport capacity. This is a very demanding scenario, and produces most cognitive strain. There are many degrees of freedom to the problem setting, and many paths are possible.

A new asset introduction scenario is ideal for training sessions. The game is set-up in such a way that the technical system (fleet) and the technical service system are given. The participants are instructed to play two rounds. During these two rounds, the game is introduced. During the third round a challenge is introduced in which they are asked to identify a specific train card that they would replace to either reduce costs or increase their income. No changes to the technical service system are allowed. This fleet replacement problem triggers the discussion, and helps participants engage and ask questions during the training session.

A new service system scenario is used to trigger the discussion about new service development. This scenario is very similar to the new asset introduction scenario. The main difference appears on round three. At the beginning of that round, participants are instructed to make investments or changes to the technical service system to either reduce costs or increase their income. Participants are not allowed to make changes to the fleet, i.e., they may not invest in new train cards. Although this scenario has many similarities to the previous one, the decision process is much more complex for new service development. Mainly, there are more intervening variables and the participants must be familiar with the game dynamics to produce a fertile discussion.

A cost reduction scenario is made for the case session. This scenario shares elements of the previous two scenarios. However, in the case session participants are allowed to make an unrestricted investment decision after the second round. Unrestricted means that they may choose to lower costs by either changing the technical service system, by changing the technical system, or by doing both.

B.5 Questionnaires for evaluation of test sessions

To the participant: Please answer the following questions.

The session

1 What did you think of the session?

2 Did you find it useful? Why?

3 Did you enjoy it? Why?

4 What do you think of the duration of the session?

5 Would you want to do a similar session again? Why?

6 If so, when and how many times would you want to this?

7 What did you think of the group? Think, for example, about the number of people and the various functions they have.

8 Do you have any suggestions for improvement?

The game

9 Do you think the purpose is clear and understandable? Why?

10 What do you think of the decisions that are included?

11 Are any decisions lacking? If so, which?

12 Are any decisions redundant? If so, which?

The decision

13 During the session some of the train cards were chosen by your team. Would you still have chosen the same ones? Why?

14 Do you feel you better understand the way the decision was made?

15 For which level in the system would you ideally want to select a maintenance significant item using such a session?

16 Do you have any other remarks?

Difficulty

17 During the game, you selected train models...(write down which):

18 What aspects did you consider when making this decision?

19 How did you expect this to influence the game outcome?

To the participant: Rate the following statements by using the scale provided (1 means strongly disagree, 7 means strongly agree).

20 I didn't take a lot of time to choose a train

21 I was careful about which train I chose

22 I thought very hard about which train to pick

23 I didn't pay much attention while making this choice

24 I concentrated a lot while making this choice

25 It was difficult for me to make this choice

26 I did not understand the rules for making this choice

27 I had enough information to make this choice

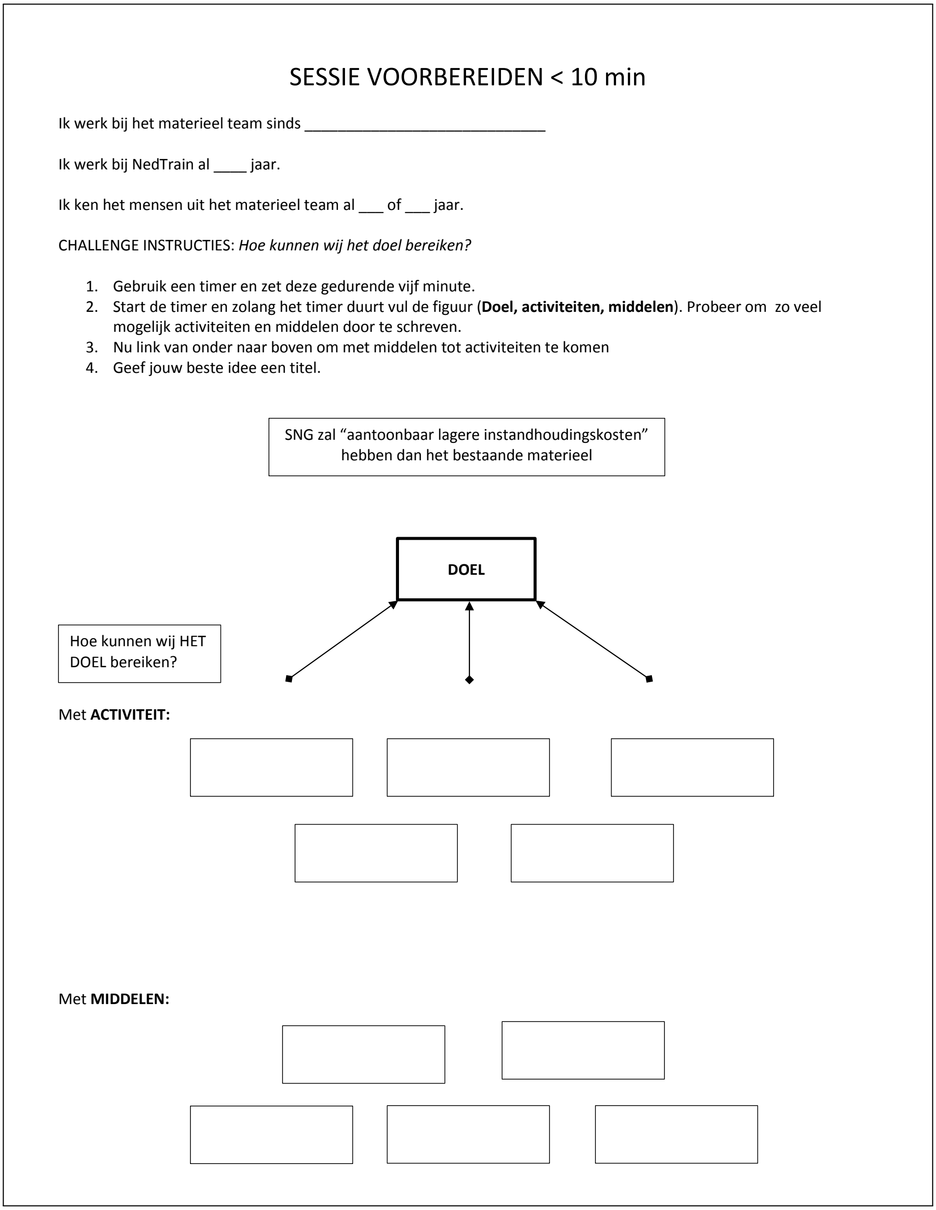
28 The information on the train card was useful

To the participant: Answer the following question by using the scale provided (1 means very little effort, 7 means great deal of effort).

29 How much effort did you put into making this decision?

B.6 Preparation for the case session

A problem solving questionnaire is provided by email in preparation for the case session. The survey instrument is displayed in Figure B.1.



SESSIE VOORBEREIDEN < 10 min

Ik werk bij het materieel team sinds ______________________________

Ik werk bij NedTrain al ____ jaar.

Ik ken het mensen uit het materieel team al ___ of ___ jaar.

CHALLENGE INSTRUCTIES: *Hoe kunnen wij het doel bereiken?*

1. Gebruik een timer en zet deze gedurende vijf minute.
2. Start de timer en zolang het timer duurt vul de figuur (**Doel, activiteiten, middelen**). Probeer om zo veel mogelijk activiteiten en middelen door te schreven.
3. Nu link van onder naar boven om met middelen tot activiteiten te komen
4. Geef jouw beste idee een titel.

SNG zal "aantoonbaar lagere instandhoudingskosten" hebben dan het bestaande materieel

DOEL

Hoe kunnen wij HET DOEL bereiken?

Met **ACTIVITEIT:**

Met **MIDDELEN:**

Figure B.1: *A survey instrument is used to measure individual perceptions of the game sessions.*

Ik zou de volgende titel voor mijn beste idee gebruiken

____

Sketch jouw titel:

Figure B.1: *(Continued).*

Appendix C

LRU definitions

C.1 Notation Summary

In this appendix, we summarize the notation that we use in this thesis. First, we define the sets, then the parameters, and finally the decision variables.

Sets	
I	set of all maintenance significant items. For convenience we denote $i = \{1, 2, \ldots, \|I\|\}$, where $\|I\| \in \mathbb{N}$.
Γ_i	set of items that are direct children of item $i \in I$.
A_i	set of items that are ancestors of item $i \in I$.
D_i	set of all descendants of item $i \in I$.

Parameters	
m_i	individual failure intensity of item $i \in I$; $m_i \geq 0$.
r_i	mean replacement time for item $i \in I$; $r_i \geq 0$.
c_i	cost per replacement of LRU item $\forall i \in I$; $c_i \geq 0$.
c_0	periodic acquisition cost for an asset; $c_0 > 0$.
k	target number of available assets; $k \in \mathbb{N}$.

(Auxiliary) Variables	
λ_i	failure intensity of item $i \in I$, including the failure intensity of direct descendants that are SRU.

Decision Variables	
N	Number of (systems) products, $N \in \mathbb{N}$
X_i	$\begin{cases} 1, & \text{if component } i \in I \text{ is defined as LRU,} \\ 0, & \text{otherwise;} \end{cases}$

C.2 Linearization

In this appendix, we linearize the mathematical model described in Section 8.5.2. The objective function, and Constraints 8.2-8.4, contain products of the cumulative failure rate λ_i and the decision variable X_i. This product is a nonlinear expression. We linearize these expressions by introducing an auxiliary variable ρ_i that is equal to $\lambda_i X_i$. We further define Λ_i as the failure intensity of item $i \in I$, including the failure intensity of all its descendants. It is a Big M variable and it is computed recursively: $\Lambda_i = m_i + \sum_{j \in \Gamma_i} \Lambda_j$. The linearized LRU definition problem is shown below. The objective function and constraints C.2 to C.4 are the same as the objective function and constraints 8.2 to 8.4 in the original model, with $\lambda_i X_i$ being replaced by ρ_i. Constraints C.5 to C.8 are added.

$$\min \quad c_0 N + \sum_{i \in I} c_i \rho_i \tag{C.1}$$

$$\text{s.t.} \quad N - \sum_{i \in I} r_i \rho_i \geq k \tag{C.2}$$

$$\lambda_i = m_i + \sum_{j \in \Gamma_i} (\lambda_j - \rho_j), \; \forall \; i \in I \tag{C.3}$$

$$\lambda_i \leq \rho_i + \sum_{j \in A_i} \rho_j, \; \forall \; i \in I \tag{C.4}$$

$$\rho_i \leq \Lambda_i X_i, \; \forall \; i \in I \tag{C.5}$$

$$\rho_i \leq \lambda_i, \; \forall \; i \in I \tag{C.6}$$

$$\rho_i \geq \lambda_i - \Lambda_i (1 - X_i), \; \forall \; i \in I \tag{C.7}$$

$$\rho_i \geq 0, \; \forall \; i \in I \tag{C.8}$$

$$N \in \mathbb{N} \tag{C.9}$$

$$X_i \in \{0, 1\}, \; \forall \; i \in I. \tag{C.10}$$

C.3 Proof that the LRU definition problem is NP-hard

We show that the binary knapsack problem (BKP) can be reduced to the LRU defintion problem in polynomial time. Since the BKP is known to be NP-hard, see for example Martello and Toth (1990, p. 6), this proofs that also the LRU definition problem is NP-hard.

The BKP is the problem of selecting items $j \in J$ to put in a knapsack with a fixed capacity C, such that a profit is maximized. Each item $j \in J$ gives a profit p_j and has a weight w_j. An item $j \in J$ is selected to be put in the knapsack if $x_j = 1$;

$x_j = 0$ otherwise. The mathematical model formulation is then:

$$\begin{aligned} \text{minimize} \quad & \sum_{j \in J} p_j x_j \\ \text{subject to} \quad & \sum_{j \in J} w_j x_j \leq C \\ & x_j \in \{0, 1\}, \forall j \in J \end{aligned}$$

We next construct an instance of the LRU definition problem. We set $k = 1$ and below we will show that as a result of our formulation, $N = 2$. For now, we thus assume that $k - N = -1$. We define a product structure with one dummy component, indicated by -1, that has $|J|$ subcomponents; to be more precise, $\Gamma_{-1} = J$. We define $p^{\max} = \max_{j \in J}\{p_j\}$ and set $c_{-1} = p^{\max}$ and $m_{-1} = 0$. We then set, for $i \in J$, $m_i = 1$, $c_i = p^{\max} - p_i$, and $r_i = w_i/C$. We come back to r_{-1}, but we assume for now that $r_{-1} = 0$. The LRU definition problem for this instance is then:

$$\begin{aligned} \text{minimize} \quad & 2c_0 + p^{\max}\lambda_{-1} + \sum_{i \in J}(p^{\max} - p_i)X_i && \text{(C.11)} \\ \text{subject to} \quad & \sum_{i \in J} \frac{w_i}{C} X_i \leq 1 && \text{(C.12)} \\ & \lambda_{-1} = \sum_{i \in J}(1 - X_i) \\ & \lambda_i = 1, \forall i \in J && \text{(C.13)} \\ & \lambda_i \leq X_i + \lambda_{-1} X_{-1} && \text{(C.14)} \\ & X_i \in \{0, 1\}, \forall i \in J \cup \{-1\} && \text{(C.15)} \end{aligned}$$

To see that the objective function is correct, notice that $X_{-1} = 0 \iff \lambda_{-1} = 0$, while $X_{-1} = 1$, otherwise, and that $\lambda_i = 1$ for $i \in J$ as a result of Constraint (C.13). Using that $\lambda_{-1} = \sum_{i \in J}(1 - X_i)$, following Constraint (C.13), and that $X_i \in \{0, 1\}$, we can rewrite the objective function to become:

$$\text{minimize} \qquad 2c_0 + p^{\max}|J| - \sum_{i \in J} p_i X_i,$$

and since the first two terms are constant, this is equivalent to:

$$\text{maximize} \qquad \sum_{i \in J} p_i X_i.$$

By further noticing that in Constraint (C.12) we can multiply both sides of the equation by C and that Constraints (C.13) and (C.14) are basically used for book keeping, we see that we have constructed an instance of the LRU definition problem that, when solved, gives the solution for our original binary knapsack problem. (Notice that to find Constraint (C.12) we have used that we can make both sides positive instead of negative, which means that the inequality is reversed.)

The only point remaining is that we need to ensure that $N = 2$. We can achieve this by, on the one hand, ensuring that there is always a strictly positive (small) workload, so that $N > k = 1$, and on the other hand, setting $c_0 \geq p^{\max}|J|$ so that $N \leq 2$. Ensuring that there is always a small workload can be achieved by setting $r_{-1} = \epsilon$ and setting $r_i = \epsilon + w_i(1-\epsilon|J|)/C$, with $\epsilon|J| << \min_{i\in J}\{w_i\}$. Instead of Equation (C.12) above, Equation 8.2 in the LRU definition model will then become (notice that $\lambda_{-1} = \sum_{i\in J}(1 - X_i)$):

$$N - \sum_{i\in J}\left[\epsilon + \frac{w_i(1-\epsilon|J|)}{C}\right]X_i - \epsilon\sum_{i\in J}(1-X_i) \geq k$$

$$\epsilon|J| + \sum_{i\in J}\frac{w_i(1-\epsilon|J|)}{C}X_i \leq N - k,$$

which ensures that there is always a small positive workload, while the same optimal solution will still result.

C.4 Problem instance generator

In this appendix, we explain the problem instances generator. The settings that we use for the parameters are listed in Table 8.3 in Section 8.6.1. In the explanation here, we assume setting 1 for each parameter.

The number of items per indenture level are given in Table 8.2 in Section 8.6.1. Each item at indenture level $L+1$ is randomly assigned to a parent (at indenture level L) using a uniform distribution on the parent indenture's index range. The number of children per parent will thus differ per parent.

The annual demand for an item, m_i, is drawn per item from a uniform distribution on the interval $[0.01; 0.1]$. The leaf item's replacement costs, i.e. c_i, for $i \in I \mid \Gamma_i = \emptyset$, are drawn from a shifted exponential distribution with shift factor 1,000 and rate parameter $7/(10{,}000 - 1{,}000)$. As a result, we do not have items with a price below €1,000 and approximately 5% of the items' prices exceed €10,000. Therefore, there are typically more cheap than expensive items.

The parameter f_c is drawn from a uniform distribution on the range $[0.5; 1.5]$. The item replacement lead time per hour, r_i, is drawn from a uniform distribution on the range $[0.25; 2]$. Asset prices are drawn from a uniform distribution on the range €$1{,}000 \times [200; 400]$.

C.5 LRU requirements at Thales

Table A1 shows a summary of the LRU requirements at Thales, including mandatory and preferred criteria.

Table A1: *LRU requirements at Thales.*

Criteria	An LRU shall be...
	(Mandatory Criteria)
Structure	physically separable from the asset
Identification	uniquely identifiable for codification as a spare part
Testing	independently testable and reproducible
Task	replaced using prescribed maintenance procedures
	(Preferred Criteria)
Fault detection	detected and localized by use of built-in testing
Handling	sized not to exceed the following limits (95th percentile, weighed with the failure rates†): weight of one LRU is lower than 16 kg, dimensions (mm) of one LRU are lower than 600×450×450. Remaining LRUs (max. 5th percentile) shall be in accordance with the requirements of MIL-STD-1472F, §5.9.11
Weight	of a target weight of less than 10 kg. If the LRU weight is between 10 kg and 25 kg, provisions shall be made for two-handed transportation. If the weight is between 25kg and 45kg, transportation by two persons or hoisting facilities shall be in place. If the LRU weight exceeds 45kg, the LRU shall be equipped with hoisting facilities
Interface	secured in place by mechanical fastening (clip or screw) to a maximum of 4
Interface (electric)	connected via free mounted plug and socket connectors, to a maximum of 3
Interface (fluid)	provided with "quick disconnect" type liquid or air connections
Reliability	every equipment, assembly, or part contributing to the asset MTBF with a failure rate of more than 2 per million hours
Task	replaced within a time of 30 minutes (hands-on-tool-time 95th percentile, weighed with the failure rates†)
Adjustment	pre-tuned, so that it can be replaced without readjustment

† At least 95% of all maintenance actions should conform to this requirement.

C.6 Results summary

Table A2 shows the results for PS1, PS2 and PS3. We only show the full list of results for parameter settings in PS1, because these parameter settings had similar results in PS2 and PS3.

Table A2: *Cost increases for settings of parameters in all three problem sets.*

PS	Par.	Set.	C^lvs C^*(%)			C^svs C^*(%)		
			min	*mean*	*max*	*min*	*mean*	*max*
1	$\lvert\Gamma_0\rvert$	1	5	62	132	4	32	68
		2	10	62	117	7	33	64
	$\overline{\lvert\Gamma_i\rvert}$	1	5	49	113	4	28	61
		2	19	75	132	11	38	68
	f_c	1	5	45	81	7	45	68
		2	14	79	132	4	21	33
	c'_i	1	5	55	130	4	29	66
		2	21	69	132	12	37	68
	m_i	1	5	56	131	4	29	66
		2	19	68	132	11	36	68
	r_i	1	5	62	132	4	33	68
		2	5	62	132	4	33	68
	k	1	5	62	132	4	33	68
		2	5	62	132	4	33	68
	c_0	1	15	67	132	10	35	68
		2	5	57	131	4	30	67
	w	1	5	63	132	4	33	68
		2	5	62	132	4	32	68
2	$\lvert L\rvert$	1	5	47	113	4	27	61
		2	13	73	133	12	48	86
		3	28	88	141	25	62	97
		4	39	113	179	34	78	126
3	$^\dagger c'_i$	1	5	60	132	4	27	68
		2	5	60	132	4	27	68
		3	24	202	423	5	33	61

† Setting 1, 2 and 3 are $c'_i = \frac{f_c}{|\Gamma_i|}\sum_{j\in\Gamma_i} c'_j$, $c'_i = f_c \max c'_j \mid j \in \Gamma_i$, and $c'_i = f_c \sum_{j\in\Gamma_i} c'_j$, respectively, for all $i \in I \mid \Gamma_i \neq \emptyset$.

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About the Author

Jorge Eduardo Parada Puig was born in Mérida, Venezuela. He is still mostly both a happy kid, and a curious entrepreneur. He loves people, music, travel, food, industrial maintenance and robotics.

He is a Mechanical Engineer and M.Sc. in Control and Automation Engineering from the Universidad de Los Andes, Venezuela. He enjoyed the guidance of many great people. In 2002, he took his first steps in engineering research with the group at LARM, doing his apprenticeship at the University of Cassino (Cassino, Italy). There, he was mentored by Prof. Marco Ceccarelli, Chiara Lanni, Erika Ottaviano and Giuseppe Carbone, while back in Venezuela Sebastián Provensano reviewed his work, and Miguel Angel Diaz R. supervised his graduation assignment in the area of design of machines and mechanisms. In 2005 he became part time teaching instructor in his alma mater, the Universidad de Los Andes. He was appointed as lecturer under the chair of Production and Operations Management. There, Prof. José Domingo Nava introduced him to the field of maintenance engineering. He worked closely with students on industry problems which involved facilities planning, maintenance planning, reliability assessment, maintenance documentation and maintainability analysis. His deep interest in complex artifacts and their social impact has lasted ever since. His interests from his experience at LARM remained, and with the supervision of Pablo A. Lischinsky, Jorge received his Master of Science in 2008.

Outside his academic career Jorge has followed his diverse interests. In 2003 he began a small career in agriculture, followed by free-lance work on mechanical design for Zamuro, a startup of mechanical and industrial designers. Jorge continued pursuing his engineering interests and co-funded Iguano, a startup also specialized in mechanical and industrial design consulting. Jorge was Managing Director for Iguano in 2005-2007.

As of September 2010, Jorge has been conducting research in the supportability analysis part of the so called "Rolling Stock Life Cycle Logistics" R&D program of NS/NeTrain. He was the first in the chair of Maintenance Engineering of the Department of Design, Production and Management at the University of Twente.

Jorge will continue to pursue his interests in technical services, robotics and people.

I suspect that in the not so distant future, machines will take care of each other.
It may be time for people to do the same.