UNIVERSITY OF TWENTE.

Public

Academic year 2018-2019

Faculty of the Behavioural, Management and Social sciences

M.Sc. thesis

Reducing the duration and variance of external repair lead times

Author

Coen van Ommeren

Graduation committee members

First supervisor: Dr. ir. Petra Hoffmann

Second supervisor: Dr. ir. Fredo Schotanus

Daily supervisor: Klaas Stek, M.Sc.

Company supervisors

First supervisor: Company supervisor A

Second supervisor: Company supervisor B

Colofon

Document:

Master thesis

Title:

Reducing the duration and variance of external repair lead times

Author:

Coen van Ommeren

Email address author:

Coen.vanommeren@gmail.com

University:

University of Twente

Faculty:

Faculty of Behavioural, Management and Social Sciences

Programme:

Industrial Engineering and Management

Specialization:

Production and Logistic Management

Graduation date:

September 2019

University supervisors:

Dr. ir. Petra Hoffmann
Dr. ir. Fredo Schotanus
Klaas Stek, M.Sc.

Company supervisors:

Company supervisor A
Company supervisor B

Glossary

Bounded rationality According this theory, the rationality of decision making is limited by the information the decision maker has due to the uncertainty of future contingencies. Page 10,11,12.[1]

Corrective maintenance unplanned maintenance as a result of unexpected failures. Page 8, 9, 13, 14.[2]

Ex works The buyer is responsible for the transport to and from the supplier. This places minimum responsibility on the supplier. Page 49.[3]

Facultative part A sub component which could be possibly the reason of repair. Page 13, 41, 45, 46, 47, 53.

Forecast error A measurement for the accuracy of the forecast. Page 44.

Incoterms Set of rules which define the responsibilities of the suppliers and buyers for the delivery of components by contracts. Page 27, 49, 50, 52, 54.

Logistic critical An article is said to be logistical critical if the system may not function without this article being built in. Page 22.

Obsolescence "the loss of, or in process of losing, the last known supply or availability of an item or component". Page 41, 46, 47, 54.[4]

Opportunism Acting only according one's own goals, regardless of what is morally desired. Page 10, 12, 59.[5]

Preventive maintenance Scheduled maintenance to prevent corrective maintenance. Page 8, 22.[6]

---

[1] See Cox (2002), p.13
[2] See Andrzejczak, Mlynczak & Selech (2018), p.1
[3] See Van Wezel (2017-2018), p.6
[4] See Meyer, Pretorius & Pretorius (2003),p.122
[5] See Luo & Meyer (2016), p.528
[6] See Andrzejczak, Mlynczak & Selech (2018), p.1

Resource Based View In line with this theory four criteria are most relevant for a company's resources to distinguish for sustainable competitive advantage in a business environment: Value, rareness, substitutability and imitability. Page 11.[7]

Saturation of salience This principle supports the idea of obtaining the most salient items rather than obtaining all possible items including the very rare with less impact. Page 26, 27, 29, 32.[8]

Strategic supply risk The risk of not being treated as a preferred customer. Page

System dynamics "technique used for modelling and simulating dynamically complex issues and analysing their resulting non-linear behaviours over time in order to develop and test effectiveness of complex systems". Page 56. [9]

Transaction Costs Economics In line with this theory, prices do typically not reflect all the various aspects which are relevant for making the make-or-buy decision. Page 10.[10]

Turn Around Time The Time it takes to fulfil a request. Page 48, 49, 52, 54.

Upstream the supply chain The supply network of suppliers and sub suppliers. Page 7, 9, 14, 44, 46, 53.

Returned Material Authorization The process of providing the supplier information regarding the reason of disassembling before sending the item. Depending on the capacity, subcomponents and expertise available, the supplier could communicate its preference for a specific production site the repair must be send to. Page 45, 46, 47, 52, 53.

[7] See Barney (1991), p.99
[8] See Weller, Vickers, Bernard, Blackburn, Borgatti, Gravlee & Johnson (2018), p.1
[9] See Pruyt & Hamarat (2010), p.3
[10] See Christopher & Lee (2004), p.6

List of acronyms

CBM Condition Based Monitoring. Page 49.

ERP Enterprise Resource Planning. Page 8, 19, 35, 38, 48, 49, 50, 51, 54, 56.

IP Intellectual Property. Page 52.

KPI Key Performance Indicator. Page 41, 48, 49, 50, 54.

MRO Maintenance Repair and Overhaul. Page 3, 49.

Location X Central stock and repair shop Company X. Page 19, 20, 35, 37, 38, 49.

Company X The Dutch segment X group.

OEM Original Equipment Manufacturer. Page 51.

O&S Operation and Service. Page 1, 3.

RBV Resource Based View. Page 10, 11.

RMA Returned Material Authorization. Page 45, 46, 47, 53, 54.

SCO Supply Chain Operation. Page 1, 2, 4, 5, 6, 10, 20, 23, 31, 34, 35, 39, 41, 44, 48, 49, 51, 52, 53.

SQA Supplier Quality Assurance. Page 40.

SD System Dynamics. Page 56.

SSW Sum of Squares Within groups. Page 21.

TAT Turn Around Time. Page 48, 49, 52, 54.

TCE Transaction Costs Economics. Page 10.

TCO Total Cost of Ownership. Page 9.

Management samenvatting

Deze Master thesis *Het reduceren van de variatie en duur van levertijden van de reparaties welke worden uitbesteed*, beschrijft in eerste instantie het onderzoek naar de mogelijkheden om de variatie en duur van de huidige levertijden van uitbestede reparaties te reduceren voor Afdeling X. This sentence has been removed fort his public version. De directe beschikbaarheid van gebruiksklare Xonderdelen zijn van essentieel belang voor Company X Onderhoud en Service om haar onderhoud effectief uit te voeren. Company X Operatie had over de afgelopen vier jaar gemiddeld een voorraad nodig van X euro om deze beschikbaarheid te garanderen. De variatie in de levertijden van de reparatie van deze Xonderdelen heeft een directe impact op de veiligheidsvoorraden welke benodigd zijn om de gewenste beschikbaarheid van Xonderdelen te garanderen. Het reduceren van de variatie en duur van deze levertijden kan voor een significante afname zorgen van de benodigde veiligheidsvoorraden zonder dat er moet worden ingeleverd op de effectiviteit van het onderhoud. Op deze manier kan Afdeling X bijdragen aan een efficiëntie slag voor Company X door het reduceren van haar uitbestede reparatielevertijden.

De hoofdvraag van dit onderzoek luidt: **Hoe kan Company X de variatie en duur van haar levertijden reduceren betreffende de reparaties welke worden uitbesteed?** Om deze vraag te kunnen beantwoorden, hebben wij eerst een literatuuronderzoek gedaan naar mogelijke relevante onderdelen of aspecten van de mogelijke oorzaken van een variatie in levertijd. Aanvullend is hiervoor ook de expertise binnen Afdeling X geraadpleegd. Deze bevindingen hebben geleid tot veelbelovende interview vragen voor de interviews welke gevoerd zijn met een relevante subset van leveranciers van Company X. Op basis van deze interviews kon geconcludeerd worden dat de aspecten ‘Forecasting’, ‘Onzekerheid tijdens het reparatieproces’ en ‘Focus on X’ de meeste potentie hebben voor Afdeling X om de variatie en duur van haar levertijden te reduceren. De volgende drie paragrafen zullen de betreffende methodes per aspect samenvatten. Deze methodes trachten gebruik te maken van het beschikbare potentieel per aspect om de variatie en duur van uitbestede reparatielevertijden naar beneden bij te stellen. Voor een detailoverzicht van deze methodes verwijzen wij u door naar paragraaf 4.3 van deze thesis.

Momenteel wordt er bij Department X geen gebruik gemaakt van het volle potentieel wat forecasting technieken te bieden hebben. Een duidelijke forecast vergezeld met een zakelijke overeenkomst betreffende de gewenste levertijd, motiveert de leverancier en zijn toeleveranciers

om op tijd te anticiperen. Zakelijke overeenkomsten in combinatie met een forecast zijn nodig gebleken om de leverancier te motiveren om vooruit te bestellen en om vervolgafspraken te maken met zijn toeleveranciers. Wij adviseren om deze afspraken betreffende levertijden te relateren aan een zakelijk overeengekomen zekerheidsinterval van de forecast.

Zelfs in het geval Afdeling X een 100% accurate forecast af zou geven van het aantal te verwachte reparaties, zal de leverancier nog steeds een onzekerheid ondervinden betreffende de facultatieve delen welke benodigd zijn om het reparatieproces te vervullen. Een RMA (Return Material Authorization) proces waarbij de leverancier op voorhand informatie verschaft krijgt betreffende de reden van uitbouw is daarom onder andere geadviseerd. Een RMA-proces geeft de leverancier meer informatie over de sub componenten die waarschijnlijk benodigd zijn om de reparatie uit te voeren. Door formeel met de leverancier in te stemmen over een gemiddelde prijs en levertijd, zal de leverancier daarnaast gemotiveerd zijn om op basis van deze RMA-informatie sub componenten vooruit te bestellen. Niet alleen de onzekerheid aan de vraagzijde van deze sub componenten draagt bij aan een variatie in levertijd. Ook de onzekerheid aan de aanbodzijde van deze sub componenten bleek wezenlijk bij te dragen aan de variatie in levertijden. Wij adviseren Afdeling X daarom om met haar leveranciers formeel overeen te komen tot uiterste productie- en reparatiedata. Daarnaast zal de leverancier gemotiveerd en geïnstrueerd moeten worden om de forecast welke hij ontvangt van Afdeling X letterlijk te vertalen naar zijn toeleveranciers. De leverancier zal daarvoor een vertaling moeten maken naar het aantal sub componenten welke benodigd zijn om aan de forecast van Afdeling X te kunnen voldoen. Deze vertaling van de forecast blijkt een randvoorwaarde voor de leverancier om formele afspraken te kunnen maken met zijn toeleveranciers betreffende levertijden.

This paragraph has been removed for this public version

Management Summary

This Master graduation thesis *Reducing the variance and duration of external repair lead times*, is initially about researching the possibilities for reducing the variance and duration of lead times for the repairs which are being outsourced by Department X (Supply Chain Operations). Department X experiences pressure from the Dutch government to improve its efficiency in maintaining and operating its X. The availability of ready-for-use spare parts is essential for Company X Maintenance and Service to conduct its maintenance in an effective way. During the last four years Company X had on average a spare parts inventory equalling 125 million Euros per year in order to ensure its availability of spare parts. Variance in lead times corresponding to the supply of spare parts influences the safety stock needed to reach the desired availability of spare parts. Reducing the variance and duration can dramatically reduce the needed stock levels without harming the maintenance effectiveness. In this way, Department X can contribute to the goal of making Company X a more efficient organization by reducing the variance and duration of its outsourced repair lead times.

The main question for this research is therefore the following: **How can Company X reduce the variance and duration of its external repair lead times?** In order to answer this question first parts of or aspects related to the causes of a variance in these outsourced repair lead times have been obtained from literature and available expertise within Department X. These insights led to promising inquiry areas for the interviews which have been conducted with a subset of Company X' suppliers. Based on the results of these interviews it could be stated that the aspects 'Forecasting', 'Uncertainty in repair process' and 'Focus on X' have most potential for Department X to reduce the variance and duration of its outsourced repair lead times. The next three paragraphs will concisely summarize the methods related to these aspects.

Currently, the full potential of forecasting techniques is not being used by Department X. A clear and reliable forecasting technique in combination with formal agreements regarding the desired repair lead time, enables the supplier and its upstream suppliers to anticipate sufficient ahead in time. Formal agreements regarding lead times appeared to motivate suppliers to subsequently make formal agreements with their sub suppliers and to order subcomponents in advance. We

advise Department X to form these agreements with its suppliers in conjunction with a formally agreed confidence interval relating to the communicated forecast.

Even when Department X communicates a 100% reliable forecast regarding the number of repairs it will send, the supplier still faces uncertainty regarding the facultative parts needed to fulfil the corresponding repair processes. An RMA (Returned Material Authorization) process which informs the supplier in more detail about what could be possibly the reason of repair, already improves the knowledge upfront regarding the subcomponents needed. In combination with formally agreed standard delivery times and prices, the supplier will be more motivated to perform actions ahead in time. Not only the uncertainty on the demand side of subcomponents appeared to be contributing to a variance in repair lead times. Also, the uncertainty regarding the supply side of subcomponents appeared to be a significant cause of a variance in repair lead times. Therefore, we advise Department X to formally agree with its suppliers on obsolescence dates for each article or subcomponent they produce or repair. Besides, suppliers must be motivated to translate the Company X forecast into the subcomponents needed for repair and communicate this undistorted to their sub suppliers. This forms a precondition for these suppliers to make subsequently formal agreements with their sub suppliers regarding lead times.

This paragraph has been removed for this public version

Preface

There it is! My final thesis, which describes the result of the research I did in the field of supply chain operations. This research allowed me to gain valuable and practical insights in the world of lead times and spare parts from a logistic point of view. I believe that these insights will provide me a launch in my future career. Therefore, I am grateful for Department X for assigning me such a complex and extensive research.

For realizing the result of this research, I have been to places I did not expect to be. I made my first ever business trip, to Berlin. I additionally visited the Hutchison ports of Company C in Rotterdam and conducted in-depth interviews with Military D and Fokker. It was an astonishing discovery to see the similarities in maintenance and supply chain operations even though organizations like Military D and Fokker certainly do not maintain X.

I should like tobegin by thanking my girlfriend Nora, for always providing me coffee when I needed one and for reminding me not to stare too long at my thesis. I also would like to thank my parents and brother, for always supporting me during this study.

Then I also would like to thank Company supervisor A and Company supervisor B. First, I do like to thank Company supervisor A for his wise words during this study and showing me the ins and outs of Department X. Secondly, I would like to thank of course Company supervisor B for always bringing me positive energy, being there when I needed a second eye and last but not least for making the necessary jokes.

I certainly also would like to thank my supervisors Petra Hoffmann, Fredo Schotanus and Klaas Stek. I always felt welcome in the cosy office of Klaas Stek. I really appreciated your enthusiasm in providing me relevant literature, books and structure. Besides, I greatly valued your listening ear.

I would like to thank Contractmanager A for having a critical look at my thesis and simultaneously giving me so now and then a compliment for the advancements I made regarding my English. Supply Chain specialist B, I really appreciated your willingness and enthusiasm for sharing your valuable knowledge and insights regarding the underlying principles of the techniques being currently applied in the field of maintenance and supply chain operations.

Contents

1. Introduction 1

1.1. Research context 1

1.2 Research problem 2

1.2.1 Focus on efficiency 2

1.2.2 Importance of lead times in relation to maintenance 3

1.2.3 Effect of lead times on inventory 4

1.3 Research Questions. 5

2. Theory 7

2.1 Potential root causes unpredictable lead times 7

2.1.1 Uncertainty in demand 7

2.1.2 Uncertainty in supply 9

2.1.3 Uncertainty in process 10

2.2 Potential methods for decreasing unpredictability of lead times according to literature 12

2.2.1 potential methods for decreasing demand uncertainty 13

2.2.2 potential methods for decreasing supply uncertainty 14

2.2.3 potential methods for decreasing uncertainty in process 15

2.3 Classification for the approached suppliers 16

2.4 conclusion 17

3. Methodology 18

3.1 Approach for clarifying current situation and agreements regarding external repair lead times ... 18

3.1.1 Approach for gaining an insight in current agreements between Department X and its suppliers 19

3.1.2 Approach for clarifying definition of an external repair lead time within Department X and how these are being monitored 19

3.1.3 Approach for data-analysis current variance and duration of external repair lead times 21

3.1.4 Considerations for a categorization of articles ... 22

3.1.5 Conclusion ... 23

3.2 Approach for determining a relevant subset of suppliers and clarifying what root causes are responsible for a variance in external repair lead times ... 24

3.2.1 Approach for determination of relevant subset of suppliers ... 24

3.2.2 Approach for setting up interviews with Company X' suppliers ... 26

3.2.3 Method for processing propositions into interview questions ... 29

3.2.4 Conclusion ... 30

3.3 Approach for formulating effective methods ... 30

3.3.1 A scoring model for quantifying the potential ... 30

3.3.2 Approach for formulating methods to counteract a variance in external repair lead times ... 33

3.3.3 Benchmarking approach for gaining practical insight regarding implementation of methods ... 34

3.3.4 Conclusion ... 35

3.4 Conclusion ... 35

4. Results ... 35

4.1 Current situation external repair lead times ... 36

4.1.1 Agreements between Department X and its suppliers regarding repair lead time performance ... 36

4.1.2 Definition of external repair lead time within Department X and broad segmentation of its variance ... 37

4.1.3 Current variance and duration of outsourced repair lead times ... 39

4.1.5 Conclusion ... 41

4.2 Root causes of a variance in external repair lead times for Department X ... 41

4.2.1 Subset of suppliers for conducting the interviews ... 41

4.2.2 Additional empirical evidence for propositions ... 42

4.2.3 Interview questions ... 43

4.2.4 Root causes 45

4.3 Methods for decreasing variance in external repair lead times 47

4.3.1 Methods corresponding to the forecasting aspect 47

4.3.2 Methods for counteracting uncertainty in the repair process 50

4.3.3 Methods for enhancing Focus on X on repair lead times 52

4.3.4 Implementation of methods 54

4.4 Conclusion 54

5. Discussion 56

6. Academic contribution 58

7. Conclusion 60

8. Limitations and further research. 62

References 65

List of figures

Figure 1. 1: Organogram Company X 2
Figure 1. 2: Segmentation outsourced repair lead time 3
Figure 1. 3: Relation safety stock and variance in repair lead time 4

Figure 2. 1: Visualization of demand patterns (Erratic, Lumpy, intermittent and smooth) 8

Figure 3. 1: Schematic visualization methodology 18
Figure 3. 2: Approach sub question one 23
Figure 3. 3: Approach for retrieval of the most salient causes of variance 28
Figure 3. 4: Steps scoring model at a high level of abstraction 33
Figure 3. 5: Approach for formulating methods for reducing variance 34

Figure 4. 1: Segmentation of an external repair lead time 38
Figure 4. 2: Example data-analysis conducted per article 39
Figure 4. 3: Current and potential additional measuring points 53

List of tables

Table 2. 1: Elements based on literature to characterize the interviewed suppliers 17

Table 3. 1: Drawbacks and remedies for defining relevant subset of suppliers 26
Table 3. 2: Consulted specialties within Company X for achieving an exhaustive interview...... 27
Table 3. 3: Scores of potentials for improvement 31
Table 3. 4: Scores of relevance for improvement 32
Table 3. 5: Scores for potential of reducing variance and duration external repair lead times 32

Table 4. 1: Referring to figure 4.1, the portion in percentages per segment of external lead time as monitored by Department X for suppliers located in a foreign country.................................. 38
Table 4. 2: Referring to figure 4.1, the portion in percentages per segment of external lead time as monitored by Department X for domestic suppliers ....**Fout! Bladwijzer niet gedefinieerd.**
Table 4. 3: Categorization per interviewed supplier 42
Table 4. 4 : Outline of the conducted interviews with Company X' suppliers............................. 43
Table 4. 5: per supplier its representation expressed in the number of repaired articles 45
Table 4. 6: Causes per aspect of an unpredictable repair lead time 46
Table 4. 7: Methods for decreasing the variance and duration in outsourced repair lead times relating to the forecasting aspect.. 49
Table 4. 8: Methods for decreasing the variance and duration in outsourced repair lead times relating to the forecasting aspect.. 52
Table 4. 9: Methods for decreasing the variance and duration in outsourced repair lead times relating to the forecasting aspect.. 54

1. Introduction

In order to give an understanding of the context in which this research is conducted first some background information will be provided. This chapter includes a company description, a problem description and the research questions. Since this research focuses on lead times corresponding to outsourced repairs, an emphasis will be made on the importance of lead times.

1.1. Research context

This paragraph has been removed for this public version

This research is conducted for the Supply Chain Operation (SCO) department of Department X. SCO is a division of the Maintenance and Service department (O&S) of Company X. O&S is responsible for the cleaning, maintaining and refurbishing of its X. An organization chart has been inserted in figure 1.1. SCO administers, manages and deals with all the contracts for the spare parts and equipment needed to keep the X of Department X operational. SCO has the specific task to look for an optimum balance between inventory holding cost, operational cost and stock-out costs. This department decides on which inventory levels to attain for which components at which locations.

This paragraph has been removed for this public version

Figure 1. 1: Organogram Company X[11]

As explained, SCO decides for each component which inventory levels to attain while ensuring the availability of its X. The next chapter will explain how this decision has a dependence on lead times corresponding to the (outsourced) repair of these X.

1.2 Research problem

This description of the research problem begins by explaining why Company X has recently increased its focus on efficiency. The next subsection explains how lead times have a direct impact on the extent to which Company X could keep its X operational in an efficient way. This efficiency potential of lead times will be clarified by explaining the effect of lead times on needed inventory.

1.2.1 Focus on efficiency

This paragraph has been removed for this public version

Currently Company X is on the right track towards achieving a sufficient score on all agreed performance levels for 2025[12]. The current levels of performance have been partly a result of significant investments done by Company X. In order to ensure the possibility of doing these investments also in the future, Company X should actively search for possibilities for making its

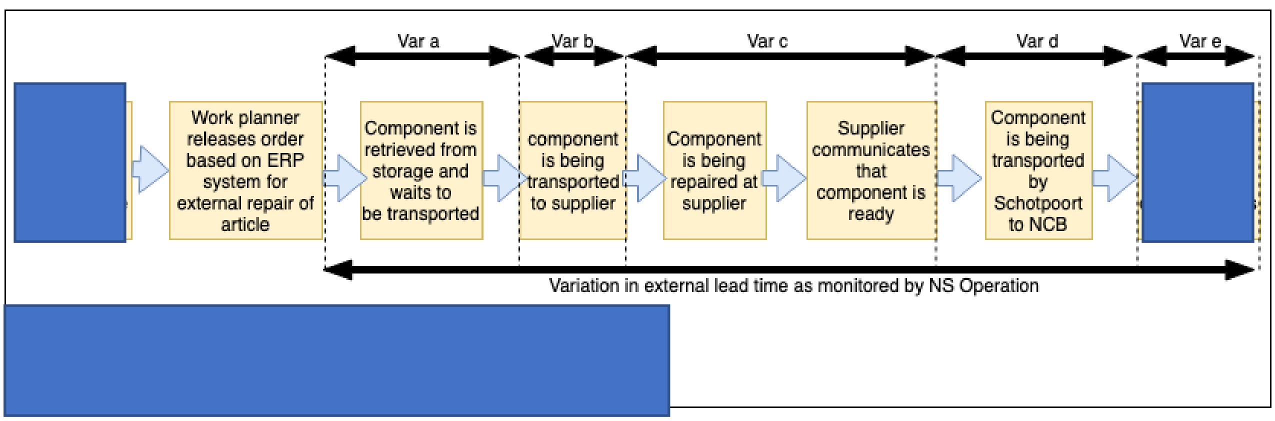
[11] See Nederlandse Spoorwegen. (2018a). Company X Insite, online platform for Company X employees.
[12] See Nederlandse Spoorwegen (2018b)

operations more efficient[13]. In the next subsection it will be explained why the current fluctuation of the duration of outsourced repair lead times hinders an efficient maintenance strategy.

1.2.2 Importance of lead times in relation to maintenance

Department X conducts its maintenance by applying a repair-by-replacement principle. This principle implies that the to be repaired article is demounted from the X and replaced by a ready-for-use article. To be able to adequately apply this principle, the availability of ready-for-use spare parts at its maintenance locations is critical. During the last four years Company X had on average a spare parts inventory equalling X euros per year in order to ensure this availability of spare parts. If a spare part is being sent to an external supplier for MRO activities, there will be an external lead time. This external lead time differs however per supplier and per type of spare part. Beside this difference in lead times per supplier and per spare part, the duration of a lead time corresponding to a specific repair fluctuates. These lead times do fluctuate in such a manner that these lead times form an unpredictable factor for Department X. Multiple steps are included in an external repair lead time and could be the reason of this fluctuation. The demarcation of a variance in an outsourced repair lead time is being depicted in figure 1.2 at a high level of abstraction.

Figure 1. 2: Segmentation outsourced repair lead time



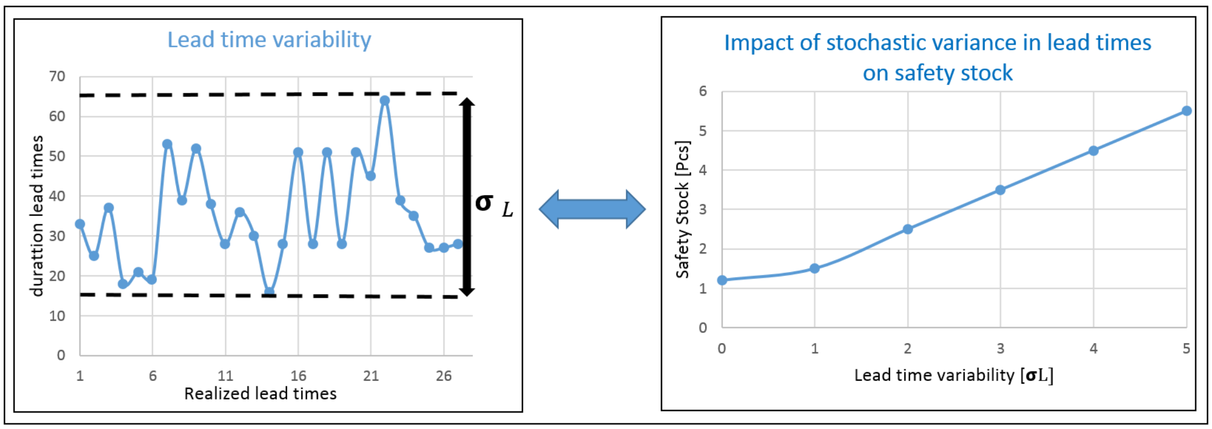
The next subsection describes how reducing the current unpredictable fluctuation in outsourced repair lead times could directly contribute to the goal of Department X towards achieving more efficiency.

[13] See Nederlandse Spoorwegen (2019b)

1.2.3 Effect of lead times on inventory

As explained, the availability of ready-for-use spare parts is essential for Company X Maintenance and Service to conduct its maintenance. Variance of lead times corresponding to the spare part supply influences the safety stock needed to reach a certain availability of spare parts[14] (see also figure 1.3). Reducing this variance can therefore dramatically reduce the needed levels of safety stock without harming the maintenance effectiveness. Besides, according queuing theories, shorter lead times require fewer spare parts needed solely for accommodating the duration of an outsourced repair lead time[15].

Figure 1. 3: Relation safety stock and variance in repair lead time[16]



Department X wishes to contribute to the goal of making Company X an organization which remains able to invest in itself by reducing the level of spare part inventories needed. As explained above, Company X could realize this by reducing the variance and duration of its outsourced repair lead times.

Insight should be gained in the driving factors behind a variance in these lead times. Based on the complete picture of what drives a lead time to be shorter or longer for Department X, methods should be determined which counteract the effect of these causes of a variance in outsourced repair lead times. The next subsection describes which essential steps must be made to gather the essential information needed for realizing these methods. Research is needed to come to a set of methods which have the most potential for successfully decreasing the variance and duration of outsourced repair lead times.

---

[14] See He & Jeang (2009), p. 1
[15] See Winston & Goldberg (2004), p.1073-1074
[16] See Chopra, Reinhardt & Dada (2004), p.17

1.3 Research Questions.

As explained above, Department X wishes to reduce the variance and duration of its outsourced repair lead times. This will directly contribute to the goal of making Company X an organization which remains able to invest in itself by being financially healthy. In this chapter it will be explained how this research will contribute in gathering sequentially the essential information. The main question for this research is the following:

"How can Company X reduce the variance and duration of its external repair lead times?"

In order to answer this main research question, three subsequent research questions have been formulated. The first research question must clarify the situation in which these external repair lead times prevail. Therefore, first there must be an understanding of what is currently being agreed upon between Company X and its suppliers regarding the condition of these lead times. It must be additionally addressed based on which information Department X evaluates these agreements. The first research question in this research is therefore an exploratory one and concerns:

1. *Which agreements has Department X currently with its suppliers regarding the variance and duration of outsourced repair lead times? Based upon which information is Department X evaluating the accomplishment of these agreements?*

The solution to the main research question will be in the form of one or multiple methods or approaches which realize a reduction of the variance and duration of outsourced repair lead times. The full potential of this desired set of methods or approaches could only be achieved based on a complete picture of the most salient causes of a variance in outsourced repair lead times. In order to ensure this full potential, the research should initially focus in obtaining the driving forces of a variance in these lead times for Department X. This brings us to the next sub-question:

2. *Which root cause or set of root causes of a fluctuation in lead times are present and have most potential for decreasing the variance and duration of external repair lead times?*

If possible, this research concentrates itself from this point onwards on a specific root cause or set of root causes which have most potential for decreasing the variance and duration of outsourced repair lead times. This research now will be fully devoted to finding possibilities for eliminating or reducing the effect of these root causes found. Root causes will be linked to a set of methods which have potential to significantly reduce their effect. A well proven method is preferred by Department X. The following research question is therefore:

3. *Which methods or approaches can significantly reduce the effects of the retrieved set of root causes in a permanent way?*

Before answering each sub-question, academic literature will be consulted to discover what already has been written in the corresponding field of interest regarding a lead time. In the next chapter these literature studies per sub-question have been organized into a logical narrative.

2. Theory

A theoretical framework for this research is provided in this chapter. Firstly, this literature study is intended to provide possible root causes of unpredictable lead times. Uncertainty is a direct consequence of the unpredictability of lead times. As expressed by Koh and Saad in 2002, uncertainty is defined as "Any unpredictable event in manufacturing environments that disturbs operations and performance of an enterprise" [17]. Due to this inherent relation of unpredictability and uncertainty in manufacturing environments, causes of uncertainty in literature have been considered and, when reasonable, explained and treated here as potential (root) causes of a variance in lead times. These potential root causes contributed in forming promising inquiry areas for the interviews conducted with Company X' suppliers during a later stage in this research.

This chapter also summarizes a literature study which provided a theoretical framework for formulating the available methods which have potential to reduce the variance in lead times for Department X.

2.1 Potential root causes unpredictable lead times

First a literature study has been done for obtaining what already has been written in academic papers about potential root causes. The sources of a variance in lead time obtained by literature study were rather general and include, uncertainty in demand, uncertainty in supply and uncertainty in process. As noticed by Angkiriwang, Pujawan & Santosa, this supply chain uncertainty could be categorized according downstream-, upstream- and process- uncertainty[18]. This categorization will also be used here to describe the potential root causes of unpredictable lead times described by literature.

2.1.1 Uncertainty in demand

The first class of supply chain uncertainty which could be distinguished in literature relates to uncertainty in demand. Andrzejczak, Mlynczak & Selech (2018) have studied the occurrence of random failures for technical complex objects which must fulfil high requirements regarding cost-consumption, safety, ecology, availability and functionality. According to this research random

[17] See Koh and Saad as cited in Wazed, Ahmed & Yusoff (2009), p.24
[18] See Angkiriwang et al. (2014), p.53

failures for these complex technical objects are as good as unavoidable during its operation.[19] These random failures result in **corrective maintenance**. Corrective maintenance concerns all the maintenance which is not included in scheduled or **preventive maintenance**. Due to the random nature of corrective maintenance, knowledge of stochastic processes is of value when trying to keep the material efficient and safe during operation. This requires extensive and detailed knowledge concerning forecasting the frequency of failures during their operation.

Syntetos, Boylan & Croston, (2004) suggest a model for the classification of demand patterns for this corrective maintenance[20]. This model is based on the variances in frequency and quantity of historic demand. As indicated in figure 2.1, the following classes could be distinguished based on this model:

- Smooth demand: Regular intervals of demand with a limited variance in the quantities
- Intermittent demand: Sporadic demand with no significant variance in the quantities
- Erratic demand: Regular intervals of demand with a significant variance in the quantities
- Lumpy demand: Great number of intervals with no demand in combination with a significant variance in the quantities

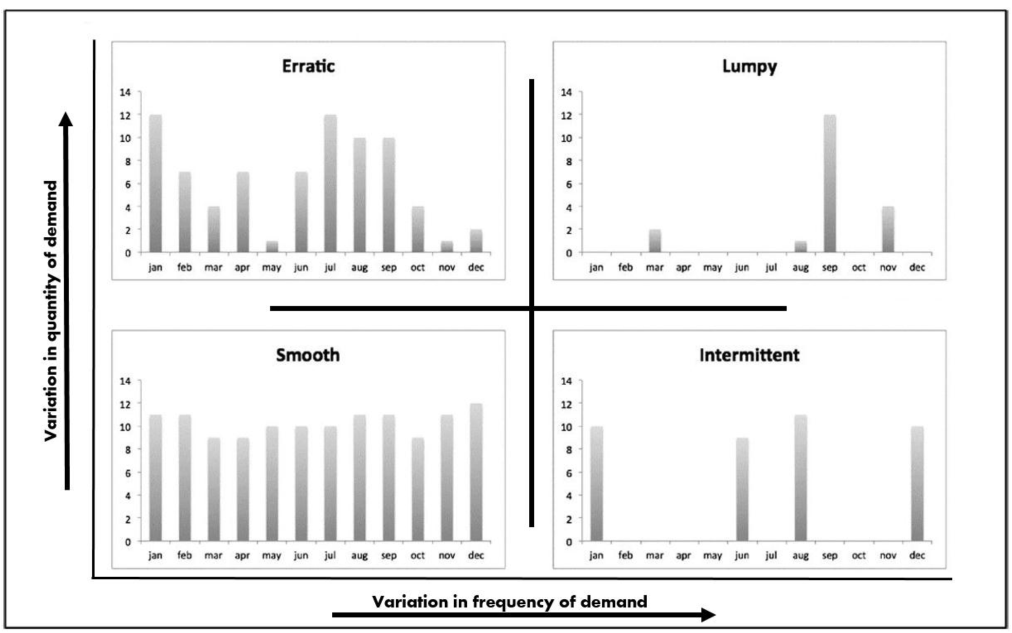


Figure 2. 1: Visualization of demand patterns (Erratic, Lumpy, intermittent and smooth)

[19] See Andrzejczak et al. (2018), p.1 - 2
[20] See Syntetos et al. (2004), p.708

The more uncertain the moments are at which demand occurs and the more uncertain the corresponding quantities are, the more unpredictable the demand will be. The Lumpy category gives therefore the most uncertainty[21].

Above, categorizations of randomness inherent to the demand for repairs corresponding to corrective maintenance has been described. There is a danger of amplification of this randomness if we go upstream in the supply chain. This is phenomenon is caused by the well-known Bull whip effect. This danger is inevitable if companies across the supply chain operate as autonomous firms even though they form a part of the supply chain. This reduces the effective information flow across the supply chain. Ineffective information sharing, in combination with the fact that each manufacturer has different views of interpreting customer information, ultimately results in the Bull whip effect[22].

In this section the uncertainty related to the often lumpy and intermittent demand of spare parts for corrective maintenance has been discussed. We argued based on this literature that this uncertainty and therefore unpredictable demand influences the variance of repair lead times. There is a danger of amplification of this uncertainty if we go upstream in the supply chain. This danger is caused by the well-known Bull whip effect.

2.1.2 Uncertainty in supply

The next class of supply chain uncertainty which could be distinguished in literature relates to uncertainty in supply. This paragraph will first discuss the relevance of material availability for lead times based on the Total Cost of Ownership (TCO) principle. According to Heijmann, TCO includes all benefits and costs over the whole lifetime of the services or goods. Opportunity costs are also included in the TCO.[23] When a component needed for a repair appears to be out of stock, the supplier must place a backorder. In case of no formal arrangements regarding lead times, the main costs of a backorder for the supplier is a loss of goodwill and customer satisfaction due to a longer repair lead time. For Company X however, the same backorder and the resulting shortcoming in supply could result in lost revenue by leaving a X not capable for being in operation. This is for example the case for **logistical critical** articles. An article is said to be

[21] See Hautaniemi & Pirrtilä (1999), p. 89
[22] See Balasubramanian, Whitman & Ramachandran (2001), p.1
[23] See Heijmann (2013), p.12

logistical critical if the system may not function without this article being built in. Hence, TCO costs corresponding to a backorder are significant higher for Company X than for the supplier. Therefore, it is argued that the supplier has less incentive to put components needed for repair on stock. Especially if these components are slow movers and relatively expensive. This assumption will be tested by asking the supplier for its driving forces for putting components on stock. As explained by Tang (2005) and by Mohebbi & Choobineh (2004), material availability and supply lead times form the major factors for determining supply uncertainty[24]. Based on this explanation we propose a proposition which states a positive correlation between uncertainty in supply at the supplier and the variance of external lead times of Department X.

2.1.3 Uncertainty in process

The next class of supply chain uncertainty which could be distinguished in literature relates to uncertainty in process. This uncertainty relates to the internal operations of a manufacturing process. Based on the theoretical considerations for sourcing activities in or out, additional potential root causes will be formulated. According Cousins et al. and Hansen & Schütter the two main theories for these make or buy decisions concern the Resource-Based View (RBV) and Transaction Cost Economics (TCE)[25].

This paragraph discusses the presence of uncertainty in process as a result of transactional difficulties described by the Transaction Cost Economics (TCE) Theory. Christopher and Lee describe that, as a consequence of outsourcing activities, uncertainty could arise as a result of low visibility or no confidence across the supply chain[26]. This low visibility and no confidence across the supply chain seems to correspond to the transactional difficulties which arise when outsourcing[27]. These difficulties are the prominent risk of **opportunism** and **bounded rationality**[28]. According the Transaction Cost Economics (TCE) theory, prices typically do not reflect all the various aspects which are relevant for making the make-or-buy decision. Opportunism is defined by Luo and Meyer as distorting information and misleading the other party by making use of an asymmetry in relevant knowledge in order to achieve one's goals[29]. As

[24] See Tang (2005), p.458 and Mohebbi & Choobineh (2004), p.1
[25] See Cousins, Lamming, Lawson & Squire (2008), p.27 and Hansen & Schütter (2009), p.1
[26] See Christopher & Lee (2004), p.6
[27] See Teece (1976), p.2
[28] See Klein, Crawford & Alchian. (1978), p.7
[29] See Luo & Meyer (2016), p.528

described by Selten, the bounds of rationality are a result of the limitations corresponding to what human beings are able perceive[30]. As a consequence of this bounded rationality, human beings are susceptible for non-optimal decision behaviour. For example, while they are trying to optimize their profits in a business environment. Due to bounded rationality a contract could be based on possibly opportunistic information and promises given by the contractor. As a result, incomplete contracts are not an exception in complex market transactions[31]. Besides, according to Hoffmann, bounded rationality can be become a problem in uncertain business environments[32]. This could for example lead to capacity or material availability problems at an Company X' supplier when Company X is not able to estimate future demands.

By using the Resource Based View (RBV) theory, this paragraph discusses potential causes of uncertainty in process due to the presence of the preferred customer status principle. In line with its RBV theory, Barney states in 1991 that four criteria are most relevant for a company's resources to distinguish for sustainable competitive advantage in a business environment: Value, rareness, substitutability and imitability[33]. Madhani summarizes these criteria in his paper in 2010 as resource heterogeneity and immobility[34]. If a firm is in the possession of resources which are to a significant extent imperfect in mobility, substitutability and imitability, it will achieve advantage which is not available in market forms of transactions. According to Company X a typical trend in Company X procurement and after-sales market can be seen in which an increase in property rights is noticed[35]. According Lazzari et al. property rights, information asymmetry, asset specificity and contracts also contribute to the heterogeneity of resources[36]. As a result, not all companies are to the same extent capable of producing and/or repairing certain products and/or services. This scenario could have resulted for Company X in being to a certain extent dependent on certain suppliers. This especially holds in a market of supplier scarcity. According to Company X (2019a), a trend in their X market could be seen in which the suppliers merge and acquire. In these resulting oligopolistic market structures, the suppliers may be highly selective to what extent they allocate

---

[30] See Selten (1999), p.4
[31] See Williamson (2002), p.8
[32] See Hoffman (2011), p.76
[33] See Barney (1991), p.99
[34] Madhani (2010), p.3
[35] See Company X (2019a), SCO Procurement Strategie 2019-2022 slide 7
[36] See Lazzari, Sarate, Gonçalves & Vieira (2015), p.95

resources and capabilities to their customers[37]. The supplier might apply privileged treatment if a bottleneck occurs due to expertise or capacity availability[38]. This could in its turn lead to lower delivery performance which corresponds to longer and less predictable lead times[39]. Based on the latter we formed a proposition which states a positive relationship between the preferred customer status of Company X at its suppliers and the variance of the corresponding repair lead times. According to Voortman (2016) customer attractiveness is strongly related to the amount of profit which the customer generates at the supplier[40].

Beside set-up times and batching, additional detailed reasons have not been found regarding the process which are directly related to a variance in lead times. This could be seen as a shortcoming in literature. According to Kuik and Tielemans, applying batching for minimization of processing time of repairs, will certainly not lead to a minimization of the lead-time variance[41]. The presence of set-up times for certain repairs could be the reason at the supplier for applying a batching technique.

In this section it has been argued based on literature that preferred customer status, bounded rationality and opportunism can have a potential effect on repair lead time variability too. These theoretical root causes will be tested for their presence during a later stage of this research. Bounded rationality brings a danger of distortion or misleading information by opportunistic suppliers regarding for example the duration of lead times. It appeared to be relevant to know if batching is applied at the supplier and if so, which batching-technique is being used. The next section will summarize the set of methods described by literature to eliminate or decrease the effect of these causes of uncertainty.

2.2 Potential methods for decreasing unpredictability of lead times according to literature

This section summarizes the methods which are suggested by literature to decrease the unpredictability of lead times. Methods for counteracting the uncertainty across the supply chain

---

[37] See Schiele, Calvi & Gibbert. (2012), p.2
[38] See Steinle & Schiele (2008), p.11
[39] See Ulaga (2003), p.684
[40] See Voortman (2016), p.3
[41] See Kuik & Tielemans (1999), p.440

have been considered and, where reasonable, explained and treated here as potential methods for Department X for decreasing the variance of outsourced repair lead times.

2.2.1 potential methods for decreasing demand uncertainty

The first class of supply chain uncertainty which could be distinguished in literature relates to uncertainty in demand. In this section methods obtained from literature are being included which relate to the downstream part of the supply chain. Especially methods for counteracting the uncertainty of demand caused by corrective maintenance gets significant attention in literature. As explained in section 2.1.1 this corrective maintenance is characterized by stochastic demand patterns.

Forecasting techniques could be used to counteract the uncertainty of the demand patterns of repairs caused by corrective maintenance. However, according to Hemeimat et al. companies face difficulties in setting up a proper forecast which is adequately in giving a proper reflection of the often lumpy and intermittent demand of spare parts[42]. Besides, as explained by Chen et al., any forecasting technique can cause the Bull whip effect[43]. The next paragraph will discuss how a contribution to the Bull whip effect by forecasting can be avoided.

Centralized demand information reduces information distortion across the supply chain. By applying this remedy each stage of the supply chain is provided with complete information on the actual customer demand. In this way, applying centralized demand information by communicating the forecast of the customer directly to all stages in the supply chain could significantly reduce the well-known effect of the Bull whip[44]. In this way the actual customer demand data can be used, rather than relying on the orders received from downstream stages in the supply chain.

The risk pooling method makes use of the principle that high demand of one customer can be offset by the low demand of another customer. Risk pooling effect can be achieved by centralizing stocks or reducing facilities across the supply chain. In this way the demand is being aggregated. As explained by Nadeem, an aggregation of demand forecast increases accuracy[45]. This theory of risk

[42] See Hemeimat, AL-Qatawneh, Arafeh & Masoud (2016), p. 1
[43] See Chen, Drezner, Ryan & Simchi-Levi (1999), p.421
[44] See Chen et al. (1999), p.431
[45] See Nadeem (2016), p.9

pooling implies that demand uncertainty can possibly be reduced by forming a consortium of segment X companies which allocate a certain type of repair to one specific supplier.

In this section methods have been summarized which can decrease the uncertainty inherent to the stochastic demand caused by repairs corresponding to corrective maintenance. Forecasting is an effective remedy to counteract this uncertainty. Therefore, according literature, it appeared to be relevant to know if a forecast is currently being shared by Company X or set up by the suppliers. Due to the Bull whip effect, it is important to know which subsequent action the supplier undertakes based on this forecast and if this forecast adequately reflects future customer demand.

2.2.2 potential methods for decreasing supply uncertainty

The second class of supply chain uncertainty which could be distinguished in literature relates to uncertainty in supply. In this section methods obtained from literature are being included which relate to the upstream part of the supply chain.

This paragraph will discuss the importance of alternative sourcing availability based on literature. As stated by Pujawan in 2004 alternative sourcing has an impact on the uncertainty in supply[46]. However, according Najafi et al., the most appropriate multiple sourcing strategy is not always evident and depends on the importance of the component, the structure of the supply market and how the suppliers are related to each other[47].

Multiple sourcing can also be used to induce the supplier to provide high performance because the buyer has the possibility to switch between suppliers. When applying this strategy, this is referred to as competitive sourcing. According to Richardson & Roumasset (1995) the proportion of business awarded to suppliers has to be varied over time to ensure their awareness of a prevailing competitive environment[48]. Switching costs must be taken into account when considering this competitive sourcing strategy.

Not all literature recommends multiple or competitive sourcing. W. Edwards Deming advocates for example forming closer relationships with fewer suppliers[49]. The rationale behind this is that substantial specific investments in a single supplier will raise quality and improve co-ordination.

[46] See Pujawan (2004), p.88
[47] See Najafi, Holmen, Lind & Pedersen (2014)
[48] See Richardson & Roumasset (1995), p.72
[49] See Deming as mentioned in Richardson & Roumasset (1995), p.71

Besides, as explained in section 2.1.3, customer attractiveness is strongly related to the amount of profit which the customer generates at the supplier. According this theory, varying the proportion of business awarded per supplier is not in favour of creating a status of preferred customer at the supplier.

Multilevel cooperation across the supply chain by setting up contractual agreements with suppliers, is suggested by Miller in 1992 as an effective method to reduce the supply uncertainty[50]. These contracts induce an interdependence between the corresponding firms. As a result, the firms will collaborate more and act less as autonomous firms. Contracting increases supply chain confidence. Without confidence throughout the supply chain, supply chain managers are liable to decision risks and feel themselves obliged to buffer against uncertainties[51].

In this section different methods have been discussed which could counteract the uncertainty inherent to supply. Pros and cons have been given for the method of competitive sourcing. Besides, the importance of multilevel cooperation by contracting for inducing an integrated supply chain has been discussed.

2.2.3 potential methods for decreasing uncertainty in process

The third class of supply chain uncertainty which could be distinguished in literature relates to uncertainty in process. In this section methods obtained from literature are being included which relate to the process part of the supply chain.

Component commonality among products is strongly advised by Mohebbi and Choobineh in a situation in which both demand- and lead time- variability prevail. Component commonality is an attribute of product design decisions[52]. When possible, component commonality enables and benefits the risk pooling effect. Component commonality has a positive effect on the on-time order delivery and with that responsiveness of the supplier. Besides commonality enables the postponement principle in the production process. The next paragraph will explain and discuss this postponement principle.

[50] See Miller (1992), p.323
[51] See Christopher & Lee (2004), p.6
[52] See Mohebbi & Choobineh (2005), p.10

Postponement is a strategy where the identity of the product is being formed at the latest possible point in time in the manufacturing process or in the supply chain. In this way the product will be completed after the receiving of a customer order. This is opposed to the strategy of performing these activities of completion in anticipation of future orders. Postponement reduces the risk of performing these completion activities beforehand, since the delay of completion leads to the availability of more information. The availability of more information reduces the risk which is inherent to the uncertainty in demand[53].

According to Kumar & Aouam in 2018, systematic investments in setup time reduction can decrease the variability in the duration of manufacturing lead times[54]. They studied the impact of set up times on manufacturing lead times. Setup times can often be reduced by modifying fixtures and tools, making investments in revising setup procedures, or introducing robotic equipment. Shorter setup times often results in shorter lead times which supports smaller batch sizes which directly impacts needed levels of safety stock.

In this section different methods have been discussed which could counteract the uncertainty in process. Component commonality has been discussed as an enabler for the postponement and risk pooling strategies. Component commonality in combination with postponement and risk pooling, reduces the risk which is inherent to the uncertainty of demand. Decreasing setup times and batch sizes can decrease the variability in manufacturing lead times.

2.3 Classification for the approached suppliers

In this section literature is summarized based on which the interviewed Company X' suppliers have been categorized. Each supplier will be categorized based on its experienced uncertainty in demand, uncertainty in supply and complexity of its process. This categorization is a mixed version of the typology of suppliers applied by Angkiriwang and the proposed model of Driessen et al.[55]. Angkiriwang et al. used this typology for evaluating the degree of uncertainty for its set of examined suppliers while researching possibilities for supply chain flexibility. The model for a

[53] See Xiaxun & Jiajun (2016), p.58
[54] See Kumar & Aouam (2018), p.1
[55] See Angkiriwang et al. (2018), p.61 and Driessen, Wiers, Van Houtum & Rustenburg (2013)

typology of repair shops proposed by Driessen et al. was originally intended for determining which control principles should be applied for which type of repair shop.

The categorization used for this research uses elements of the above-mentioned models. The elements regarding the uncertainty in demand and supply are according the model of Angkiriwang et al. However, the uncertainty in process element of this model has been replaced by the complexity element of the model of Driessen et al. Uncertainty in process is expressed by Angkiriwang et al. in terms of variability in processing time, cycle time, yield and availability. This research has however an interest in the causes of these variabilities. The choice has therefore been made to include the complexity of the repair process and to exclude this uncertainty in process element. Table 2.1 summarizes which elements of the considered models has been used in this research to characterize the suppliers.

Table 2. 1: Elements based on literature to characterize the interviewed suppliers

Considered elements based on literature	**Model proposed by Driessen et al. (2013)**	**Model as applied by Angkiriwang (2014)**	**Classification model applied during this research**
Uncertainty in supply	▪	▪	▪
Uncertainty in demand		▪	▪
Uncertainty in process		▪	
Complexity of process	▪		▪

In this section, a categorization of Company X' suppliers has been proposed. This categorization consists of elements for which it is argued based on literature that they have possibly an effect on the variance of repair lead times. These elements concern the complexity of the repair process and the experienced uncertainty in supply and demand by the supplier. In section 2.1.3 it has been explained how a status of preferred customer status is also possibly positive correlated with the variance in lead times for Company X. Section 3.2.3 clarifies what propositions are made in conjunction of these elements and how these propositions has contributed in revealing causes of a variance in external repair lead times.

2.4 conclusion

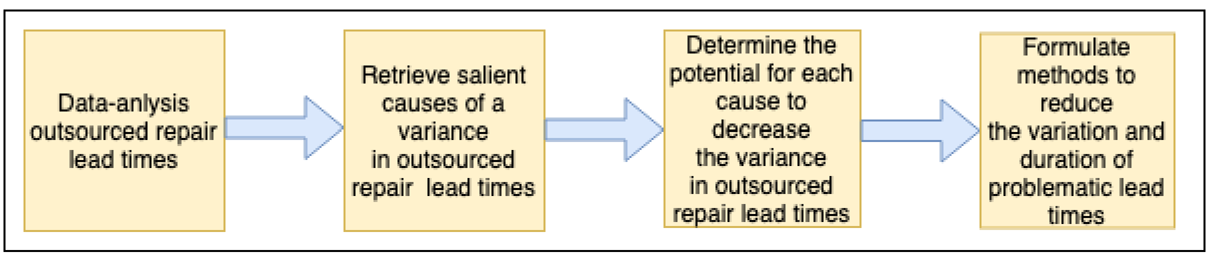
In this chapter, possible root causes have been discussed and possible correlations have been argued based on literature. These theoretical root causes and propositions helped in setting up promising inquiry questions for during the interviews with Company X' suppliers. In section 3.2

it is explained how this literature has been used during the research to discover causes of the variance in outsourced repair lead times. In section 3.3 it is subsequently explained how this literature study contributed in formulating methods to counteract the variance in lead times.

3. Methodology

The goal of this research is to reduce for Department X the duration and variance of their outsourced repair lead times. First the root causes of this variance have been obtained. Knowledge of these causes created an understanding of the dynamics of lead times. The complete picture of what drives a lead time to be longer or shorter, created also an insight in how to reduce its duration. Based on this knowledge we formulated methods which have most potential for decreasing the variance and duration of outsourced repair lead times. Figure 3.1 summarizes this methodology. The subsequent sections in this chapter explain for each sub question its applied methodology.

Figure 3. 1: Schematic visualization methodology



3.1 Approach for clarifying current situation and agreements regarding external repair lead times

This section explains by which method the first research question has been answered. To answer the first sub question, it must first be clarified what agreements currently prevail regarding the variance and duration of outsourced repair lead times. A method for data-analysis was needed to gain insight in the current variance and duration of external repair lead times. Finally, the considerations for focusing on a certain subdivision of articles, based on the variance in lead times, will be explained.

3.1.1 Approach for gaining an insight in current agreements between Department X and its suppliers

This section describes the attempt which has been done for revealing the agreements which are operational between Department X and its suppliers regarding external repair lead times. Since no subsequent methods are being formulated based on these findings, it has been chosen not to obtain a level of saturation. Therefore, instead of conducting extensive interviews, explorative conversations have been held with Company X' employees (see next paragraph). These explorative conversations gained an initial understanding in the type of agreements Department X has with its suppliers. This initial insight helped in formulating promising interview questions regarding the effect of these agreements at the suppliers. These structured interviews with a relevant subset of Company X' suppliers are held during a later stage in this research.

The explorative conversations are held with five contract-managers spare parts (see appendixes M, N, O, P), an administrative employee and a buyer spare parts and equipment. The contract managers spare parts have been chosen because they are actively involved in managing the possible formal arrangements which have been made with specific suppliers. The buyer spare parts has been chosen because they have specific knowledge of how arrangements are documented in the ERP system Baan. The administrative employee has been chosen because this employee in question undertakes the first action when a supplier is not delivering in compliance with the existing agreements.

The seven mentioned employees have been asked based on which prevailing agreements they evaluate and contact a supplier regarding its lead time performance. These conversations gave us an insight in what currently drives Department X to contact a supplier regarding its lead time performance. This insight is described in section 4.1.

3.1.2 Approach for clarifying definition of an external repair lead time within Department X and how these are being monitored

To create an understanding of what is actually being measured by Department X when monitoring their external repair lead times, first an insight had to be gained in the way these lead times are defined and being logged. According Alad & Deshpande (2014) a lead time in a manufacturing environment comprises the time span between the moment of placing an order till the moment of receiving the goods ordered[56]. It will be verified if Department X monitors its lead times according this prominent definition of a lead time and if this definition is desired for Department X.

To clarify the process steps which are performed during the monitored lead time of Department X, first a generic process flow has been set up which comprises all the basic process-steps performed internally at the supplier during a general outsourced repair. This global description of an overall repair process serves also as a framework for going into more detail per supplier during the interviews conducted with Company X' suppliers. The resulted initial overall process description is verified by a literature study, a visit at a supplier and an observation at the internal repair process of Department X in the Location X. This description shows the repair process in a stepwise manner in the form of a flow chart. This technological flow chart has been drawn in accordance with EN ISO 5807. See appendix A for this flow chart.

Finally, we completed the insight in the process steps which are additionally included the monitored lead times of Department X. This has been done by gaining insight in the process steps which are being performed internally at Department X during an external lead time. To accomplish this, effort has also been put in place to clarify in detail the process from the moment a component is being demounted from a X at a maintenance location until the moment of shipping this component to the supplier. Also, effort has been put in place to clarify in detail the process of receiving the repair back from the supplier at Company X and the process of processing this receiving in the Company X' ERP system. To accomplish this, 12 employees who support and control these processes within Department X have been asked about their tasks which they perform to realize this process. These employees include two storage managers, two material managers, two storage employees, three mechanics, one administrative employee and one work planner (see appendix R). These managers and employees have been asked because they are daily actively involved in realizing and controlling these internal processes.

Section 4.1.2 explains and visualizes how Department X defines and monitors its external repair lead times. A comparison of this definition is made with the definition according literature. It is additionally explained which process steps of an external lead time are included and excluded in

[56] See Alad & Deshpande (2014), p.1

the definition of a lead time Department X applies. This created an understanding in how Department X currently evaluates its suppliers regarding lead time performance.

3.1.3 Approach for data-analysis current variance and duration of external repair lead times

A systematic data analysis has been done in order to understand the current situation of prevailing lead times corresponding to outsourced repairs. This data has been retrieved from the Company X ERP-system Baan on 02-01-2019 by head support office of the Location X and covers the period from January 2014 till January 2018 (see next paragraph for motivation). According the scope of this research, this data contains the external lead times corresponding to the repair of X components which have been outsourced via the Location X. Per article we determined the variance in repair lead times and visualized these by Box plots (See appendix B). To gain insight as to which articles show the most variance in lead time, these articles have been sorted in a decreasing manner according their variance by the Bubble sort algorithm. This Bubble sort algorithm has been chosen because its code is relatively easy to program in Excel VBA[57]. Since the algorithm running time of Bubble sort is bounded from above by O(n^2) operations and based on an assumption that each exchange operation will not take longer than 0.10 seconds, this algorithm has been chosen and effectively applied[58]. Per exchange operation two articles are switched from position in order to obtain a decreasing order of variances.

For this data-analysis a reference period from January 2014 till January 2018 has been taken. A time period of minimal four years is assumed to give a plausible representation of current lead times. This time span of four years is also based on the interval Company X Supply Chain Operations updates its procurement strategy[59]. Based on the update interval of SCO strategy it is assumed that a time span of four years takes into account the dynamics of the market in which Company X sources out its repairs for X components. A time span longer than four years is assumed to reflect a time span which comprises lead times which have arisen in a no longer relevant market situation.

Given the variances in lead times per article and per supplier per article, the variance has been determined for each supplier in total. For each supplier its corresponding articles could be viewed

[57] See Bharadwaj & Mishra (2013), p. 1
[58] See Schutten (2018), Discrete optimization of business processes PowerPoint, slide 97
[59] See Company X (2019a), SCO Procurement Strategie 2019-2022 slide 1

as separate groups. This enables it to apply mean square within groups. This has been done by applying the following formula's in Excel VBA:

$$Sum\ of\ Squares\ Within\ groups\ for\ a\ specific\ supplier = \sum_{j=1}^{c}\sum_{i=1}^{n_j}\left(X_{ij} - \bar{X}_j\right)^2$$

Where:

$X_{ij} = The\ ith\ lead\ time\ for\ article\ group\ j$ [days]
$\bar{X}_j = The\ sample\ mean\ for\ article\ group\ j$ [days]
$c = Number\ of\ article\ groups\ which\ has\ been\ repaired\ at\ this\ specific\ supplier$
$n_j = Number\ of\ repair\ lead\ times\ realized\ for\ a\ specific\ article\ group$

Having these SSW's per supplier makes it possible to calculate the total variance in repair lead time per supplier. This has been done according the following formula:

$$Mean\ of\ Squares\ Within\ groups\ for\ specific\ supplier = \frac{\mathrm{SSW}}{n - c}$$

Where:

n= Total number of lead times for all article groups j
c= Number of article groups j

The resulting within-group variance has been summarized per supplier (See appendix B). Due to the way Department X currently monitors its lead times, these variances are not only due to transport and the processes at the supplier itself but also due to processes at Company X internally. However, these variances per supplier formed a first step towards determining the variance which is actually due to processes at the supplier itself. In a later stage during this research effort has been put in place to give a further insight in the extent to which the variance in lead times, as monitored by Company X, is due to transport and processes at Company X internally (see section 4.1.2).

3.1.4 Considerations for a categorization of articles

A subdivision of articles has been considered based on the extent to which the article has shown a variance in its duration of repair lead times. However, during this research the decision has been made not to exclude possible root causes of a variance in lead time just because they are inherent to a certain type of article. The articles which show the most variance in lead times are assumed to have the most potential for revealing explanations in how a difference in lead time could arise. In a later stage during this research it has been indicated by the supplier which causes of a variance in repair lead times are prominent. It is then up to the supplier to indicate that these causes of variance are inherent to a certain type of article, progress step or repair.

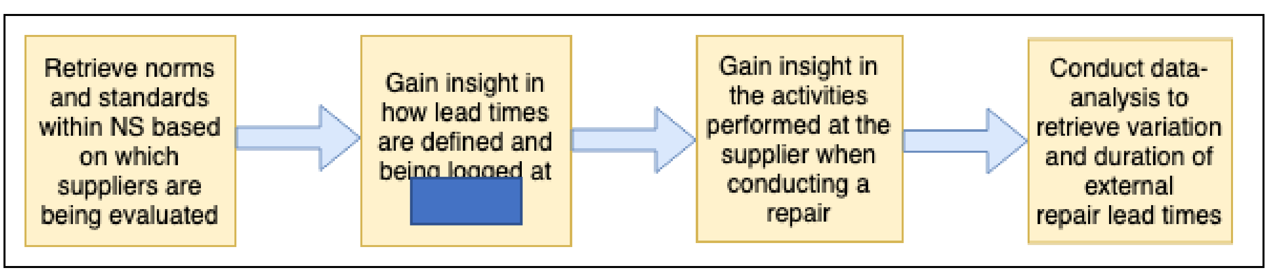
Based on the findings of this research, an advice will go out to Company X. Therefore, a choice has been made during this research to have focus on the articles which are **logistic critical**. For Department X articles should be of more importance when the availability of the X depends on it.

This paragraph has been removed for this public version

3.1.5 Conclusion

In this section first the methodology for answering sub question one has been explained. It has been clarified based on which information action is being undertaken against suppliers regarding its repair lead time performance. Then an insight has been gained in the way Company X defines and monitors its external repair lead times. A technical process description has been set up for gaining an understanding of what activities are actually being performed at the supplier internally when conducting a repair. Next a data analysis has been done in order to understand the current situation of prevailing lead times corresponding to outsourced repairs. This analysis obtained the variance in lead times per article and per supplier per article. A choice has been made during this research to have a focus on the articles which are logistical critical. Besides, a choice has been made not to exclude possible root causes of a variance in lead time by focussing on a certain class of articles for which the variance appears to be the most prominent. Figure 3.1.1 schematically summarizes this approach for sub question one. In the next section we describe how the results of the data-analysis are used in formulating a relevant subset of suppliers.

Figure 3. 2: Approach sub question one



3.2 Approach for determining a relevant subset of suppliers and clarifying what root causes are responsible for a variance in external repair lead times

This section explains by which method the first and second sub-question have been answered. A qualitative research has been conducted for retrieving the root causes of a variance in external repair lead times. The first sub section explains how the subset of suppliers has been determined for conducting the interviews. The goal of interviewing these suppliers was to retrieve the most salient causes of a variance in lead times. Therefore, for this subset it was desired that it had the most potential for revealing causes of a variance in external repair lead times. The second sub section explains how sample efficiency is guaranteed. It is explained which efforts are being done to retrieve the most salient causes of a variance in external repair lead times.

3.2.1 Approach for determination of relevant subset of suppliers

This paragraph discusses why a not yet existing subset of suppliers had to be defined for conducting the interviews and which method has been used for achieving this relevant subset. Department X has currently allocated a valuable team of contract-managers to a self-established top 20 of suppliers. According the social exchange theory in marketing described by Bagozzi the cost of having an intense social contact with a supplier should not outweigh the gained benefits of having this kind of relationship with the supplier[60]. Therefore, since repair lead times are not the only important aspect of a supplier for Department X, this top 20 has not been set up solely based on the supplier performance regarding repair lead times. In order to come to a top 20 suppliers which is however solely based on historic and current lead time performance, an additional analysis has been performed. The goal of this analysis was to create a subset of suppliers which have the most potential for revealing salient causes of a variance in external repair lead times. This analysis implies a systematic examination and evaluation of the already realized dataset (see appendix B) which comprises the variance in repair lead times per article. For this analysis it has been chosen to apply an approach which creates a subset of suppliers which correspond to the articles which show the most variance in duration of their repair lead times. The approach is based on the common sense that articles which show the most variance in lead times have theoretically

[60] See Bagozzi (1978), p.19

the most potential for revealing explanations in how a difference in lead time could arise. The approach consists of the following steps:

1. Step 1: Take an initial number of n suppliers. For this research this number has been initially set to six (see section 3.2.2 for note on sample efficiency and how a low number of interviewees could already result in a level of saturation).
2. Step 2: Determine the article which shows the most variance and has not been encountered yet by this approach.
3. Step 3: Keep adding articles in a manner of decreasing variance in repair lead time. Keep a record of the articles with corresponding suppliers. Multiple articles could be encountered belonging to the same supplier.
4. Step 4: When a subset of n different suppliers has been realized and interviewed, evaluate if a level of saturation has been achieved.
5. Step 5: In case a saturation level has not been attained, increase n by one (n+1) and return to step one. Otherwise, stop.

This paragraph discusses the drawbacks of this method in combination with its remedies. Firstly, this method only examines the articles which show the most fluctuation in the duration of repair lead time. This has been counteracted to refer, during the interview with the supplier, to comparable articles which show significant less variance. However, based on the available information it could not be determined beforehand if both articles have the same level of complexity. This comparison could only be prepared beforehand based on a classification of e.g. electronical, mechanical, pneumatic, hydraulic. A second drawback of this method holds that it does not make use of the possibility to compare variability in lead time for the same article between different suppliers. This issue has been countered by making sure the subset of articles provided the opportunity to compare between different suppliers for the same articles. If this possibility is not included in the data set of articles we must evaluate if this is possible for an additional article relating to the same set of suppliers. A last drawback of this method stresses the fact that it is not known beforehand which number of n leads to a saturated level of suppliers. After performing each interview, it could only be assessed if an additional interview and thus supplier is needed. We therefore started initially with a number of n at which a level of saturation could already possibly be attained (see section 3.2.2 for how a low number of interviewees could already result in a level of saturation). This enabled to plan the interviews sufficient ahead in time. Table 3.1 on the nest page summarizes the discussed drawbacks and its corresponding remedies.

Table 3. 1: Drawbacks and remedies for defining relevant subset of suppliers

Drawback method	**Remedy**
Examination is limited to only the articles which show most variance in repair lead time	Refer during the interview to comparable articles which show less variance in repair lead time
No possibility for comparison included for the same article between different suppliers	Evaluate if a common article exists within the current subset of suppliers
It is not known beforehand which number of n corresponds to a level of saturation	Do not begin by n=1 but by a number at which saturation could already possibly be achieved

In this sub section the approach is explained by which the relevant subset of suppliers has been defined. The goal of this method is to obtain a subset of suppliers which has the most potential for revealing causes of a variance in lead time. This approach gathered in a stepwise manner the articles which have shown the most fluctuation in repair lead times. In table 3.1 it is concisely indicated how each drawback has been mitigated. The next section will explain how the level of saturation has been determined.

3.2.2 Approach for setting up interviews with Company X' suppliers

This section starts by explaining the principle by which the level of saturation has been defined for the interviews conducted with Company X' suppliers. The goal of interviewing these suppliers was to retrieve the most salient causes of a variance in lead times. It will be subsequently explained how the open form of the interviews contributed in obtaining sample efficiency. Finally, the requirements are explained which must be fulfilled by the interviewee at the supplier for conducting the interview.

After conducting each interview, a choice has been made whether an additional interview is needed. This choice has been made by applying the **saturation of salience** principle[61]. This principle supports the idea of obtaining the most salient causes of a variance in repair lead time rather than obtaining all possible causes of a variance in lead time including the very rare with less impact. Not only are these very rare causes of a variance in repair lead time less interesting for contributing to an effective solution, a saturation defined by obtaining all possible causes is also not desirable given the timespan of this research.

[61] See Weller et al.(2018), p.1

In order to keep the sample size needed for saturation of salience as small as possible, it has been chosen to conduct extensive interviews in open form (See appendix D, E, F, G, H, I, J, K). This is because a greater amount of information given per person increases the retrieval of salient items (Weller et al. 2018). The interviews are extensive in such a way that it has been tried to make these exhaustive in all relevant aspects for the management of a(n) (external) repair lead time. Hence, interviews in open form give the most freedom to discover undiscussed problems and with that sample efficiency.

This paragraph explains what sources of information have been consulted as an attempt to ensure that the interviews are exhaustive for the relevant aspects of an external repair lead time. The different sections of the interview and their corresponding questions have been set up by making use of available expertise within Company X, the conducted literature study and the realized EN ISO 5807 segmentation of an overall repair process (See appendix A). Company X employees have been approached for their contribution and feedback on the realized interview questions. In the generic interview (Appendix L) it is motivated why the approached employee has a relevant expertise for contributing to or evaluating the content of the interview questions. Table 3.2 summarizes why we considered an approached Company X' employee to be relevant for evaluating the interview questions.

Table 3. 2: Consulted specialties within Company X for achieving an exhaustive interview

Specialty	**Functions**	**Relevance for evaluating content interview**
Supply Chain specialists	Supply chain manager	Has an overall knowledge of current Company X supply chain. This is relevant for the sections 'Monitoring lead times', 'Forecasting' and 'Incoterms'.
Procurement specialists	Senior strategic purchaser, Purchaser	Have an overall knowledge of Company X purchasing strategies. This is relevant for the sections 'Preferred customer status' and 'Material ordering process'.
Engineering	Supply Quality Assurance engineer, Head engineer Location X configuration, Head technical support service center Maastricht	Have an overall knowledge of the technical aspects regarding the repair process and the articles itself. This is relevant for the sections 'The repair process', 'Initiation of the repair process', 'Complexity of the repair process' and 'Diagnosis step'.

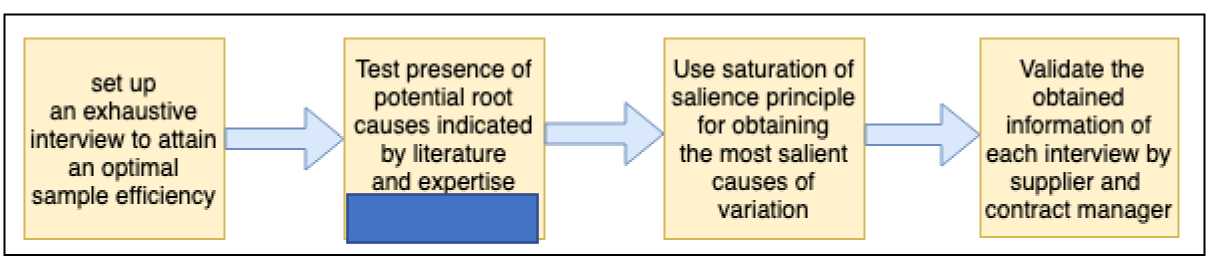
In the outline of the interview we additionally indicate which sections test the presence of theoretical root causes of a variance in lead time (see section 4.2.3). In this way the potential theoretical causes of a variance in lead times, obtained by the literature study, have been processed in the interview.

For these interviews, the subset of Company X' suppliers will be asked to assign a logistic manager or more preferably an aftersales manager. We formed a prerequisite for performing this interview which states that this manager must have at least four years work experience in the logistic or after sales field of the company. These four years of company experience correspond to the historical basis of the lead time dataset which originates from roughly 2014 until 2018. Given the time span and available resources for this project, we made the choice to only visit suppliers physically for performing the interview if these are located in Location X.

After performing each interview, the interview is transcribed and sent to the supplier accompanied with a request for confirmation. In this way the content of the documented interview has been validated. As a final validation check, the confirmed content of the interview is sent to the corresponding contract manager. This manager has been asked if he is familiar with the content of the interview.

This paragraph gives a conclusion of this section 3.2.2. The saturation of salience principle has been used to guarantee the retrieval of the most salient causes of a variance in external repair lead times. Sample efficiency is being realized by conducting extensive interviews in open form. The interview questions have been set up by making use of the expertise of Company X employees, the literature and the realized EN ISO 5807 segmentation of an overall repair process. In this way the interview has also been set up with the aid of expertise and knowledge available within Company X. In the generic interview it has been indicated which questions test the presence of theoretical root causes obtained by literature. Figure 3.2.2 summarizes this approach of the qualitative research. Section 4.2.3 provides an outline of the generic interview.

Figure 3. 3: Approach for retrieval of the most salient causes of variance



3.2.3 Method for processing propositions into interview questions

Based on literature, a categorization of Company X' suppliers has been proposed in section 2.3. This categorization is based on the complexity of its repair process and the extent to what the supplier experiences uncertainty in its demand and supply. In section 2.1.3 it has been additionally explained how a status of preferred customer status could also be possibly correlated with the variance in lead times for Company X. For each of these elements, propositions have been formed which argue a correlation between these elements and a variance in outsourced repair lead times. These propositions formed promising inquiry areas for the interviews done with Company X' suppliers for revealing causes of this variance. This section describes these propositions and how the corresponding suggested correlations has been measured by the interview questions.

A proposition made in section 2.3 states that an increase in the complexity of the repair process at the supplier causes for Company X an increase in the variance of its outsourced repair lead times. Conform the interpretation of Driessen et al., this complexity has been referred to in the interview as the extent to which specialized skills and specific equipment is needed to fulfil the repair process. This positive relationship has also been suggested for the relation between variance in repair lead times and the uncertainty in demand (see section 2.1.1.) and between this variance and the uncertainty in supply (see section 2.1.2). The uncertainty in demand has been evaluated and classified by the demand patterns as described by Syntetos, Boylan & Croston, (2004). Conform the interpretation of Angkiriwang et al., the uncertainty in supply is classified based on the extent to which the supplier experiences a variance in its supply lead times. In section 2.1.3 a proposition has been made which states that an increase in the preferred customer status will result for Company X in a decrease of variance in its outsourced repair lead times. Following the logic of Voortman (2016), the degree of being preferred customer has been evaluated during the interviews by the amount of profit which is generated by Company X at the supplier[62].

For each measure above mentioned it was needed to ask the supplier to what extend a certain statement holds. During the interviews the interviewees could indicate the extend by 'low', 'moderate' and 'high'. A coarse rating was needed to attain a convincing level of fidelity since only eight suppliers have been approached for the interviews. At a number of eight interviews the level of saturation was obtained for the causes of a variance in lead time. Given this number of

[62] See Voortman (2016), p.3

interviews, a coarse rating was needed to obtain a fidelity score per measurement being evaluated by these interviews.

Section 4.2.2. provides further verification of the suggested correlations based on empirical results retrieved from the interviews with Company X’ suppliers. This provided a reasonable impression for the extent to what these propositions based on literature tend to be true in practice. In case the results of this empirical research formed additional support in favour of these propositions, we spur further research regarding these propositions.

3.2.4 Conclusion

This paragraph gives a conclusion for section 3.2. First a relevant subset of suppliers has been determined which has been approached for conducting the interviews. The relevance of this subset is being determined based on the potential for revealing causes of a variance in lead time. A choice has been made to retrieve the most salient causes of a variance in lead times. Therefore, the saturation of salience principle has been applied. The propositions made have been tested according the measures described by literature.

3.3 Approach for formulating effective methods

This section starts by describing the model based on which each set of root causes is being assessed for its potential to reduce the variance in outsourced repair lead times. Based on the additional knowledge and insights resulted from the performed interviews with the suppliers, a scoring model has been set up. This scoring model quantifies the potential for each set of root causes to reduce the variance in outsourced repair lead times. Finally, it will be explained how this quantification helps in formulating effective methods.

3.3.1 A scoring model for quantifying the potential

Based on the performed interviews the most salient causes of a variance in outsourced repair lead time have been obtained. These root causes have been linked to its corresponding aspect of a lead time. Several of these aspects have been distinguished based on the literature studies and based on the interviews. These aspects are ‘Forecasting’, ‘Fault indication’, ‘Obsolescence issues’, ‘Uncertainty of repair process’, ‘Focus on X for repair lead time’, ‘Market between Company X and its suppliers’, ‘Market between Company X’ suppliers and its sub suppliers’, ‘Manpower planned repair’, ‘Manpower unplanned repair’, ‘Unplanned repair without formal agreement’, ‘Planned repair without formal agreement’, ‘Unplanned repair based on formal agreement’, ‘Planned repair based on formal agreement’.

Each such an aspect corresponds per supplier to a specific set of root causes. A root cause can however be possibly related to multiple aspects of a lead time. Therefore, if the elimination of root-causes of a certain aspect would also result in the total elimination of root causes of another aspect, the latter aspect will be excluded from further consideration.

A scoring model was needed to assign priorities regarding which set of root-causes deserve first preference for eliminating or reducing its effects on external repair lead times. These priorities are determined based on the potential each set of root causes has for reducing the variance and duration of these lead times. In order to assess the potential each, set of root causes has for reducing the variance and duration, the qualitative results per interview must be transformed into quantitative results.

In order to determine the potential per set of root causes for reducing the variance and duration, its corresponding aspect has been evaluated. First the potential for improvement regarding this aspect must be evaluated. Based on the insights gathered during the interviews, this model comprises per aspect relevant questions to convert the qualitative answers to a quantitative score. By answering the questions in this model, the potential for improvement has first been scored based on the information obtained by the interviews. For this model we used a five-point Likert scale to initially indicate the current performance of an aspect. We indicated per aspect to which extent a specific indicator for performance is true. These answers ranged from 1 “Not present” to 5 “Highest significance”. As a second step the score of potential for improvement is calculated by subtracting this score from the maximum possible score for performance. This resulted in answers ranged from 0 “Low or not present” to 4 “Highest significance”. This is being clarified in table 3.2.

Table 3. 3: Scores of potentials for improvement

Score current performance	Maximum score performance	Score potential for improvement	Classes potential for improvement
1	5	5-1 = 4	Highest significance
2		5-2 = 3	Significantly high
3		5-3 = 2	Present
4		5-4 = 1	Low
5		5-5 = 0	Not present

Next, the relevance of this improvement per aspect must be determined. An aspect could for example have significant room for improvement. However, it must also be assessed to what extent this improvement contributes to decreasing the variance and duration of external repair lead times. By answering the questions in this model, we scored the relevance of this improvement per aspect based on the information obtained by the interviews. Again, these answers ranged from 1 “Not present” to 5 “Highest significance” based on a five-point Likert scale. These scores are being depicted in table 3.3.

Table 3. 4: Scores of relevance for improvement

Score for relevance of improvement	Classes for relevance of improvement
1	Not present
2	Low
3	Present
4	Low
5	Not present

Finally, we came per aspect to the final score of potential for decreasing the variance and duration of external repair lead times. This final score per aspect concerns the product of the score for potential of improvement and the score for the relevance of this improvement. This resulted in a score ranging from 1 “Low” to 20 “Highest”. As a last step, the aspects have been allocated to one of the four classes according to their score for potential. Four classes appeared to be specific enough for determining where to focus on for formulating corresponding methods. These classes include a ‘low’, ‘moderate’, ‘high’ and ‘highest’ class of potential for decreasing the variance and duration of outsourced repair lead times. These potential scores are depicted in table 3.4.

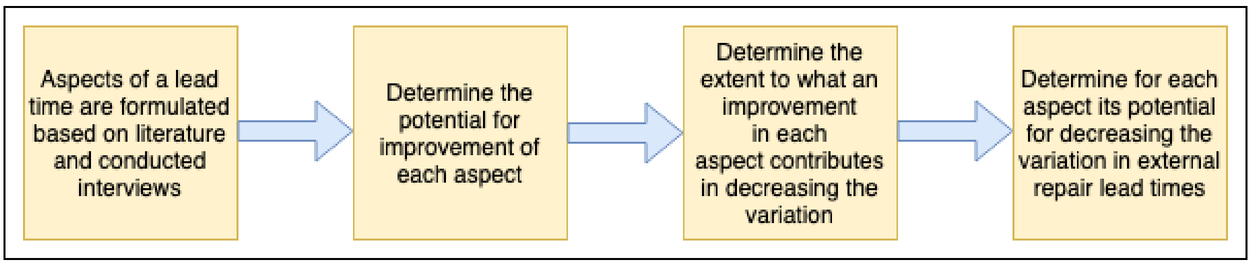
Table 3. 5: Scores for potential of reducing variance and duration external repair lead times

Potential score of aspect	Class of potential
1 up to and including 5	Low
5 up to and including 10	Moderate
10 up to and including 15	High
15 up to and including 20	Highest

In order to obtain a higher robustness of these scores obtained by the scoring model, we tried to obtain a confirmation on these scores from the corresponding interviewed Company X’ suppliers. However, due to the limited time span of this research, we did not succeed in receiving the confirmations of all the interviewed suppliers. However, the interviews itself have been validated by the interviewees. Therefore, these quantitative scores are based on a robust basis of qualitative information.

Figure 3.4 summarizes the working of the scoring model at a high level of abstraction. Appendix Q provides a process flow and explanation of this model in more detail, accompanied with an example. In the next section it is explained how the results of this scoring model contributed in formulating effective methods to reduce a variance in external repair lead times.

Figure 3. 4: Steps scoring model at a high level of abstraction

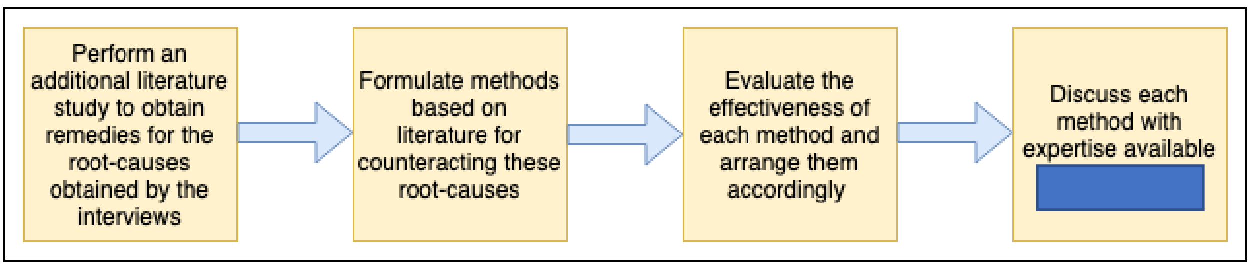


3.3.2 Approach for formulating methods to counteract a variance in external repair lead times

In this section it is explained how methods have been formulated to reduce a variance in external repair lead times. First an additional literature study was needed based on the additional root causes obtained by performing the interviews. For each set of root causes, corresponding to an aspect, remedies have been looked for in literature. As a second step, for each aspect methods have been formulated based on this literature study. Per aspect these methods have been discussed and evaluated by expertise within Department X. Based on the score of potential for each aspect, the potential of these methods has been determined per supplier. As a final step, the relevance of each method has also been additionally expressed in the percentage of articles for which it is relevant. The introduction of section 4.2 describes in detail how these percentages have been determined. Methods are most effective when they correspond to an aspect with the highest score for potential. The additional representation in percentages creates an insight for which number of articles these methods are relevant.

A drawback of this approach concerns the omission of evaluating the required funds needed for the implementation of each method. Per aspect there has however been strived to research and formulate proactive methods rather than reactive methods. Reactive approaches try to counteract and deal with uncertainty, by applying buffering strategies. Buffering strategies include increasing safety stock and introducing a safety lead time when conducting calculations for safety stock and/or order up to levels. Proactive approaches on the other hand, try to reduce the uncertainty itself by eliminating its root causes. For companies it is often easier to carry out reactive approaches rather than proactive approaches. This could be explained by the fact that reactive approaches require less effort and resource investment[63]. These reactive methods could however be more expensive in the long term. According Angkiriwang et al., managers should therefore be focussed on looking for opportunities to apply proactive strategies rather than reactive ones. A consideration of both proactive and reactive methods, while attaining a preference for proactive methods, has resulted in considering the financial needs and consequences of each proposed method.

Figure 3. 5: Approach for formulating methods for reducing variance



3.3.3 Benchmarking approach for gaining practical insight regarding implementation of methods

A benchmarking study has additionally been conducted in order to gain practical insights for the implementation of the proposed methods. This benchmarking study formed an extension of the conducted literature study, since the methods we encountered in literature were formulated rather general and from a theoretical point of perspective. Companies and organizations have therefore been contacted which operate and maintain assets which show similarities with the assets in the segment X industry in terms of their complexity, technological advancement and customization. Companies Company A, Company B and the Company C have been chosen to discuss the effectiveness and practical implications of the methods we advise. These organizations have been interviewed regarding their methods for reducing the variance and duration of their outsourced repair lead times (see appendixes X, Y and Z). Methods will be discussed sequentially per aspect ‘Forecasting’, ‘Uncertainty during the repair process’ and ‘Focus on X on repair lead times’.

[63] See Angkiriwang et al. (2014), p.66-67

3.3.4 Conclusion

This sub section gives a conclusion for section 3.3. Each aspect of an external repair lead time which became apparent has been linked to a certain set of root causes. A set of root causes could for example relate to the aspect ‘fault-indication’ or ‘forecast’. Per aspect it has been quantified by the scoring model to which extent it could reduce the variance. By the aid of an additional literature study and consultation of expertise within Company X, methods have been formulated per aspect to counteract the root causes of a variance in external repair lead times. Due to financial considerations, we preferred proactive methods rather than reactive methods. The effectiveness of each method is evaluated based on the score generated by the scoring model. This score relates to the potential of an aspect for reducing the variance in external repair lead times.

3.4 Conclusion

This section gives a conclusion for chapter three. First an insight has been gained in the way Company X defines, monitors and controls its external repair lead times. A choice has been made during this research to have a focus on the articles which are logistical critical. A data analysis has been done in order to analyse the current variance and duration of prevailing lead times corresponding to outsourced repairs. This analysis is per article and per supplier per article. These variances are used to formulate a relevant subset of suppliers for conducting the interviews. The goal of forming a subset is to obtain a set of suppliers which have the most potential for revealing causes of a variance in lead time. The saturation of salience principle has been used to guarantee the retrieval of the most salient causes of a variance in external repair lead times. Each root cause could be linked to a certain aspect of a lead time. In this way, each aspect corresponds per supplier to a specific set of root causes. For each aspect it is being indicated which causes are the most prominent in contributing to a variance in external repair lead times for Department X. For each aspect with a high potential score, methods are advised for eliminating or reducing the impact of each cause. These methods are based on literature and expertise available within Company X. The most appropriate method is determined based on the scores assigned the scoring model in combination with its level of representation expressed in number of articles. The next chapter will explain which results the above described methodology has produced.

4. Results

In this chapter we describe the results of applying the methodology as defined in chapter 3. First we clarified which agreements prevail between Department X and its suppliers and based on which information these agreements are being evaluated. Then the results of the data analysis will be shown which gained an insight in the actual variance of current outsourced repair lead times. Then it will be explained what salient causes of a variance in external repair lead times became apparent based on the interviews. These root causes of a variance in lead time have been scored for their potential to reduce this variance. For each set of root causes we advised a variety of methods. To keep the implementation of these methods manageable, we indicated a preferred sequence for implementation.

4.1 Current situation external repair lead times

In this chapter we first provided the situation in which the outsourced repair lead times arise. A segmentation of the repair lead time is given at a high level of abstraction. Based on this segmentation, the variance in lead time due to processes at the supplier, internal processes at Company X and transport can be further specified during a later stage of this research. Finally, the results of our data-analysis are provided.

4.1.1 Agreements between Department X and its suppliers regarding repair lead time performance

Based on the explorative conversations held with Company X' employees (see section 3.1.1), we conclude that Department X evaluate the repair lead time performance of its suppliers based on the delivery times stated in the ERP system Baan. These delivery times have been mainly inserted by Company X' contract managers and/or buyers based on their experience and intuition in repair lead times, possibly in consultation with the supplier. Delivery times in Baan related to outsourced repair based on formal agreements with the supplier appears to be rather the exception than the rule. The delivery times which have been documented in Baan based on informal arrangements could be adjusted at any time and possibly in consultation with the supplier.

This sub section gave an answer to the first research question. We concluded that the agreements regarding the duration of lead times are based on the lead time data documented in Baan. This documentation for the duration of repair lead times is either based on formal or informal arrangements with the supplier. As aforementioned, repair lead times based on formal agreements with the supplier appears to be rather the exception than the rule. During the interviews with Company X' suppliers it must be clarified to what extent Company X' suppliers have an incentive for undertaking subsequent action based on formal and informal agreements. This lack of formal agreements formed therefore a promising inquiry area for during the interviews with Company X' suppliers.

4.1.2 Definition of external repair lead time within Department X and broad segmentation of its variance

This subsection starts by explaining the way in which Department X monitors its external repair lead times. Then we provide a broad segmentation of these lead times which show the process steps which are included in these lead times. In section 3.1.2 we explained based on which information this segmentation has been generated and why this segmentation was desired. This subsection then continues by quantifying the variance for the segments being distinguished. For this analysis we introduced a differentiation between suppliers being located in a foreign country and suppliers located in Location X. We made this distinction because an Company X' work planner indicated that transport for repairs corresponding to foreign located suppliers occurs at a lower frequency than for domestic located suppliers.

This paragraph has been removed for this public version.

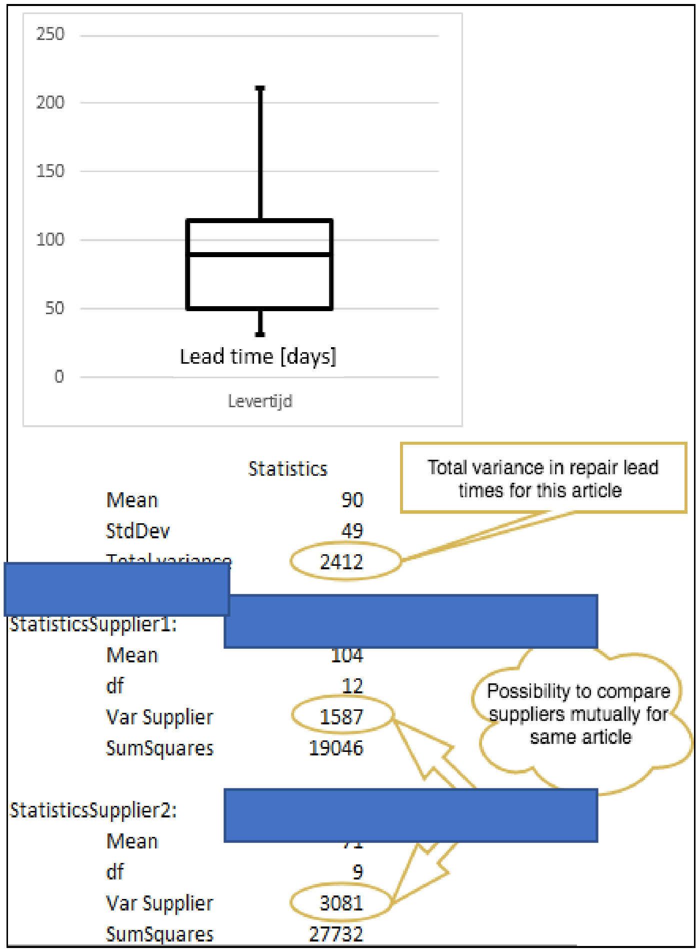
Based on these findings we could conclude that Department X monitors its lead time according this generally accepted definition of a lead time in literature (see section 3.1.2).

This paragraph has been removed for this public version.

4.1.3 Current variance and duration of outsourced repair lead times

The variance in repair lead time has been determined per article and additionally per supplier per article. This has been done for all 900 articles which are being outsourced via the Location X. Figure 4.2 shows an example of how this has been done for each article. The variance per supplier per article made it possible to compare and evaluate suppliers in their realization of lead times for the same article. For each article it has been chosen to visualize its dispersion in lead times by a boxplot. This made it possible to determine if the variance is due to outliers. It has been chosen to not exclude outliers from further consideration. It has been assumed that outliers are inherent to the data. There was no indicative evidence that these outliers were due to incorrectly entered or measured data.

Figure 4. 2: Example data-analysis conducted per article



During the data-analysis it transpired that 12 percent of articles have been outsourced for their repair to multiple suppliers. Despite the application of multiple sourcing for the repair of a specific article, it can be stated that Department X has not applied competitive sourcing. As mentioned in the literature study, Richardson & Roumasset notified in 1995 that the proportion of business awarded to suppliers must be varied over time to ensure their awareness of a prevailing competitive environment[64]. The Data-analysis showed this has not been the case for Department X in the past 4 years. There have been multiple suppliers for the repair of a specific article, this has been however over a time span of 4 years at separate periods of time. It can therefore be concluded that Company X is not applying a competitive sourcing method. However, as mentioned in section

[64] See Richardson & Roumasset (1995), p.72

2.2.2 not all literature recommends competitive sourcing. The rationale behind this is that substantial specific investments in a single supplier will raise quality and improve co-ordination. To assess the need for this improved co-ordination and specific investments, the Company X' suppliers will be asked during the interviews to what extent the repair process is complex and to what extent special equipment and specialisations are needed to conduct the repair (see section 4.2.3, section 7 of the interview). If complexity is low for a certain supplier, we argue that co-ordination is to a less extent needed and therefore competitive sourcing could be treated as a potential method for reducing the variance and duration of outsourced repair lead times.

This paragraph has been removed for this publication

4.1.5 Conclusion

This sub section gives a conclusion for section 4.1. Repair lead times based on formal agreements with the supplier appears to be rather the exception than the rule. Department X evaluates lead time performance of its suppliers based on the durations of lead times documented in the ERP system Baan.

This paragraph has been removed for this public version

4.2 Root causes of a variance in external repair lead times for Department X

First the resulted subset of suppliers which have been approached for an interview has been provided in section 4.2.1. Then section 4.2.2 provides additional empirical evidence for the propositions formulated in section 3.2.3. An outline of the conducted interviews with Company X' suppliers is being provided in section 4.2.3. These interviews retrieved the most salient root causes of a variance in outsourced repair lead times for Department X. These root causes are being provided in section 4.2.4.

4.2.1 Subset of suppliers for conducting the interviews

A subset of Company X' suppliers has been determined based on the approach mentioned in section 3.2.1. Based on the approach mentioned in section 3.2.1, we concluded that this subset of suppliers is the most relevant for conducting the interviews. See table 4.3 for this subset of suppliers. In appendix T the articles could be found based on which the subset of suppliers has formed.

After conducting the interviews, the suppliers have been classified according to the classification mentioned in section 2.3. The measurements and rating scales as explained in section 3.2.3, have therefore been applied during the interviews to make this classification possible. This categorization of Company X' suppliers is being depicted in table 4.3 on the next page.

Table 4. 1: Categorization per interviewed supplier

	Process uncertainty	Supply uncertainty	Demand uncertainty	
Interviewed supplier	**Complexity capacity needed**	**Uncertainty material availability**	**Typology demand**	**Appendix interview**
Supplier A	High	High	Lumpy, Intermittent	G
Supplier B	High	Moderate	Erratic	D
Supplier C	High	Moderate	Erratic	E
Supplier D	High	High	Erratic	F
Supplier E	Moderate	Moderate	Smooth	H
Supplier F	High	High	Lumpy, Intermittent	I
Supplier G	High	Moderate	Erratic	K
Supplier H	High	Moderate	Intermittent	J

Referring to the outline of the interview as provided in section 4.2.3, the complexity of the capacity needed is derived from answers obtained by section 7 of the conducted interview. Based on the information obtained from section 6 of the interview, an assessment could be made regarding the uncertainty in material availability. The typology of demand is derived from the information obtained by section 5 of the interview.

4.2.2 Additional empirical evidence for propositions

Propositions have been stated in section 3.2.3 based on literature. It was argued that an increase in the complexity of the repair process at the supplier results for Department X in an increase in the variance in outsourced repair lead times. Referring to table 4.3, this proposition appeared to be valid for seven out of eight suppliers. Therefore, this proposition gained additional convincing evidence for being true. A second proposition stated a positive relation between uncertainty in material availability at the supplier and a variance in repair lead times. As can be seen in table 4.3, all eight suppliers have a high or moderate uncertainty in material availability. This proposition is therefore partly true. The third proposition state that uncertainty in demand is positively correlated with a variance in lead times for Company X. Seven out of eight suppliers experience lumpy, intermittent or erratic demand patterns. The third proposition seems therefore still valid. The fourth proposition states that being a preferred customer status decreases the variance in external repair lead times. Based on the interviews it could be stated that Company X has a low as well as a moderate and high status of preferred customer at the approached suppliers. Therefore, this correlative evidence did not provide additional support for this proposition.

The above-mentioned propositions have been based on literature. The additional correlative evidence obtained by the performed interviews did not disprove the correlations suggested by these propositions. Additional empirical research is however needed to either accept or reject these proposed correlations. We therefore spur for further research onto these correlations in (see section 8).

4.2.3 Interview questions

Based on the methodologies mentioned in sections 3.2.2 and 3.2.3, a variety of promising interview questions has formulated. These questions have been subdivided in sections. Table 4.4 concisely indicates which information is tried to be obtained per section. This table provides a short outline of the interviews held with Company X' suppliers.

Table 4. 2 : Outline of the conducted interviews with Company X' suppliers

Section 1: Causes of a variance in lead time for three specific articles
In this section three articles are being mentioned which have shown a distinctive variance in repair lead time. The interviewee is being asked what the main causes were for these lead times to fluctuate.
Section 2: Monitoring of repair lead times at supplier
In this section it is evaluated to what extent there is a Focus on X on repair lead times at the Company X' supplier. The main questions of this section relate to what the supplier monitors regarding its lead times and how is this being measured practically. What action does the supplier subsequently undertake based on these measurements?
Section 3: Initiation of the repair processes
The main question here relates to the main reasons for not starting a repair immediately at the moment of receiving an article. According to literature (see section 2.1.3) and DEPARTMENT X it is relevant to know if batching is being applied and if so, which batching-technique is being used.
Section 4: Diagnosis step
In this section of the interview it is being evaluated to what extent the supplier keeps a record of occurring failures per article. This is relevant because this forms a precondition for translating the Company X forecast to second-tier suppliers and all subsequent stages upstream the supply chain. According literature this translation is needed to realize centralized demand information (see section 2.2.1).
Section 5: Forecasting
According literature (see sections 2.1.1 and 2.2.1) it appears to be relevant to know if a forecast is currently being shared with the supplier. The main questions of this section relate to the action which the supplier does undertake based on this forecast and the extent to which this forecast is adequately reflecting future demand. The importance of a reliable forecasting method is being derived from the extent to which this supplier faces uncertainty in demand.
Section 6: The material ordering process
According literature (see section 2.1.2) significant stochastic delay could arise due to the uncertainty regarding the supply side of subcomponents needed for the repair process. This

section includes therefore, inter alia, questions which refer to what extent the supplier experiences delay due to backordering. The supplier will also be asked for its driving factors for putting components on stock.
Section 7: Complexity of the repair process
The main questions in this section relate to the extent to which a variance in repair lead time is due to the need for specialized skills and equipment. This section could result in additional empirical evidence for the proposition formulated in section 3.2.3 which states that the complexity of the repair process and the variance of repair lead times are positively correlated.
Section 8: The repair process
Based on the input from DEPARTMENT X questions are being asked here referring to, inter alia, the rules for sequencing repairs, the existence of priorities for certain repairs and the motives for communicating a new planned delivery date.
Section 9: Preferred customer status
According the literature mentioned in section 2.1.3, the supplier might apply privileged treatment if a bottleneck occurs due to expertise or capacity availability. The main questions in this section should clarify the customer attractiveness of Company X at the supplier. This section could result in additional empirical evidence for the proposition formulated in section 3.2.3 which states that preferred customer status and variance in repair lead time are negatively correlated.
Section 10: Incoterms
Questions in this section must clarify how the property transfer is arranged between Company X and the supplier regarding the repairs. A check could be made if the supplier and Company X are monitoring their lead times according the agreed incoterms.

We refer to the generic interview (appendix L) for the specific questions per section. The next section explains the root causes obtained by conducting these interviews with Company X' suppliers.

4.2.4 Root causes

After conducting six interviews a level of saturation was achieved for the most salient causes of a variance in repair lead times for Department X. The seventh and the eighth interview did not reveal any additional salient causes of a variance in lead time. These eight suppliers represent in total 287 of the 900 articles which have been outsourced for their repair. With this the sample represents 32% of all articles which have been outsourced for their repair to external suppliers. This 32% generated a level of saturation for the most salient cause of a variance in lead time. Therefore, we argue that this percentage is sufficient to draw conclusions regarding the most salient causes of a variance in repair lead time. The number of articles per supplier has been depict in table 4.5.

Table 4. 3: per supplier its representation expressed in the number of repaired articles

Supplier	**# of articles**
Supplier B	130
Supplier C	99
Supplier E	20
Supplier D	18
Supplier A	10
Supplier H	7
Supplier F	2
Supplier G	1
∑	287
% of total amount of articles	**32%**

According the explanation in section 3.3.1, the scoring model has determined for each supplier the potential each aspect of a repair lead time has for decreasing the variance and duration of external repair lead times. The resulted potential scores per aspect per supplier can be found in appendix U. According to these scores, each aspect has been qualified as having a ‘low’, ‘moderate’, ‘high’ or ‘highest’ potential for decreasing the variance and duration of outsourced repair lead times. Table 4.6 on the next page depicts per aspect what causes are the most prominent in contributing to the variance in these lead times. In the next section we explained that this research had a focus on the aspects which correspond to a ‘high’ or ‘highest’ class of potential. Table 4.6 on the next page therefore only displays causes which relate to these aspects qualified as such by the scoring model. Appendix V provides an overview of all causes relating to the complete set of aspects.

Table 4. 4: Causes per aspect of an unpredictable repair lead time

Aspect	Potential	Corresponding causes
Forecasting	Highest	• Supplier does not receive a forecast • Supplier does not undertake any subsequent actions based on the forecast because it does not trust the forecast based on experience • It is not clear for the supplier whether the forecast corresponds to planned or unplanned repair • The supplier sees forecasting not as a realistic tool due to the random nature of failure behaviour of corresponding articles. This holds especially for e.g. pure electronic articles
Focus on X	High	• Supplier has no (client specific) KPI regarding its **Turn Around Time** for its repairs • Supplier is not proactively in contact with its sub suppliers regarding their lead time performance • Supplier does not have any agreements regarding lead time performance with its sub suppliers • Repair KPI's are available but they are not actively managed by the production staff • Supplier has no knowledge of causes of delay for material unavailability at its sub suppliers
Obsolescence	High	• Suppliers and sub suppliers only communicate reactively obsolescence issues. Once the item is not available anymore • No agreements exist regarding the obsolescence dates of articles • Articles which relay on outdated technologies are subject to failure even though they are designed to function during the complete life cycle of a X. Its subcomponents are no longer in production anymore • Sub suppliers do communicate proactively regarding obsolescence risks but not sufficient ahead in time
Uncertainty in repair process	High	• Supplier is not willing to attain sub part inventories for repairs being sent ad hoc which are not covered by formal agreements. Especially not for sub parts corresponding to customized slow movers • Article contains a significant number of facultative parts which could be the reason of corrective maintenance • Repair process appears to be outside the scope of the agreed regular repair processes. Delay is experienced due to waiting on approval from Department X on new planned delivery date and price

4.3 Methods for decreasing variance in external repair lead times

In this section we formulate methods for each aspect which have a high potential for decreasing the variance and duration of external repair lead times. As explained in section 3.3.1, each aspect is scored for this potential by the scoring model (see appendix U). Considering the available time span for this research, the choice has been made to only evaluate aspects which correspond to the 'high' or 'highest' class of potential. The next subsections describe the methods for these aspects concerning 'Forecasting', 'Uncertainty in repair process' and 'Focus on X'.

Each statement made in the following sub sections is true for a certain number of suppliers which have been approached for conducting the interviews. Each supplier corresponds to a specific range of articles which it has been repairing. In the following sub sections, it is indicated for which number of the approached suppliers the statement holds. This number of suppliers has also been translated into the percentage of articles of the total sample. The same logic has been applied per method to indicate for which percentage of the total sample of articles the method is relevant. These percentages are provided in-text and summarized in tables 4.6 - 4.8. Appendix W gives a clarification of these percentages and links them to the approached suppliers. The eight suppliers approached for this research correspond to 32% of all articles being outsourced. As we explained in section 4.2.4, this percentage of the total population generated a level of saturation for the most salient causes of a variance in external repair lead times.

4.3.1 Methods corresponding to the forecasting aspect

Six out of the eight approached suppliers (corresponding to 93% of articles) experience their significant and stochastic delay in their repair processes due to waiting on materials from their sub suppliers. These materials could be ordered in advance if a clear and reliable forecast of expected repairs is being shared by Company X on regular intervals. Currently only one of the approached suppliers relies on the forecast it receives regarding the unplanned repairs (corresponding to 45% of the sample articles). This supplier receives a forecast in combination with an underlying contract. According to this contract it must assure a certain lead time if the demanded number of repairs by Company X is within a certain confidence interval of the communicated forecast. However, no forecast for unplanned repairs is being shared with five out of eight suppliers (corresponding to 41% of the articles). These suppliers explained that they are not willing to take the risk for attaining an inventory level for which it is not clear whether Company X takes these goods in the future. Nor do they have an incentive for making subsequent formal agreements regarding lead times with their suppliers, given this uncertainty. This especially holds for customized **slow movers**. Moreover, two out of eight suppliers (13% of articles) receive a forecast, but they do not trust this forecast. This is mainly due to the fact that it is not clear in this forecast whether the expected number of repairs relates to planned or unplanned repair.

It is initially advised to create transparency in the forecast by providing insight in how the forecast has been build up (effective for 54% of the articles). In order to achieve this, the forecasted number of unplanned repairs must be clearly separated from the expected number of planned repairs. Based on the conducted interviews with the approached Company X' suppliers we can state that a reliable forecast motivates the supplier to make subsequent agreements with its sub suppliers regarding delivery lead times of its subcomponents. This forecast must then be provided on regular intervals (Effective for 54% of the articles). We argue, based on what additionally has been discussed during the interviews with the Company X' suppliers, that at least three months in advance is sufficient ahead in time. It is additionally recommended to ascertain that the supplier received the forecast under good conditions and is able to anticipate accordingly (Effective for 54% of the articles). Therefore, we advise to agree formally on the principle that the supplier proactively notifies Department X when it could not anticipate on the communicated forecast by providing the agreed repair lead times.

In order to realize that the supplier provides certain lead times based on the communicated forecast, the supplier must rely on the forecast and anticipate accordingly. Formal agreements with the suppliers appeared to be a precondition for stimulating them to agree on realizing certain lead times. Based on the interviews it appeared to be convenient for the Company X' suppliers to formulate these lead time agreements in relation to the number of repairs which are within an agreed confidence interval corresponding to the forecast (Effective for 54% of the articles). To accomplish this, it is advised for Department X to guarantee formally the acquisition of the subcomponents needed to realize the agreed lead times at the supplier. Otherwise, agree formally on obligations for Company X or supplier regarding the acquisition of already acquired subcomponents, when the forecast has been higher than the actual demand. All suppliers which have been approached keep and update fault reports per article which includes the expected number of subcomponents needed per repair. To be able to accompany the forecast with a confidence interval, the forecast must be foreseen with its **forecast error**.

Condition based monitoring (CBM) could reduce the forecasting error in order to enhance the forecasting accuracy[65]. It is therefore advised to invest in CBM technologies. CBM generates real-time data regarding the condition of X components obtained from embedded sensors. The data generated by these sensors could also be used to learn more about the failure behaviour of X components. The sharing of this knowledge with suppliers contributes to the goal of making Department X an interesting X company to invest in for testing advanced and state-of-the-art techniques. As a welcome addition, the possibility of sharing this extensive usage-based knowledge increases for Department X the status of preferred customer at its suppliers.

Applying centralized demand information by communicating the forecast of the customer directly to all stages in the supply chain could significantly reduce the well-known Bullwhip effect[66]. To realize this the supplier should translate and communicate the Company X forecast undistorted to its sub suppliers. This translation must be done by the supplier based on the average number of subcomponents needed per repair. The proposed method implies with this to make the demand data of Company X available to all subsequent **upstream** stages in the supply chain. Centralized demand information will result in a lower forecasting error for the upstream stages in the supply chain by mitigating the Bullwhip effect.

Table 4. 5: Methods for decreasing the variance and duration in outsourced repair lead times relating to the forecasting aspect

Aspect: Forecast **Potential: Highest**	
Implement first	• Realize a transparent forecast (Effective for 54% of the articles) • Provide forecast on regular intervals (Effective for 54% of the articles) • Ask the supplier for an acknowledgement (Effective for 54% of the articles)
Implement second	• Formal lead time agreements for the number of repairs which correspond to a certain confidence interval of the forecast (Effective for 54% of the articles) • Agree formally on obligations for Company X or supplier regarding the acquisition of subcomponents (Effective for 54% of the articles)
Implement third	• Discuss proactively the experience of the supplier regarding the forecast (Effective for 54% of the articles) • Centralize demand information (Effective for 100% of the articles) • Reduce the forecasting error by CBM (Effective for 100% of the articles)

[65] See DeFrank (2017), p.1
[66] See Wilck (2006), p.3

4.3.2 Methods for counteracting uncertainty in the repair process

The more **facultative parts** an article contains, the more uncertainty there is regarding the subcomponents needed for the repair of this article. A facultative part is a sub component which can possibly be the reason of repair of an article. Even when Company X communicates a 100% reliable forecast regarding the number of repairs it will send, the supplier still faces uncertainty regarding the facultative parts needed for the corresponding repair processes. During the diagnosis step of a repair the concerning facultative parts are being exposed.

Company X practices for only four out of the eight approached suppliers (corresponding to 11% of the articles) a **Returned Material Authorization** (RMA) process. When an RMA process is operational, the reason of dismounting the to be repaired article is being communicated to the supplier before the supplier actually receives the article. An RMA process is appreciated because the supplier has in this way a better view on which subcomponents could be possibly the reason of repair. They could decide to order subcomponents in advance or adjust accordingly capacity and expertise based on this information. It is therefore advised to also implement this RMA process for the remaining suppliers (effective for 89% of the articles). When an RMA process is absent, there is no information available beforehand regarding which facultative parts are possibly the reason of repair. At least one supplier (corresponding to 34% of the articles) has indicated to lose administrational capacity because of the effort needed for retrieving corresponding order numbers. A simple remedy for this is to state clearly the corresponding order number on the physical repair. Each repair must be foreseen with its corresponding order number familiar within Company X and at the supplier. This also forms a precondition for introducing an effective RMA process. It is advised to agree with the supplier on common order numbers, for smoothening the communication (Effective for 34% of the articles).

Five out of eight suppliers (corresponding to 95% of the articles) have indicated that the information they receive is rather global and not of significant added value during the diagnosis step of the repair process. Therefore, in order to make the RMA process more effective, more information regarding the reason of disassembling is desired. It is therefore advised that the mechanic employee has the possibility to digitally indicate more specifically the reason of disassembling the article from the X. This indication should then be automatically linked to the corresponding order number. An app on a portable device is therefore desired which suggests initially multiple article specific reasons (effective for 100% of the articles).

All suppliers which have been interviewed indicate that they are keeping track of the subcomponents needed for the repair of each article. These records are based on the fault reports and are updated after every repair. Only three out of eight suppliers which have been approached (corresponding to 87% of the articles) do currently share proactively this diagnosis data with its customers. This diagnosis data could however be of value for Company X. A frequently recurring error could be an indication for misuse by Company X or a fault inherent to its design. If a repair frequently contains a certain facultative part, Company X could also for example decide to include this facultative part in the list of parts which must be replaced during a planned revision. As a first step, it is therefore initially advised to realize that the supplier proactively shares its fault report data with Company X (effective for 13% of the articles). Then, Company X should proactively examine these fault reports and try to diminish the root causes of recurring failures by discussing them with the corresponding supplier. (Effective for 100% of the articles)

Not only the uncertainty on the demand side forms an unpredictable factor for the facultative parts. Four out of eight suppliers (corresponding to 56% of the articles) indicated during the interviews that the peaks in their duration of lead times have been due to **obsolescence** issues. Obsolescence issues relate to the uncertainty on the supply side of subcomponents. During the interviews it became apparent that especially suppliers which repair mainly electronic articles (Supplier A, Supplier F) experience their significant delay due to obsolescence issues. In these electronic markets the technological developments could be at a fast pace. These suppliers complain that they receive reactively a signal from their sub suppliers when a subcomponent has availability problems due to obsolescence. Based on this it is concluded that for an effective obsolescence method all upstream stages in the supply chain should communicate in a proactively manner the likelihood for its articles for becoming obsolete. These suppliers and sub suppliers must however be motivated by Company X to assign sufficient effort in monitoring and communicating their obsolescence risks. For the proper assessment of an obsolescence risk the suppliers must consider facts as market trends, laws and regulations, availability of their sub suppliers, complexity of equipment, type of equipment and maturity of the article[67]. It is therefore initially suggested to

[67] See Povolná & Povolný (2015), p.4

form initial agreements and preconditions in maintenance contracts which state that suppliers and sub suppliers must proactively communicate trends, plans, facts and technological developments which will probably result in obsolescence issues, once they are known (effective for 56% of the articles). Most effective is to realize that the suppliers and sub suppliers communicate a yearly report which shows the obsolescence dates for each article or subcomponent they produce or repair. Then there must be formally agreed on the commitment of these dates (effective for 100% of the articles).

Five out of the eight approached suppliers (corresponding to 20 % of the articles) indicated that they experience significant delay due to waiting on an approval from Company X for conducting a repair based on their proposed price and delivery date. To avoid this delay, it is advised to agree formally on standard prices and delivery dates. Additionally, we advise to trust the supplier when the price exceeds this standard price, a proactive explanation must then be provided by the supplier afterwards.

Table 4. 6: Methods for decreasing the variance and duration in outsourced repair lead times relating to the forecasting aspect

Aspect: Uncertainty repair process regarding facultative parts **Potential: High**	
Implement first	• Agree formally on the principle that supplier proactively shares fault report data (effective for 13% of the articles) • Agree on common order numbers (effective for 34% of the articles) • Suppliers proactively communicate obsolescence risks (effective for 56% of the articles)
Implement second	• Proactively examine fault reports (effective for 100% of the articles) • Evaluate regularly if additional parts must be included for revision (66% of the articles) • Improve quality of information for reason of disassembling (100% of the articles)
Implement third	• Implement RMA process (effective for 89% of the articles) • Trust supplier when repair exceeds standard price (effective for 20% of the articles) • Formally agree on the commitment of obsolescence date (effective 100% of the articles)

4.3.3 Methods for enhancing Focus on X on repair lead times

One precondition for forming formal agreements regarding repair lead time concerns that the supplier also measures and monitors its internal lead time. All approached suppliers do satisfy this precondition and have the required data available for realizing these agreements. However, only four out of eight suppliers (Corresponding to 89% of the articles) do translate this data into a KPI for managing their internal lead times. The remaining suppliers (Corresponding to 11% of the articles) only communicate the data of these lead times on request to their customers. Only one supplier (Corresponding to 45% of the articles) attains a KPI of its Turn Around Time (TAT) performance and communicates and discusses this proactively with Company X on a regular basis. With this supplier there has been formally agreed on repair lead times in relation with a reliable forecast given by Company X. All suppliers indicated that they are willing to monitor, evaluate and decrease their repair lead times when formal agreements have been made regarding these lead times. We therefore advise to motivate the supplier for having Key Performance Indicators by formally agreeing on a certain level of lead time performance (effective for 54% of the articles). It is additionally advised to include a discussion of these KPI's during regular supplier meetings. Ask for an explanation and subsequent measures when an increase in the duration or variance becomes apparent (effective for 48% of the articles).

This paragraph has been removed for this public version

Figure 4.3 visualizes the current measuring points and the potential additional measuring points which become available when realizing the proposed data exchange between Company X and its suppliers and transport agency.

Depending on the agreed incoterms the transport is arranged by the supplier or by an external transportation agency. This external transportation agency for Company X is currently Transport agency X.

This paragraph has been removed for this public version

Table 4. 7: Methods for decreasing the variance and duration in outsourced repair lead times relating to the forecasting aspect

Aspect: Focus on X at supplier regarding repair lead time Priority: High	
Implement first	• X (effective for 100% of the articles) • Agree on DDP incoterms (effective for 100% of the articles)
Implement second	• Realize an ERP connection with supplier (effective for 100% of the articles) • Motivate the supplier formally for attaining KPI's (effective for 54% of the articles)
Implement third	• Discuss KPI trends during regular supplier meetings (effective for 48% of the articles) • Attain KPI's per supplier at Company X internally (effective for 100% of the articles)

4.3.4 Implementation of methods

Per aspect the advised methods have been logically structured. For each set of methods, it is advised to carry them out according to the sequence indicated by tables 4.6 - 4.8. Per subsection of section 4.3 it is clarified why this sequence is relevant for carrying them out. Additionally, to keep the implementation manageable, it is advised to finish the implementation of each method per supplier. The general sequence for this implementation per supplier is shown in table 4.4 from top to bottom. The sequencing rule for the approach per supplier is based on the number of articles each supplier repairs. After implementing the methods for these eight suppliers, additional interviews must reveal which suppliers deserve next preference for implementation.

4.4 Conclusion

Currently, the full potential of forecasting techniques is not being utilized by Department X. A clear and reliable forecasting technique in combination with formal agreements regarding the desired repair lead time, enables the supplier and its upstream suppliers to anticipate sufficient ahead in time. Formal agreements regarding lead times appeared to motivate suppliers to subsequently make formal agreements with their sub suppliers.

An RMA process which informs the supplier in more detail about what could be possibly the reason of repair, already improves the knowledge upfront regarding the subcomponents needed. In combination with formally agreed standard delivery times and prices, the supplier will be more motivated to perform actions ahead in time. Also, the uncertainty regarding the supply side of subcomponents appeared to be a significant cause of a variance in repair lead times. This uncertainty could be reduced by agreeing formally on obsolescence dates for each article or subcomponent they produce. Besides, suppliers must be motivated to translate the Company X forecast into the subcomponents needed for repair and communicate this undistorted to their sub suppliers. This forms a precondition for these suppliers to make subsequently formal agreements with their sub suppliers regarding lead times.

This paragraph has been removed for this public version

Since these methods are interrelated to each other while each method contributes to the same main goal, we chose to express and visualize the complexity of these methods by a causal loop diagram. A Causal loop diagram forms a qualitative tool for displaying the interconnected nature of a complex system[68]. This causal loop diagram is provided in appendix AA.

[68] See Building Blocks, Guidelines for Drawing Causal Loop Diagrams (2011), p.1-3

5. Discussion

The benchmarking study also revealed possible methods to reduce a variance in lead time which we did not encounter during our literature study. A well proven method which is being described by academic literature deserved our preference while formulating the methods for Department X. This chapter however discusses also the practical suitability of methods for Department X which we did not encounter in literature.

Regarding the forecasting aspect it has been advised as a first step to establish the communication of a clear and reliable forecast on which the supplier must give an acknowledgement. Flight Company A and the Military D effectively apply a comparable forecasting methodology. A difference here between Company X and Military D is that the latter is almost fully transparent to a certain set of its OEM'ers and shares all relevant maintenance data with them. These suppliers then provide the forecast of unplanned repairs based on this data in combination with current and historical global fleets data. This global fleets data is available to these suppliers from clients located all over the world, operating in different environments. As an extra step, Military D communicates also its own forecast to these suppliers for enabling them to perform an extra check regarding the reliability of their forecast. The same forecasting method could also be applied for Department X. This requires however that Department X is fully transparent to its suppliers regarding relevant maintenance data. It additionally requires an ERP data-connection between Department X and corresponding suppliers. This will increase the dependence of Company X to these corresponding suppliers. On the other hand, Company C advocated during the interviews for being less dependent on its suppliers. One way they tried to achieve this is to reallocate their inventories at a central point owned by Company C instead of attaining inventories at their suppliers. Their main reason for preferring less dependency is that it enables them to switch more easily between suppliers and with that apply effectively dual sourcing. A current trend could however be noticed in the segment X industry which concerns an increasing amount of IP-rights and safeguarding of engineering and design knowledge by the suppliers[69]. Dual sourcing seems therefore not an effective method for all articles Department X does currently outsource.

[69] See Company X (2019a), SCO Procurement Strategie 2019-2022 slide 7

One of the main methods we advised for reducing the uncertainty regarding the repair process is to implement an RMA process for all articles being outsourced for their repair. In order to retrieve more detailed information regarding the reason of disassembling, it has been advised to use a portable device which enables to indicate the reason more specifically. Company C already applies effectively such an RMA process. They encounter to a less extent the description ‘No failure found’ from their suppliers. It appeared to be very effective to provide the mechanic employee with a tablet which enables him or her to indicate the reason of repair at the moment of disassembling the article from the X. This indication could then be automatically linked to the corresponding repair order. Before sending a repair to the supplier, Company C checks if this indication is explanatory and complete. In this way detailed information is successfully retrieved for making the RMA process more effective.

This paragraph has been removed for this public version

In this discussion additional insight has been created in how additional methods could be of value for Department X for reducing the variance and duration of lead times. Additional benchmarking interviews are possibly needed in order to create a more holistic overview of methods being currently applied in practice. Therefore, we argue that achieving a level of saturation for methods being currently applied in practice can be of significant added value for the approach of formulating effective methods.

6. Academic contribution

Literature studies have been conducted in order to obtain possible theoretical causes of a variance in lead times and for corresponding methods to counteract them. However, it seems that scholars have concentrated mainly on parts of or aspects related to the causes and methods for a variance in external repair lead times, rather than realizing a holistic approach. Besides, the sources of a variance in lead time obtained by literature study were rather general and include, uncertainty in demand, uncertainty in supply and uncertainty in process.

As explained the theoretical causes of a variance in lead time regarding the downstream-, upstream- and process-uncertainty were rather general. Andrzejczak, Mlynczak & Selech (2018) described for instance a possible categorization of randomness inherent to the demand for repairs corresponding to corrective maintenance. Tang (2005) and Mohebbi & Choobineh (2004) shed light on the relation between material availability and the uncertainty in supply. Kuik & Tielemans (1999) agued a positive correlation between batching repairs and a variance in repair lead time.

Also the methods suggested by literature seems to be mainly concentrated on part of or aspects related to a variance in lead times. Regarding methods to counteract the uncertainty in demand, Hemeimat et al (2016) discusses for instance the implementation of forecasting techniques for realizing a proper reflection of the often lumpy and intermittent demand of spare parts. To overcome the uncertainty in supply, Miller (1992) suggested for instance a multilevel cooperation across the supply chain by setting up formal agreements with suppliers. Mohebbi & Choobineh (2005) advocated for instance component commonality among products to reduce the uncertainty in process and with that improve the responsiveness of the supplier.

To date, only a minor part of the scholars seems to have focussed on a holistic approach to reduce the variance and duration of lead times. Angkiriwang et al (2018) and Voortman (2018) suggested for example a set of methods in order to reduce the total of upstream-, downstream- and process-uncertainty. The root causes for these uncertainties are however stated in such a general form that these could merely be used for forming promising inquiry areas for conducting interviews with suppliers. This also holds for the methods as these have not been processed in detail.

We did not encounter any literature which formulates an approach for retrieving the most salient causes of a variance in lead times for a specific organization (or in general). Nor has an approach been encountered for determining the potential a method has for an organization to reduce the variance or uncertainty of lead times. By publishing this piece of literature we believe we did a good attempt for filling up this hiatus in literature. Additionally, this research provides a holistic overview of possible specific causes of a variance in external repair lead times and links them to effective methods for reducing their effect. These causes and methods are not generally applicable for every organization. However, we argue that the approach for retrieving these causes and formulating promising methods is generally applicable.

7. Conclusion

This conclusion starts by restating the main research question. In the next paragraphs we will answer the sub questions in more detail. In the explanation of the third research question, we indicated per root cause for which percentage of the total sample of articles it is related. We refer to appendix W for an explanation of these percentages. The main question for this research was the following: *How can Company X reduce the variance and duration of its external repair lead times?*

The short answer for Department X to this question is: *By agreeing formally with Company X' suppliers on lead time performance in relation to the number of repairs which are within an agreed confidence interval corresponding to the communicated forecast. This sentence has been removed for this public version. We advise to establish ERP data-connections between Department X and its suppliers for supporting the proactive sharing of information regarding the repairs itself and lead time performance.*

The first research question concerned: *Which agreements has Department X currently with its suppliers regarding the variance and duration of outsourced repair lead times? Based upon which information is Department X evaluating the accomplishment of these agreements?*

The agreements Department X has with its suppliers regarding lead time performance are either based on formal or informal arrangements with the supplier. Repair lead times based on formal agreements with the Company X' supplier appears to be rather the exception than the rule.

This paragraph has been removed for this public version

The second research question concerned: *Which root cause or set of root causes of a fluctuation in lead times are present and have most potential for decreasing the variance and duration of external repair lead times?*

This paragraph has been removed for this public version

Six out of the eight approached suppliers (corresponding to 93% of articles) experience their significant and stochastic delay in their repair processes due to waiting on materials from their sub suppliers. These materials could be ordered in advance if a clear and reliable forecast of expected repairs is being shared by Department X on regular intervals. However, no forecast for unplanned repairs is being shared with five out of eight suppliers (corresponding to 41% of the articles). These suppliers explained that they are not willing to take the risk for attaining an inventory level for which it is not clear whether Company X takes these goods in the future. Nor do they have an incentive for making subsequent formal agreements regarding lead times with their suppliers, given this uncertainty.

Even when Company X communicates a 100% reliable forecast regarding the number of repairs it will send, the supplier still faces uncertainty regarding the facultative parts needed to fulfil the repair processes. All approached suppliers have indicated that they repair technical complex articles containing a significant amount of facultative parts (corresponding to 100% of the articles). In current practice only during the diagnosis step of a repair the concerning facultative parts are being exposed by the Company X' supplier. Not only the uncertainty on the demand side forms an unpredictable factor for the facultative parts. Four out of eight suppliers (corresponding to 56% of the articles) indicated during the interviews that the peaks in their duration of lead times have been due to **obsolescence** issues.

Without a formal agreement, the incentive is low for the supplier to order subcomponents in advance or make subsequent agreements with its sub suppliers regarding the availability of subcomponents. However, repair lead times based on formal agreements with the Company X' suppliers appears to be rather the exception than the rule. All approached suppliers have the required data available for realizing an accurate monitoring of their internal lead times. Only four out of eight suppliers (Corresponding to 89% of the articles) do translate this data actually into a KPI.

The final research question concerned: *Which methods or approaches can significantly reduce the effects of the retrieved set of root causes in a permanent way?*

The Company X' suppliers experience a risk when they are preparing for uncertain future repairs. Based on the interviews it could be stated that most suppliers are not willing to take this risk on behalf of Company X. Forecasting appeared to be an effective tool for decreasing this risk. Currently, the full potential of forecasting techniques is not being utilized by Department X. A clear and reliable forecasting technique in combination with formal agreements regarding the desired repair lead time, enables the supplier and its upstream suppliers to anticipate sufficient ahead in time. Formal agreements regarding lead times appeared to motivate suppliers to subsequently make formal agreements with their sub suppliers.

An RMA process which informs the supplier in more detail about what could be possibly the reason of repair, already improves the knowledge upfront regarding the subcomponents needed. In combination with formally agreed standard delivery times and prices, the supplier will be more motivated to perform actions ahead in time. Also, the uncertainty regarding the supply side of subcomponents appeared to be a significant cause of a variance in repair lead times. This uncertainty could be reduced by agreeing formally on obsolescence dates for each article or subcomponent they produce. Besides, suppliers must be motivated to translate the Company X forecast into the subcomponents needed for repair and communicate this undistorted to their sub suppliers. This forms a precondition for these suppliers to make subsequently formal agreements with their sub suppliers regarding lead times.

This paragraph has been removed for this public version

8. Limitations and further research.

This research has several limitations. A first limitation concerns the data-analysis. We obtained a level of saturation for the most salient causes of a repair lead time at a number of articles which correspond to 32% of the total population of articles. However, since the remaining 68% has not been researched for their causes of a variance in lead time, we could not be a 100% sure if all salient causes have been retrieved. This 32% of the articles correspond however to the suppliers which have shown the most variance in their repair lead times. We therefore argue that we formed a robust and relevant sample of articles for obtaining the most salient causes of a variance in external repair lead times for Department X.

As an additional suggestion for further research, We recommended to gain additional insight in the variety of relevant methods being currently applied in practice. The methods finally advised by this research are formulated based on an extensive literature study and available knowledge within Company X. It is therefore desired to interview **best practice** organizations till a level of saturation has been achieved. The goal here is to realize a more holistic view of all effective methods being currently applied for reducing the variance and duration of outsourced repair lead times. A pre-research must first define here when an organization could be marked as a best practice organization, regarding its monitoring and controlling of outsourced repair lead times.

An additional limitation concerns that the time span of this research did not allow for defining each method in the very detail. A certain level of abstraction has therefore been attained. However, all methods have been elaborated till such an extent that these are clear, motivated and implementable. Especially further research is needed for the knowledge to realize ERP-connections with all suppliers. For now, an EDI-system has been suggested. This advice for EDI can be more motivated by researching the different possible ERP-systems and substantiating the final choice by weighted factor scoring. EDI is however able to realize the desired sharing of data.

During the data-analysis part of this study, we tried to clarify which realized lead times correspond to planned and unplanned repair. However, it is not documented by Department X which repairs are being sent to the supplier on a planned or unplanned basis. Noteworthy, it is documented which articles are being demounted of a X for preventive maintenance or corrective maintenance. These articles corresponding to preventive and corrective maintenance are then however being combined and sent mixed to the supplier. A limitation therefore of the data-analysis implies that we did not succeed in quantifying beforehand the difference in variance of repair lead time between planned an unplanned repairs. We advise Department X therefore to clarify per order number if the repair has been due to planned or unplanned repair. We argue that this could be easily implemented if our suggested RMA process is operational at Department X (see appendix AB for this advice).

Propositions have been stated in section 3.2.3 based on literature. It was argued that an increase in the complexity of the repair process at the supplier results for Department X in an increase in the variance in outsourced repair lead times (1). A second proposition stated a positive relation between uncertainty in material availability at the supplier and a variance in repair lead times (2). The third proposition state that uncertainty in demand is positively correlated with a variance in lead times for Company X (3). The fourth proposition states that being a preferred customer status decreases the variance in external repair lead times (4). The additional empirical evidence we obtained by interviewing the Company X' suppliers did not disprove the correlations suggested by the propositions (1), (2), (3). Additional empirical research is however needed to either accept or reject these proposed correlations. We spur further research onto these correlations as these correlations appeared to be of value for retrieving causes of a variance in lead time. We suggest therefore to transform these three propositions into hypothesises.

References

Alad, A. H., & Deshpande, V. A. (2014). A Review of Various Tools and Techniques for Lead Time Reduction 1. *International Journal of Engineering Development and Research, 2*(1), 1159 - 1164.

Andrzejczak, K., Mlynczak, M., & Selech, J. (2018). Poisson-distributed failures in the predicting of the cost of Corrective Maintanance. *Eksploatacja i Niezawodnosc, 20*(4), 602 - 609. doi:10.17531/ein.2018.4.11.

Angkiriwang, R., Pujawan, I. N., & Santosa, B. (2014). Managing uncertainty through supply chain flexibility: reactive vs. proactive approaches. *Production & Manufacturing Research, 2*(1), 50-70. doi:10.1080/21693277.2014.882804

Bagozzi, R. P. (1978). Marketing as exchange: a theory of transactions in the marketplace. *American Behavioral Scientist, 21*(4), 535-556.

Balasubramanian, S., Whitman, L., Ramachandran, K., & Sheelavant, R. (2001). *Causes and remedies of bullwhip effect in supply chain.* Paper presented at the 10th Annual Industrial Engineering Research Conference, Dallas, TX, May.

Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of management, 17*(1), 99-120.

Bharadwaj, A., & Mishra, S. (2013). Comparison of Sorting Algorithms based on Input Sequences. *International Journal of Computer Applications, 78*(14).

Building Blocks. (2011). Guidelines for drawing causal loop diagrams. *Systems Thinker*, *22*(1). Retrieved June 15, 2019, from https://thesystemsthinker.com/wp-content/uploads/pdfs/220109pk.pdf

Cox, A. (2002). *Supply chains, markets and power : mapping buyer and supplier power regimes*. London: Taylor & Francis Books Ltd.

Chen, F., Drezner, Z., Ryan, J. K., & Simchi-Levi, D. (1999). The bullwhip effect: Managerial insights on the impact of forecasting and information on variability in a supply chain. In *Quantitative models for supply chain management* (pp. 417-439): Springer.

Chopra, S., Reinhardt, G., & Dada, M. (2004). The effect of lead time uncertainty on safety stocks. Decision Sciences, 35(1), 1-24.

Christopher, M., & Lee, H. (2004). Mitigating supply chain risk through improved confidence. *International journal of physical distribution & logistics management, 34*(5), 388-396.

Cousins, P., Lamming, R., Lawson, B., & Squire, B. (2008). *Strategic supply management: principles, theories and practice*: Pearson Education.

DeFrank, J. D. (2017). *A Condition Based Maintenance Approach to Forecasting B-1 Aircraft Parts*. Theses and Dissertations. 793. Retrieved July 28, 2019, from https://pdfs.semanticscholar.org/fc6b/0d0129e18e3a27c5ef0dd0a3a8d83101b5f6.pdf

Driessen, M., Wiers, V., Van Houtum, G., & Rustenburg, W. (2013). Typology of repair shops for maintenance spare parts. *Beta Research School WP-427, Eindhoven University of Technology*.

Foroughi, A. (2008). MRO and e-procurement: Opportunities and Challenges. 5 th International Conference on Business Management, Athens Institute for Education and Research.

Hansen, J. Ø., & Schütter, H. (2009). *The Resource-based View and Transaction Cost Economics in Managerial Decision-Making: A Sequential Approach*. Retrieved from

Hautaniemi, P., & Pirttilä, T. (1999). The choice of replenishment policies in an MRP environment. *International Journal of Production Economics, 59*(1-3), 85-92.

He, X., & Jeang, M. (2009). *The Impact of Stochastic Lead Time: the Mean or the Variance.* Paper presented at the Proceedings of the International Multi Conference of Engineers and Computer Scientists.

Heijmann, W. W. (2013). The influence of TCO consideration by the sales personnel on customer loyalty and satisfaction (master's thesis). Retrieved June, 2018, from https://pure.tue.nl/ws/portalfiles/portal/46950982/761577-1.pdf

Hemeimat, R., Al-Qatawneh, L., Arafeh, M., & Masoud, S. (2016). Forecasting spare parts demand using statistical analysis. *American Journal of Operations Research, 6*(02), 113.

Hoffmann, P. (2011). *Innovative Supply Risk Management. The Development of Comprehensive Innovations with Suppliers.* PhD Thesis, Technical University of Twente

Klein, B., Crawford, R. G., & Alchian, A. A. (1978). Vertical integration, appropriable rents, and the competitive contracting process. *The journal of Law and Economics, 21*(2), 297-326.

Kuik, R., & Tielemans, P. F. (1999). Lead-time variability in a homogeneous queueing model of batching. *International Journal of Production Economics, 59*(1-3), 435-441.

Kumar, K., & Aouam, T. (2018). Effect of setup time reduction on supply chain safety stocks. *Journal of manufacturing systems, 49*, 1-15.

Lazzari, F., Sarate, J. A., Gonçalves, R. B., & Vieira, G. B. B. (2015). Competitive advantage: the complementarity between TCE and RBV. *Revista de Administração FACES Journal, 13*(3).

Luo, J., & Meyer, J.-J. (2017). A formal account of opportunism based on the situation calculus. *AI & SOCIETY*, *32*(4), 527-542.

Madhani, P. M. (2010). Resource based view (RBV) of competitive advantage: an overview. *RESOURCE BASED VIEW: CONCEPTS AND PRACTICES, Pankaj Madhani, ed*, 3-22.

Meyer, A., Pretorius, L., & Pretorius, J. H. C. (2003). A management approach to component obsolescence in the military electronic support environment. South African Journal of Industrial Engineering, 14(2), 121-136.

Miller, K. D. (1992). A Framework for Integrated Risk Management in International Business. *Journal of International Business Studies, 23*(2), 311-331.

Mohebbi, E., & Choobineh, F. (2005). The impact of component commonality in an assemble-to-order environment under supply and demand uncertainty. *Omega, 33*(6), 472-482.

Nadeem, S. P. (2016). Risk Pooling, A Technique to Manage Risk in Supply Chain Management, LSCM Regional Conference and International Seminar 2016. Logistics and Supply Chain Management Publication (pp. 86-93). Bishkek: Kyrgyz Russian Slavic University.

Najafi, N., Holmen, E., Lind, F., & Pedersen, A.-C. (2014). *Changing sourcing strategies to make the most out of them.* Paper presented at the IMP Conference, Bordeaux, September 4-6, 2014.

Nederlandse Spoorwegen. (2018a). Company X Insite, online platform for Company X employees. Retrieved November 2018,

Nederlandse Spoorwegen. (2018b). Reizigersvervoer. Retrieved November 29, 2018, from https://www.ns.nl/over-ns/activiteiten/reizigersvervoer.html

Nederlandse Spoorwegen (2019a). SCO Procurement Strategie 2019-2022 [PowerPoint presentation]. Retrieved from Company X.

Nederlandse Spoorwegen (2019b). Vervoersplan, p.37, Retrieved July 1st, 2019 from www.ns.nl

New Zealand Government (2013). Total Cost of Ownership – An introduction of whole-of-life costing. A guide for government agencies and suppliers. Retrieved from https://www.procurement.govt.nz/assets/procurement-property/documents/guide-total-cost-ownership.pdf

Pruyt, E., & Hamarat, C. (2010). *The concerted run on the DSB bank: An exploratory system dynamics approach.* Paper presented at the Proceedings of the 28th International Conference of the System Dynamics Society.

Pujawan, I. N. (2004). Assessing supply chain flexibility: a conceptual framework and case study. *International Journal of Integrated Supply Management, 1*(1), 79-97.

Richardson, J., & Roumasset, J. (1995). Sole sourcing, competitive sourcing, parallel sourcing: Mechanisms for supplier performance. *Managerial and Decision Economics, 16*(1), 71-84.

Schiele, H., Calvi, R., & Gibbert, M. (2012). Customer attractiveness, supplier satisfaction and preferred customer status: Introduction, definitions and an overarching framework. *Industrial Marketing Management, 41*(8), 1178-1185.

Schutten, M. (2018). Discrete optimization of business processes [PowerPoint presentation]. Retrieved from Blackboard archive University of Twente.

Selten, R. (1999). *What is bounded rationality? Paper prepared for the Dahlem Conference 1999.* Paper presented at the Dahlem Conference.

State secretary of Infrastructure and the Environment. (2014). Concessie voor het hoofdXnet 2015-2025. Den Haag. Retrieved November 29, 2018, from https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2014/12/15/bijlage-1-vervoerconcessie-2015-2025/bijlage-1-vervoerconcessie-2015-2025.pdf

Steinle, C., & Schiele, H. (2008). Limits to global sourcing?: Strategic consequences of dependency on international suppliers: Cluster theory, resource-based view and case studies. *Journal of Purchasing and Supply Management, 14*(1), 3-14.

Syntetos, A. A., Boylan, J. E., & Croston, J. D. (2005). On the categorization of demand patterns. *Journal of the Operational Research Society, 56*(5), 495-503. doi:10.1057/palgrave.jors.2601841

Tang, C. S. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics, 103*(2), 451-488.

Teece, D. J. (1976). Vertical Integration and vertical divestiture in the US oil industry: economic analysis and policy implications.

Ulaga, W. (2003). Capturing value creation in business relationships: A customer perspective. *Industrial marketing management, 32*(8), 677-693.

Van Wezel, C.I. (2017-2018). The costums implicaton of Incoterms and how Incoterms and costums are actually misaligned. Post-Master European Costums Law. Retrieved May, 2018, from https://www.europesefiscalestudies.nl/upload/Paper%20Chenette%20van%20Wezel.pdf

Voortman, D. (2016). Preferred customer status with key suppliers: a case study at Paauwe Installaties (master's thesis). Retrieved November 29, 2018, from https://essay.utwente.nl/70991/1/Voortman_BA_BMA.pdf

Wazed, M., Ahmed, S., & Yusoff, N. (2009). Managing quality and lead time uncertainties using component commonality in a production environment. *Engineering e-Transaction (ISSN 1823-6379), 4*(1), 21-34.

Weller, S. C., Vickers, B., Bernard, H. R., Blackburn, A. M., Borgatti, S., Gravlee, C. C., & Johnson, J. C. (2018). Open-ended interview questions and saturation. PLoS ONE, 13(6), e0198606.

Williamson, O. E. (2002). The lens of contract: private ordering. *American Economic Review, 92*(2), 438-443.

Winston, W. L., & Goldberg, J. B. (2004). *Operations research: applications and algorithms* (Vol. 3): Thomson Brooks/Cole Belmont.

Xiaoxun, Y., & Jiajun, L. (2016). The Role of Postponement Strategies to Reduce Supply Chain Risk. *International Journal of Liberal Arts and Social Science, 4*(4), 57-64.