MASTER

The influence of proximity between design and manufacturing on learning

Janssen, N.

Award date:
2020

Eindhoven, January 2020

The influence of proximity between design and manufacturing on learning

Niels Janssen
Student number: 0818763

Master thesis Innovation management
Eindhoven University of Technology

University supervisors

First supervisor:	dr. A. A. (Alex) Alblas	TU/e, ITEM
Second assessor:	Prof. dr. F. (Fred) Langerak	TU/e, ITEM
Third assessor:	dr. N. (Néomie) Raassens	TU/e, ITEM

Keywords: *Design-manufacturing interface, geographically dispersed teams, global manufacturing, global product development, global production, learning curve, organizational learning, proximity, remote teams, virtual teams*

TUE. School of Industrial Engineering
Series Master Theses Innovation Management

Eindhoven University of Technology
Faculty of Industrial Engineering & Innovation Sciences
Innovation, Technology, Entrepreneurship & Marketing Group

Preface

The completion of this master thesis marks the end of my time as a student. I look back on an amazing period in which I've grown a lot as a person and have made countless great memories. This graduation project has been challenging at times, but simultaneously a great learning opportunity to make sense of complex and strategic matters.

I would like to thank Sander Schepens and Jeroen Karel for providing me the opportunity to do my master thesis at this great company. Additionally, I'm thankful for the help of supervisors Jeroen Schoonen and Sander Schepens. Due to their guidance I was able to make sense of the chaotic, dynamic and complex world of the company. I also want to thank Alex Alblas for the much-needed academic perspective during this project. Especially in the last phases of the project, the fruitful discussions led me to understand and improve my research.

Lastly, I want to thank my family and friends for the support during my master thesis period. I was not always the best company during this time, but could always count on support. Special thanks to my father for the great interest in my project and the willingness to help me improve my work. I look back on a successful and eventful period and I look forward to what the future holds.

Management Summary

Introduction

Rapid developments in the field of information and communications technology have led to opportunities regarding the coordination of global projects. In the manufacturing industry the concept of global distributed manufacturing, which makes use of a network of geographically dispersed manufacturing facilities. Global distributed manufacturing often causes geographical dispersion between the design and manufacturing departments. A high degree of proximity between these departments has shown to be beneficial for operational performance and inter-organizational learning. Present-day technological possibilities offer accessible tools that allow for instant global knowledge sharing and access to knowledge repositories. These possibilities may have redefined the interplay of learning on the DMI and the proximity between design and manufacturing. The aim of this study is to uncover how a change in proximity between design and manufacturing influences learning on the design-manufacturing interface (DMI). Proximity representing a multidimensional construct that is broader than just the spatial or geographical aspect.

Methodology

The influence of a proximity change is investigated via a multiple embedded case study at a high-tech manufacturing company in the semi-conductor industry and is aimed to draw inferences on a future scenario at the company where manufacturing activities will be relocated to the customer sites. This relocation has a proximity change between design and manufacturing as a consequence for the concerning activities.

Current manufacturing activities at the headquarters factory and the customer sites are compared on learning and proximity. Via quantitative data on manufacturing issues and cycle time, manufacturing cycle time learning rates are calculated. By the means of semi-structured interviews the proximity differences between the two different DMI's are determined and proximity related drivers and blockers of learning are determined. The interviews are conducted with employees involved in communication on the DMI via issue resolution. By combining data from interview outcomes and quantitative data analyses, the expected outcomes on learning that will result from the proximity change are determined and measures are proposed to optimize learning on the DMI after the relocation of the manufacturing activities.

Results

The learning rate of the factory at the headquarters is highly significant and between approximately .70 and .78, $p < .001$. The learning rates at the customer are insignificant with the exception of an observed learning rate for the number of issues (.90, $p < .05$). The initial performance of the customer factory is substantially

better for all three measures, but these performances converge after an output of approximately 10 machines.

All three proximity dimensions differ substantially between the two manufacturing locations at the company and all three dimensions have been found to directly influence learning. Geographical through face-to-face contact which is preferred and considered superior to alternatives. Besides the geographical proximity of people the geographical proximity of the activities performed on the machines is deemed essential for learning in the NPI phase and to sufficiently train people. Organizational proximity through language and culture differences, which have inefficient communication and unmet expectations as a result. Social capital is in this case a hindering factor in learning as it promoted bypassing formal processes and thereby the structural resolution process. Technological limitations at one manufacturing environment has direct negative effects on learning through the high threshold for and low quality of communication. A number of measures to optimize learning after the manufacturing relocation of activities from the company: (1) Facilitate 24x7 available, knowledgeable and enabled support teams for customer manufacturing and co-locate issue resolution expertise on site during the NPI phase. (2) Enable IT and communication tools for customer manufacturing. (3) Connect customer manufacturing with design by formalizing involvement in follow-up. (4) Adapt training and knowledge management for absence of module integration at headquarters

Practical implications

The insights provided by this study can be used to compose a set of measures relating to proximity that can be taken to optimize the cycle time learning rate at the customer site after the transition to the HLQS.

(1) <u>Co-locate issue resolution support during NPI phase</u>

In the NPI phase of the machine (machines 1 to 5), issue resolution expertise needs to be co-located at the customer site to successfully manage learning and thereby cycle time reduction. When the machine design matures and stabilizes, the local company expertise at the customer sites can slowly be scaled back, depending on the performance at that time. This however should be assessed at a future time and also highly depends on the effectiveness of the independent qualification of the modules that is implemented at the headquarters.

(2) <u>Set up three globally dispersed strategically geographically dispersed sites for a continuous feedback-loop</u>

Three geographically dispersed company sites strategically located globally with issue resolution expertise should be set up. One America-based, one Asia-based and the current headquarters location in Veldhoven, the Netherlands. This reduces the coordination problems that arise from time zone differences that are currently. The three continents should have a standard knowledge sharing timeslot build in their day to pass on information from Asia based customers to U.S. based customer when it is night time at the headquarters (cross-ocean learnings). This way the feedback-loop between customer sites and the company can be functional continuously and knowledge can be passed on to active sites via the follow-the-sun principle.

(3) Enable IT and communication tools or customer manufacturing

The end goal for the company is to have similar liberties regarding the accessing and sharing of data relevant for issue resolution as at the headquarters, at least during the install activities..

(4) Balance formal and informal communication by properly formalizing communication on the DMI

To connect customer manufacturing with design & engineering, it needs to be heavily involved in follow up of issues. The way social capital currently plays a role needs to be replaced by functioning formal communication. In this process it is essential that the formal mechanisms are still sufficiently convenient in order to discourage bypassing. The goal is a healthy balance between formal and informal communication. To achieve this the quality of the issue loggings needs to be improved and the involvement of customer manufacturing in the follow-up of issues needs to be adequately formalized. Frequent temporarily allocation of install engineers at the headquarters site is advisable. Close collaboration between issue resolution support and install engineers builds understanding and improves future collaboration.

(5) Adapt training and knowledge management for absence of module integration at headquarters

With the relocation of activities from the headquarters to the customer site, there is the risk of knowledge displacement. It is important to retain the required absorptive capacity at the headquarters to be able to integrate the relocated activities later. This knowledge retention can be realized by continuous involvement of customer manufacturing in design iterations (ECs) and the other way around by involving D&E in operations at customer install. Frequent mutual visits should be stimulated and cross-functional routines should be set up to create structural and lasting alignment between the departments.

Besides the capacity to absorb, sufficient in-depth technical knowledge level is needed at the headquarters to oversee consequences of decisions and policies for manufacturing at other sites. Hands on experience with the machines is necessary for adequate training of operators and support teams. Technologies like virtual reality can partly be used to mitigate the absence. However, these substitutes are not a sufficient full replacement. New employees trained on these parts will have to travel regularly and new hires should be selected that are willing to do this.

Table of contents

List of abbreviations

D&E – Design & engineering
DMI – Design-manufacturing interface
DN – Disturbance notification (manufacturing issue at the headquarters factory)
DRB – Disturbance review board
EC – Engineering change
EUV – Extreme ultraviolet
HLQS – Independent qualification strategy
IRM – Issue resolution management
KD – Knowledge diffusion
KT – Knowledge transfer
MF – Manufacturing
RQ – Research question
SO – Disturbance service order (manufacturing issue at the customer site)
TMS – Transactive memory system

1. Introduction

The past decades have seen increasingly rapid developments in the field of information and communications technology. This has led to opportunities with regards to the coordination of complex global projects that require intensive collaboration of geographically dispersed actors. Especially in software development the use of geographically dispersed, or virtual teams is already an established practice (Conchúir, Ågerfalk, Olsson & Fitzgerald, 2009). In the manufacturing industry this concept has gained major traction in recent years as a means to optimize the efficiency of the supply chain using distributed manufacturing. This is a practice that uses a network of geographically dispersed manufacturing facilities in order to benefit from local advantages (e.g. costs, expertise, strategic positioning). Examples in the automotive and aerospace industry that take advantage of distributed manufacturing are Boeing and Volvo (Chowdhury & Saleh, 2013; Kennedy-Reid & Bombassei, 2015).

Collaboration and integration of the design and manufacturing department has been shown to increase operational performance, especially in high-tech manufacturing (Thomé & Sousa, 2016). However, global distributed manufacturing often causes a geographical dispersion between these departments. While a lower geographical proximity of these departments not necessarily has to result in less collaboration, research has shown that physical co-location of these departments does have a positive effect on the successful collaboration, communication and performance on the design-manufacturing interface (DMI) (Adler, 1995; Argote & Ingram, 2000; Pinto et al. 1993). This suggests that geographical proximity on the design-manufacturing interface has a prolonged positive effect on manufacturing performance, as is also reported by other studies (Knudsen & Madsen, 2014; Sharifi & Pawar, 2002; Snoo et al. 2011).

However, present-day technological possibilities offer accessible tools that allow for instant global knowledge sharing and access to knowledge repositories. These possibilities have opened doors for businesses to utilize global strategies in manufacturing as sheer geographical proximity no longer seems to be a requirement for intensive collaboration. Additionally, these possibilities may have redefined the interplay of manufacturing performance and proximity on the DMI. The aim of this study is to uncover how a change in proximity influences the manufacturing cycle time learning rate in a design-manufacturing context. Proximity representing a multidimensional construct that is broader than just the spatial or geographical aspect. The influence of a proximity change is investigated via a multiple embedded case study at a high-tech manufacturing company and is aimed to draw inferences on a possible future scenario at the same company. This company has multiple manufacturing locations that each have a different proximity to the design department and is looking into a relocation of manufacturing activities that will have a change in proximity on the DMI as a consequence.

This thesis is structured as follows: the business context, problem statement, research objective and research question are introduced in the following paragraphs of this chapter. In Chapter 2 the theoretical framework is discussed, the relevant concepts are defined and a conceptual model is composed. Chapter 3 contains a detailed description of the methodology of the study. In Chapter 4 the results of the study are presented and subsequently conclusions and implications are discussed in Chapter 5.

1.1 Business context

The case study is performed at a company with the headquarters located in the Netherlands and is a producer of machines that are involved in the fabrication of semiconductors. In short the company is characterized by its cutting-edge complex high-tech machines, relatively high R&D spending, cyclical sales, low sales volume and high collaboration with a select group of suppliers and customers.

The company highly values collaboration on the design-manufacturing interface (DMI). Since its creation it has always worked with the 'lab-fab concept' (laboratory-factory). This concept prioritizes the close proximity of the design & engineering department (development) and the factory (manufacturing). Currently the departments reside in the same building (or connected building) on different floors. This concept of close collaboration and co-location has been a core strategy in assuring an effective iterative design process. This process entails continuously updating the product design after each manufacturing sequence, with more frequent and radical updates in the new product introduction (NPI) phase and only minor updates as the product matures and enters the high-volume manufacturing phase. The frequent updates that follow from the iterative design have an instable manufacturing cycle time as a consequence, especially in the NPI phase where the majority of the updates are implemented. Since the machines require an elaborate and cautious install procedure at the customer, the manufacturing cycle time is defined as the time from the start of the manufacturing sequence in the factory at the headquarters until the time the machine is up and running at the customer site. This means that manufacturing activities are performed at two locations: (a) the factory at the headquarters and (b) the factory at the customer site. This process is explained in more detail in 1.2.

The manufacturing cycle time can be split up in three categories: A-time, B-time and C-time. A-time is the duration of value-adding activities, B-time is the duration of unexpected down-time which is caused by disturbances in the manufacturing sequence and C-time is planned down-time. While A- and C-time are relatively constant, substantial cycle time reductions can be realized by focusing on B-time reduction. While B-time is autonomously reduced as a consequence of experience (see section 2.2) and as the design of the machines mature, the company aims to reduce the manufacturing cycle time by actively reducing B-time. This is done through issue resolution management (IRM), which is a collaboration between design, manufacturing and issue resolution support teams to contain issues on the short-term and collectively assess if structural follow up is needed to prevent the issue on future machines. Earlier research done at the company has shown that the handling of disturbances during manufacturing (and thus IRM) is an important driver for improving the manufacturing cycle time learning rate (Alblas, Zwaans & Schepens, 2017; de Kadt, Peeters, Langerak & Alblas, 2015). The manufacturing cycle time learning rate is the rate at which the cycle time duration decreases as the machines are produced (i.e. cycle time of machine 10 should be shorter than the cycle time of machine 1).

The issue resolution process has the following set up. In the case of a disturbance, the operator from manufacturing (at either the headquarters factory or the customer factory) contacts first line support and simultaneously logs the issue. The operator is then assisted by first line support to contain the issue. First line support can either solve the issue or if this is not feasible within a certain time frame or within the available solving capacity, escalate the issue to second line support and likewise second line support can either solve or escalate further to design & engineering if additional help is needed. After the disturbance is contained it is sent to the disturbance review board (DRB), which is a board that periodically evaluates issues and assesses if structural action is needed for future machines. This board consists of representatives from manufacturing, issue resolution support teams, and design & engineering. This process applies both for: (a) manufacturing at the headquarters and (b) customer manufacturing, for a simplified flowchart of this process see Figure 1.1.

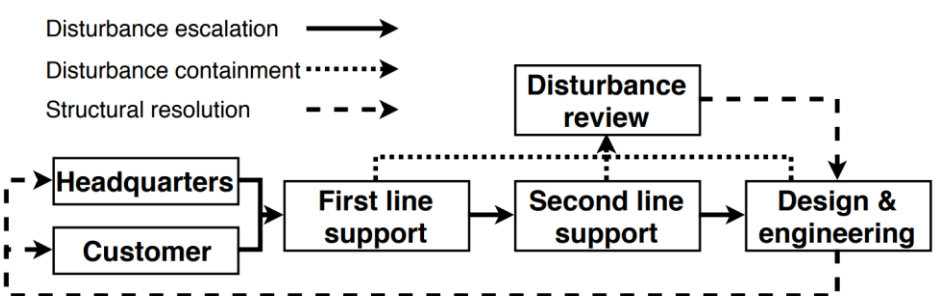


Figure 1.1 Simplified issue resolution information flow chart

1.2 Problem statement

the company's EUV machines consist of 5 modules which are produced in parallel at the headquarters factory. In the current manufacturing sequence the 5 modules are integrated and tested as a whole at the headquarters factory before disassembly and shipment to the customer where the integration and test activities are repeated, see Figure 1.2.

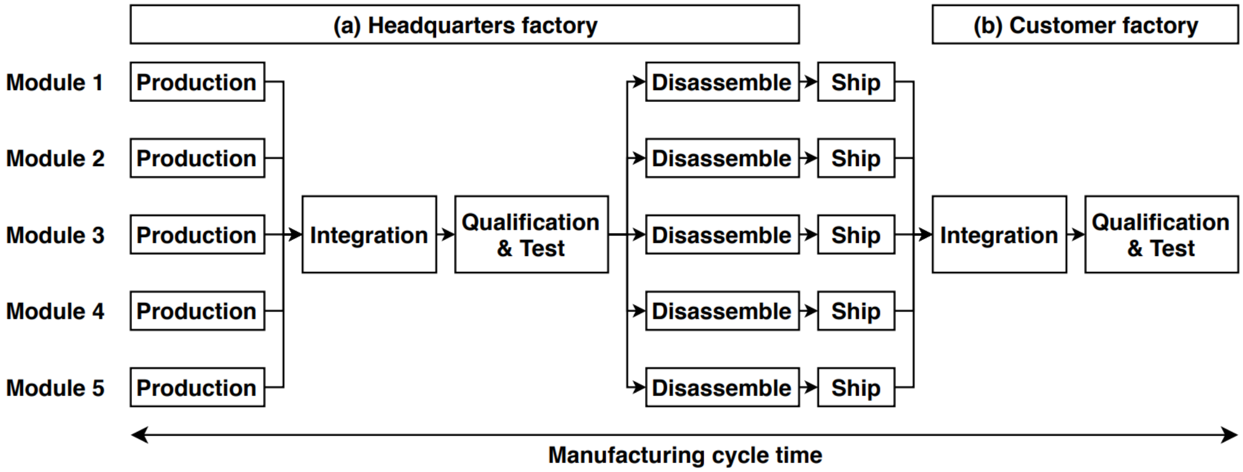


Figure 1.2 Current manufacturing sequence

In the current way of working most issues during module integration and machine testing are captured in the headquarters factory, because once the machines reach the customer factory they have already been integrated and qualified once before. This means that most cycle time reduction through learning from IRM currently takes place at the headquarters and IRM at the customer factory is of less importance as most learning opportunities are already utilized at the headquarters factory.

To reduce the total manufacturing cycle time of the company's newest generation of EUV machines, the company is looking into testing and qualifying each module independently at the headquarters factory and relocate the first-time module integration and machine testing to the customer factory, see Figure 1.3.

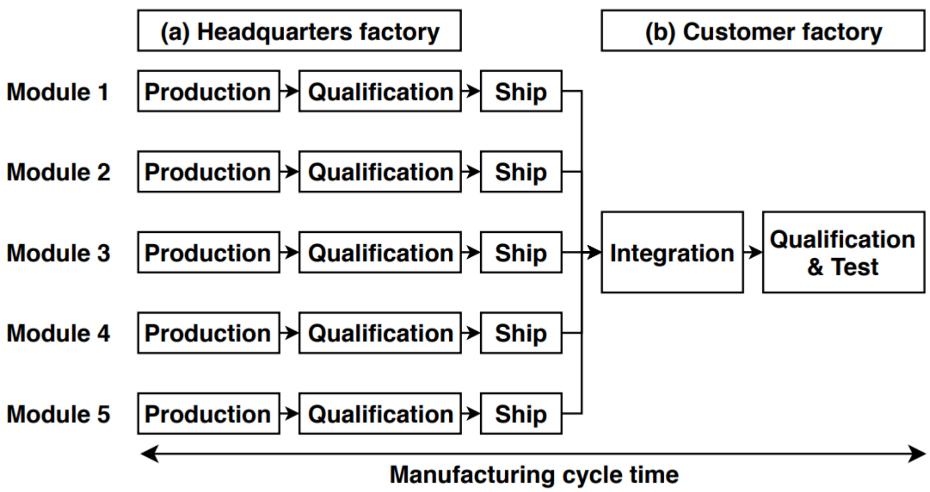


Figure 1.3. Possible new manufacturing sequence (HLQS)

This relocation reduces the value adding manufacturing process time (A-time) as the module integration and machine testing only needs to be performed once. This new way of manufacturing is the 'higher level qualification strategy (HLQS). Using this strategy the company aims to qualify each module independently at a higher level at the headquarters in order to capture the majority of the issues that currently come up during the in-house integration and test activities. This in order to minimize the number of issues during first time integration and testing at customer manufacturing. Although this strategy should reduce the total manufacturing cycle time by a reduction of A-time, the number of issues that will come up at the customer site will in all probability increase More issues subsequently lead to longer B-time. More issues at the customer sites are expected because the HLQS way of working cannot be assumed to capture 100% of the current integration and test issues that come up in-house. Additionally, the learning opportunities that the first-time integration and testing provide now lies at the customer factory, making IRM at the customer factory much more important than it currently is.

After the transition to the HLQS, the manufacturing cycle time reduction on module integration and machine testing activities will completely be dependent on the effectiveness of the feedback-loop between the customer site factory and the design and issue support departments at the headquarters (IRM on the customer DMI). It is of great importance for the company to know what the manufacturing cycle time learning rate at the customer sites will be, this is currently unknown. Ideally the relocation of the first-time module integration and machine test activities should have no effect on IRM and the feedback-loop from manufacturing to design and back should not be influenced by the relocation (the feedback-loop is visualized in Figure 1.4). However, this new way of production has a large proximity change between design and manufacturing as a consequence, because the factories at the customer sites are far removed from the headquarters of the company (where the design and issue resolution departments reside). This can have unforeseen effects on the performance of the feedback-loop from manufacturing to design that is necessary for successful IRM and thus cycle time reduction. This makes the HLQS a very risky endeavor since an ineffective feedback-loop from the customer factory to the headquarters can have disastrous consequences for the company (e.g. order delays, a drainage of issue resolution capacity, financial losses, reputational damage). The company therefore wants to know how this relocation will affect the cycle time learning rate that is achieved through issue resolution and requires an effective feedback-loop. Additionally, it wants to know what measures it can take to optimize learning after the transition to the HLQS.

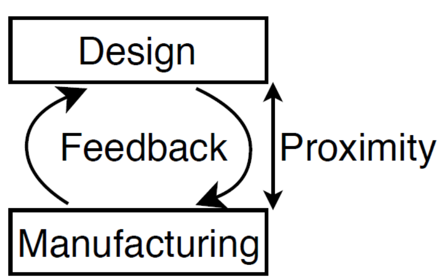


Figure 1.4 The feedback-loop

1.3 Research objective & Questions

The objective of the study is to: (1) give the company insight on what manufacturing cycle time learning rate they can expect at the customer factory after the manufacturing relocation of their newest EUV machines and additionally; (2) advise on how they can organize their transition to the HLQS while optimizing this learning rate; and (3) shine light on the role of proximity in learning on the DMI in the current highly globalized and connected business environment. Proximity representing a multidimensional construct that is broader than just the spatial or geographical aspect. Learning represents the process of improving manufacturing performance through experience (cycle time reduction). The main research question that corresponds to the objective of the study is:

Main research question: How does a change in proximity influence the cycle time learning rate within a design-manufacturing context?

To answer this main research question, proximity and learning rate need to be defined and established in the design-manufacturing context to indicate the scope. The cycle time learning rate for the current module integration and machine testing activities can be calculated for the two manufacturing locations to see if there is learning at all. This leads to sub question 1.

Sub research question 1: What is the current cycle time learning rate on the design-manufacturing interface at (a) the headquarters factory and (b) the customer factory?

In the case that the learning rates between the two manufacturing locations differ, these differences may be attributed to a difference in proximity. To understand the role of proximity in this process the difference in proximity between these two manufacturing sites needs to be established in order to draw a fitting comparison. Manufacturing is done at the headquarters factory and the customer site factories. The design department is also located at the headquarters in the Netherlands. Issue resolution support which is essential in IRM and acts as a link between design and manufacturing is also located at the headquarters. This support mainly consists of communication on the DMI and is thus relevant for learning on the DMI. This leads to sub question 2.

Sub research question 2: What is the difference in proximity between (a) the headquarters factory and the issue resolution support and development departments; and (b) the customers site factories and the issue resolution support and development departments?

When sub research questions 1 and 2 are answered the different learning rates and the difference in proximity to the design and issue resolution departments is clear for both (a) the headquarters factory and (b) the customer site factories. To understand the interplay between learning and proximity, not only the magnitude of the influence is of interest, but also how proximity influences learning. In order to draw inferences for the HLQS it is then important to understand how proximity plays a role by searching for the proximity related drivers and blockers of learning on the DMI are. This leads to sub question 3:

Sub question 3: What are the proximity related drivers and blockers of learning on the DMI?

Whether or not learning exists and differs between the two locations is answered by the first research question, what the difference in proximity is in the second question and in the third question how proximity plays a role in learning. By combining the answers of these research questions the expected impact of the manufacturing relocation on cycle time learning can be projected on the HLQS scenario and the main research question can be answered: How does a change in proximity influence the cycle time learning rate within a design-manufacturing context?

To answer the research questions a conceptual model is established in the next chapter. This is the outcome of an extensive literature study on proximity and learning on the DMI context (see Appendix A). Afterwards, the methodology of the study is explained in detail Chapter 3. In Chapter 4 the results are presented. Finally, in Chapter 5 the implications and conclusions of the findings of this study are discussed.

2. Theoretical Framework

This chapter outlines the relevant literature and serves as a theoretical foundation and starting point for this study. In order to answer the research questions introduced in 1.3, the concepts learning, proximity and the design-manufacturing interface are explored and defined using extant literature. This is done by the means of a systematic literature review on the combination of the three concepts and through discussion of seminal work of each concept. First the synopsis of a systematic literature review regarding learning, proximity and the design-manufacturing interface is presented in tabular form. Thereafter the three concepts are discussed individually and defined in the context of this study. The current state of literature on the combination of the three concepts is discussed afterwards. At the end of this chapter a conceptual model regarding the relations of these concepts is introduced and the position of this study within current literature is discussed.

2.1 Systematic literature review on learning, proximity and the design-manufacturing interface

As preparation for this master thesis a literature review is performed about the interplay between proximity and learning on the design manufacturing interface. The goal of this literature reviews is to find out what the current role of proximity is in the learning process and additionally to enhance and acquire the vocabulary, distinguish what research had been done and identify gaps in literature on the concepts.

The literature search engine Web of Science is used to index all relevant articles from a selection of journals. A search query is constructed on the concepts proximity, learning and DMI which yielded 162 relevant papers. After a selection on relevance by filtering on the abstract 43 papers were reviewed in depth and summarized in a Table. A core selection of these papers is presented in Table 2.1. The detailed method and results of the literature study are attached in Appendix A. In Table 2.1 learning is divided into induced and autonomous learning, these types of learning are later explained in section 2.2. Proximity is divided into geographical, organizational and technological dimension, these dimensions are explained and defined in section 2.3.

Table 2.1. Research on Learning and proximity on the DMI core selection

	Learning		Proximity				
Author(s)	**Autonomous**	**Induced**	**Organizational**	**Technological**	**Geographical**	**DMI Context**	**Implications for information exchange**
Akgun et al. (2006)		✓		✓			TMS positively affects team learning, speed-to-market, and new product success
Argote & Ingram (2000)		✓	✓		✓		Recipient's productivity recovers faster when knowledge source is geographically close
Cohen & Levinthal (1990)		✓					Requisite breadth of knowledge is needed in order to absorb more specialized knowledge
Dixon (2017)		✓		✓	✓		Routines to ensure virtual team learning are trust, agreed goals and experimentation
Dutton & Thomas (1984)	✓	✓					Progress functions progress attained not only through maximizing cumulative output
Kauppila et al. (2011)		✓	✓	✓	✓		Knowledge repositories, sense of community, member rotation and team building and training stimulates knowledge sharing in global company
Knudsen & Madsen (2014)		✓		✓	✓	✓	Increased interaction between dispatching and receiving units will benefit knowledge transfer
Pedersen & Slepniov (2016)	✓	✓		✓	✓	✓	Creating and enhancing knowledge repositories very helpful in overseas expansion
Peeters et al. (2014)		✓		✓		✓	Absorptive capacity routines should be aligned with the phase of absorption.
Pinto et al. (1993)		✓			✓		Physical proximity increases cross-functional cooperation
Sharifi & Pawar (2002)				✓	✓	✓	An initial face-to-face meeting for virtual teams is important to establish trust, effective team leadership and management
Snoo et al. (2011)				✓	✓	✓	Close physical proximity leads to more face-to-face collaborative communication
Sorenson et al. (2006)		✓	✓		✓		Social proximity to the source is important for KD with knowledge of moderate complexity
Thomé & Sousa (2016)					✓	✓	KT on the DMI is important for operational excellence in high-tech environments
Tripathy & Eppinger (2011)			✓	✓	✓	✓	Far-reaching decision making should lie with the headquarters home location
Tripathy & Eppinger (2013)		✓			✓	✓	Product development tasks should first be properly modularized before offshored
Vandevelde & Dierdonck (2003)			✓			✓	Overcoming language barriers, formalizing mechanisms and increasing empathy should be stimulated by senior management

Abbreviations used in Table: DMI = design-manufacturing interface, KD = knowledge diffusion, KR = knowledge repository, KT = knowledge transfer, TMS = transactive memory system

2.2 Learning

Learning is a process that can occur on many levels, have different sources and can be quantified or observed in a variety of ways. Learning on an organizational level which is known as organizational learning, is an important topic in management, innovation and economics as it serves as an important tool to stay ahead in the competitive business environment. Although the process of organizational learning itself is quite complicated and multilateral, it is generally defined as: improved future performance due to the accumulation of experience (Argyris & Schön, 1997; Dutton & Thomas, 1984). Experience in this case is often measured in terms of cumulative number of task performances and forms the basis of learning curve theory (Argote, 2013).

Learning curve theory states that performance should increase with experience (Argote, 2013). In manufacturing, it is very straightforward to track performance, since the output is a physical product. This can be visualized in a learning curve by plotting a resource measure (e.g. cycle time, production costs) over the experience (cumulative manufactured products). The resources needed for a 'to be produced' product should be less than the resources that were needed for the last finished product. This phenomenon was first empirically documented by Wright (1936) in the aeroplane industry with a mathematic formula and is also observed in many similar production environments (Baloff, 1966, 1970; Nadler & Smith, 1963). The formula describes the relationship between experience and resources needed to manufacture the next product in relation to the resources that were needed for the production of the first product (Wiersma, 2007). The basic formula is shown in Equation 1:

$$\textit{Equation (1)} \;\; Y = aX^{-b}$$

Y is the average cost (resources) for the last produced product, a is the cost for the initial product produced, X is the experience measured in cumulative finished products and -b is the learning rate and can be used to calculate the progress rate. The formula for this progress rate is calculated with Equation 2:

$$\textit{Equation (2)} \;\; p = 2^{-b}$$

In this Equation p is the percentage of resources needed after a doubling of cumulative production. This progress rate is a measure that varies among industries and organizations. It is generally between 70% and 95%, in the case of the Wright it was 80% which is still a percentage that is generally perceived as being the average (Argote & Epple, 1990). A progress rate of 80% means that after a doubling in cumulative output the required resources for the production of the next product are reduced to 80% of the initial required resources.

So far in this chapter learning has been a concept that is passively observed and seems to be a side effect of executing an activity, but learning is considered to be a process that can be influenced. Dutton & Thomas (1984) have made the distinction between autonomous and induced learning. Autonomous learning, also learning by doing is the process of learning which follows from mere experience in executing a certain task, which is in line with learning curve theory and also known as single-loop learning (Argyris & Schön, 1997).

Induced learning is a type of learning in which it is the outcome of deliberate actions aiming to increase performance. See Figure 2.1 for an overview of the two types of learning and their relations. Some examples actions to steer induced learning are: imitating competitors, making design changes or making manufacturing process changes (Mansfield, 1961; Middleton, 1945; Wright, 1936). Absorptive capacity, which is defined by Cohen & Levinthal (1990) as "the firm's ability to recognize the value of new external knowledge, assimilate it, and apply it to commercial ends", is another influenceable factor in learning. A proactive approach towards steering R&D in a relevant direction for organizational opportunities creates a level of absorptive capacity that enables learning (Cohen & Levinthal, 1990). Having routines in place to retain and expand absorptive capacity should be a priority to managers, these routines however are not easily generalized and should be tailored to the company (Peeters, Massini & Lewin, 2014). Intuitively deliberate learning to improve performance is done by focusing on increasing successes, however learning can also be achieved by focusing on reducing failures. Failure reduction has shown to have a similar effect as learning from production in a variety of industries (train, mining and airline) and on both industry and firm level (Dahlin, Chuang & Roulet, 2018). In high-tech iterative environments the amount of disturbances is an important driver behind manufacturing cycle time. Earlier research done at the company has shown that the handling of disturbances during manufacturing is an important driver for improving the manufacturing cycle time learning rate (Alblas, Zwaans & Schepens, 2017; de Kadt, Peeters, Langerak & Alblas, 2015). Likewise in a paper by Hatch & Mowery (1998) problem solving effort showed to have more impact than product output on process innovation in the semi-conductor industry. This implies that substantial performance gains can be realized by focusing on decreasing the number of disturbances in the manufacturing sequence. Thus disturbance or issue resolution performance qualifies as an appropriate measure for learning.

Not only are there considered to be different types of learning, the source of learning can also differ. It can either originate within the firm (by observation or experience), or come from outside (general new knowledge freely entering the firm) (Dutton & Thomas, 1984). In other words the source can be endogenous or exogenous (Levy, 1965; Dutton & Thomas, 1984). This study focusses on deliberate learning through issue resolution management aiming to improve future cycle time and efficiency, and thus classifies as an induced type of failure learning from an endogenous source (see Figure 2.2).

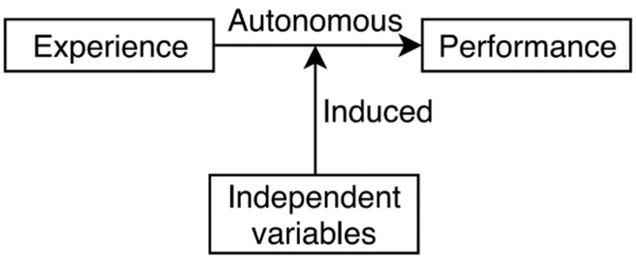


Figure 2.1 Types of learning and their relation

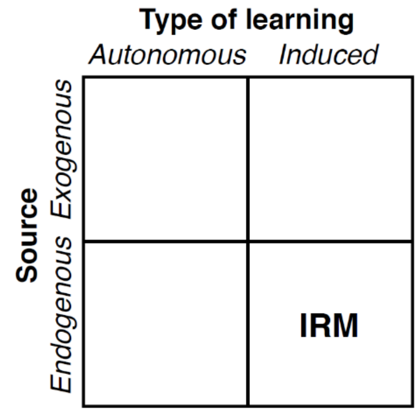


Figure 2.2 Types and sources of learning

2.3 Proximity

Proximity is an important concept in this study, as the geographical dimension of proximity serves as the moderating variable. It is therefore important to specify the exact definition, because proximity is often purely thought of as a geographical concept. It can however considered to be a multidimensional construct in which also other aspects like culture, language and technology are relevant. Especially due to globalization and increased opportunities in communication and knowledge sharing, geographical proximity is not as crucial as it once was in collaboration. This has led to the rise of teams that intensively work together but are not geographically proximate. These teams are known as geographically dispersed teams, globally dispersed team, virtual teams or remote teams and have increased the interest in proximity or dispersion in combination with collaboration. Research on geographically dispersed teams is getting more prevalent as technology only makes this way of working more accessible and businesses strategically try to cut costs on real estate and utilize global expertise (Richman, Noble & Johnson, 2002).

How to set up, manage and facilitate these geographically dispersed teams or virtual teams is studied in a number of papers (Dixon, 2017; Kauppila, Rajala & Jyrämä, 2011; Sharifi and Pawar, 2002). Three conditions that have been found to support learning in geographically dispersed teams are: agreed upon goals, independence to experiment and an environment of trust. Setting up routines to stimulate these routines is recommended (Dixon, 2017). A tool used for knowledge sharing between geographically dispersed sites is a transactive memory system, which also has been shown to have a positive impact on team learning and speed to market in product development teams (Akgun et al., 2006; Sharifi & Pawar, 2002). In overseas production knowledge repositories like a transactive memory system have shown to be useful in setting up parallel production environments and drove the manufacturing learning curve (Pedersen & Slepniov, 2016).

Even though technological progress has made direct communication across the world with visual and audible feedback much more accessible, the need for true face-to-face contact and informal relationship-building to accomplish a sense of community and trust among workers still appears to be of crucial importance in the performance of these teams (Sharifi and Pawar, 2002; Dixon, 2017; Snoo, Wezel and Wortmann, 2011).

Some firms may currently even be overestimating the substitution capabilities that technology offers to replace the need for geographical proximity, see for example recent studies emphasizing this (Choudhury & Prithwiraj, 2017; Knudsen & Madsen, 2014). Other examples of challenges that these teams meet are time zone differences that lead to coordination problems (Espinosa & Carmel, 2003; Espinosa & Pickering, 2006; Rutkowski et al. 2007) and a reduction of spontaneous face-to-face contact that a geographically dispersed team brings about (Van den Bulte & Moenaert, 1998). This lack of face to face meetings can in turn lead to a lack of incentive to communicate about the context which can create miscommunications (Cramton, 2001). Additionally, cultural or national differences can create conflict (Armstrong & Cole, 1995; Jehn, 1994). A shared identity and context between team members and spontaneous communication in and between teams has been found to reduce conflicts (Hinds & Morenson, 2005). A study by O'Leary and Mortenson (2009) stresses the important of geographical configuration of geographically dispersed teams, which comes down to the number of employees at each site and the level of isolation of each team member site to the rest of the team. They state that the geographical configuration may even be a more important factor than spatial and temporal distance and socio-demographic factors.

Although there is plenty research on geographically dispersed teams and proximity, there is no widespread common division of proximity or dispersion in several dimensions in this context (Knoben & Oerlemans, 2006; O'Leary & Cummings, 2007). O'Leary and Cummings (2007) have made the distinction between the dimensions of: (1) spatial; (2) temporal; and (3) configurational for dispersion in order to fully cover the concept with relation to geographically dispersed teams. The spatial dimension being the geographical distance, the temporal dimension meaning the overlap of work hours of team members and the configurational dimension constitutes the arrangement of the team members across sites. Knoben and Oerlemans (2006) have collected the uses of proximity in literature for inter-organizational collaboration and concluded that proximity can be placed in the following six dimensions: (1) geographical, (2) institutional, (3) cultural, (4) cognitive, (5) social and (6) technological. Geographical proximity describing the spatial distance, institutional proximity based on the societal frameworks of shared constraints, cultural proximity based on shared norms and values, cognitive proximity defined as 'the similarities in the way actors perceive, interpret, understand and evaluate the world' by Wuyts et al. 2005, social proximity describing the personal albeit intimate proximity and finally technological proximity based on shared technological experiences and knowledge bases. To further restrict the number of dimensions they can be reduced to three by grouping together the behavioral types of proximity. These behavioral types are: cognitive, institutional, cultural and social proximity. This leaves three dimensions of proximity: (1) geographical proximity; (2) organizational proximity (the behavioral types: cognitive, institutional, cultural and social); and (3) technological proximity.

For this study the terminology of proximity and the three corresponding dimensions of Knoben and Oerlemans will be used. Although the geographically dispersed team literature is very relevant for this research, this study extends beyond the distribution of work between geographically dispersed team members. This study concerns moving manufacturing activities down the supply chain to customer sites which also substantially impacts the work environments in which these relocated activities are performed. This makes technological proximity an important aspect which is underrepresented in the dimensions put forward by O'Leary and Cummings. For the remainder of this thesis proximity will be used as a measure for distance divided in: (1) geographical; (2) organizational; and (3) technological proximity.

Geographical proximity

This dimension denotes the literal spatial distance and the ease of bridging this distance (travel time). Only denoting the literal spatial distance would often not suffice for a fair comparison, since obstacles that are in the way are ignored while relevant for the ease of bridging of this distance. In this study geographical proximity can be seen as dichotomous concept. There is either the case of physical co-location or not.

Organizational proximity

This dimension represents the behavioral types of proximity (cognitive, institutional, cultural and social). The human aspect of proximity, it covers the personal relation, beliefs and understanding. This includes language barriers and also temporal distances.

Technological proximity

The technological proximity denotes the difference in technological knowledge, experience and communication tools available. This definition of technological proximity differs slightly from the definition by Knoben & Oerlemans as they limit this dimension of proximity to the discrepancy in technological experiences and know-how, while in this study technological proximity is broader in the sense that the available technological tools are included. For example: the quality of a data or cell-phone connection, availability of software tools, and other IT tools used to communicate.

2.4 The design-manufacturing interface

The design-manufacturing interface concerns the link between 'product design and engineering' and manufacturing. Although the design-marketing interface has frequent occurrences in literature since the 70s, there is relatively little research on the design-manufacturing interface (DMI), as was already noticed by Riedel and Pawar (1991) again by Vandevelde and Dierdonck (2003) and continuous to be the case as was concluded after an extensive literature review on DMI studies by Dekkers, Chang and Kreutzfeldt (2013). However, the importance of inter-functional collaboration is increasingly valued and integration of departments is attempted with proposed means as physical co-location, team training and building and stimulation by management to build trusting relationships and a sense of community between departments (Thomé and Sousa, 2016; Snoo et al., 2011).

The DMI is relevant for this study, because of the proximity change on this interface in the case of the case company. An example of a previous proximity change on this interface is the Boeing 787 Dreamliner project. This project was a risky endeavor by Boeing where it performed all functional design in house, but outsourced 60% of the detailed design and production to a variety of suppliers (Wagner & Norris, 2009). The project failed and after six delays of the project the Boeing 787 Dreamliner, Boeing had to insource the operation. The outsourcing of both design and production in the new product introduction phase without understanding the conditions in which it would work turned out to be a mistake (Mauboussin, 2009). Another important and overlooked factor as stated by Dekkers, Chang and Kreutzfeldt (2013) in the Boeing Dreamliner case, was the underestimation of the need for in-depth technical knowledge in order to overcome problems that are common with novel products. Similarly, after a case study at Rolls Royce the importance is stressed by Prencipe (1997) to always keep full design capability in-house even when outsourcing activities and to make sure to have the absorptive capacity available to be able to integrate outsourced components back later.

In high-tech environments where firms frequently reiterate their design, close integration and collaboration specifically between manufacturing and product design has found to been essential for operational performance (Thomé & Sousa, 2016). With close collaboration and integration in this case coming down to continuous interaction and feedback on the design-manufacturing interface. The successful integration of the design-manufacturing interface however, poses some challenges since barriers such as personality, cultural, language, organizational, and spatial differences have to be overcome for successful integration to be accomplished (Vandevelde & Dierdonck, 2003). Adler (1995) posed that successful integrated teams typically require physical proximity. Technological progress since then however has been substantial and may have reduced this need for physical closeness in today's modern business environment.

2.5 Proximity on the DMI and learning

The core selection of papers and the previous elaborations on the individual concepts taken together suggest that the combination of the three concepts is not commonly researched. Learning in a design-manufacturing context where proximity is approached holistically taking into account the multidimensional aspect of the concept is currently underrepresented. No such study has been found (see Table 2.1). The interplay between learning and proximity however is more commonly researched with research on interorganizational learning and the importance of social capital, see Woolcock and Narayan (2000). Social capital is very much relevant for organizational proximity, as it refers to the supportive relationships among people sharing the same norms and values (Coleman, 1988). Social capital can be divided in three dimensions: (1) bonding; (2) bridging and (3) linking, as proposed by Woolcock (1998). Bonding concerns connections with people who are alike (internal cohesion), bridging is the term for a connection between clearly different communities, groups or organizations and linking concerns the communication between 'vertical connections' in which hierarchy plays a role and norms and respect are usual in communication. Concerning the bonding aspect of social capital, a challenge in a manufacturing relocation with regards to learning is to retain the form of knowledge embedded in the interactions of people (Argote & Ingram, 2000). The interdepartmental empathy is an important factor in performance and communication within organizations and is driven by continuous interaction which is enabled by close proximity (Pinto et al., 1993; Vandervelde & Van Dierdonck, 2003). It has also been reported that high social capital within groups can lead to increased cooperation, because of the frequent interactions within that group that cultivates reciprocity (Narayan & Pritchett, 1999). Following this, it has been suggested that a high degree of social capital can allow people to resolve problems more easily by employing this capital (Putnam, 2000). Taken together, this suggests that organizational proximity on the DMI could be very important factor in successful issue resolution.

The relation between learning and proximity is also frequently occurring theme in a manufacturing context, however this mostly entails only one-way information transfer from headquarters to the offshore location to get this location up to speed (Asmussen, Larsen and Pedersen 2016; Mihalache et al., 2012; Pedersen and Slepniov, 2016; Knudsen and Madsen, 2014). In extant literature learning on the DMI is mostly seen as a unilateral process concerning one-way information transfer. Learning on the DMI however is a reciprocal process, a constant feedback-loop alternating between design and manufacturing to improve and stabilize a maturing product.

All dimensions of proximity seem to have a substantial positive effect on learning, geographical proximity (Argote & Ingram, 2000; Kauppila et al., 2011; Knudsen & Madsen, 2014; Pinto et al., 1993), organizational proximity (Kauppila et al., 2011; Sorenson et al., 2006) and technological proximity (Akgun et al. 2006; Kauppila et al., 2011; Pedersen & Slepniov, 2016). The concept proximity however, in relation to geographically dispersed teams, or virtual teams is a concept that varies among studies and is currently not treated as a uniform notion (Knoben & Oerlemans, 2006; O'Leary & Cummings, 2007). The geographical aspect of proximity seems to be dominant in most studies and the concept seldom approached holistically, including all dimensions.

2.6 Conceptual model

As the trend of globalization and the shortening of product lifecycles continues, manufacturers are in all likelihood driven towards a global, adaptive and heavily integrated organizational structure in order to stay competitive. Conditions very much like the concerning high-tech manufacture. In these conditions it has huge value to know how relocation of manufacturing activities will affect collaboration on the DMI and hereby cycle time learning. This study aims to uncover all relevant effects of proximity on learning through intensive reciprocal collaboration on the DMI (see Table 2.2).

Table 2.2. Study scope

	Learning		***Proximity***			
	Autonomous	Induced	Organizational	Technological	Geographical	DMI Context
This study (2019)		✔	✔	✔	✔	✔

Learning as defined in section 2.2, is improved future performance due to the accumulation of experience (Argyris & Schön, 1997; Dutton & Thomas, 1984). Experience is commonly measured in cumulative number of products produced (Argote, 2013). In this study, learning is the rate of manufacturing performance improvement (cycle time reduction) over manufacturing experience (cumulative products produced). This process is studied in a design-manufacturing context and is considered to be influenced by the multidimensional concept proximity (see Figure 2.3). The research objective is to show what the influence of each proximity dimension is on the learning process and how the dimensions relate to each other in this process. To clarify the relations of concepts, the conceptual model that corresponds with the research questions and research objective is visualized in Figure 2.3. This visualizes the learning rate which is represented as the effect of experience on performance and is the dependent variable within a design-manufacturing context. The proximity on the DMI is the moderating variable and divided into the three dimensions discussed (shown on the right in Figure 2.3). Not only influence of proximity as a whole is of interest but also how each dimension contributes to this process and how these relate to each other.

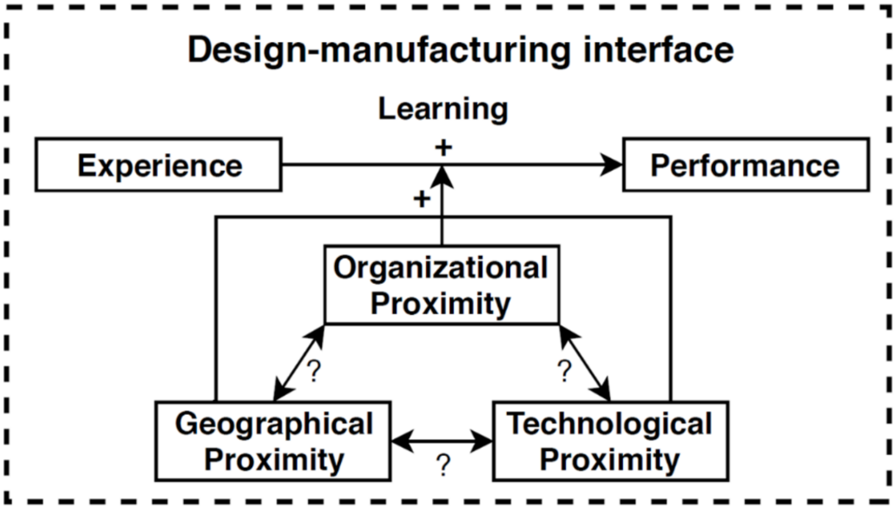


Figure 2.3 Conceptual model

This conceptual model is empirically tested in this case study, the methodology to accomplish this is described in the next chapter.

3. Methodology

This chapter outlines the methodology that is used to answer the research questions composed in Chapter 1. First the research design is introduced and secondly it's explained how the methods relate to the research questions. Thereafter the ways of inquiry are described in detail, first the quantitative method, second the qualitative method and afterwards how the results of these methods are combined to answer the main research question.

3.1 Research design

To answer the main research questions and the 3 sub research questions, a multiple embedded case study methodology with across case analyses is employed. This method is appropriate for 'how?' and 'why?' research questions and allows for the combination of qualitative and quantitative methods in a single study (Eisenhardt, 1989; Scholz & Tietje, 2002; Yin, 2003). Using this method, two cases embedded within the design-manufacturing context are explored and compared to draw inferences on the HLQS. The two cases that are compared are: (a) the DMI of the headquarters factory and (b) the DMI at the customer factories, which differ in terms of proximity to the support and design & engineering departments. The two manufacturing sites are selected because they have different proximities on the DMI, but perform the same manufacturing activities and both have comparable reciprocal collaboration on the DMI. This collaboration between the two manufacturing sites and design has the same goal of a stable and reducing cycle time. A discrepancy in manufacturing cycle time learning between (a) and (b) can be (partially) attributed to the difference in proximity, because as discussed in Chapter 2 proximity has been shown to influence cycle time learning. Subsequently the existence and magnitude of this difference are useful insights for conjecture on the future HLQS scenario which will have a proximity change as a consequence.

To answer the main research question, three sub research questions are composed, each tackling an aspect of the main research question. The first sub research question is used to establish if cycle time reduction takes place at all at case (a) and case (b). This can determined by comparing the duration of cycle times as more machines have been produced. If the cycle time decreases there is a non-zero cycle time learning rate. To determine the cycle time learning rate, three different quantitative performance metrics are used and each plotted over the same experience measure. All three performance metrics are slightly different ways to measure cycle time progress. Two metrics are based on a reduction of B-time through issue resolution management. These are: (1) the number of manufacturing issues per machine, and (2) the duration of all manufacturing issues per machine. As discussed in Chapter 1 and Chapter 2, a focus on B-time reduction is an important driver for cycle time reduction and therefore a suitable measure for total cycle time reduction. The third metric is the cycle time measured in the number of days a machine is in the factory from start to finish of the concerning manufacturing activities. The measure used for experience is the cumulative number of machines produced. So, each of the three cycle time performance metrics are plotted over the cumulative number of machines produced to create three different learning curves. The reason for using multiple metrics to calculate the cycle time learning rates is that this benefits the validity of the claims made following from the learning rates as they are based on multiple sources of information.

To answer sub research question 2 and 3 which are about proximity differences and proximity related drivers of cycle time learning, semi-structured interviews are conducted with representatives of design, manufacturing and issue resolution support teams. In this study the research regarding proximity is exploratory and proximity is a concept that includes subjective aspects like culture and engagement. Using a semi-structured interviewing method allows for an exploratory way of research and provides the researcher with the opportunity to ask follow-up questions which helps to gain in-depth understanding of the concepts and processes described by the interviewees on proximity.

The learning rates of sub question 1 say something about the existence and magnitude of the influence of proximity, sub question 2 says something about how the proximity differs on the different dimensions and sub question 3 uncovers how proximity influences cycle time learning. By combining these answers, the main research question can be answered and the expected influences of a proximity change on the DMI that the HLQS will bring about can be inferred. Additionally, a focus group session is held with a subset of the interviewees. This focus group is a reflective session to confront the interviewees with the results and discuss consequences and potential measures for the HLQS. For a visual overview of the multiple embedded case methodology and the relations of research questions to the methods and cases Figure 3.1.

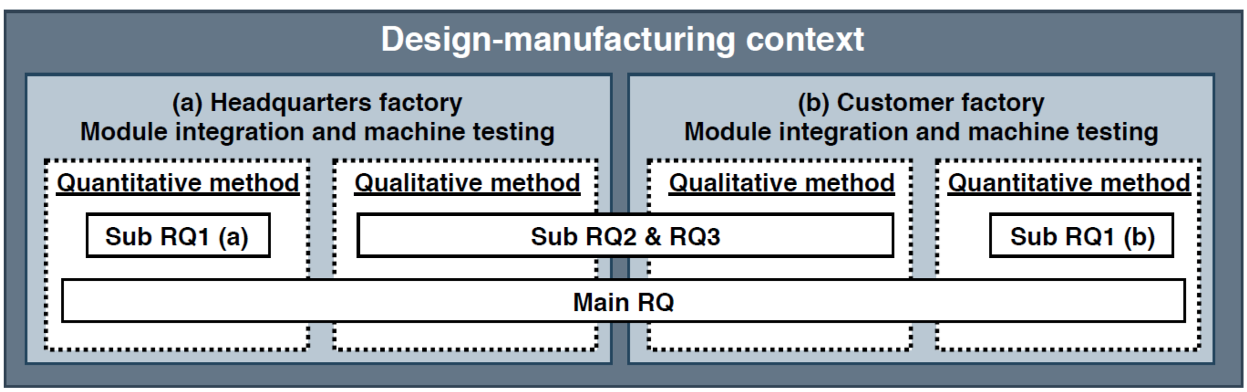


Figure 3.1 Multiple embedded case study overview

3.2 Quantitative company data

Quantitative data is used to answer sub research question 1 and later combined with the qualitative data to answer the main research question. Three manufacturing performance metrics are used to calculate learning rates for the headquarters and the customer factories. The metrics are: (1) number of manufacturing issues; (2) manufacturing issue duration; and (3) manufacturing cycle time. The result of successful learning on the DMI should be long-term reduction and stabilization of the manufacturing cycle time. Because focusing on B-time (cycle time that is the result of issues) has been shown to be an important driver of cycle time reduction as is shown by earlier research at the case company (Alblas, Zwaans & Schepens, 2017), the three measures are deemed suitable indicators of cycle time learning. The three analyses are carried out with data from both manufacturing sites and then compared. For the combining, cleaning and analyses of the data sets, the open source software for statistical and data analyses R is used. The analyses are performed on the most recent EUV machines of the company (the NXE:3400B). The selection for this specific machine type is made to render the outcomes of the analyses as relevant as possible for the new type of EUV machines which will be produced via the HLQS.

3.2.1 Quantitative data collection

The quantitative company data is retrieved from both the business engineering department and SAP (the ERP system in use at the case company). Multiple datasets are combined to create an information rich dataset on issues. An information overview of the samples used in the analyses are attached in Appendix D. The datasets used for analyses in this study are preserved, for an overview see Appendix E.

Issue resolution data case (a)

Two datasets on manufacturing issues are combined for case (a). One is directly exported from SAP via Eagle which is a data management platform in use by the case company. The other dataset is a file that is used by the DRB (Disturbance Review Board) and periodically sent to the business engineering department. Both files contain issues from 2013 to 2019 and show information for each issue (e.g. machine type, issue duration, issue type). The dataset from SAP contains the machine number which is needed to link an issue to a specific machine. The DRB dataset contains the correct issue duration value. For this reason both datasets are needed.

Issue resolution data case (b)

Four datasets on manufacturing issues are combined for case (b). One is again directly exported from SAP via Eagle (the data management platform) and the second dataset is again retrieved from the DRB responsible in case responsible for issues in case (b). These two datasets are supplemented with two other datasets that are necessary to link issues to certain machine parts and activities. This linkage of the concerning parts and activities is used for additional analyses that are not part of this thesis. Issues at case (b) are categorized into regular issues and disturbance issues. Disturbance issues are the type of issues that are similar to issues at case (a) and cause cycle time delays. With the 'end-script file' which is obtained via Business Engineering, a selection can be made on disturbance issues, since only disturbance issues contain an 'end-script'. Another dataset is obtained via the DRB tool through Business Engineering which is used to make a categorization on the part of the machine that is concerned in the issue, either the 'scanner' or the 'source' (SMS data). This categorization is not relevant for the content of this thesis but was used for additional analyses on the data.

Manufacturing cycle time data

The data on the cycle time (days in the factory for the duration of the manufacturing activities) was obtained via the business engineering department. The cycle time data contains information on the start and finish time of manufacturing activities and the lead time of the activities. Manufacturing cycle time data is obtained from 2014 to 2019.

3.2.2 Quantitative data cleaning

Most of the data cleaning and preparation is performed with the help of the open source statistical software package R. The exception are some errors in date formats which were corrected with MS Excel. Substantial filtering and processing are done via scripts which are used on raw data files, which make this process easy to reproduce. The raw data files and corresponding R scripts are preserved an overview is attached in Appendix E.

Issue resolution data case (a)

The two datasets containing information on issues from case (a) are combined using the 'issue number' as an identifier (key-field). In the case where an issue contained multiple values for the same variable, the SAP data is deemed correct and used. This exception are the issue duration values for these values the DRB file is considered correct. The disturbance review board (DRB) that periodically checks the contained issues and decides potential follow-up also corrects the duration of machine break down caused by each issue in the database, because the automatic logging of this information is often inaccurate and results in incorrect data. Although formally all issues have to be reviewed by the disturbance review board, in reality this is not the case. Therefore, two different data samples are discriminated. One sample for the analysis of issue frequency and a subsample for the analysis of issue resolution time. This subset includes all issues that were reviewed by the DRB, since review was necessary for the correct values for issue resolution time (see Appendix D).

After the datasets are combined, the relevant issues are selected by dropping all issues that are not related to the module integration or test activities of the manufacturing sequence. This is done by filtering on issues that are logged on certain ‘work-centers’ which are clusters of similar manufacturing activities (for details see the ‘DN-data preparation’ R script in Appendix E). Machines that were used for in-house prototype testing were also dropped from the data, as they contained an irregular number of issues. Which machines were used for in-house prototype testing is determined by the means of a list provided by a company insider and is cross-validated by checking the machine data.

Issue resolution data case (b)

The four datasets on manufacturing issues are combined to one using the ‘issue number’ an identifier (key-field). Since these datasets were often incomplete and combining was necessary for sufficient information, a hierarchy is used in the R script to prioritize which value to use in the case that multiple datasets had deviating values for the same variable and issue. This hierarchy that is used is SAP data > DRB data > SMS data > End-script data (for details see the ‘SO-data preparation’ R script in Appendix E). The exception to this hierarchy are the issue duration values which are only considered to be correct if they are in the DRB data (for the same reasoning as for the issue resolution data of case (a)).

After the datasets are combined, a filtering on the relevant disturbance issues is performed by removing all issues that are logged as facility issues (see ‘SO-data preparation’ R script for details in Appendix E). These ‘facility issues’ are issues that are not part the manufacturing activities. Machines that were used for in-house prototype testing were also dropped from the data, as they contained an irregular number of issues.

Manufacturing cycle time data

The dataset on cycle time obtained from Business Engineering is self-contained and consists of statistics on manufacturing activities for all NXE:3400 machines. The determination of cycle time for each machine is very straight-forward by using the start date of the first relevant manufacturing activity and he end date of the last relevant manufacturing activity. This is done for module integration and testing for case (a) and likewise for case (b) (see the ‘CT calculation’ R script for details in Appendix E).

3.2.3 Quantitative data analysis

The data analyses are completely performed with the statistical open-source package R. The analyses are the outcomes of scripts which are preserved (see Appendix E). The data analysis takes place on machine level, so the three measures (1) number of issues; (2) break down duration of the issues and (3) manufacturing cycle time are reduced to one data point per machine for case (a) and (b). For measure (1) this is the total number of relevant issues logged on that particular machine, for measure (2) that is the sum of the break-down duration caused by the relevant issues on that particular machine and for measure (3) that is the number of calendar days the machine is in the relevant manufacturing sequence. This data is subsequently plotted over the cumulative number of machines produced to visualize the learning curve. To calculate and visualize the learning curve discussed in 2.1, the learning curve formula (Equation 1) is transformed taking the natural logarithm on both sides of the equals sign to allow for linear regression (see Equation 3).

$$\text{Equation (3)} \quad \ln Y = -b \cdot \ln aX$$

To fit the learning curve Equation 3 is used and the value for Y is adjusted for each measure. The X-value which represents experience, is always the cumulative number of machines produced. The values used for the parameters for each measure are as follows:

$$b = Learning\ rate\ coeficient$$

$$a = Resources\ needed\ for\ first\ unit$$

$(1)\ Y = Total\ number\ of\ issues\ per\ machine \qquad X = cumulative\ machines\ produced$

$(2)\ Y = Summed\ break\ down\ duration\ per\ machine \qquad X = cumulative\ machines\ produced$

$(3)\ Y = Manufacturing\ cycle\ time\ per\ machine \qquad X = cumulative\ machines\ produced$

A simple linear regression line based on ordinary least squares is fitted on the transformed data for all three measures. The learning rate coefficient b is used to calculate the progress rate via Equation 2 as discussed in Chapter 2 section 2.2.

$$\text{Equation (2)} \quad p = 2^{-b}$$

The progress value p is equal to the percentage of resources needed after a doubling of cumulative production. Resources in this case are 1 (number of issues), 2 (summed break down duration) and 3 (manufacturing cycle time in days).

3.3 Qualitative interview data

Qualitative interview data is used to answer sub research questions 2 and 3 and later combined with the learning rates following from the quantitative data to answer the main research question.

Proximity and the influence of proximity on cycle time learning are determined via the means of in-depth semi-structured interviews. Since proximity is a multidimensional construct that includes subjective aspects like culture and engagement, interviews allow for these aspects to be discussed in-depth and included in the data. Additionally, the interviews are not only complementary to the quantitative analysis, but also confirmatory since certain claims made by interviewees can be checked with objective data and on the other hand explanations of observed trends in the quantitative analysis may be provided by the interviewees. By performing semi-structured interviews with representatives of all relevant stakeholders in the issue resolution process there is the possibility to have in-depth follow up questions that facilitate an explorative manner of data gathering. For the processing of the semi-structured interviews, the free software package QDA miner lite is used.

3.3.1 Qualitative data collection and categorization

For the semi-structured interviews, a balanced short list is made with the help of informed and involved insiders at the company. Since different experts are consulted for different issues depending on the manufacturing sequence step, the experts involved in module integration and machine testing are selected as interviewees. 16 Potential interviewees are selected, who are all involved in issue resolution with different roles in the process. Four are part of design & engineering, two of first line support, two of second line support and six of manufacturing (see Figure 3.2). For an overview of the exact roles of all the participants see Appendix F.

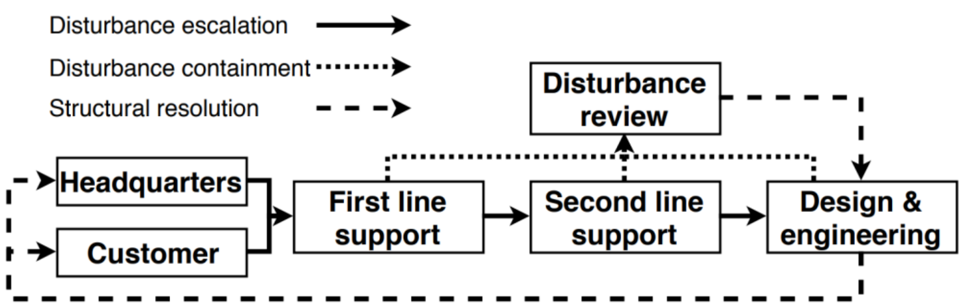


Figure 3.2 Simplified issue resolution information flow chart

By having a sample of interviewees that is spread over the relevant departments all the different perspectives are included in the data. A sample size of around 16 is considered to be enough to draw conclusions, but still manageable in workload for the conducting and transcription process as these activities are very time consuming. The selected employees were initially approached via e-mail and were later contacted by phone if there was no response. 15 of the 16 selected employees agreed to be interviewed for the study, some of which were already involved in earlier exploratory interviews that are not part of the data, but merely had the goal of improving the general understanding of the company and its way of working.

Before the start of the interview a brief introduction of the project was provided and the interview procedure is clarified, following the protocols of Emans (2004). This to make sure the interviewees felt comfortable, understood that the interviewer is an independent researcher and data would be anonymized. An interview guide was used to structure the 40 to 55 minute lasting interviews, this guide is attached in Appendix C. The interview guide functioned as a rough guideline for the discussion of themes. Follow-up questions and answers of respondents triggered side paths and questions were tailored to the interviewee during the interview to match their position in the company. The audio of the interviews is recorded and the dialogue was later digitally transcribed.

One of the 15 interviews was dropped during the transcription phase, because the interviewee spoke with a strong and difficult to comprehend accent and only the audio without non-verbal cues turned out to be insufficient to reliably recreate the answers given during this specific interview. The audio of this interview is preserved with the other interview audio files.

After the transcription phase, the raw text is categorized by assigning codes using the free software package QDA miner lite. The text is categorized on relevant themes to simplify later analyses (see Table 3.1).

Table 3.1. Categories of interview text data

Situation	***Proximity***	***Performance & Learning***
Headquarters	Geographical	Driver
Factory	Organizational	Blocker
Both	Technological	Additional

Every relevant piece of text is coded with one or more of the possible values in Table 3.1. This categorization is used to easily group the pieces of text based on the situation, the related proximity or how it is related to performance or learning. This pre-categorization is used to ease the process of analyzing, because the pieces of text are already grouped on the common categories. This coding is done using QDA miner.

3.3.2 Qualitative data analysis

After the categorization is completed common themes sought within the categories and transcending categories. When multiple coded excerptions have the same underlying notion, a theme is created. This is similar to the open coding methods for axial coding in grounded theory as described by Strauss and Corbin (1990). This theory uses inductive reasoning to build theory, this means that there is are no clear statements that are confirmed or denied. This method is appropriate for exploratory research, because it allows for the searching for new patterns and common themes. The themes that are found are summarized in Tables and supplemented with illustrative quotes. To illustrate the process of creating themes two excerptions linked to the theme that they contributed to. The following excerption is 1 out of 5 which was used for the same theme:

Translation excerption 1 to English (original is in Dutch see Appendix G)

"Yes, that does help, I have the feeling that if people are present at the meeting, that tis generally positively influences the resolution time, so when people are present, because even if a few, some are on the same floor, 20 or 10 meter away from us, but if they are not present at the meeting, then I think the issue resolution time is a lot lower. I have the feeling that when you look each other in the eye and say you didn't do something, that is harder to do than when you're not there and get an e-mail after half an hour, I think that really differs."

From this follows that the opportunity of face to face collaboration is a proximity related driver for learning and "improves issue resolution performance". This is presented along with other themes in Table 4.2. All excerptions used for this theme are attached in Appendix G.

The following excerption is 1 out of 6 which was used for the same theme:

Excerption 1 original in English:

"We have the procedures, the people that solved the DN and sometimes even the team leaders of the people executing the tasks in the same room and if we want we can get more data very easily, but when the system is at install, so that is separate from the HLQS, just when something is at install it's difficult."

From this it follows that the quality of the communication from the customer sites is subpar and a blocker for learning (see Table 4.2.) The remaining 5 excerptions used for this theme and all excerptions from the previous theme are attached in Appendix G.

3.4 Combining results & focus group

To answer the main research question the insights provided by the answers of the sub research questions are combined with the results of a focus group session that is conducted with a subset of the interviewees. The learning rates of sub research question 1 clarify the existence and magnitude of the influence of proximity, sub research question 2 clarifies how the proximity differs on the different dimensions and sub research question 3 uncovers how proximity influences cycle time learning.

Additionally, a 60 minute focus group session is organized. The purpose of this focus group is threefold: (1) it functioned as a closure session for the interviewees: (2) it is used to check if the interviews agree with the interview outcomes and (3) it gave the opportunity to provide explanations or reasons for the observed trends in the quantitative data. In the focus group the quantitative data is presented and four themes are discussed with several statements relating to the theme presented by the researcher. Because of a limited amount of time the 4 most relevant themes are discussed. The themes are selected based on the assessment of the researcher on which themes would lead to fruitful discussions. The themes and the statements are attached in Appendix H. The researcher did not participate in the discussions, but facilitated and led the discussions and objectively presented the outcomes of the analyses. All 15 interviewees were invited for the session, 6 of the 15 interviewees participated. The session was audio recorded. No thorough analyses on the focus group session is applied, since the output of the session consisted of a relatively small number of comments and suggestions. These were taken into account in combination with the insights from the sub research question in answering the main research question.

4. Results

This chapter contains the results from the quantitative and qualitative methods. First the calculated cycle time learning rates for case (a) and case (b) are presented for each performance metric. Observed trends and differences between the cases are indicated, thereby answering sub research question 1. The interview outcomes are presented in the second part of the chapter. An overview in tabular form is displayed, explained and supplemented with illustrative quotes. The qualitative results aim to answer research questions 2 and 3. In last part the main research question is answered using the answers of the sub research questions.

4.1 Cycle time learning rates (sub research question 1)

The three measures for performance that are used to calculate the different learning curves are presented in this part of the results. Each measure has the same set-up with slight differences in time interval, number of issues and number of machines included in the data. The actual numbers on the y-axes are omitted due company confidentiality. First the data for the headquarters factory is presented and thereafter the same analysis for the customer factory is presented. The Y-axes for each measure have the same scale and are thus comparable. For an overview of the data samples that are used for each analysis see Appendix D.

4.1.2 Performance metrics correlations

To check how these performance measures relate to each other a correlations matrix is calculated, see Table 4.1. The correlations are calculated using the Pearson r correlations coefficient formula.

Table 4.1. Correlation matrix performance measures ($p < 0.05$* $p < 0.01$ $p < 0.001$***)**

	Issue frequency	***Issue breakdown duration***	***Cycle time***
Issue frequency		(Customer) 0.78**	(Customer) 0.40*
Issue breakdown duration	(HQ) 0.83		(Customer) 0.24
Cycle time	(HQ) 0.84***	(HQ) 0.82***	

A correlation of 1 in this case would mean that the analyses of the performance indicators would be identical and it therefore wouldn't make sense to perform both analyses. Moderate to high correlations between the indicators are expected, because all three metrics are directly or in-directly related to cycle time. As expected the three performance measures at the headquarters factory all have strong highly significant correlations with each other. At the customer site factories however, the only significant strong correlation measured at the customer is the relation between issue frequency and total breakdown time per machine. The customer install manufacturing cycle time seems to be relatively independent from the install issue resolution metrics, which is unexpected. A possible explanation for these low or insignificant correlations could be the parallel logging of issues. To illustrate: when there are 10 issues logged in parallel which each are documented to have caused 10 hours of breakdown time and in real time all these issues are fixed in 20 hours, then the cycle time increases by only 20 hours, but the breakdown duration by 100.

4.1.3 Issue frequency analysis

Case (a)

Figure 4.1. shows the graph containing the number of issues that each machine endured during the module integration and machine testing in the manufacturing sequence for the headquarters factory (disturbance notifications, DN's). On the horizontal axis the cumulative number of machines produced is plotted (measure of experience). On the vertical axis the number of issues per machine is displayed (the actual numbers are omitted due to confidentiality). The learning curve is plotted by fitting a linear regression curve on the natural log transformed data as is explained in 3.2.3.

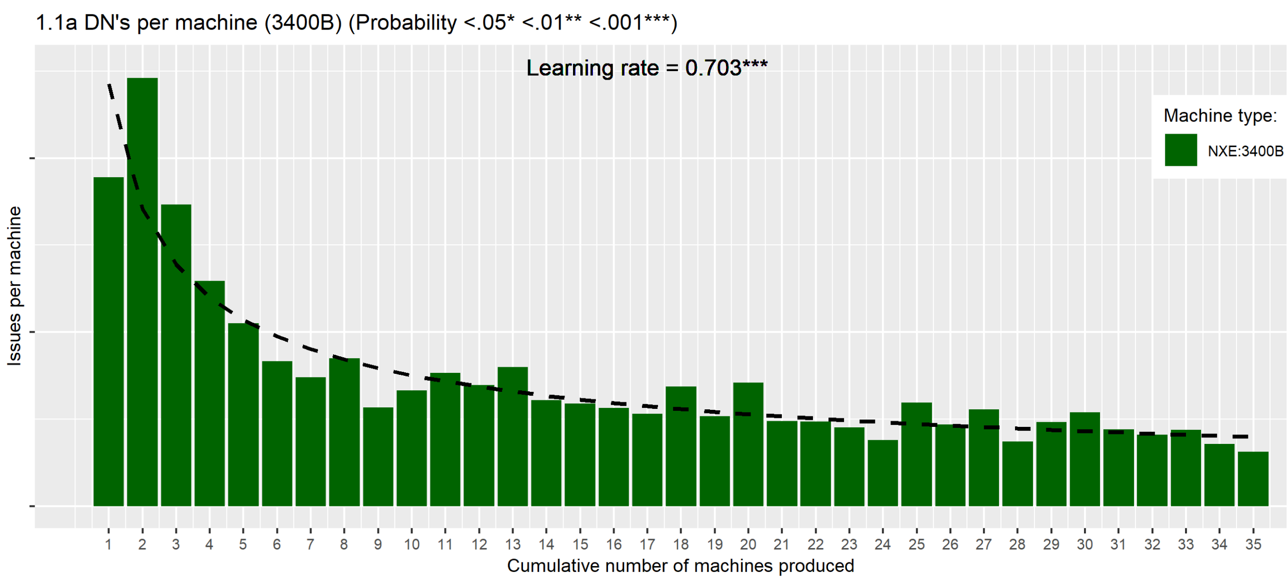


Figure 4.1 Headquarters issue frequency development per cumulative machines produced

The graph shows a clear decreasing trend in the number of issues per machine as more machines are produced. Especially in machines 1 to 5 there is a high declining rate in the number of issues. The first machines start at approximately 4 times the number of issues of the last machine (35^{th}). The progress rate is .70, $p < .001$. This means that on average with a doubling of the cumulative production the number of issues is reduced to 70% of the initial number.

Case (b)

Figure 4.2. shows the graph containing the number of issues that each machine endured during the manufacturing install of the machine at the customer which is comparable to the module integration and machine testing at the headquarters. Issues at the customer are disturbance service orders (SO's). The layout of the graph is the same, however the install order of the machine differs slightly from the order of production at the headquarters and there are 6 machines less in the data, because data was not yet available due to ongoing installs. The dates on the horizontal axis represent the start date of the install of the machine.

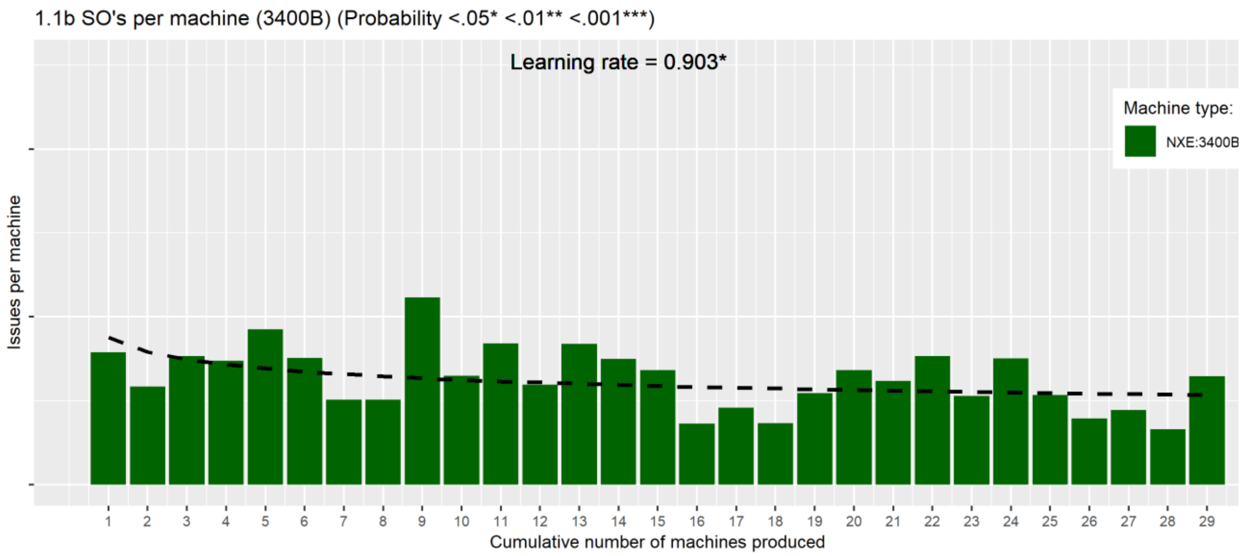


Figure 4.2. Customer install issue frequency development per cumulative machines produced

The learning curve displays a slight downward trend, although the number of issues seems to stay relatively constant per machine. Remarkable is that the number of issues for the first machines is substantially less than the issues for the machines at the headquarters, however the number of issues at machines later in production there are more issues at the customer factory than at the headquarters factory. The learning rate is .90, $p < .05$. The significance is low compared to the learning rate significance for the learning rate at the headquarters factory

Comparison case (a) and case (b)

A clear significant strong learning rate is observed at the headquarters factory regarding the number of issues per machine. A learning rate of .70 is well above the .80 to .85 that is considered average in comparable manufacturing environments. This learning rate is much stronger than the barely significant observed learning rate of .90 at the customer location. The customer factory starts off with about a third of the number of issues that come up at the headquarters which could be argued would reduce the opportunity to learn. The reason for this is that the low hanging fruit is already reaped at the headquarters. Then still, the performance of the headquarters factory surpasses that of the customer factory after approximately 10 machines.

4.1.4 Issue break down duration analysis

Case (a)

Figure 4.3. shows the graph containing the summed value of the break down durations of issues for the headquarters factory. This break down duration value is the number of hours the machine manufacturing cycle time is delayed due to the concerning issue. This value is first automatically generated by the issue logging, but later corrected by the disturbance review board if needed (e.g. incorrect logging, other value adding activates could be performed in the meantime). There is a possibility that breakdown is logged by several issues in parallel, summed value for breakdown duration per machine is not corrected for this potential effect. On the horizontal axis the machines are displayed in chronological order, each machine indicated with pilot number and the date the module integration activities began. On the vertical axis the total breakdown duration of all issues per machine is displayed. A learning curve is again plotted by fitting a linear regression curve on the natural log transformed data.

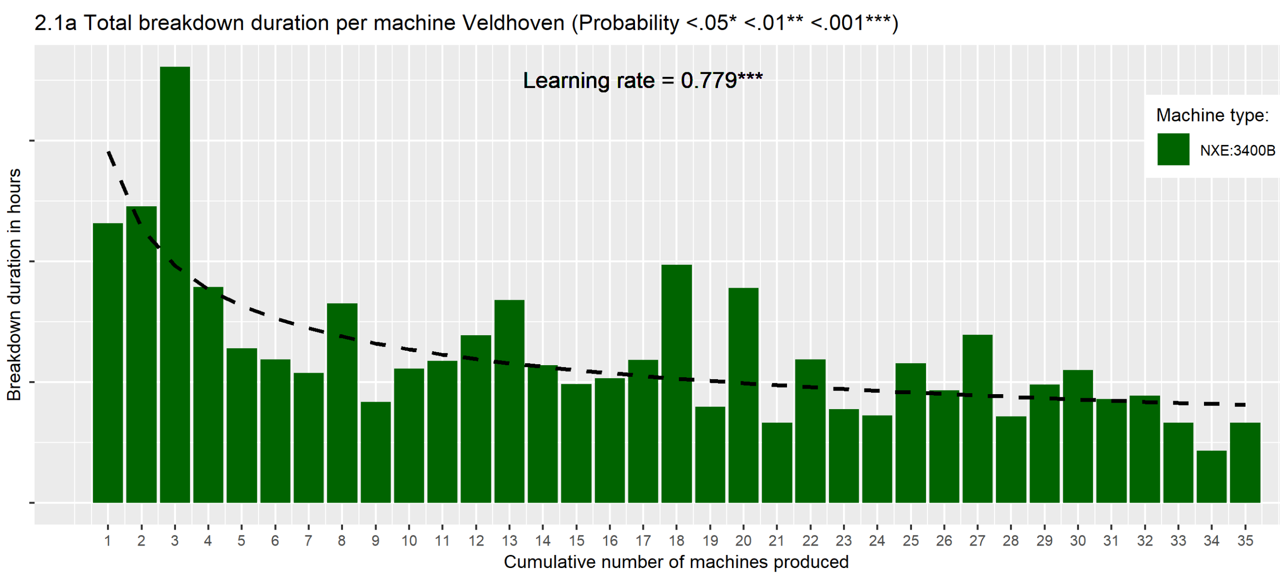


Figure 4.3. Headquarters issue break down duration per cumulative machines produced

A steep highly significant learning curve is observed with a progress rate of .78, $p < .001$. Which means that at a doubling of cumulative input the machine total breakdown duration is reduced to 78% of the initial breakdown. The breakdown duration starts at more than double the value of the last machine (35th).

Case (b)

Figure 4.4. shows the graph containing the summed value of the break down durations of issues for the customer factory. The graph has the same layout as 4.3 and the same side note about the possibility of breakdown of issues logged in parallel applies here. The order of customer install again is slightly different than the production order at the headquarters factory.

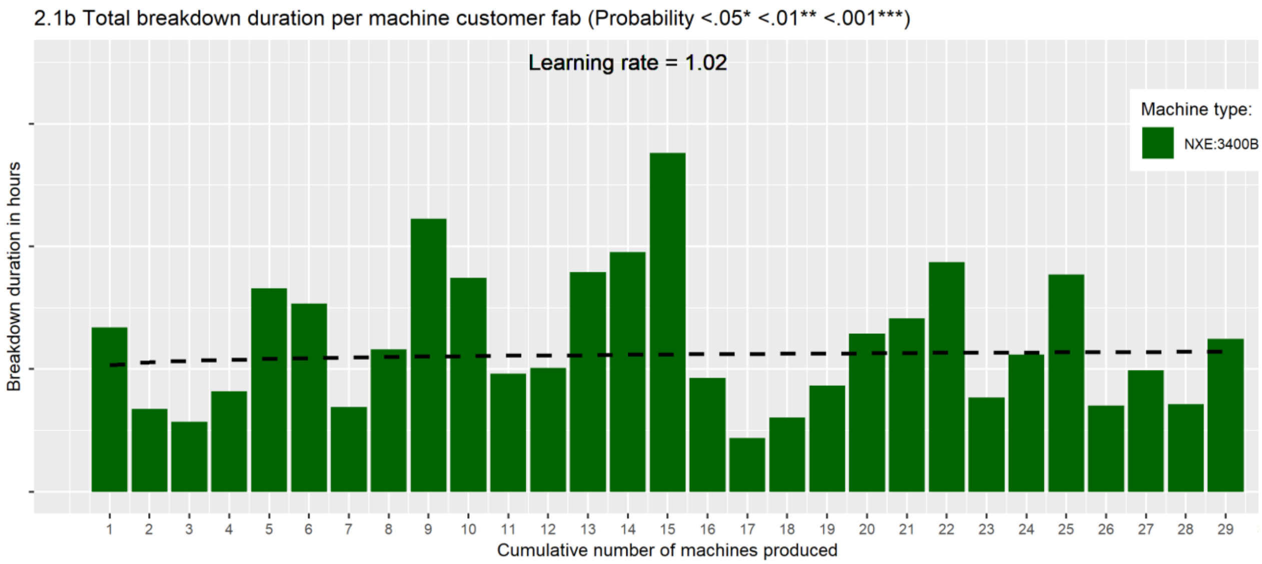


Figure 4.4. Customer install issue break down duration per cumulative machines produced

The breakdown duration during the install at the customers seems to be relatively variable. The variability doesn't seem to reduce at later machines and there is no clear trend visible. No significant learning rate is observed.

Comparison case (a) and case (b)

Like the analysis on issue frequency, the analysis on breakdown duration per machine shows the same patterns. A clear steep highly significant learning rate at the headquarters of .78, $p < .001$, and in this case an insignificant learning rate at the customer. The initial breakdown is again much longer during the manufacturing at the headquarters factory, but as the cumulative output is increased the breakdown of machines at the headquarters seems to structurally be less than the breakdown duration of machines at the customer.

4.1.5 Manufacturing cycle time analysis

Case (a)

Figure 4.5 shows the manufacturing cycle time of the module integration and test activities in days at the headquarters factory. On the horizontal axis the machines are in chronological order, each machine indicated with pilot number and the date the module integration activities began. A learning curve is plotted by fitting a linear regression curve on the natural log transformed data.

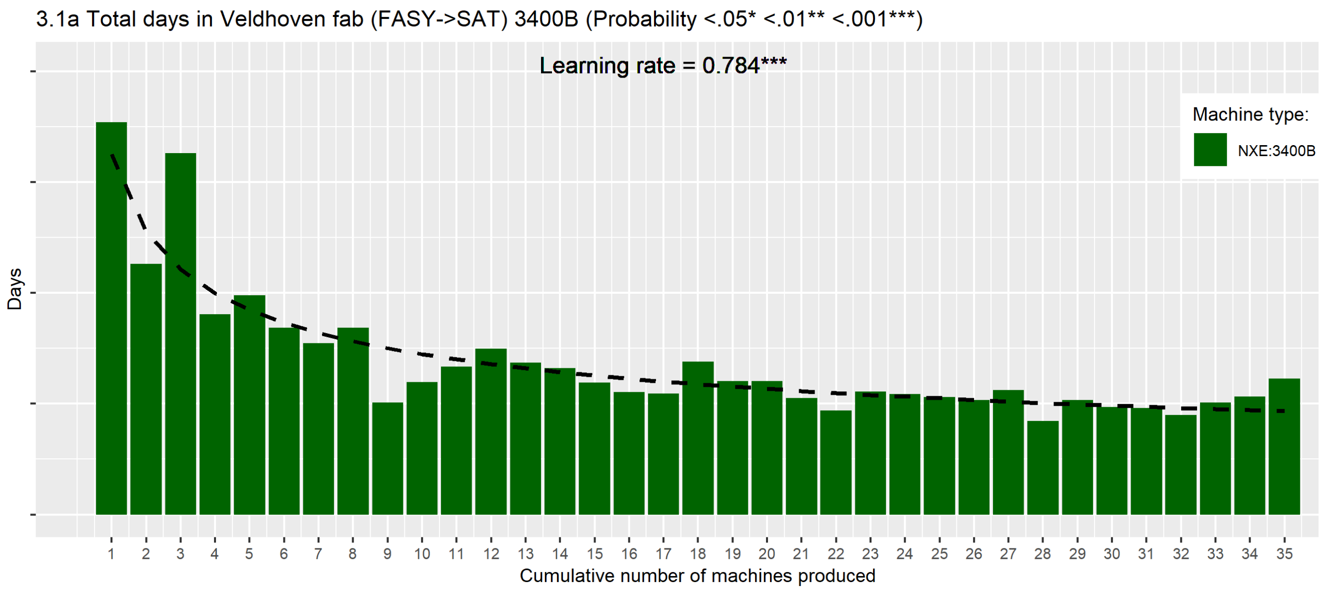


Figure 4.5. Headquarters manufacturing cycle time per cumulative machines produced

The graph shows a clear decreasing trend with a highly significant learning rate of .78, $p > 0.001$. The clear downward trend is especially noticeable for the first 10 machines, after that the cycle time seems to stabilize with a slight increase in the cycle time of the most recent machines.

Case (b)

Figure 4.6 shows the manufacturing cycle time for the install manufacturing sequence at the customer sites. The graph layout is identical to Figure 4.5

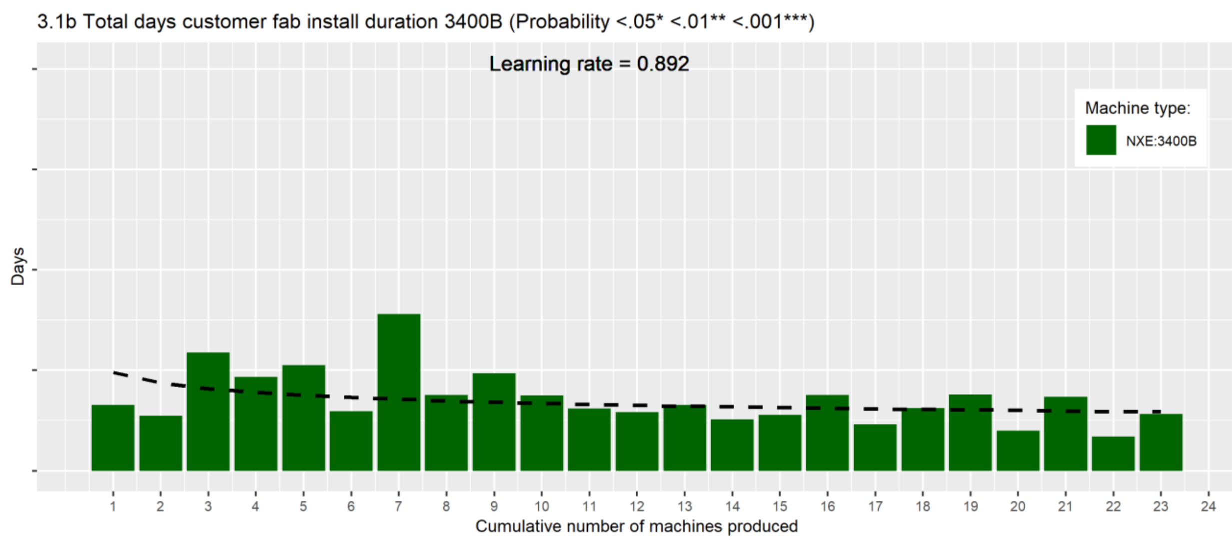


Figure 4.6. Customer install cycle time per cumulative machines produced

The manufacturing cycle time at the customer sites seems to decrease slightly over time, although the fitted learning curve is insignificant. The cycle time also seems to stabilize in more recent machines. Remarkable is the relatively short cycle time in days compared to the cycle time at the headquarters. An explanation may be that some activities in the module integration are simpler at the customer, because certain small parts that are assembled during integration at the headquarters stay integrated during shipment making the process shorter at the customer.

Comparison case (a) and case (b)

Like for the analyses on issue frequency and breakdown duration, the analysis on manufacturing cycle time shows similar patterns. A strong learning curve at the headquarters factory (.70, $p < 0.001$) with initially a big discrepancy between cycle time at the headquarters and at the customer, but after the output of several machines the values converge to similar values.

4.1.6 Learning rates of headquarters factory (a) and customer factory (b)

Observations on all three measures show similar results. The learning rate of the factory at the headquarters is highly significant and between approximately .70 and .78. The learning rates at the customer are insignificant with the exception of an observed learning rate for the number of issues (.90, $p < 0.05$). The initial performance of the customer factory is substantially better for all three measures, but these performances converge after an output of approximately 10 machines. For the analyses of issues, the headquarters seems to outperform the customer factory with the most recent machines on the issue frequency and the issue caused machine breakdown time.

4.2 Qualitative data results – (sub research questions 2 & 3)

In this section the results pertaining to the semi-structured interviews are presented. The semi structured interviews aim to give answers to sub research questions 2 and 3. The findings are summarized in tabular form and discussed thereafter. In the first part the proximity differences are presented and supplemented with illustrative quotes, thereafter the influence proximity has on learning on the DMI is presented likewise. When percentages are stated in relation to statements from interviewees, this means that this percentage of interviewees brought up the specific point and therefore does not mean the other interviewees disagree with the concerning statement.

4.2.1 Proximity differences (sub research question 2)

To answer sub research question 2, the differences between in proximity between the two DMI's are summarized in Table 4.2. The Table values are elaborated on per proximity type following the Table.

Table 4.2. Proximity differences headquarters DMI and customer sites DMI

Proximity	***DMI Headquarters***	***DMI Customer sites***
Geographical	Reachable in minutes via staircase	Daylong plane flight away
Organizational	No time zone difference	Time zone differences (5 to 9 hours)
	Homogeneous work culture	Variation in working culture
	Ongoing contact during workweek	Less (perceived) contact by design & support
	No language barriers	Occasional language barriers
Technological	IT communication and imagery sharing	Restrictive IT and communication tools
	Remote takeover possible	Sharing of data in consultation with customer
	Connected smart software environment	Stand-alone simple software environment
	Direct contact with operators	Contact via local office

Geographical proximity

The difference between the geographical proximity between the two DMI's is considered to be dichotomous. While in the literal sense there is variation in geographical proximity between the different customer sites. In practice all customers are a long plane flight away, while at the headquarters the design and issue resolution support departments can take the stairs and be physically present in a matter of minutes. This big difference is frequently mentioned by the interviewees, some examples are:

"[…] they sit on the same floor 20 to 10 meters away from us." ~Production engineer

"[…] in five minutes he can go to cleanroom, see the problem, he can see the module […]" ~Quality engineer talking about his colleague from quality engineering in Veldhoven.

"[...] Here in the factory, people are close by […]" ~Team leader of first line support

This makes the geographical proximity on the customer sites DMI de-facto equal and in high contrast to the geographical proximity at the headquarters.

Organizational proximity

The discrepancy in organizational proximity between the two DMI's is not as straight-forward to define as it is for the geographical proximity. This is because aside from very practical matters like time zone differences, this proximity type contains subjective concepts like beliefs, understanding and connectedness. Of the interviewees, 71% noted that they had less frequent contact on the customer site DMI. All three levels of support stated that they had less contact with manufacturing at the customer than manufacturing at the headquarters.

"I think that the feedback from things that take place in the field is cumbersome […]" ~Production engineer

"When I look at the 3400 […] I noticed that we got very little feedback from the field." ~Manufacturing engineer

Of the interviews, 57% stated that they occasionally experienced language barriers when communicating to customer sites (the manufacturing team at the customer also consists of local people).

"So, you have a language barrier and need good English proficiency [...]" ~Project leader of install

"Sometimes it's hard to clarify something in calls due to a language barrier." ~Manufacturing engineer

62% Of the interviewees stated that the clearly noticed (working) cultural differences when communicating with people outside the headquarters to customer sites.

"For example, when someone does something wrong they can't say that there, it's in their culture" ~Manufacturing engineer

"[…] people with an American background have a different stance on things than Korean and Taiwanese, there are clear culture differences between Asia and America, we also notice that." ~Team leader of first line support.

Time zone differences with America and Asia is also frequently mentioned as a substantial difference in organizational proximity.

"[…] because that's always a little bit more complex at install to fix an issue compared to here in the factory and that's driven by time zone difference." ~Project leader at customer install

"[…] where they are both in America and Asia, one is 6 hours earlier the other six hours later, how should I plan that?" ~Team leader of first line support

<u>Technological proximity</u>

The discrepancy in available IT tools to communicate and exchange data with the headquarters and the customer sites is a vexed topic. Although these possibilities vary somewhat between customers, most customer sites have a relatively primitive IT environment relative to the headquarters factory.

"[...] It's a little like MacGyver compared to here". ~Project leader at customer install describing the situation at the customer sites compared to the factory at the headquarters.

No smartphones are allowed, taking pictures is forbidden and sending data to the headquarters can only be done in consultation with the customer.

"[..] the operators next to the machine, they are in the fab and had to hand in their phone and laptop, so they have less, way less communication channels." ~Second line support team member

"Yes, with issues in the field that's not possible, you are dependent on what is sent, you can't look for information yourself." ~Manufacturing engineer

Here in the factory people are close by, they have internet, the tools and facilities available, so they can communicate and start solving the issues themselves, in the field we have situations where they can't even call us directly" ~Manufacturing Engineer

4.2.2 Influence of proximity on learning (sub research question 3)

To answer research question 3, frequent or by interviewees stated as important answers on proximity related drivers and blockers of learning are summarized in Table 4.3. The answers are grouped by de dimension and theme. Each statement is categorized as a driver or blocker of learning. The top row indicates in which of the following three department the interviewee is active: design & engineering (DE), issue resolution support (SP), or part of manufacturing (MF). The themes and statements are discussed individually per proximity dimension with illustrative quotes and sub themes which are elaborated on with percentages.

Table 4.3. Influences of proximity interviewee answers

Proximity dimension / *Driver or blocker*	***Influences of proximity***	***Interviewees*** 1 DE	2 DE	3 DE	4 DE	5 SP	6 SP	7 SP	8 SP	9 MF	10 MF	11 MF	12 MF	13 MF	14 MF	SUM
Geographical	**(1) Face-to-face interaction**															
Driver	Face-to-face contact preferred and considered superior	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓		**10**
Driver	Provides substantial positive impact on collaboration between departments		✓			✓		✓			✓	✓				**5**
Driver	Improves issue resolution performance	✓	✓					✓			✓		✓			**5**
	(2) Absence of complete machines at HQ															
Driver	Local presence at machine essential for learning in NPI phase							✓	✓		✓					**3**
Driver	Machine knowledge more important for HLQS			✓	✓								✓	✓		**4**
Driver	Hands on experience is needed for training							✓	✓							**2**
Organizational	**Culture, language & importance of social capital**															
Blocker	Culture barriers lead to problems		✓				✓	✓			✓	✓		✓		**6**
Blocker	Language barriers lead to problems				✓	✓	✓	✓				✓				**5**
Blocker	Social capital essential to be effective at the case company		✓	✓	✓	✓		✓		✓	✓			✓		**8**
Technological	**Customer install manufacturing restrictions**															
Blocker	Current technological infrastructure at customer insufficient for HLQS		✓		✓	✓	✓								✓	**5**
Blocker	Subpar quality communication from customer sites	✓		✓	✓	✓			✓	✓		✓	✓	✓	✓	**10**
Blocker	Unavailable software tools lead to inefficiency at customer		✓	✓			✓	✓				✓	✓	✓	✓	**8**

Abbreviations used in Table: DE = Design & Engineering, HQ=Headquarters, HLQS= Independent qualification strategy, MF = Manufacturing, NPI = New product introduction phase, SP = Issue resolution support team

Geographical proximity

The answers relating to drivers of cycle time learning related to geographical proximity are divided in two categories: Face to face contact and the absence of complete machines at the headquarters resulting from the HLQS.

(1) Face-to-face contact

The big discrepancy in geographical proximity results in two extremes. Either de-facto co-location at the headquarters versus an intercontinental plane flight away. A frequently brought up topic relating to geographical proximity is the ease to have face-to-face contact at the headquarters with colleagues of your own but also other departments. When discussing collaboration at the headquarters it is frequently mentioned that colleagues are close by and opportunities to have face-to-face interactions are used (see examples provided in 4.2.1). Of the interviewees, 71% stated that they visit colleagues in person to have a face-to-face interaction concerning work-related issues and that they perceive added value from this interaction compared to other communication options. It is posed by 36% of the interviewees that face-to-face contact with people from other departments improves the collaboration between the departments. Additionally, the physical presence of issue resolution support and design is perceived to a positive influence on the resolution time (36%). Physically being present in for example the DRB meeting where follow-up actions of contained issues are discussed, is often mentioned as beneficial in performance.

"I think that when people are present at the meeting, it generally positively influences the resolution time […] I have the feeling that when you look each other in the eye it's harder to say that you didn't do something then when get an e-mail, that really makes a difference." ~Production engineer

"We have the procedures, the people that solved the DN and sometimes even the team leaders of the people executing the tasks in the same room and if we want, we can get more data very easily, but when the system is at install it is different." ~Quality engineer

In the case that employees from customer install are at the headquarters, they are invited to physically walking along with the first line support team to learn and keep knowledge up to date. This has been stated to be a positive factor in the understanding between customer manufacturing and design & support. As put by an employee of first line support what an install engineer told him during walk along:

"I thought there were 15 to 20 guys responsible for these types of issues, but you only do this with 2 people, now I understand that you are busy a lot of times".

(2) *Absence of machines at headquarters*

The drivers mentioned for issue resolution performance are not only related to geographical proximity of the people, but also of the machines. It was stated by 21% of the interviewees that less information needs to be exchanged because issue resolution support can physically look at the problem. As stated by an interview:

“Sometimes I hear things as PE, but I have no idea what they mean, well I walk over to them and look myself and it becomes crystal clear, I only have to look 10 seconds and I know what they mean.” ~Production engineer”

This however depends on the problem, for software related issues this is considered to be a less important factor as was stated by two employees from first line support (14%). The physical presence of the machine not only has a positive influence on the resolution of current issues, but is also considered to be essential for learning in the NPI phase (21%). Two interviewees stated that local issue resolution teams are essential in the structural resolution of problems and suggested that the disturbance review board meetings, should be decentralized and be held at the customer location for issues that take place there.

Of the interviewees, 71% expressed their concerns for the problems the absence of complete machines at the headquarter might cause after the transition to the HLQS. Especially for knowledge retention, learning and training. Because the products after the transition to the HLQS will leave the headquarters as modules, employees from the design and issue resolution department that are located at the headquarters are not granted the opportunity to experience the module integration in person and thus are worried about training and knowledge retention concerning this part of the manufacturing sequence. It is posed by 29% of the interviewees that machine knowledge will become more important for HLQS when module integration only takes place outside of the headquarters. The following excerption illustrates the concerns:

“That will be hard to know, how the machine is assembled, so now you easily walk to a machine that is assembled, how it is constructed, how it looks in practice, that experience will be less and harder to get with HLQS […] If you don’t do the module integration here anymore, you won’t have that experience here anymore and it will be hard to get.” ~ Production Engineer

A new way of training should be developed for HLQS as hands on experience with the machine is necessary to develop the skills needed in order to be a fully functioning in the support teams (43%).

[…] well in the new situation, you need a lot more troubleshoot skills, because you get something and assemble it for the first time, well if it doesn’t initialize, why not? I think you need a more elaborate skills, more than we generally have now” ~Customer install project manager

An employee from first line support stated that especially in the ‘build line support’ expertise which pertains to hardware related problems, the absence of the machines as a whole will be a big challenge, because currently he is dependent on the module integration at the headquarters factory for training and knowledge retention. An employee from second line support stated:

“If I don’t see the machine, I lose the affinity with it.”

Organizational proximity - Culture, language and the importance of social capital

In communication overseas to customer sites frequently stated factors with impact are: language and (work) culture barriers. Interviewees indicated that the working culture at the headquarters is different than the working culture at the customers in Asia or the U.S., this can lead to miscommunications or unmet expectations (see the excerptions at 4.2.1 for examples. Meeting each other in person provided better understanding and was mentioned by a few employees as a solution for long time collaboration. In verbal communication to customer sites (by phone, conference call) language barriers are experienced. Some interviewees stated that they communicated via a chat tool after a phone call, since they couldn't understand the person on the phone and need the information in writing to comprehend it. The severity of the impact of these differences was assessed differently among interviewees. 43% of the interviews stated that (work) culture barriers lead to problems and 36% stated that language barriers lead to problems.

Aside from language and culture, the importance of social capital within the case company was a frequently brought up topic. Social capital is perceived to be very important within the organization to get things done (57%). To build this required social capital geographical proximity is important. As stated by a production and manufacturing engineer:

"I think that will be hard, to build contacts, you need face-to-face contact to build a relation. To have strong connections, that will be an obstacle." ~Production engineer

"That means that install engineers have to do everything over the phone with FLS, so if they already have a good relation beforehand, it might be no problem, but if you are not familiar it may be hard." ~Manufacturing engineer

Processes are regularly bypassed by contacting the right people. A manufacturing engineer stated:

"Sometimes the operator calls D&E directly when there is an issue, because he knows someone there that has knowledge on a specific issue, the formal process is bypassed and no issue is logged and I'm not involved, this is not good for the feedback-loop" ~Manufacturing engineer

Besides bypassing, extra information is often needed that is missing in the formal communication via internal tools. To illustrate: the quality of a DN (issue logging at headquarters) or SO (issue logging at customer) is perceived to be low (71%), this leads to the need for extra information. This information is much easier to obtain for a DN, because the people involved are at the headquarters and can easily be reached. For an SO however, this is a tedious process and often takes too long or it is cumbersome to find the person with the extra information. This also applies for communication in the opposite direction, when the manufacturing team at the customer site notices that parts are damaged, it is hard to get this information back to the responsible party at the headquarters.

As a project leader from install put it:

"The big distance between the issue causing party (packing at headquarters) and the issue solving party (manufacturing at customer) leads to problems for feedback." ~Customer install project leader

<u>Technological proximity - Limitations of customer manufacturing work environment and its consequences</u>

The main theme that came up during interviews with employees relating to technological proximity are the technical restrictions at the customer factories and what consequences they bring about. The current technological infrastructure at the customer is considered to insufficient for HLQS by 36% of the interviewees. As an employee from second line support put it:

"[…] The current digital infrastructure is 100% unworkable for HLQS"~ Second line support

Another factor is the unclear communication from customer sites, due to a lack of pictures and options to share information (50%).

"[…] they work in a different structure, you're working at a customer it's hard to get this information, the majority of the people, except the engineers themselves are in a local office that is often not even on site." ~Quality Engineer

Besides that support is completely dependent on what is send from customer site to help with issues, instead of the possibility to look around yourself as issue resolution support (21%).

"Yes, with issues in the field that's not possible, you are dependent on what is sent, you can't look for information yourself." ~Manufacturing engineer

The stand-alone software environment at install is considered to be sub-par compared to the headquarters software and can lead to inefficiencies (50%). An example is that when there is a disturbance during manufacturing and the operator needs to start the issue escalation process, the software environment at the headquarters notifies the operator what other manufacturing activities' the operator can perform in the meantime without it affecting the issue. This is currently not possible within the customer software environment and demands in-depth knowledge of the machine by the operator in order to know what other activities he can do. Additionally, personal (phone) contact with the concerning operator who logged an issue at customer manufacturing is often impossible and cumbersome and leads to missing information (21%).

"[…] but I often hear that FLS for example that when they directly communicate with people in the field, that it is more difficult because they often don't have direct contact with people next to the machine, they are in the fab and had to hand in their phone and laptop and therefore have a lot less communication options. […]. ~Second line support

4.3 Expected consequences of proximity change (main research question)

By combining the qualitative and quantitative data, projections can be made of the consequences of the manufacturing relocation on cycle time learning of the HLQS. To illustrate the possible scenarios for manufacturing cycle time at the customer sites after the transition to the HLQS are visualized in a matrix. The scenario's are mapped on two factors that determine: (1) the number of issues that will come up at the customer site in the new product introduction phase; and (2) the slope (learning rate) at which this number will decrease as the company gains more experience. The number of issues that will come up at the customer site in the NPI phase is mostly determined by the effectiveness of the independent qualification of the modules. If this qualification is just as effective at capturing issues as actual integration and testing, then the number of issues that will come up at the customer site will most likely be approximately the same as they are now. This is because currently at the customer sites the machines also have already been integrated and tested once before. If the independent qualification of the modules is completely ineffective, then the same amount of issues that currently come up during first-time integration and testing of the machines (at the headquarters) can be expected. The cycle time learning rate determines the rate at which this number of issues will decline. Thus in Figure 4.1 the four scenarios are visualized. The cycle time learning rate is indicated as the feedback-loop performance and the effectiveness of the independent qualification of the modules is indicated at the top. The four scenarios are based on the two current situations (headquarters = scenario 1, customer sites = scenario 3) and variations of these two on two factors on the axes.

Scenario 1. Fast learning and ineffective qualification at the headquarters

One possibility is that the learning rate for module integration and testing activities will be just as high in the field as they are now at the headquarters and the qualification is ineffective. This scenario is the current headquarter scenario since, they encounter all the issues for the first time during the integration and testing activities. In this scenario the company can expect 2 to 2,5 times the issues of the current install in the new product introduction phase and a steep learning curve of .75.

Scenario 2. Fast learning, effective module qualification (best case scenario)

The best-case scenario is that both the qualification of the modules at the headquarters is effective and the learning rate is the same as it is currently at the headquarters. In this case little issues are encountered and the cycle time still decreases at a high rate.

Scenario 3 No to little learning, ineffective qualification (worst case scenario)

The worst-case scenario is that the learning rate at install remains at the current level and the qualification of the modules turns out to be ineffective. In this case the company can expect the number of issues it currently has at the headquarters for the integration and testing activities at the customer sites (like in scenario 1). However, with the current learning rate of the customer sites this number of issues will not or very slightly decrease.

Scenario 4 No to little learning, effective module qualification

This scenario is similar to current machine installs, since most issues relating to integration and testing are already captured at the headquarters. The rate at which the cycle time and number of issues will decrease however is minimal.

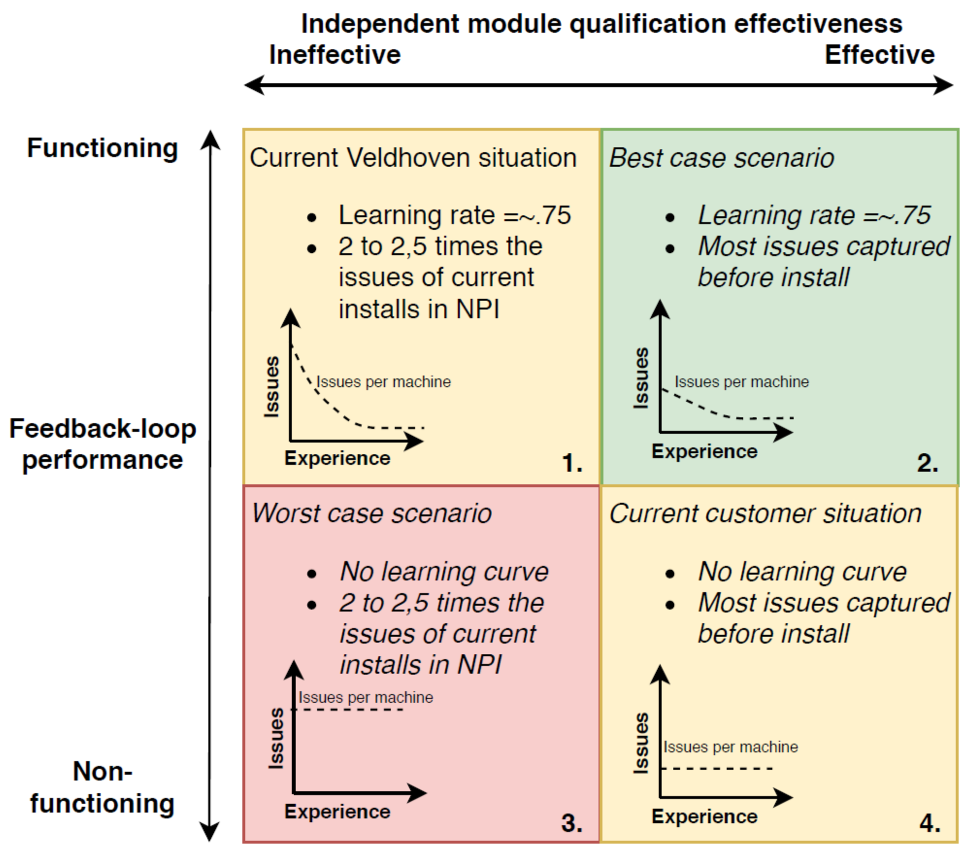


Figure 4.1 Four scenarios for the HLQS

<u>*Evaluation of scenarios and consequences*</u>

From the quantitative company data analysis follows that the current learning rate at the headquarters factory for the module integration and test activities is between 70% and 78%, $p < .001$. There is currently little to no learning at the customer factory site for the module integration and test activities, although this may partly be the consequence of less learning opportunity, since a lot of issues are captured at the headquarters factory. The number and duration of issues at the headquarters factory is approximately double the amount of the customer factory for the first 5 machines. The cycle time is approximately three times as long at the headquarters factory for the first 5 machines. While the learning opportunity is a possible explanation, it is no evidence that leaning will actually occur at the customer site after the relocation of the module integration and test activities. The expected influence on learning at the customer factories after the manufacturing relocation, in current conditions is that no to little learning will take place (scenarios 3 and 4). The number of issues that will come up in the HLQS way of working during the module integration and testing is dependent on the effectiveness of the independent qualification of the modules at the headquarters factory which is not a subject of study in this research. This number however cannot be assumed to decrease with the rate it is doing currently at the headquarters. From the measured different learning rates in combination with the qualitative interviews and focus group, follows that the discrepancy in learning rates can at least partially be explained by the proximity differences. All three dimensions of proximity are perceived to be beneficial towards learning by the interviewees, this notion is supported by the learning rates calculated.

This means that the company cannot assume significant learning regarding cycle time reduction on the DMI at the customers sites provided that they keep the current way of working. Therefore the company should take measures to prevent scenarios 3 or 4 that are caused by no to little learning rates. To optimize the performance of the feedback-loop (cycle time learning rate) and steer towards scenario 1 or 2, measures are proposed. These are discussed in the next chapter in section 5.3 Practical implications.

5. Discussion & Conclusions

This study set out with the aim of assessing the influence of proximity between the design and manufacturing department on learning in order to advise the company on what to expect regarding cycle time development and to understand the underlying proximity related drivers and blockers of learning. This knowledge can be used to take measures that can optimize learning after the transition to the higher level qualification strategy. Additionally, the goal is to contribute to the literature on proximity and learning on the design-manufacturing interface. In this chapter the findings are discussed and linked with the relevant literature presented in Chapter 2. Aside from the theoretical contribution, the study has practical implications that are discussed. Finally possible directions for future research are suggested and limitations of this study are discussed.

5.1 Key findings and answers to research questions

This study has showed the influence on cycle time learning in a design-manufacturing context by the means of three sub research questions and one overlying main research question. In this section the key findings are discussed based on the structure of the research questions.

Sub research question 1: What is the current cycle time learning rate on the design-manufacturing interface at (a) the headquarters factory and (b) the customer factory?

The two compared manufacturing environments showed a big discrepancy in the magnitude of the cycle time learning rates. Three different performance metrics that measured cycle time progress were used. The learning rates at the headquarters were highly significant ($p < .001$). The learning rates at the customer site factories were none to barely significant and varied between 89% and 102% and therefor no progress can be assumed at the customer sites. The fact that there is no observable learning rate at the customer site is remarkable, since learning is expected to occur anyhow via autonomous learning (Dutton & Thomas, 1984). An explanation for this may be that learning does take place but is offset by new issues that are caused by the continuous changes that follow from the iterative design of the machines of the case company. An additional factor may be that there are less learning opportunities at the customer site as the integration is performed for the second time around and therefore the low hanging fruit of the learning opportunities is already reaped at the headquarters factory.

Sub research question 2: What is the difference in proximity between (a) the headquarters factory and the issue resolution support and development departments, and (b) the customers site factories and the issue resolution support and development departments?

The differences of the proximity dimensions between the headquarters DMI and the customer sites DMI turned out to be great (Table 4.2 for an overview). Although the dichotomous difference in geographical proximity between the headquarters and the customer sites is evidently known beforehand, as de-facto co-location versus a daylong plane flight away, the differences in organizational and technological proximity turned out to be very big as well. The big difference in technological proximity in this study is largely caused by external factors (customer-imposed restrictions). However, organizational proximity in this study doesn't seem to be a self-contained dimension. Meaning that it is directly affected by the other dimensions of proximity. Geographical proximity for example drives spontaneous interactions that provide opportunities to the origination of fruitful relations which are later embedded in social capital and drive organizational proximity. This is conform the social capital literature discussed in Chapter 2 and underlined by the interview outcomes in this study.

Sub question 3: What are the proximity related drivers and blockers of learning on the DMI?

Every dimension of proximity seems to directly affect cycle time learning that is driven by collaboration on the DMI. From the interview analysis of this study follows that each dimension has multiple substantial drivers or blockers of learning (summarized in Table 4.3). Although technological opportunities present employees with rich communication options, face-to-face meetings remain to be considered superior in day to day work. The co-location of the departments and the traditional 'lab-fab' concept of the company appears to be an effective strategy. The co-location or integration of the design and manufacturing departments has also been shown to be increase operational performance in a number of studies (Argote & Ingram, 2000; Pinto et al., 1993; Sorenson et al., 2006). From the interviews with employees also followed that periodically meeting the people you work with in geographical dispersed teams create better understanding and improves collaboration. This is in line with recommendations from studies on the management of virtual or geographically dispersed teams discussed in Chapter 2 (Kauppila et al., 2011; Sharifi & Pawar, 2002). Language barriers, (working) culture differences and social capital are the three most prominent aspects of organizational proximity that are of influence on learning in this study. Language barriers leads to cumbersome communication (e.g. stopping a phone conversation and continuing via a chat tool, because spoken language is not understood). Culture differences lead to misunderstandings and unmet expectations, as the exact same wording has different connotations in other (working) cultures. These differences seem to be reinforced by the low geographical proximity. From the interviews conducted it followed that individuals with a different cultural background integrate quickly in the working culture that is in place, however when it concerns communication between teams that are not geographically (and therefore also often organizationally) proximate it can be challenging to reach common understanding. Besides language and culture, social capital is another aspect of organizational proximity that plays an is important role at the case company. While a high degree of social capital has been shown to allow people to resolve problems more easily (Putnam, 2000). From this study at the case company it follows that social capital is a hindering factor for learning from issue resolution, because social capital is used to bypass formal processes in order to get things done quicker. As a result, issues are not documented and transparency lacks (e.g. issues are for example not discussed during disturbance review board meetings). A tool that can be used to tackle these challenges is the formalizing of mechanisms and communication (see measure 5.3.4). By using appropriate formalization the risk of misunderstandings and false expectations can be mitigated (Vandevelde & Dierdonck, 2003).

The insights provided by the answers on the sub research questions can be used to answer the main research question of the study. The quantitative learning rates combined with the measured proximity differences and the influence of proximity on learning can be used for conjecture on the situation of a change of proximity on the DMI.

Main research question: How does a change in proximity influence the cycle time learning rate within a design-manufacturing context?

For the case company the results of this study imply that learning at the customer in the HLQS way of working cannot be assumed as a proximity change will in all probability have major consequences for learning. Projecting results from both the quantitative and the qualitative outcomes to the HLQS scenario, it follows that no significant learning will likely take place after the transition to HLQS ceteris paribus. A framework with 4 (extreme) scenarios is discussed in section 4.3 to explain what the company should be prepared for. In short: substantial action is needed to close the proximity gap in order to create an effective feedback-loop and successfully manage cycle time after the transition to the HLQS. A number of measures is proposed with the aim to optimize the learning process on the customer site DMI after the transition to the HLQS, which are further discussed in 5.3 Practical implications.

5.2 Theoretical implications

This study aims to add to the literature in the fields of organizational learning, proximity and the DMI. As discussed in Chapter 2, proximity is seldomly holistically approached in research and the concept is often not clearly specified (Knoben & Oerlemans, 2006; O'Leary & Cummings, 2007).

Proximity

Using a multidimensional approach towards proximity provides the opportunity to explore how the different dimensions relate to each other. In the conceptual model of Chapter 2 the unclear relations between the proximity dimensions are indicated, with each dimension potentially interacting with the other. Based on the results of this study, geographical and technological proximity don't appear to interact. Both dimensions appear to be self-contained, which means that they are not influenced by other dimensions of proximity. Organizational proximity however seems to be highly dependent on the geographical and technological proximities. This can be explained by the fact that these dimensions provide the opportunity to communicate, this becomes clear from the interview data (see the illustrative quotes from interviewees mentioning limited communication channels because of low technical proximity and face-to-face interactions driven by high geographical proximity in section 4.2.1). Face-to-face interaction that is driven by geographical proximity allows for relationship building, team bonding and cohesion within the workplace (Oertig & Buergi 2006). This in turn drives organizational proximity. Additionally time zone differences which act as barriers for communication logically disappear as geographical proximity increases. Technological proximity can lower the threshold for interactions by facilitating tools which allow for rich communication (sharing of data, imagery or other relevant supplements).

While interactions between the dimensions of proximity certainly exist, geographical and technological proximity are not just facilitating organizational proximity. The findings of this study implicate that all three dimensions have their own individual direct effect on learning. The geographical aspect itself is still of high importance in successful communication. Being physically proximate ensures being able to show something in person and this results in less need for information exchange and leads to easier understanding. It allows for approachable contact and fosters day to day understating through spontaneous and context rich communication. This remains to be substantially superior even with the current alternatives for communication. This is in line with literature discussed in Chapter 2 (Sharifi and Pawar, 2002; Dixon, 2017; Snoo, Wezel and Wortmann, 2011). Organizational proximity leads to fast mutual understanding, because of a common nuance of words which makes communications more efficient and less prone to miscommunications. Technological proximity in this context is very important as it serves as a means to share complex data needed for issue resolution support.

The multidimensional approach towards proximity and clear specification of the concept in this study has proved to be helpful in uncovering the underlying mechanisms with relation to (cycle time) learning. This multidimensional approach towards proximity, clear specification of the concept and perhaps a standardization in subdivision of the concept is recommended in future research.

Collaboration on the design-manufacturing interface in high-tech manufacturers

Besides the arbitrary and often narrow uses of proximity in current literature, research on the interplay of learning and proximity in design-manufacturing context is rare. Learning in global manufacturing currently mostly consists of unilateral knowledge transfer to an offshore manufacturing location (see section 2.5 and the literature Table from the systematic literature review in Appendix A). The iterative nature of the high-tech machines of the company require intensive reciprocal collaboration on the DMI instead of mere one-way knowledge transfer. This required reciprocity only reinforces the influence of proximity, since sending and receiving of information needs to be well organized on both ends. This study illustrates the importance of proximity on the DMI for cycle time learning of high-tech iterative products.

Organizational learning

Learning curve management as it is shaped at the company, focusses on learning from failures. Failure learning has been shown to be effective outside the company in a variety of industries (train, mining and airline) and on both industry and firm level (Dahlin, Chuang & Roulet, 2018), but also within the case company as earlier research has shown that the handling of disturbances during manufacturing is an important driver for improving the manufacturing cycle time learning rate (Alblas, Zwaans & Schepens, 2017; de Kadt, Peeters, Langerak & Alblas, 2015). The high correlations of issue resolution performance with overall cycle time (see Table 4.1) underlines the effectiveness of focusing issue resolution as a means to reduce total manufacturing cycle time.

5.3 Practical implications

The insights provided by this study can be used to compose a set of measures relating to proximity that can be taken to optimize the cycle time learning rate at the customer site after the transition to the HLQS (optimize the feedback-loop performance as shown in Figure 4.1). Based on this study all three dimensions of proximity have a direct positive impact on cycle time learning and should therefore be maximized where possible. As is discussed in detail in 4.2.1 the proximity on the customer site DMI is relatively low and this has consequences as can be seen in the big discrepancy in the cycle time learning rates (section 4.1) and is underlined by employees during interviews (section 4.2.2). The manufacturing relocation brings about a lower geographical proximity to the headquarters where the support and design departments currently reside. This lower geographical proximity to the headquarters is a given for the HLQS, however the geographical proximity to the support and design departments can partially be adapted and additionally other measures can be employed to maximize the future organizational and technological proximity. Following from the results of this study a number of specific measures are proposed for the case company.

5.3.1 Co-locate issue resolution support during NPI phase

The current low technological proximity prevents the support team to fully use their potential solving capacity when assisting customer manufacturing. This needs to be fixed on the long-term (see also measure 5.3.3), however on the short-term in the NPI phase of the machine (machines 1 to 5), issue resolution expertise needs to be co-located at the customer site to successfully manage learning and thereby cycle time reduction. The disturbance review board meeting should in this case also be held at the customer site to be able to discuss the issues directly with the involved operators. Not only because it is unrealistic to expect enormous changes in technological proximity this soon, but also because the majority of the issues take place in the NPI phase (see Figure 4.1 and Figure 4.3). Additionally, from the interviews it follows that face-to-face meetings and being able to physically go to the machine are important drivers for learning and especially during the NPI phase (see the geographical drivers of learning in Table 4.3). Three employees that were interviewed underlined this and explicitly stated that they would at least temporality move expertise to the customer sites (Table 4.3). This measure is in line with literature on the influence of proximity on collaboration discussed in section 2.3. There seems to be widespread support for the notion that co-location directly improves collaboration performance (see Adler, 1995; Argote & Ingram, 2000; Knudsen & Madsen, 2014; Pinto et al., 1993; Snoo, 2011). When the machine design matures and stabilizes, the local expertise at the customer sites can slowly be scaled back, depending on the performance at that time. This however should be assessed at a future time and also highly depends on the effectiveness of the independent qualification of the modules that is implemented at the headquarters. The success of this strategy influences the number of issues that will come up at the customer sites and thus determines the issue resolution need at the customer sites.

5.3.2 Set up three globally dispersed strategically geographically dispersed sites for a continuous feedback-loop

After the NPI phase when local expertise at the install site level is scaled back, it is important that there is still adequate issue resolution expertise available. Currently the issue resolution support teams that are located at the headquarters don't operate during (local) nighttime. During these hours manufacturing at the customer can contact the company's global support team, which is a team that is part of customer service and responsible for the machines that are already up and running. This team is not specialized in issues that occur during manufacturing and because of this, as is indicated by multiple interviewees, has a knowledge gap in manufacturing issues compared to the support teams at the headquarters. This is explainable by the fact that they are less informed on recent engineering and manufacturing procedural changes. After the transition to HLQS it is important that there is a knowledgeable team that is available 24x7 for the handling of these issues. A way to shape this on the long term organizational wise is to have three geographically dispersed sites strategically located globally. One America-based, one Asia-based and the current headquarters location in Veldhoven, the Netherlands. This reduces the coordination problems that arise from time zone differences that are currently encountered (see the two excerptions from project leaders at install in section 4.2.1) and relevant literature discussed in Chapter 2 (Espinosa & Carmel, 2003; Espinosa & Pickering, 2006; Rutkowski et al. 2007). The three continents should have a standard knowledge sharing timeslot build in their day to pass on information from Asia based customers to U.S. based customer when it is night time at the headquarters (cross-ocean learnings). This way the feedback-loop between customer sites and the company can be functional continuously and knowledge can be passed on to active sites via the follow-the-sun principle. Which is a more commonly used principle in software development and support (Carmel, Espinosa & Dubinsky, 2010).

5.3.3 Enable IT and communication tools or customer manufacturing

The low technological proximity on the customer factory DMI caused by the current IT and communication limitations imposed by the customers, holds back the learning potential. Five of the interviewees explicitly stated that the current technological infrastructure is insufficient for the HLQS. The discrepancy between the headquarters and the customer factories is night and day (see the blockers of technological proximity in Table 4.2). Possibilities like remote take over, a smart software environment and quickly sharing data are important drivers for issue resolution time. This is partly addressed by co-locating issue solving capacity on site for the NPI phase, however not being able to have a wireless phone, or not being allowed to share certain data (e.g. error logs, diagnostics software analyses) will still stand in the way of effective support. Additionally, the IT and software tools that enable operators for example connection with SAP (the ERP system) will cause the operators in the cleanroom to be more independent and able to perform non-issue related tasks more easily. This will ease the burden of a higher level of required machine knowledge for HLQS which is predicted by a number of employees (see the second part of the drivers for learning of geographical proximity in Table 4.3). The availability of such software systems (e.g. knowledge repositories, transactive memory systems) have been shown to be successful in team learning, see Akgun and colleagues (2006) and Kaupilla and colleagues (2011) and specifically in driving the manufacturing learning curve in parallel production environments (Pedersen & Slepniov, 2016). These terms need to be negotiated with the customer, who is hesitant in facilitating all this. In the end it is in both the interest of the company and the customer to enable the company to reduce the time needed for the installation of machines. The end goal for the company is to have similar liberties regarding the accessing and sharing of data relevant for issue resolution as at the headquarters, at least during the install activities..

5.3.4 Balance formal and informal communication by properly formalizing communication on the DMI

The feedback-loop from customer manufacturing is much more important after the transition to HLQS as it is the only source of information on the module integration and machine testing in operation. Currently this feedback-loop functions relatively poorly as is demonstrated by the manufacturing cycle time learning rates. This is caused by the low proximity to the headquarters and thus low proximity to the departments that facilitate structural resolution of issues. It follows from the interviews conducted that low proximity leads to a certain self-reliance of customer manufacturing operators, because support is less accessible and less able to assist. To change the focus to long term cycle time reduction and B-time management, customer manufacturing needs to be more involved with D&E. To connect customer manufacturing with design & engineering, it needs to be heavily involved in follow up of issues. The proposed disturbance review board meetings at the customer sites also contributes to the involvement of customer install. For the follow up of issues it is important that the issues contain sufficient information. Currently for the quality of the issue loggings for both issues at the headquarters and at the customer site is deemed sub-par by 71% of the interviewees (see section 4.2.2 organizational proximity). Missing information is obtained by contacting the involved people (if they are reachable). This has caused social capital to be important at the case company to be effective (see organizational proximity driver in Table 4.3). Social capital as discussed in Chapter 2, arises from spontaneous face to face contact (Van den Bulte & Moenaert, 1998), which evidently is scarce between employees that work at the headquarters and install operators. The way social capital currently plays a role needs to be replaced by functioning formal communication. By using appropriate formalization the risk of misunderstandings and false expectations can be mitigated (Vandevelde & Dierdonck, 2003). The goal is a healthy balance between formal and informal communication as this can be skewed too far in either direction (Vandevelde & Dierdonck, 2003). To achieve this the quality of the issue loggings needs to be improved. A concise information rich DN and SO logging standard needs to be created in consultation with D&E, FLS and (install) manufacturing. The involvement of customer manufacturing in the follow-up of issues needs to be formalized. This can be done by making sure that customer install fulfills a prominent role in cross-functional IRM routine meetings like the DRB. By making sure that the operators directly involved with the concerning issues are participating in these meetings the direct flow of first-hand information to D&E can be ensured. Another example of formalization are the cross-ocean learning timeslots proposed as part of measure 5.3.2. The three continents should have a standard knowledge sharing timeslots build in their day to pass on information from Asia based customers to U.S. based customer when it is night time at the headquarters (cross-ocean learnings).

While functioning formal communication is necessary, informal, face-to-face communication is also essential in successful intensive collaboration. Even though technology offers a rich variety of options to substitute meetings in person, periodic face-to-face meetings are essential for successful intensive collaboration. Team building and bonding, a sense of community and mutual benevolence between teams and employees has frequently be shown to be important in team performance (Sharifi & Pawar, 2002). This is also underlined by several employees (see the drivers of learning on face-to-face contact in Table 4.3). Frequent temporarily allocation of install engineers at the headquarters site is advisable. Close collaboration between issue resolution support and install engineers builds understanding and improves future collaboration (see Appendix F, example 1, excerptions 4 and 5 for examples of this).

5.3.5 Adapt training and knowledge management for absence of module integration at headquarters

The absence of the module integration and testing at the headquarters will have an effect on the knowledgeability of the employees at the headquarters on this part of these manufacturing activities. With the relocation of activities from the headquarters to the customer site, there is the risk of knowledge displacement. Since the relocated activities are no longer performed at the headquarters, experience and knowledge will over time be lost at this site without counteraction. This is a widespread concern of the employees that were interviewed (see the drivers relevant for the absence of the machines at the headquarters in Table 4.3 and supplementing quotes in section 4.2.2 for geographical proximity). It is important to retain the required absorptive capacity at the headquarters to be able to integrate the relocated activities later in case of need as is posed by Prencipe (1977). Besides the capacity to absorb, sufficient in-depth technical knowledge level is needed at the headquarters to oversee consequences of decisions and policies for manufacturing at other sites. This is one of the factors that went wrong with the Boeing Dreamliner project according to Dekkers and colleagues (2013). This knowledge retention can be realized by continuous involvement of customer manufacturing in design iterations (ECs) and the other way around by involving D&E in operations at customer install. Frequent mutual visits should be stimulated and cross-functional routines should be set up to create structural and lasting alignment between the departments.

Besides knowledge retention, it follows from the interviews that hands on experience with the machines is necessary for adequate training of operators and support teams. Technologies like virtual reality can partly be used to mitigate the absence, however is not fit to be a full substitute as several members from issue support teams have indicated during the focus group. Examples that were given on the inadequacy of this solution are that sometimes the smell gives a hint on what is wrong, or in order to give instructions to the local operator on where a part is located on the machine, having not seen it in full will complicate this. New employees trained on these parts will have to travel regularly and new hires should be selected that are willing to do this. Several current support team members have indicated that they expect that the employees with their expertise for the new machines in the HLQS way of working will need to travel a lot more and that they would be prepared to do. The willingness of current issue resolution support members needs to be taken into account. The rotation of team members across sites is a way to stimulate knowledge sharing and inter-organizational learning.

5.4 Study limitations & future research

This study aimed to uncover the influence of proximity on the DMI on learning at the case company by comparing two manufacturing sites where the same activities are performed. The most fitting comparison that was available in practice is used to draw inferences on a future situation. This projection on the future situation however, has to be done with caution because the comparison is not completely fair. While the activities that are performed at the two sites are very much comparable, the fact that these actions are repeated on the same product makes the circumstances not completely similar. The assembly of an already tested and qualified product can be considered to be less error prone than the first-time assembly and testing of the same product. Since performance in this context is directly related to the number of issues that comes up during the integration and testing, there is less opportunity for improvement of this performance when it concerns a more stable, less error prone product. While this does not make the findings invalid, the magnitude of the difference in observed learning rates should be interpreted with caution. Tracking the manufacturing performance and cycle time improvements by the means of live data during and after the implementation of the new way of working is recommended in order to gain hard data instead of relying on the forecasting provided by this study.

The factories on the customer sites are treated as equal in this study, even though they also differ from one another in terms of culture, IT possibilities and the case company's product experience. While this generalization was a necessity due to the scope and time frame of this research, it detracts from the information richness that the independent customer site factories could provide. It may be of interest to explore the relation between proximity and the cycle time learning rates between the different customer sites.

The technological possibilities to increase technological proximity have seen rapid developments in recent years and are currently very advanced. Since the DMI with the lowest geographical proximity in this study also had a relatively low technological proximity due to customer-imposed restrictions, it would be interesting to perform a similar study on a manufacturing environment that fully utilizes available technology to see the full potential of technology in bridging the proximity gap.

References

Adler, P. S. (1995). Interdepartmental interdependence and coordination: The case of the design/manufacturing interface. *Organization Science*, 6(2), 147-167.

Akgun, A. E., Byrne, J. C., Keskin, H., & Lynn, G. S. (2006). Transactive memory system in new product development teams. *IEEE Transactions on Engineering Management*, 53(1), 95-111.

Alblas, A.A., Zwaans, F. & Schepens, S. (2017). *Insight driven design: balancing production speed and development learning in smart industries*. Eindhoven: Technische Universiteit Eindhoven.

Argote, L., & Epple, D. (1990). Learning curves in manufacturing. *Science*, 247(4945), 920-924.

Argote, L. (2013). Organization learning: A theoretical framework. In *Organizational Learning* (pp. 31-56). Springer, Boston, MA.

Argote, L., & Ingram, P. (2000). Knowledge transfer: A basis for competitive advantage in firms. *Organizational Behavior and Human Decision Processes*, 82(1), 150-169.

Argyris, C., & Schön, D. A. (1997). Organizational learning: A theory of action perspective. *Reis*, (77/78), 345-348.

Armstrong, D. J., & Cole, P. (1995). Managing distances and differences in geographically distributed work groups. In S.E. Jackson, & M.N. Ruderman (Eds.), Diversity in work teams: *Research Paradigms For A Changing Workplace* (pp.187-215). Washington, DC: American Psychology Association.

Asmussen, C. G., Larsen, M. M., & Pedersen, T. (2016). Organizational adaptation in offshoring: the relative performance of home-and host-based learning strategies. *Organization Science*, 27(4), 911-928.

Baloff, N. (1966). Startups in machine-intensive production systems. *Journal of Industrial Engineering*, 17(1), 25.

Baloff, N. (1970). Startup management. *IEEE Transactions on Engineering Management*, EM-17, 1970, 132-141.

Bryman, A. (2004). Triangulation and measurement. Retrieved from Department of Social Sciences, Loughborough University, Loughborough, Leicestershire: www.referenceworld.com/sage/socialscience/triangulation.pdf.

Carmel, E., Espinosa, J. A., & Dubinsky, Y. (2010). " Follow the Sun" Workflow in global software development. *Journal of Management Information Systems*, *27*(1), 17-38.

Choudhury, P. (2017). Innovation outcomes in a distributed organization: Intrafirm mobility and access to resources. *Organization Science*, 28(2), 339-354.

Chowdhury, S., & Saleh, A. (2013). Building trust in virtual teams-evaluating online collaboration from a Human-Centered Design Perspective. *Chalmers University of Technology. Gothenburg, Sweden*.

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterly*, 35(1), 128-152.

Coleman, J. S. (1988). Social capital in the creation of human capital. *American Journal of Sociology*, 94, S95-S120.

Conchúir, E. Ó., Ågerfalk, P. J., Olsson, H. H., & Fitzgerald, B. (2009). Global software development: where are the benefits?. *Communications of the ACM*, 52(8), 127-131.

Cramton, C. D. (2001). The mutual knowledge problem and its consequences for dispersed collaboration. *Organization Science*, 12(3), 346-371.

Dahlin, K. B., Chuang, Y. T., & Roulet, T. J. (2018). Opportunity, motivation, and ability to learn from failures and errors: Review, synthesis, and ways to move forward. *Academy of Management Annals*, 12(1), 252-277.

Dekkers, R., Chang, C. M., & Kreutzfeldt, J. (2013). The interface between "product design and engineering" and manufacturing: A review of the literature and empirical evidence. *International Journal of Production Economics*, 144(1), 316-333.

Dixon, N. (2017). Learning together and working apart: Routines for organizational learning in virtual teams. *The Learning Organization*, 24(3), 138-149.

Dutton, J. M., & Thomas, A. (1984). Treating progress functions as a managerial opportunity. *Academy of Management Review*, 9(2), 235-247.

Eisenhardt, K. M. (1989). Agency theory: An assessment and review. *Academy of Management Review*, 14(1), 57-74.

Emans, B. (2004*). Interviewing: Theory, techniques and training*. Groningen: Stenfert Kroese.

Espinosa, J. A., & Carmel, E. (2003). The impact of time separation on coordination in global software teams: a conceptual foundation. *Software Process: Improvement and Practice*, 8(4), 249-266.

Espinosa, J. A., & Pickering, C. (2006, January). The effect of time separation on coordination processes and outcomes: A case study. In *Proceedings of the 39th Annual Hawaii International Conference on System Sciences (HICSS'06)* (Vol. 1, pp. 25b-25b). IEEE.

Hatch, N. W., & Mowery, D. C. (1998). Process innovation and learning by doing in semiconductor manufacturing. *Management Science*, *44*(11-part-1), 1461-1477.

Hinds, P. J., & Mortensen, M. (2005). Understanding conflict in geographically distributed teams: The moderating effects of shared identity, shared context, and spontaneous communication. *Organization Science*, 16(3), 290-307.

Jehn, K. A. (1994). Enhancing effectiveness: An investigation of advantages and disadvantages of value-based intragroup conflict. *International Journal of Conflict Management*, 5(3), 223-238.

de Kadt, N., Peeters, T. J. G., Langerak, F., & Alblas, A. A. (2015). *Accelerating the Learning Curve at ASML*. (Master of Science in Innovation Management. Eindhoven University of Technology, Eindhoven). Retrieved from: https://pdfs.semanticscholar.org/870f/9d9df44f46997466108026931db9eb823ceb.pdf

Kauppila, O. P., Rajala, R., & Jyrämä, A. (2011). Knowledge sharing through virtual teams across borders and boundaries. *Management Learning*, 42(4), 395-418.

Kennedy-Reid, Sherry & Bombassei, Francesco. (2015). Global Team Effectiveness at Boeing: A Practice-Based Approach to Team Learning in Action.

Knoben, J., & Oerlemans, L. A. (2006). Proximity and inter-organizational collaboration: A literature review. *International Journal of Management Reviews*, 8(2), 71-89.

Knudsen, M., & Madsen, E. (2014). The managerial issues related to transferring shop floor knowledge in manufacturing relocation. *International Journal of Operations & Production Management*, 34(11), 1389-1416.

Levy, F.K., Adaptation in the Production Process, *Management Science*, 11 (1965), B136-B-154

Mansfield, E. (1961). Technical change and the rate of imitation. *Econometrica: Journal of the Econometric Society*, 741-766.

Middleton, K. A. (1945). Wartime productivity changes in airframe industry. *Monthly Labor Review 61,* no 2: 215-5

Mihalache, O. R., Jansen, J. J., Van Den Bosch, F. A., & Volberda, H. W. (2012). Offshoring and firm innovation: The moderating role of top management team attributes. *Strategic Management Journal*, 33(13), 1480-1498.

Nadler, G., & Smith W. D. Manufacturing progress functions for types of processes. *International Journal of Production Research*, 1963, 12(2), 115-135.

Narayan, D., & Pritchett, L. (1999). Cents and sociability: Household income and social capital in rural Tanzania. *Economic Development and Cultural Change*, 47(4), 871-897.

Oertig, M., & Buergi, T. (2006). The challenges of managing cross-cultural virtual project teams. *Team Performance Management: An International Journal*, *12*(1/2), 23-30.

O'Leary, M. B., & Cummings, J. N. (2007). The spatial, temporal, and configurational characteristics of geographic dispersion in teams. *MIS quarterly*, 433-452.

O'Leary, M. B., & Mortensen, M. (2010). Go (con) Figure: Subgroups, imbalance, and isolates in geographically dispersed teams. *Organization Science*, 21(1), 115-131.

Pedersen, P. C., & Slepniov, D. (2016). Management of the learning curve: a case of overseas production capacity expansion. *International Journal of Operations & Production Management*, 36(1), 42-60..

Peeters, C., Massini, S., & Lewin, A. Y. (2014). Sources of variation in the efficiency of adopting management innovation: the role of absorptive capacity routines, managerial attention and organizational legitimacy. *Organization Studies*, 35(9), 1343-1371.

Pinto, M. B., Pinto, J. K., & Prescott, J. E. (1993). Antecedents and consequences of project team cross-functional cooperation. *Management Science*, 39(10), 1281-1297.

Prencipe, A. (1997). Technological competencies and product's evolutionary dynamics a case study from the aero-engine industry. *Research Policy*, 25(8), 1261-1276.

Putnam, R. D. (2000). *Bowling alone: The collapse and revival of American community*. New York: Simon & Schuster.

Richmand, A., Noble, K., & Johnson, A. When the workplace is many places: The Extent and Nature of Off-site work today, 2002. *American Business Collaboration, online publication:(last accessed July 2011) http://www.wfd.com/PDFS/Workplace_is_Many_Places. pdf*.

Riedel, J. C., & Pawar, K. S. (1991). The strategic choice of simultaneous versus sequential engineering for the introduction of new products. *International Journal of Technology Management*, 6(3-4), 321-334.

Roh, J., Hong, P., & Min, H. (2014). Implementation of a responsive supply chain strategy in global complexity: The case of manufacturing firms. *International Journal of Production Economics*, 147, 198-210.

Rutkowski, A. F., Saunders, C., Vogel, D., & Van Genuchten, M. (2007). "Is it already 4 am in your time zone?" Focus immersion and temporal dissociation in virtual teams. *Small Group Research*, 38(1), 98-129.

Scholz, R. W., & Tietje, O. (2002). *Embedded case study methods: Integrating quantitative and qualitative knowledge*. Sage.

Sharifi, S., & Pawar, K. S. (2002). Virtually co-located product design teams: Sharing teaming experiences after the event?. *International Journal of Operations & Production Management*, 22(6), 656-679.

de Snoo, C., Van Wezel, W., & Wortmann, J. C. (2011). Does location matter for a scheduling department? A longitudinal case study on the effects of relocating the schedulers. *International Journal of Operations & Production Management*, 31(12), 1332-1358.

Sorenson, O., Rivkin, J. W., & Fleming, L. (2006). Complexity, networks and knowledge flow. *Research Policy*, 35(7), 994-1017.

Thomé, A. M. T., & Sousa, R. (2016). Design-manufacturing integration and manufacturing complexity: a contingency investigation of job rotation and co-location. *International Journal of Operations & Production Management*, 36(10), 1090-1114.

Tripathy, A., & Eppinger, S. D. (2011). Organizing global product development for complex engineered systems. *IEEE Transactions on Engineering Management*, 58(3), 510-529.

Tripathy, A., & Eppinger, S. D. (2013). Structuring work distribution for global product development organizations. *Production and Operations Management*, *22*(6), 1557-1575.

Van den Bulte, C., & Moenaert, R. K. (1998). The effects of R&D team co-location on communication patterns among R&D, marketing, and manufacturing. *Management Science*, 44(11-part-2), S1-S18.

Vandevelde, A., & Van Dierdonck, R. (2003). Managing the design-manufacturing interface. *International Journal of Operations & Production Management*, 23(11), 1326-1348.

Wagner, M., & Norris, G. (2009). *Boeing 787 dreamliner*. Zenith Press.

Wiersma, E. (2007). Conditions that shape the learning curve: Factors that increase the ability and opportunity to learn. *Management Science*, 53(12), 1903-1915.

Woolcock, M., & Narayan, D. (2000). Social capital: Implications for development theory, research, and policy. *The World Bank Research Observer,* 15(2), 225-249.

Woolcock, M. (1998). Social capital and economic development: Toward a theoretical synthesis and policy framework. *Theory and Society*, 27(2), 151-208.

Wright, T. P. (1936). Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences,* 3(4), 122-128.

Wuyts, S., Colombo, M. G., Dutta, S., & Nooteboom, B. (2005). Empirical tests of optimal cognitive distance. *Journal of Economic Behavior & Organization,* 58(2), 277-302.

Yin, R. K. (2003). Case study research design and methods third edition. *Applied social research methods series, 5(1).*

Yin, R. K. (2006). Mixed methods research: Are the methods genuinely integrated or merely parallel. *Research in the Schools*, 13(1), 41-47.

Appendix A. Systematic literature Review method and Table

The search is limited to a selection of journals from the ERIM journal list. This list is compiled by the Erasmus Research institute of Management and aims to contain the best journals in the field of management.

The selection of the ERIM journal list is used to limit the search results to relevance on both the subject and credibility of the research. The list of journals included in the search is attached in Appendix B. No were no further restrictions in the search on year, country, language etc.

A search query was constructed and reiterated after testing on relevance and the inclusion of seminal work on the concepts. Older versions is attached in Appendix C. Multiple search terms were used in the search query for each theme to cover all relevant material. Each keyword relating to the same concept is separated by the 'OR' operator in the query. The final search query is displayed in Table 1.

The search query is split in three, where the concepts were searched stand-alone and in combination with the other concepts. The search was conducted in may 2019, the results are displayed a Venn diagram in Figure 2.

The papers overlapping on two or more concepts were reviewed and selected based on the abstract. The selected papers are examined and categorized on themes, methodology and outcomes.

By snowball cross-referencing papers were added to the selection for review. The selection procedure in visualized in a Prisma flow diagram in Figure 2.

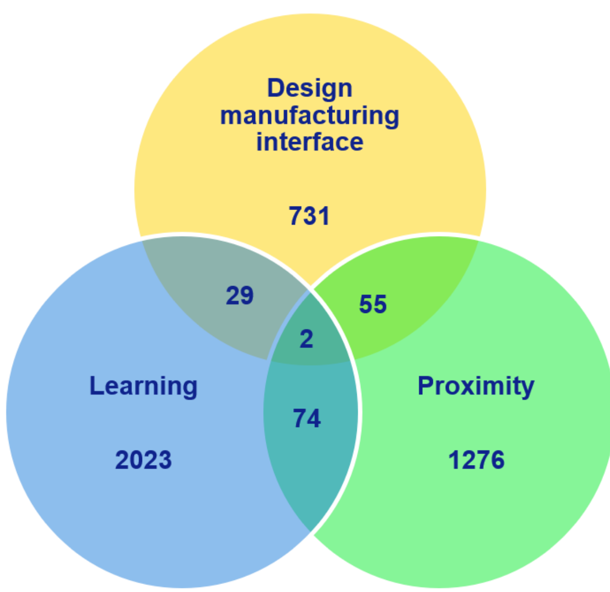
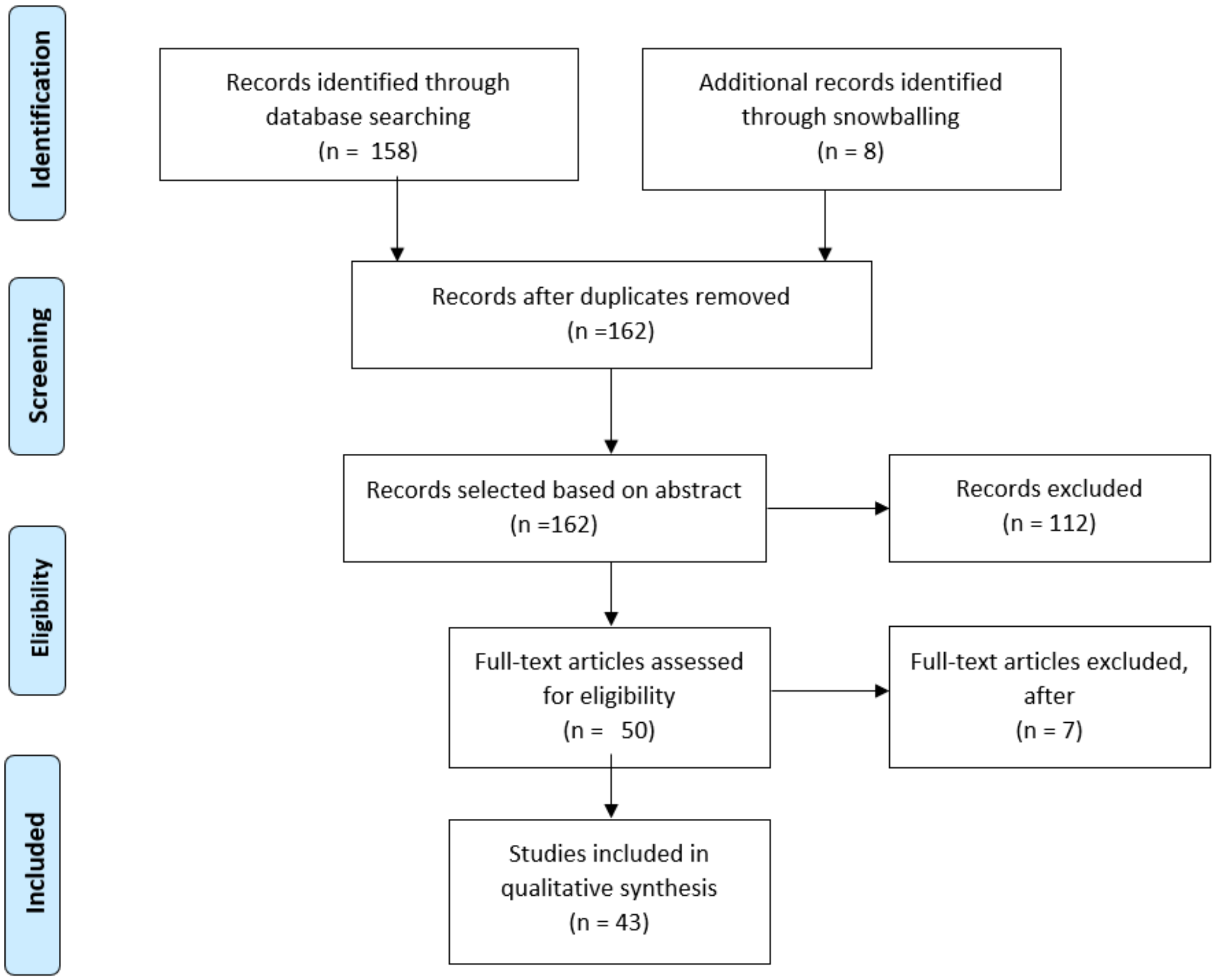


Figure 2 Venn diagram literature results

Figure 3. Prisma diagram Paper selection



Search query

TS=("organi$ational learning" OR "learning curve" OR "organi$ational memory" OR "knowledge transfer" OR "knowledge development" OR "learning by doing")

AND TS=("global operation*" OR "global product development" OR "global organi$ation*" OR "proximity" OR "dispersed team*" OR "virtual team*" OR "organi$ational design" OR "offshor*" OR "distributed organi*" OR "global supply chain")

AND TS=("engineering change*" OR "design iteration*" OR "design change*" OR "iterative design" OR "iterative engineering" OR "design" AND ("manufacturing" OR "operation*" OR "marketing" OR "NPD") AND ("interface" or "collaboration*") OR "modular*" OR "concurrent engineering")

AND IS=(1941-6067 OR 0001-4273 OR 0363-7425 OR 1558-9080 OR 0001-8392 OR 1045-3172 OR 0011-7315 OR 0017-8012 OR 0018-9391 OR 0960-6491 OR 1047-7047 OR 0144-3577 OR 0925-5273 OR 0021-9010 OR 0148-2963 OR 0149-2063 OR 0742-1222 OR 0022-2380 OR 0022-2429 OR 0894-3796 OR 0272-6963 OR 0737-6782 OR 1094-6705 OR 0276-7783 OR 1350-5076 OR 0025-1909 OR 1523-4614 OR 0305-0483 OR 0030-364X OR 1047-7039 OR 0170-8406 OR 0749-5978 OR 1059-1478 OR 1095-9203 OR 0048-7333 OR 1532-9194 OR 0143-2095 OR 0040-1625 OR 0969-6474)

Table A.1. Research on Learning and proximity on the DMI

	Learning		Proximity				
Author(s)	**Autonomous**	**Induced**	**Organizationa**	**Technological**	**Geographical**	**DMI Context**	**Implications for information exchange**
Knudsen & Madsen (2014)		✓		✓	✓	✓	Increased interaction between dispatching and receiving units will benefit knowledge transfer
Pedersen & Slepniov (2016)	✓	✓			✓	✓	Creating and enhancing knowledge repositories very helpful in overseas expansion
Peeters et al. (2014)		✓		✓		✓	Absorptive capacity routines should be aligned with the phase of absorption.
Tripathy & Eppinger (2013)		✓			✓	✓	PD tasks should first be properly modularized before offshored
Yang et al. (2016)		✓			✓	✓	Offshoring manufacturing and fabrication of technology reduces innovation on onshore site
Yayavaram & Ahuja (2008)		✓			✓	✓	Innovation can be limited by modularization due to decomposed knowledge bases
Argote & Ingram (2000)		✓	✓		✓		Recipient's productivity recovers faster when knowledge source is geographically close
Akgun et al. (2006)		✓		✓			TMS positively affects team learning, speed-to-market, and new product success
Caimo & Lomi (2015)		✓	✓				Knowledge sharing relations are more likely to be established across organizational subunits when they are reciprocated
Choudhury & Prithwiraj (2017)		✓			✓		Face-to-face contact between headquarters and distant locations increases patenting budget for R&D
Dixon (2017)		✓		✓	✓		Routines to ensure virtual team learning are trust, agreed goals and experimentation
Duarte & Snyder (1997)		✓	✓				Centralized training of employees on the PD process improves performance
Espinosa & Lindahl (2016)		✓	✓				Formalization does not hinder learning as long as it's not excessive
Hatch & Mowery (1998)	✓				✓		Problem solving effort has more impact than product output
Kauppila et al. (2011)		✓	✓	✓	✓		Knowledge repositories, sense of community, member rotation and team building and training stimulates knowledge sharing in global company
Mason & Leek (2008)		✓	✓		✓		Soft (besides hard) knowledge transfer mechanisms can help leverage effectiveness
Mihalache et al. (2012)		✓	✓		✓		Knowledge at international locations is important only in so far as the firm can transfer and assimilate it successfully
Myers & Cheung (2008)		✓	✓				Cultural difference have only limited impact on knowledge sharing value in supply chains
Olivera et al. (2008)		✓			✓		Awareness, searching and matching, and formulation and delivery important dimensions KT
Pinto et al. (1993)		✓			✓		Physical proximity increases cross-functional cooperation
Sorenson et al. (2006)		✓	✓		✓		Social proximity to the source is important for KD with knowledge of moderate complexity

Table A.1. Research on Learning and proximity on the DMI Continued

Adler & Clark (1991)	✓	✓				✓	Second order learning may cause disruption on short term
Borgatti & Cross (2003)		✓				✓	Success of interactions determine future influence frequency
Li et al. (2014)		✓				✓	Trusting relationships promotes information sharing
Lindkvist et al. (1998)		✓				✓	Time-based controls supports parallel production by inter-functional communication
Macher & Mowery (2003)	✓	✓				✓	Co-location of production and development engineers speeds up learning
Ozkan-Seely et al. (2015)		✓				✓	Development of KD and KT return rates depends on initial product and process knowledge
Sherman et al. (2005)		✓				✓	KR with information of previous projects and efficient systems of retrieval support learning
Bennett & Klug (2012)					✓	✓	Integrating suppliers with close proximity is a good strategy in a modular driven product
Bulte & Moenaert (1998)					✓	✓	Co-location of R&D teams increases communications, while not widening gap with manufacturing
Gray & Massimino (2014)			✓		✓	✓	Difference between HQ and plant in power distance and language hinder process compliance
Nagati & Rebolledo (2012)			✓			✓	Knowledge sharing routines improve operational performance of suppliers
Pashaei & Olhager (2017)				✓	✓	✓	The suitability of a modular product architecture depends on the business environment
Sharifi & Pawar (2002)				✓	✓	✓	An initial face-to-face meeting for virtual teams Is important to establish trust, effective team leadership and management
Snoo et al. (2011)				✓	✓	✓	Close physical proximity leads to more face-to-face collaborative communication
Thomé & Sousa (2016)					✓	✓	KT on the DMI is important for operational excellence in high-tech environments
Tripathy & Eppinger (2011)			✓	✓	✓	✓	Far-reaching decision making should lie with the headquarters home location
Vandevelde & Dierdonck (2003)			✓			✓	Overcoming language barriers, formalizing mechanisms and increasing empathy should be stimulated by senior management
Cohen & Levinthal (1990)		✓					Requisite breadth of knowledge is needed in order to absorb more specialized knowledge
Dutton & Thomas (1984)	✓	✓					Progress functions progress attained not only through maximizing cumulative output
Ettlie (1995)						✓	Active integration mechanism boost performance (e.g. per employee)
Irwin & Klenow (1994)	✓						Firms learn 3x more from an additional unit of their own cumulative production than from another firm's production
Whitehead et al. (2016)		✓					Symmetry between distributive and absorptive capacity between sender and receiver in KT plays an important role

Abbreviations used in Tables:
KT = knowledge transfer, KD = knowledge diffusion, DMI = design-manufacturing interface, KR = knowledge repository, PD = Product development, TMS = transactive memory system

Appendix C. Interview guide

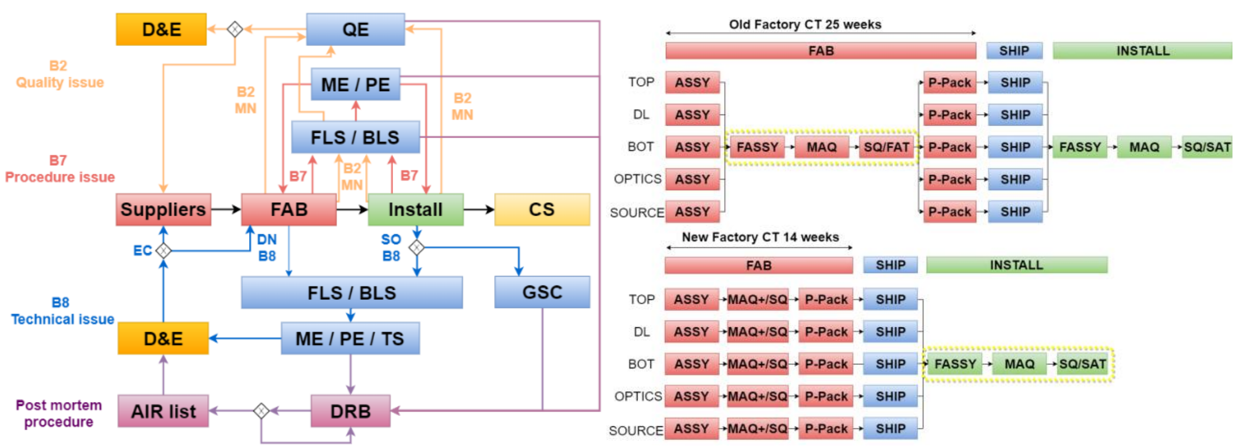
Interview guide Interview guide (Duration ~60 minutes)

The purpose of this document is to serve as an interview guide during qualitative data gathering for the master thesis: “Proximity changes in the issue resolution learning curve”

Opening (5 min)
Dit interview is deel van het kwalitatieve data verzameling voor het afstudeerproject voor de Technische universiteit Eindhoven. De onderzoeker werkt onafhankelijk en resultaten worden anoniem verwerkt. De zaken besproken tijdens dit interview zullen geen directe gevolgen hebben voor de geïnterviewde.

<u>Issue resolution, Independent qualification strategy & drop-shipment</u>
Eerst zal ik kort de context en relevante begrippen voor afstudeeropdracht introduceren. Vervolgens wordt de opname gestart en zullen we het interview starten.
Tijdens het oplossen van bepaalde issues, zijn er escalatie procedures die de informatiestroom door verschillende afdelingen sturen, dit is zo genoemd de feedbackloop (zie afbeelding 1)..

Voor de introductie van de EXE:5000 zullen de strategieën HLQS en drop-shipment worden geïmplementeerd wat het issue resolution process zal beïnvloeden (upstream issue finding geen complete assemblage meer Veldhoven, maar mechanical install voortaan voor het eerst op de klantlocatie. Aangezien deze nieuwe manier van werken de afstanden tussen de actoren in het issue resolution process aanpast, is het van belang om te weten wat de invloed van afstand in het feedback proces. In het specifiek zijn we geïnteresseerd in de effecten van de geografische, organisationele en technologische dimensies van afstand op het issue resolution process.



Persoonlijke gegevens

Naam:	
Functietitel:	
Verantwoordelijk voor:	
Betrokken bij project/product:	NXE/EXE/beide
Ervaring met werken met:	VH FAB/klant FAB/beide
Betrokken bij issues	B2/B7/B8

Start opname

Learning process (20 min)

1. Wat is je rol als functietitel in het issue resolution proces?
2. Hoe wordt informatie over issues aan je doorgegeven a. Voldoende?
3. Hoe worden lessen getrokken uit issue resolution? a. Effectief? b. Belemmerende/ondersteunde factoren?
4. Welke routines of mechanisms zijn er in jouw functie/competentie om het leerproces te ondersteunen (e.g. KT's, competence meetings, learning by doing)? a. Hoe gaat dit in zijn werk? b. Wat is het doel hiervan? c. Hoe zou je de effectiviteit beoordelen d. Hoe wordt dit beïnvloed door HLQS? e. Belemmerende/ondersteunende factoren?

Proximity and impact on performance (30 min)

Geographical (10 min)

1. Hoe beinvloed de fysieke afstand tussen jou en je collega's van afdeling de communicatie met betrekking tot issue resultion?
    a. Hoe vaak zie je elkaar in persoon?

    b. Hoe waardeer je in person contact in vergelijkingen met andere communicatie (e.g. telefoon, e-mail, company-tool)? Waarom?

    a. Hoe wordt dit beïnvloed door HLQS?

    b. Belemmerende/ondersteunende factoren?

Organizational (cognitive, institutional, cultural, social) (10 min)

1. Beinvloeden cultuur (land/regio) verschillen de communicatie tijdens issue resolution?
    a. Hoe? (arbeidsethos, expertise, sociaal)? Waarom?

    c. Hoe wordt dit beïnvloed door HLQS?

2. Heb je het idee dat er verschillen in bedrijfscultuur zijn tussen de afdelingen betrokken bij issue resolution?
    a. Hoe zijn deze merkbaar? (e.g. elkaar begrijpen, neerbuigende houding, behulpzaamheid) Waarom?

    d. Hoe wordt dit beïnvloed door HLQS?

3. Welk informeel contact heb je me the collega's?
    a. Beinvloed dit werkgerelateerde communicatie? Hoe?

    b. Belemmerende/ondersteunende factoren?

Technological (10 min)

2. Gebruik je elk van de volgende communicatiemiddelen: mail/telefoon/in-persoon/company tool? (aanvullend?)
    a. Wanneer gebruik je welk communicatiemiddel ? Waarom?
    b. Verschilt dat met hoe goede je de college kent? Hoe?
    c. Vind je dat je dezelfde communicatiemiddelen tot je beschikking hebt als je collega's. Verschillen?
    d. Hoe wordt dit beïnvloed door HLQS?
    e. Belemmerende/ondersteunende factoren?

Concluding (5 min)

1. Wat zou er veranderen met betrekking tot communicatie in de feedback-loop met de nieuwe manier van werken bij de EXE:5000?
2. Welke maatregelen denk je dat er genomen zouden moeten worden om negatieve gevolgen te voorkomen of de situatie te verbeteren?

Appendix D. Quantitative data analyses samples

	Issue frequency		**Break down duration**		**Manufacturing cycle time**	
Unique	Headquarters	Customer	Headquarters	Customer	Headquarters	Customer
Issues	12.660	9.224	10.714	9122		
Machines	35	29	35	29	35	23
Time interval	May 2015 - Aug 2019	Jan 2017 - May 2019	Sep 2015 - Aug 2019	Ja 2017 - May 2019	May 2015 - Jan 2019	Jan 2017 - Feb 2019

Appendix E Quantitative data cleaning and analyses scripts

In total 4 R scripts and 7 raw data source files are used. These are handed over to case company and the viewing of the content of these files can be requested. All files only consist of data from the NXE:3300, NXE:3350 and the NXE:3400B

R data scripts

Filename	**Function**
Final DN data prep January.R	Combines datasets on issues at the headquarters Cleans the data and prepares for analysis
Final SO data prep January.R	Combines datasets on issues at the customer sites Cleans the data and prepares for analysis
Final CT calculation.R	Calculates the cycle times for each machines with an additional cycle time data source
Final plots January.R	Performs the analyses and plots the graphs used in the thesis

Raw data source files

Filename	**Function**
DRB DN.csv	Contains the database of issues from disturbance review board at the headquarters
Eagle DN machine type.csv	Contains issues extracted from SAP of the headquarters (filtered on machine type is not empty)
DRB SO.csv	Contains the database of issues from disturbance review board at the customer sites
Eagle SO machine type.csv	Contains issues extracted from SAP for the customer sites (filtered on machine type is not empty)
Install SO logbook.csv	The logbook that is used by install engineers to note their time on specific activities
end_script_db.csv	A database of end-scripts from issues in the field used for selection on disturbance SO's
SO data (combinatie SMS + DRB tool)	A database for additional data on issues from the customer sites

Appendix F Function roles of Interviewees

Interviewee number	Part of	Role	Focus group
1	Design & Engineering	Manufacturing Engineer	Yes
2	Design & Engineering	Manufacturing Engineer	Yes
3	Design & Engineering	Manufacturing Engineer	No
4	Design & Engineering	Manufacturing Engineer	No
5	Issue resolution support	Trouble shoot (second line support)	Yes
6	Issue resolution support	First line support	Yes
7	Issue resolution support	Trouble shoot (second line support)	No
8	Issue resolution support	Build line support	Yes
9	Manufacturing	Quality engineer	Yes
10	Manufacturing	Production Engineer	No
11	Manufacturing	Quality engineer	No
12	Manufacturing	Install project leader CT	No
13	Manufacturing	Install project leader	No
14	Manufacturing	SQ DRB	No

Appendix G process of creating themes from interview data

Example 1 face-to-face collaboration improves issue resolution performance

From the next excerptions it follows that the opportunity of face to face collaboration is a proximity related driver for learning and "improves issue resolution performance". This is presented along with other themes in Table 4.2.

Excerption 1 original in Dutch:

"Ja dat helpt wel, ik heb het idee als mensen aanwezig zijn bij die meeting, dat het over het algemeen de oplossnelheid positief beïnvloed, dus als mensen aanwezig zijn, want zelfs een aantal, sommige zitten op dezelfde verdieping of 20m of 10 van ons vandaan, maar als ze dan niet bij die meeting aanwezig zijn, dan denk ik dat die oplossnelheid toch wel een stuk lager is, dus ik heb wel het idee dat, als je elkaar in de ogen kijkt en je zegt dat je iets niet gedaan hebt, is dat toch moeilijker als dat je er niet bent en na een half uurtje een keer een e-mailtje krijgt, dat is denk ik wel echt een verschil."

Translation excerption 1 to English

"Yes, that does help, I have the feeling that if people are present at the meeting, that is generally positively influences the resolution time, so when people are present, because even if a few, some are on the same floor 20 or 10 meter away from us, but if they are not present at the meeting, then I think the issue resolution time is a lot lower. I have the feeling that when you look each other in the eye and say you didn't do something, that is harder to do than when you're not there and get an e-mail after half a hour, I think that really differs."

Excerption 2 original in English:

"We have the procedures, the people that solved the DN and sometimes even the team leaders of the people executing the tasks in the same room and if we want we can get more data very easily, but when the system is at install, so that is separate from the HLQS, just when something is at install."

Excerption 3 original in Dutch:

"Ik weet wel dat FLS heeft gezegd dat het werd gewaardeerd dat ik elke week naar die meeting ging, dat ik fysiek aanwezig was. Dat vonden ze fijn, want omdat ik fysiek aanwezig was hebben ze gezien dat ik belangstelling had voor hun."

Translation excerption 3 to English:

"I do know that FLS have said they appreciated that I went to the meeting each week, that I was physically present. They liked that, because I was physically present they seen that I care for them."

Excerption 4 original in Dutch:

"Nee, maar dan zorgen we meestal wel dat we contact krijgen, of via de lokale coordinatoren of via mail van kunnen jullie het verduidelijken, of soms zijn ze ook terug in nederland, dan komen ze terug he de monteurs van install die dan betrokken waren bij de issue en dan trekken we ze er even bij, van he we hebben deze follow up gedaan, klopt dat, matcht dat met jouw verwachting en daar hebben ze ooit nog wel eens goede toevoegingen en het andere goede is, is dat ze ook zien, dat is ook wel echt het success van de DRB dat mensen zien dat er wat gedaan wordt met hun SO's, zal ze terugkomen dat ze zeggen van oh dat issue ja, dan weten ze ook inderdaad er is een platform in Veldhoven die in ieder geval probeerd te voorkomen voor de volgende keer."

Translation excerption 4 to English:

"No, but then we most of the time make sure that we get contact, either via the local coordinatiors or via e-mail, with can you clarify, or sometimes they are back in the Netherlands then they come back and we involve the install engineers in what follow up we've performed, does it match your expectations and they often have useful additions and besides that, is that they see, this is the real success of the DRB, that they see that something is done with their SO's, that when they come back, they know there is a platfrom in Veldhoven that tries to help to prevent this issue the next time around."

Excerption 5 original in Dutch:

"Ja, we krijgen die feedback heel concreet, wij laten namelijk, wij bieden aan, aan de install afdeling, als jullie hier in Veldhoven zijn, dus ze zijn een tijd in het veld en een tijdje hier, die kunnen met ons meelopen om kennis op te doen. Maar dat is niet alleen om kennis op te doen, dat is ook voor socializing […]we horen dat wel eens terug van, ow jullie zijn maar met z'n 2e dat is gewoon heel de competentie, ik dacht dat jullie hier met een man of 10 of 20 deze competentie zouden draaien, nee, oke dan snap ik wel dat je het af en toe druk hebt omdat er ook nog andere machines zijn, mensen hebben daar geen besef van, hoeven ze op zich ook niet, maar als ze het besef wel hebben scheelt toch in hoe je met elkaar samenwerkt en hoeveel begrip je voor elkaar hebt en weet wat je aan elkaar hebt."

Translation excerption 5 to English:

"Yes, we get very specific feedback, we offer them, the install department, if you are here in Veldhoven, so they are a while in the field and back here, they can walk along with us to gain knowledge. This is however not only to gain knowledge, but also for socializing, […] A number of times we her, oh you are only with two, that is the whole competence, I thought you were with 10 to 20 people that are responsible for this competence, no then I understand that you are busy sometimes, because there are also other machines, people are not aware of these things, they also don't have to be, but having the awareness helps in how you collaborate, having understanding and knowing what you can expect."

Example 2 subpar communication quality from customer sites

From the next excerptions it follows that the quality of the communication form the customer sites is subpar and a blocker for learning (see Table 4.2.)

Excerption 1 original in English:

"We have the procedures, the people that solved the DN and sometimes even the teamleaders of the people executing the tasks in the same room and if we want we can get more data very easily, but when the system is at install, so that is separate from the HLQS, just when something is at install it's difficult."

Excerption 2 original in Dutch:

"Het contact tussen de monteurs in het veld tussen de verschillende continenten en D&E Veldhoven moeilijker zal zijn dan tussen de fabriek in Veldhoven en D&E in Veldhoven, ik denk dat dat nog minder wordt eigenlijk, moeilijker om iedereen te kunnen trainen face to face, dan zou je al meerdere sessies moeten gaan organiseren waarschijnlijk om iedereen, of je zou het moeten opnemen ofzo, daar zou je dan aan moeten denken, want dan kunnen mensen het ook terug zien als herinnering. Als ik kijk naar de 3400, bij de vorige machinegeneraties, viel het mij op dat we best wel weinig feedback hadden uit het veld qua DN's en dat baard me wel enigszins zorgen voor de HLQS strategie."

Excerption 2 translated to English:

"The contact between the operators in the field and the different continents and D&E Vedlhoven will be more difficult than the contact between Veldhoven and D&E VEdlhoven, I think that that will become even less actually, more difficult probably to train everyone face-to-face, then you would have to organize multiple sessions probably to get everyone, or you should record it or something like that, you would have to think about something like that, because in that case people can see it again as a reminder. When I look at the 3400 from previous machine generations, I noticed that we receive little feedback from the field regarding DN's and this concerns me for the HLQS strategy."

Excerption 3 original in Dutch:

"Ik denk dat je als BLS te ver van de vloer af staat, dus te ver van de machine af, dus je communicatie dat wordt moeilijker, je eigen ervaring op doen wordt moeilijker, het BLS, dus het is build line support hardware, het is heel iets anders als FLS, dus om daar een beeld van te krijgen wat er precies mis gaat in het veld dat wordt lastig en ook, wat kan je daarin betekenen om het op te lossen,"

Excerption 3 translated to English:

"I think that BLS is too far removed from the shopfloor and therefore from the machine, so your communication will be more difficult, gaining experience will be more difficult, the BLS, so build line support hardware, that's something different that FLS, so to get a clear view of what's going wrong exactly in the field will be cumbersome and also what value you can add in solving the issues."

Excerption 4 original in Dutch:

"[…]maar ik hoor wel vaak dat FLS bijvoorbeeld dat als zij direct met mensen in het veld communiceren dat het lastiger is omdat ze vaak niet direct contact hebben met de mensen die aan de machine zitten, die zitten in de fab en hebben hun telefoon en laptop in moeten leveren en hebben dus veel minder, die hebben veel minder communicatiemogelijkheden."

Excerption 4 translated to English:

"[…] but I often here that FLS for example that when they directly communicate with people in the field, that it is more difficult because they often don't have direct contact with people next to the machine, they are in the fab and had to hand in their phone and laptop and therefore have a lot less communication options."

Excerption 5 original in Dutch:

"Nee, dat gaat niet goed genoeg en dat komt met name vanwege de tijdspanne, we hebben vaak wel supplier quality management nodig om nog eens extra te pushen op het aanleveren van informatie, de lead time is op dit moment gewoon te lang. , die zitten in een hele andere structuur te werken, je werkt bij een klant het is lastig om binnen te komen om informatie te halen, het merendeel van de mensen, behalve de engineers zelf zitten in een local office die vaak niet eens on site is […]"

Excerption 5 translated to English:

"No that is not going well enough and that mainly due to timezone differences, we often need supplier quality management to push extra on the delivery of information, the lead time at that moment takes too long, they work in a different structure, you're working at a customer it's hard to get this information, the majority of the people, except the engineers themselves are in a local office that is often not even on site […]"

Excerption 6 original in Dutch:

"Ik vind alleen de terugkkoppeling van dingen die in het veld gebeuren naar hier, dat dat nu stroef gaat, dus ik denk dat de items die nu hier zitten, dus we hebben echt het FASY stuk bij install, dat die items hier in Veldhoven landen, daar maak ik me wel zorgen over, omdat dat nu ook moeizaam gaat namelijk en nu doe je een veel groter stuk."

Excerption 6 translated to English:

"I think that the feedback of things that take place in field back to here, that is rough currently, so I think that the items currently located here, so I'm talking about the FASY part at install, that those items are fed back to Veldhoven, that's what I'm worried about, because that's currently difficult an then you will do even more."

Appendix H Focus group statements

Theme 1 Limitations in the field and their consequences - Statements:

What are differences that operators in the field deal with in comparison with the FAB in Veldhoven?

What effect does this have on the feedback from the field to Veldhoven?

How does this influence issue resolution?

Theme 2 Importance of personal contact – Statements:

Personal contact can be replaced by technology.

Personal contact with my colleagues has an significant effect on my job performance.

Theme 3 People before procedures – Statements:

The company's formal procedures and protocols function sufficiently in order for me to do my job without commonly using work arounds

I am adequately informed by the procedures and protocols in place.

Theme 4 Training of support teams – Statements:

Is the training for operators and support team employees impacted by HLQS?

If so how?

Potential measures?