THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Digital Lean Disturbance Management

ONUR KAYA STAFFANSSON

Department of Industrial and Materials Science

CHALMERS UNIVERSITY OF TECHNOLOGY

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ONUR KAYA STAFFANSSON
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Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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The evolution of lean disturbance management: physical, hybrid, digital.

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ONUR KAYA STAFFANSSON
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Chalmers University of Technology

Abstract

As a realization of visualization and simplification principles in lean, lean methods typically employ physical tools. However, being physical is both strength and weakness of lean tools. Being physical is a strength, because physical lean tools are easy to implement, easy to learn and easy to use. On the other hand, being physical is a weakness, because physical tools do not have the capability to store the information registered on them long term; which causes information waste. Eliminating waste is another important principle of lean, which this thesis focuses to add to the physical lean tools. The information written on these tools can be used to create a knowledge base as a means of reducing the aforementioned information waste. The knowledge base then can be used to increase decision making capacity through various statistical data analyses.

This thesis aims to generate knowledge about reducing the knowledge waste in lean methods that use physical visualization tools. Since the literature shows that lean and digitalization enable each other, it was hypothesized that digitalizing physical visualization tools can reduce knowledge waste. To reach the aim, a case company and a lean method (i.e., pulse disturbance management) was chosen. Design research methodology (DRM) was used to carry out the research. The work to reach the aim is guided by research questions that divide the work into three parts: defining the barriers, mitigating the barriers, and validation. In total seven barriers were defined, which are grouped under two categories: maintaining the leanness during digitalization, and making sure that the disturbance information is captured to be reused for the benefit of the case company. The barriers were mitigated. As a result, the prescribed lean digital disturbance management system has been deployed to the case company and disturbances has been captured by the employees over three years. The collected data has been analyzed to validate that the knowledge management waste is reduced. The aim has been fulfilled by, as a result of the disturbance data analysis, eliciting concrete examples on how the case company data could be used for the company's benefit. These elicited examples include: identifying latent problems, guiding improvement work and investments, and exposing seemingly trivial repetitive disturbances that incur a high cost over time.

Keywords: disturbance management, digitalization, lean, visualization.

Acknowledgements

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Finally, I would like to thank my friends and my family for their support.

Appended Publications

Paper A
Kaya, O., Catic, A., & Bergsjo, D. (2014). Exploring the possibilities of using image recognition technology to create a hybrid lean system for pulse methodology. Proceedings of the 12th annual Conference on Systems Engineering Research (CSER 2014), Redondo Beach, CA, USA, March 20-22, 2014. Procedia Computer Science, 28, 275-284.

Paper B
Kaya, O., Kero, T., & Bergsjö, D. (2015). Introducing digital pulse as a deviation management methodology for dental product development and production. International Journal of Lean Enterprise Research, 1(4), 351-372.

Paper C
Kaya, O., & Bergsjö, D. (2016). Useful deviations for deviation management information systems: From pulse methodology to a generic description. In System of Systems Engineering Conference (SoSE), 2016 11th (pp. 1-6). IEEE.

Paper D
Kaya, O., & Bergsjö, D. (2018). Learning from digital disturbance management in an integrated product development and production flow. International Journal of Product Lifecycle Management, 11(4), 295-325.

Work Distribution

Paper A: Bergsjö and Catic carried out the interviews and observations at the case company to form the research question; Kaya joined the study as master's thesis student, he developed the concept and the demonstrator as the solution, demonstrated them and got feedbacks in two of the workshops; Bergsjö and Catic carried out one of the workshops by presenting the concept and getting feedbacks from the attendees; Kaya wrote the whole paper and presented it at the conference

Paper B: Kaya initiated the article, carried out the interviews, surveys and observations, developed the demonstrator along with another software developer; Kaya and Kero carried out the long-term participant observation; Kaya wrote the whole paper.

Paper C: Kaya initiated, wrote, and presented the article.

Paper D: Kaya initiated and wrote the article.

Additional Publications

Publication 1
Kaya, O., Stenholm, D., Catic, A., & Bergsjo, D. (2014). Towards global deviation management in product development using pulse methodology: A case study. Proceedings of the 12th annual Conference on Systems Engineering Research (CSER 2014), Redondo Beach, CA, USA, March 20-22, 2014.

Publication 2
Kaya, O., Catic, A., & Bergsjo, D. (2014). Global Project Management Using Digital Pulse Methodology. Proceedings of the 23rd annual International Association for Management of Technology conference (IAMOT 2014), Washington, DC, USA, May, 2014.

Publication 3
Kaya, O. (2015). Lean Visual Management of Deviations in Product Development and Production-Coining Physical, Digital, and Hybrid Pulse Methodology. Licentiate thesis, Chalmers University of Technology, Gothenburg, Sweden.

Publication 4
Isaksson, O., Arnarsson, I.Ö., Bergsjö, D., Catic, A., Gustafsson, G., Kaya, O., Landahl, J., Levandowski, C., Malmqvist, J., Müller, J., Raja, V., Raudberget, D., Stenholm, D., Ström, M., (2017). Trends, observations and drivers for change in systems engineering design. 21st International conference on engineering design (ICED17), Vancouver, Canada.

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1 Introduction

Product and production development (PPD), is the science of bringing ideas as quick, cheap and high quality as possible to manufactured products that are appreciated by users/buyers. The product development part of PPD covers the whole span from idea (concept) to commercialization (market readiness); it starts with a market opportunity/need, and continues with producing/manufacturing, selling, delivering a product (Ulrich & Eppinger, 2012; Otto & Wood, 2001) and typically ends with end of life and recycling. The production development part of PPD focuses on improving existing production systems, developing new production systems, and creating new effective production processes and abilities (Bellgran & Säfsten, 2009).

Lean can be defined as the constant and dedicated strive for eliminating waste (Petersson et al., 2010) and it consists of a set of principles, methods and tools. It was developed by the Japanese Toyota company to be able to survive in the economic situation of the aftermath of World War II by eliminating any activity that did not add value (Sassanelli & Terzi, 2020). Lean first arose to improve production, which then referred as lean production (Krafcik, 1988). After that, it is also applied to product development, which then referred as lean Product Development (Morgan & Liker, 2006). The term lean PPD will be used to refer both lean production and lean product development in this thesis. Lean refers to a never-ending journey (Hibbs et al., 2009; Chakravorty et al., 2008; Schonberger, 2008) of iteratively and continuously improving the system (the sum of employees, machines, tools, software etc. that are involved in the processes of creating a product) by eliminating all that is not necessary (i.e., waste), and preventing losing anything that is necessary (e.g., knowledge), thus generating processes where lead time shortens, costs decrease, and quality increase continuously.

One way of continuously and iteratively improving processes in lean PPD in a long-lasting, sustaining, and affective manner is by solving the disturbances (i.e., conditions that deviate from desirable/normal (Bokrantz et al., 2016)) in the system (Petersson et al., 2015). Solving disturbances systematically (i.e., capturing, highlighting, following-up, solving, storing and re-using) using lean is referred as lean disturbance management in this thesis. Disturbance management activities generate knowledge (e.g., the knowledge of how to solve a difficult disturbance, the statistics of occurring disturbances). Lean tools are typically physical for the sake of reducing complexity (Lorenz et al., 2019). Therefore, lean disturbance management also typically uses physical lean tools such as A3s and whiteboards. The benefits of these tools are that they are easy to implement, easy to learn and easy to use. The drawbacks of them, are that they are not good at capturing the knowledge generated by lean disturbance management activities. This is referred as knowledge waste in this thesis. Alieva & von Haartman (2020) refers this as digital waste (as given in Figure 1). They state that digital

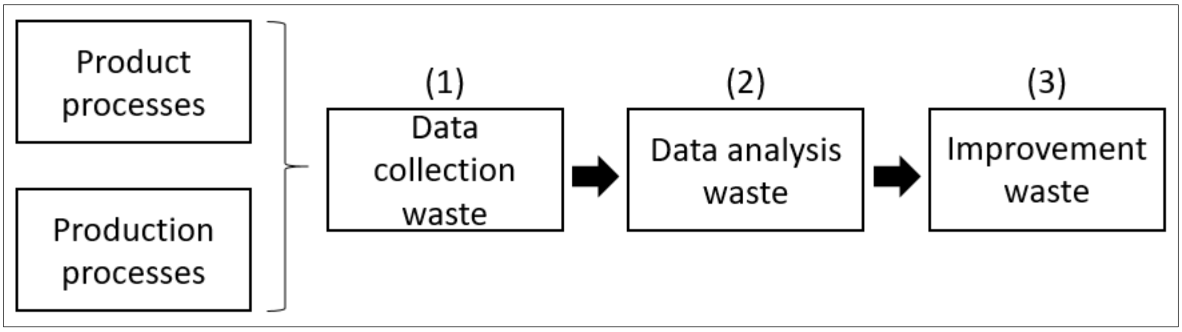

Figure 1. The source and the three layers of digital waste

waste can come from both product and production processes. They divide digital waste into three levels:

1. partial or no data collection
2. not making use of collected data, not analysing the collected data (i.e., turning data into information)
3. not making use of the analysis (e.g., for improvement)

Reducing this knowledge waste constitutes the industrial problem (Wingquist Laboratory, 2017) this thesis aims to solve. Consequently; the aim of this thesis is to

generate knowledge about reducing the knowledge waste in physical lean disturbance management

Digitization is the process of the converting analogue data (e.g., audio cassette) into digital data (e.g., MP3) (Brennen & Kreiss, 2016; Unruh & Kiron, 2017). Digitalization is the exploitation of digitization (i.e., digitized products) to create (typically disruptive) business models, business processes and improve organizations (e.g., music streaming business) (Unruh & Kiron, 2017; Westerman et al., 2011). Digital transformation is the wide adoption and internalization of digitalization that restructure economies, organizations and society (e.g., change in the human mating behaviour; using online dating apps to find partner) (Brennen & Kreiss, 2016; Unruh & Kiron, 2017). Purposeful digital transformation is using digital technologies to resolve global challenges (Unruh & Kiron, 2017). However, Unruh & Kiron (2017) states that "there is no consensus on the meaning of these terms and their definition often depends on who is using them". In the present thesis, the keyword digitalization will be used as an umbrella term (including industry 4.0). Using digitalization (or digitization as Kagermann (2015) refers to) in the industry is referred as Industry 4.0 (Kagermann, 2015). Digitalization brings many benefits; e.g., increased customer satisfaction and loyalty, optimized supply chains and resource utilization, increased efficiency and productivity, reduced costs (Kagermann et al., 2015; Loebbecke & Picot, 2015). Digital technologies and procedures, which is estimated to give an added value of 640B$ by 2025, have the potential to improve the acceptance of lean tools (Impact, 2020). Similarly, lean is considered to be an important enabler in the implementation of digitalization (Industry 4.0) (Bittencourt et al., 2019). Thus, it can be said that digitalization and lean compliment, support, and enable each other (Mrugalska & Wyrwicka, 2017; Valamede & Akkari, 2020a.); i.e., the combination of digitalization and lean enables greater performance compared to standalone implementation of digitalization or lean (Lorenz et al., 2019). In literature, various names are used for the combining digitalization and lean: “lean industry 4.0” (e.g., Ejsmont et al., 2020), “digital lean” (e.g., Powell et al., 2018), “lean 4.0” (e.g., Valamede & Akkari, 2020b; Gil-Vilda et al., 2021), “lean production systems 4.0” (e.g., Schumacher et al., 2022), “lean automation” (e.g., Kolberg & Zühlke, 2015; Tortorella et al.,2021). In addition, this combination of lean and digitalization “has the potential to impact the transition from the fourth industrial revolution to a new bias of Industry 5.0 or Society 5.0, in which, in addition to machines, employees are also a fundamental part of the industrial process, and Lean 4.0 converges along this same line of thought” (Rossi et al., 2022). Digitalization, which is mainly a technical improvement approach, cannot replace value-based lean mindset, but it can improve the established lean methods (Meissner et al., 2018). Digitalization should aim to improve the effectivity of waste reduction of classic lean methods (Metternich et al., 2017). Digitalizing allows accurate data collection (Lorenz et al., 2019). Pursuing the need of this thesis, digitalizing disturbance registries has the capability to make them available to store, share, retrieve, and analyse using digital tools, which in turn has the potential to reduce the knowledge waste in lean disturbance management.

Combining lean and digitalization is not a straightforward process. Toyota, where the lean is originated from, is a slow adopter of new technologies (Powell, 2018). Toyota introduces new technologies only after getting a proof on that the new technology to be introduced does not negatively affect leanness of the company (Lorenz et al., 2019). The new technology should either reduce waste or increase customer value (Liker, 2004). Other companies that use lean also have been slow introducing IT systems and new technologies (Pinho & Mendes, 2017; Powell et al., 2013). This is especially true for small and medium size companies due to lack of skills and financial resources, which leads to managers requiring proof of return on investment from digitalization implementations (Lorenz et al., 2019). The 8th principle of lean as given in Liker (2004) supports this statement: “use only reliable, thoroughly tested technology that serves your people and processes”. And currently the impact of implementing digitalization and data analytics in established lean practices and tools is not clear (Pereira et al., 2019). Furthermore, 70% of the digitalization efforts fail (because of lacking long-term thinking, and strategy) and become a source of waste (Impact, 2020). As can be derived from the above, lean literature traditionally sees a conflict between digitalization and lean (Lorenz et al., 2019). Even though Swedish firms employ both lean and digitalization in their business, they rarely merge the two. In contrast to the simplicity of lean, IT systems typically bears a high complexity (e.g., over process automation, unnecessary software functionality) (Maguire, 2016). In addition, they can be expensive to buy (price of Whiteboard vs MS Office) and deploy to an organization. Digitalization risks alienating employees from problem-solving processes (Lorenz et al., 2019). In addition, digital technologies bring the issue of cyber security along with them to organizations (Progress Data RPM, 2022). These drawbacks cause risks for digitalizing lean. The digitalized lean tool may lose its simplicity to learn, so much that the employees need to take a course to be able to use it properly. The user interface of the tool may lose its intuitiveness, so much that users need to pay all their attention to controlling and navigating the tool, and consequently users get distracted from the lean methodology behind. The tool may become a large software that is loaded with many fancy but unnecessary functionalities or employs expensive gadgets, so much that it costs a large amount of money, or that it takes too long time to implement to a company. In short, the risk of digitalizing lean is losing the leanness. Furthermore, no benefits may be gained after digitalization; i.e., no knowledge could be captured or made use of, and even worse, disadvantages of digitalization may cause new waste (Meissner et al., 2018). As given in the previous paragraph, digitalization has the potential of reducing the knowledge waste in lean disturbance management. However, as given in this paragraph, using digitalization in lean bears risks. Hence, the research challenge (Wingquist Laboratory, 2017) of this thesis is

maintaining the leanness of the methodology during digitalization

Accordingly, this thesis hypothesizes that it is possible that the barriers towards digitalization can be found, mitigated or eliminated, and thereafter the digitalization can be applied on lean methodologies while preserving the benefits and eliminating the drawbacks and avoiding the aforementioned pitfalls. Thus, specifically the hypothesis of this thesis is that

digitalization can reduce the knowledge waste in lean disturbance management while maintaining the leanness of the methodology.

The hypothesis will be verified at the end of the research project by the results that will be acquired from testing a prescribed solution at the case company.

1.1 Importance of the thesis

Regarding combining lean and digitalization, Ejsmont et al. (2020) states that "most of the publications are of a conceptual, philosophical or review nature and concern only preliminary considerations regarding the possibilities of synergy I4.0 and LM". This thesis fills the gap defined by Powell et al. (2018) and Ejsmont et al. (2020) that further case studies and empirical research in industrial settings are required to:

1. verify that digitalization and lean do synergize and are enablers for each other (Powell et al., 2018; Ejsmont et al., 2020)
2. examine the barriers that influence the synergy between digitalization and lean (Ejsmont et al., 2020)
3. verify the possibilities of the combination of lean and digitalization reducing waste (Ejsmont et al., 2020)

Identified research gaps in relation to the literature review is presented in detail at the end of the frame of reference chapter.

1.2 The aim of the research project

This thesis was a part of Vis-IT project, which has been funded by Vinnova. The research aim of the project was to build knowledge of the visual methods to digitize them in ways that enable their use in global teams and for continuous improvement without adversely affecting the simplicity and usability of the methods (Vinnova, 2012). The industrial aim of the project was to increase the competitiveness of Swedish product development industry. The project was set up in a cross-academic and industrial setting in order to apply and demonstrate the developed digital methods directly in industrial usage. This allowed going to the field to find problems, going back to research to find what has been done in the literature, prescribe a solution, go back to the field to try, get feedback and loop back. Through these quick loops methods and tools have been improved. The project lasted between 2012-2015. Between 2015-2017, the present thesis was funded by the DigiLean project that focuses on digitalization for learning and knowledge reuse.

1.3 The case company

The case company is a Swedish integrated product development company within dental implants business. They have the whole chain of customer specific product manufacture (scan, design, manufacture). They are a separate business unit in a large organization. The unit has around 65 employees. The process flow is as follows. The mouth casts of patients are received from dentists and scanned by the scanning department. Then the abutments are designed using a CAD program by the design department. After the design is approved, it is sent to machining to the workshop department. After the parts are produced, they are sent to verification. Once they are verified, they are packed and shipped to customers.

1.4 The digitalization journey

In the beginning, when the case company started in 2008, they shared the status about the disturbances in the meetings. They did not have a visual tool to register and visualize the disturbances. Over the years the company got bigger and the number of employees increased. Soon the meetings began to be insufficient to share the disturbance status and inform all the stakeholders. In order to solve the needs, the company introduced physical disturbance management board. That was the point where this research project started collaborating with the case company.

Romero et al. (2019) suggests technology pull for a successful digital transformation (in contrast to technology-push that came with the hype of Industry 4.0). Therefore, the journey of digitalization is carried out to fill the need of the case company. In order to keep the benefits of physical visualization tool and combine them with the benefits of digital technology, a hybrid solution was developed and demonstrated to the case company. Because of the shortcomings of the hybrid solution, it was never deployed to be tested at the industry. Instead, a fully digital solution was developed and deployed to the case company. The digitalization journey carried out in this research is illustrated in Figure 2.

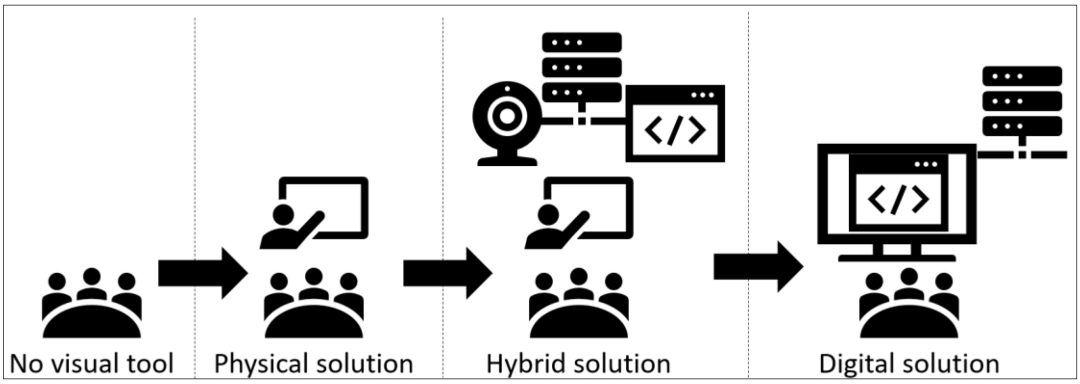

Figure 2. The digitalization journey of the research project

1.5 Research Questions

Figure 3 depicts a research project with a basic analogy: (a) destination (i.e., aim), (b) means to reach the aim, (c) start point (i.e., current status), (d) barriers that should be overcome to reach the aim, (e) means to overcome the barriers, (f) checking if the arrived point is the destination that was planned (i.e., validating the aim is reached).

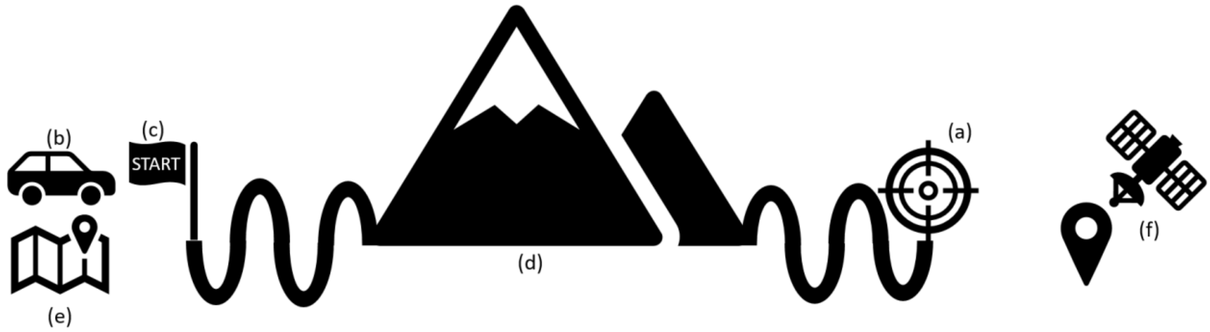

Figure 3. An analogy of this research

The aim of the thesis (a) has been defined during the research clarification step (Blessing & Chakrabarti, 2009). The means to reach the aim (b) is defined by the hypothesis (i.e., digitalziation). The start point (c) is defined by the literature study. The remaining constructs should be defined in the order they are given above. Three research questions were used, of which answers can define these constructs:

- Answer to the first research question shall define the barriers (d) that should be overcome to reach the aim
- Answer to the second research question shall define the means to overcome the barriers (e)
- Answer to the third research question shall validate that the aim is reached (f)

Thus, the research questions of this thesis are as follows:

1.5.1 Research question 1

What are the barriers towards digitalised disturbance management in lean PPD?

Description: The start state of the case company is that a physical lean tool is being used to manage disturbances. The goal state is that the case company manages disturbances using digital disturbance management, using the methodology at least as successfully as today, and in addition identifying and registering disturbances and reusing them. What are the problems that needs to be solved to bring the case company from the start state to the goal state?

Motivation: Lean tools known to be physical. They are known to be intuitive, easy to deploy, learn and use; partly thanks to being physical tools. On the other hand, some digital tools are infamous with being counterintuitive, hard to deploy, learn and use. Given the circumstances, it has utmost importance to understand the current state and how to bring the current state to the goal state while maintaining the methodology. Digitalizing the lean disturbance management is not the end goal; the new methodology should also allow capturing and reusing registered disturbances. It is important to understand the barriers towards reaching this goal, as well.

Aim: The aim is to increase the understanding regarding the current state, and define and understand the problems that needs to be solved to reach the goal state.

Method: To increase the understanding of the start state, how particularly the case company and generally other companies manage disturbances was investigated using interviews, observations, and literature study, respectively. To increase the understanding of the preferred/wished goal state of the case company, interviews (to get information from employees) and workshops (to present demonstrator prototypes) was carried out. In addition, interviews were carried out during the implementation of the digital disturbance management demonstrator to capture any unexpected problems.

1.5.2 Research question 2

How can the barriers towards digitalised disturbance management in PPD can be overcome?

Description: The second research question is about finding out how the barriers towards digital disturbance management, which were identified as the answer to the first research question, can be mitigated.

Motivation: In order to reach the aim of the thesis (i.e., reduce the knowledge waste in lean disturbance management while maintaining the leanness of the methodology by using digitalization), the barrier of "maintaining the leanness during digitalization" should be mitigated. Thus, the first motivation for the second research question is that it enabled reaching the aim. The second motivation is about enabling the validation in the case company. The validation is planned to be done by applying the prescribed solution to the case company, capturing disturbances over time, making use of the captured data for the company's benefit, and thereby validating that existence of the prescribed solution prevented the elicited benefit from being wasted. To be able to carry out the validation, the barrier of "*making sure that the disturbance information is captured to be reused for the benefit of the case company*" should be mitigated. In summary, the second research question is important in terms of reaching the aim and validation.

Aim: The aim is to mitigate the barriers that are given as the answer to the first research question.

Method: Interviews were carried in the case company in order to increase the understanding about the barriers. Literature study, interview with managers and engineers of the case company, and individual brainstorming was carried out to find out ways for mitigating the barriers. The case company employees were continuously kept informed about the ongoing change processes, and were involved in decision making processes when possible. Lastly, the ways found to overcome the barriers were implemented. As defined in the aim of the thesis, digitalization was used. Specifically, "digitalization as it is" (instead of "digitalization from scratch") was used to keep familiarity of the tool. Procedures were automatized and simplified when possible during digitalization. The mitigation of the barriers were verified by verification by acceptance (Buur, 1990).

1.5.3 Research question 3

How can disturbance data collected in a digital solution can be used to increase the decision-making capacity in an organization?

Description: The third research question is about finding ways to exploit the disturbance data that was captured by the digital disturbance management tool.

Motivation: The importance of this research question is manifold. The first point is supporting the hypothesis in terms of validating "reducing knowledge waste" and "maintaining the leanness". The second point is mitigating the barrier of capturing minor disturbances, which is defined as the answer to the second research question. The third point is verifying that the barrier of capturing the disturbance information in a way that it can be reused is truly mitigated. The last point is showing the extent that the research aim is fulfilled. A more detailed motivation is given under section 5.1.

<u>Aim</u>: The aim of the third research question is to show that (1) disturbance data can be captured by digital disturbance management tool, and (2) analyzing the captured data allows generating new insights to be used for strategic data-driven management (e.g., process improvements, improvement investment decisions such as buying new machines etc.).

<u>Method</u>: The digital disturbance management methodology was introduced iteratively by testing the implementation first at a pilot and upon success, implementing it to the rest. The captured disturbance data is stored to a database that at the case company servers. It is downloaded and analysed using MS Excel. Both qualitative (e.g., analysing free text input) and quantitative (e.g., calculating the number disturbances) analyses were carried out.

1.6 Mapping Appended papers to research questions

How each appended paper contributes to the research questions are given below and summarized in Table 1:

- Paper-A:
    - RQ-1: Increasing the knowledge on pulse methodology
    - RQ-2: Giving a candidate case for overcoming the barriers
    - RQ-2: Giving the reason why the case could not be used as the way to overcome the barriers (failing the user acceptance)
- Paper-B:
    - RQ-1: Increasing the knowledge on pulse methodology
    - RQ-1: Barrier about capturing minor disturbances
    - RQ-2: Making the employees skillful on the digital pulse methodology
    - RQ-2: Processes that governs the digital pulse methodology
    - RQ-2: Evaluating the introduction of the digital pulse methodology
- Paper-C:
    - RQ-1 & RQ-2: Analyzing why the operators did not capture minor disturbances
    - RQ-2: Overcoming the capturing minor disturbances barrier
- Paper-D:
    - RQ-2: Which data is captured while registering a disturbance to the digital board
    - RQ-3: Which analyses were carried out to be able to elicit insights from the data
    - RQ-3: The insights generated from analyzing the disturbance database

Table 1. Mapping research questions to the appended papers

	Paper-A	Paper-B	Paper-C	Paper-D
RQ-1	✔	✔	✔	
RQ-2	✔	✔	✔	✔
RQ-3				✔

1.7 Limitations and delimitations

Delimitations refers to the limitations in the scope of the thesis. They are what was not done in the thesis because it was decided so. The delimitations of this thesis are as follows:

- The following literature are excluded
    - accidents, incidents, and near-misses literature was excluded because the case company register them to a separate database, therefore they were not the focus of this thesis work.
    - Problem solving literature was excluded. Disturbance management includes problem solving activities. However, the present thesis does not focus on the problem-solving step of disturbance management.
    - A theme in this thesis is to test if teaching/learning digital lean tools is hard. However, since this was not a main theme, teaching, learning and pedagogy literature was excluded
    - Even though the "knowledge waste" keyword is used in the thesis, the knowledge management (including lean knowledge management) was excluded. The reason was that the focus is on capturing and re-using disturbances, not a generic knowledge management per se.
    - Even though a tool and process change are carried out during the research project at the case company; change management literature was excluded.
    - The PhD student carried out software development activities as a part of the research project as developing the digital demonstrator. Since the software development is not the focus of the thesis, the literature on the technologies used in the development has been excluded from the thesis.
- Vis-IT project was focused on the following four lean tools (1) pulse methodology, (2) A3, (3) visual planning, (4) checklist. As a sub-project of Vis-IT, this thesis focused on the pulse methodology.

Limitations refers to shortcomings or weaknesses of the research (or the thesis as its output) that the researcher could not address either because the necessary resource(s) was not present (e.g., time) or the issue being out of the researcher's control. The limitations of this thesis are as follows:

- Putting price tag to disturbances; i.e., quantifying disturbances. This was given as future work
- Particular method of solving individual disturbances (e.g., root cause analysis (5Whys, fishbone, etc.))
- Method of identifying disturbances
- The PhD student was employed in total 5 years to carry out this research
- The standardization process, which is the primary step before starting disturbance management, is excluded. This is not only because the case companies have already done standardizations for important points, but also, as previously mentioned, some standards are just obvious and straightforward therefore no need to set officially written standards

we did not have access to the CAPA (corrective and preventive actions) database, where non-conformances are managed. Therefore, we could not analyse any correlation between digital disturbance management and non-conformances.

1.8 Outline of the thesis

The chapters of the thesis are outlined as follows:

Chapter 1 – Introduction:
This chapter starts with an overview on the framing of the thesis. Continues with motivating the necessity and importance of the present thesis. After that, research questions, and how they are mapped to the appended publications are given. The chapter concludes with giving the limitations and delimitations of the thesis.

Chapter 2 – Research approach:
This chapter starts with explaining the framework used to design this thesis. The chapter continues with giving information on the studies carried out for the thesis, and how they are connected to the appended papers and the research questions. The chapter is finalised by giving information on the validation methodology used in the thesis.

Chapter 3 – Frame of reference:
This chapter starts with framing the thesis. Then, current knowledge on the literature was given related to the frame of the thesis. After that, the summary of the chapter is given. Finally, the identified gaps in relation to the literature review is presented at the end of the frame of reference

Chapter 4 – Results:
Appended publications are summarized in this chapter. Only the parts that contribute to answering the research questions are summarized.

Chapter 5 – Discussion:
The chapter starts with discussing the various decisions made throughout the thesis. Then opposing results from other research have been given and discussed. Then, topics that are related to the present thesis, but have not been included, are discussed under the heading further discussions. The chapter continues with discussing validity of the thesis. After that industrial and scientific contributions are given. The chapter concludes with giving the future work.

Chapter 6 – Conclusion:
The chapter starts with summarizing the thesis and concludes with answering the research questions.

Chapter 7 – References:
The list of publications that are referenced in this thesis

Chapter 8 – Appended papers:
Four articles, which constitutes the present thesis, that has been published by the PhD student are given in the appendices.

2 Research Approach

This chapter explains the research approach used to create the present thesis. The chapter starts by explaining the research approach used at designing the research project (Vis-IT project). The chapter then continues with explaining the research approach used at designing the thesis, which is a part of the Vis-IT project. After that, information on the studies carried out, and the cases company are given. The chapter is concluded with presenting the validation approach, which is followed in the validity chapter.

2.1 Research project design

The present thesis was carried out at the Wingquist Laboratory VINN Excellence Centre within the Area of Advance Production at Chalmers, as a part of Vis-IT research project. Vis-IT project was designed according to the Wingquist laboratory research implementation strategy (Wingquist Laboratory, 2017; Wingquist Laboratory, 2014). As given in Figure 4, the research implementation strategy starts with finding a research challenge and an industrial opportunity and creating a research idea by combining them. From this research idea, a research project is started. During the research project, demonstrator(s) (e.g., prototype, working procedure) are developed. These demonstrators are evaluated at industrial settings. From the learnings gathered at this step, final products or services developed. This way both a research challenge is answered, and an industrial need is fulfilled.

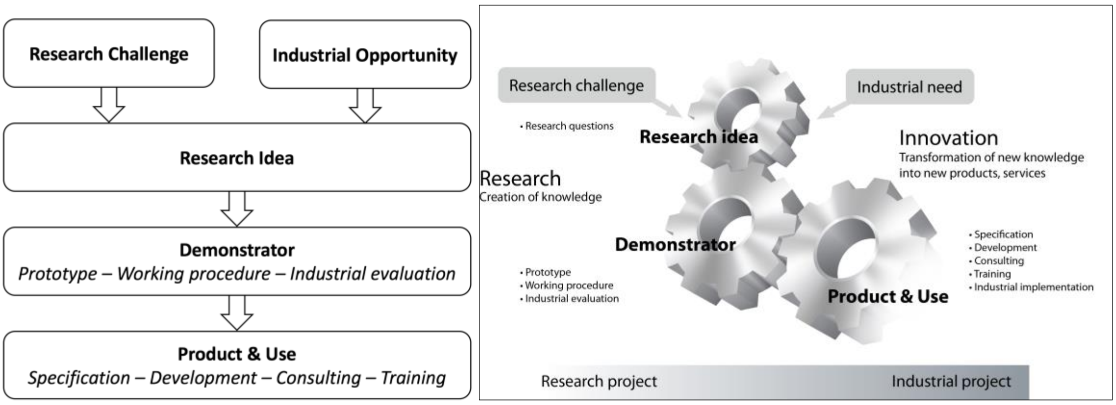

Figure 4. Wingquist laboratory research implementation strategy (Wingquist Laboratory, 2017)

2.2 Thesis design

As per Wingquist laboratory research implementation strategy, Vis-IT project was started with both industrial and scientific contributions in mind. As a sub-part of Vis-IT project, contributing to both science and industry is important for this thesis as well. Therefore, a research methodology framework that supports such aim was chosen while designing the thesis; that is, design research methodology (DRM) (Blessing & Chakrabarti, 2009). Cronje (2013) states that, "in an academic environment where the production of creative outputs and academic research are often regarded as mutually exclusive, design research presents a useful tool for extracting publication value from the production process". Design research, as the name states, integrates design and research. As shown in Figure 5, design stream gives the product, and research stream gives publication as output, and both of these streams are result of each other by test-apply cycles (Cronje, 2013). For this reason, DRM fits the nature of this thesis and thus is selected as the research design framework.

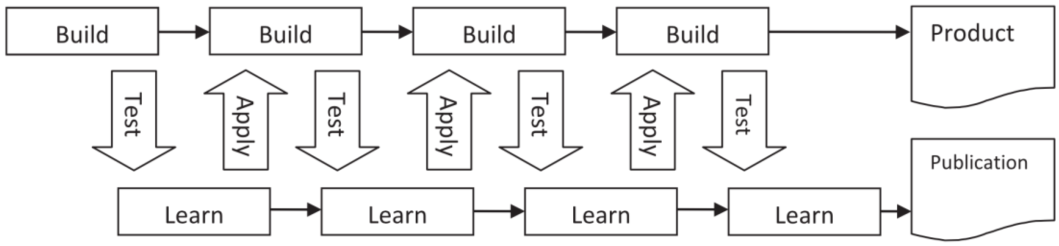

Figure 5. Product and research streams in design research methodology (Cronje, 2013).

2.2.1 Design research methodology

Design refers to the activities that generate/develop a product using various product development practices in order to fulfil the needs of the users and stakeholders (Blessing & Chakrabarti, 2009). The concern in design research is the development, articulation, and communication of the design knowledge in people, processes and products (Cross, 2006). Pahl et al. (2007) explains the design as an engineering activity as follows:

- affects almost all areas of human life
- uses the laws and insights of science
- builds upon special experience
- provides the prerequisites for the physical realisation of solution ideas
- requires professional integrity and responsibility

The generated/developed products, as the outcome of the design activities, can be/have (Blessing & Chakrabarti, 2009):

- engineering or non-engineering nature
- service, artefact or combination of both
- physical, virtual, or hybrid

Although the nature of design research still controversial, the common points of the best practices can be given as follows (Cross, 2006):

- based on identification of an issue or problem worthy and capable of investigation,
- seeking to acquire new knowledge,
- conducted from an awareness of previous, related research,
- planned and carried out in a disciplined manner,
- generating and reporting results which are testable and accessible by others

Blessing et al. (1995) defines the following four stages as a generic design research methodology to systematically address the research questions:

- criteria (aka. research clarification)
- description-1 (aka. descriptive study-1)
- prescription (aka. prescriptive study)
- description-2 (aka. descriptive study-2)

Figure 6 shows the input and output of these stages along with the flow between them, where dark arrows representing the main process flow and light arrows representing the iterations (Blessing & Chakrabarti, 2009).

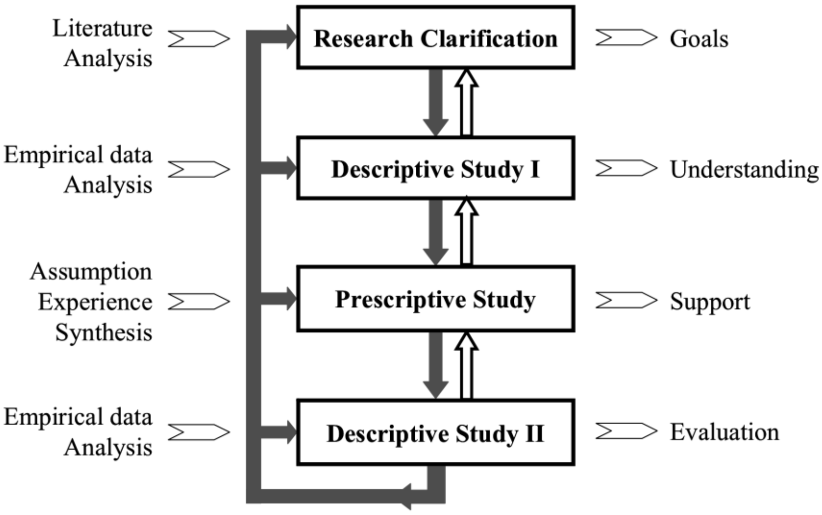

Figure 6. Design research methodology framework (Blessing & Chakrabarti, 2009).

Design research methodology is not a linear, rigid, waterfall methodology. In contrast, it is an interactive methodology. The following actions are possible and sometimes necessary: (Blessing & Chakrabarti, 2009)

- iterate between and within stages
- execute the stages parallel
- start from any stage
- concentrate only on one or two stages

Research clarification:

In this stage, by searching the literature, the research goals are formed. Initial description of the current situation and the desired situation are described. Lastly, evaluation criteria are formulated to be used in the descriptive study II.

Descriptive study-I:

This stage starts with having a clear goal and focus. Literature is further reviewed, and interviews, observations etc. is done to elaborate on the understanding gained at the research clarification stage. Here the aim is to make the description detailed enough so that the factors that would help improving the current situation and bring it to the desired situation can be determined.

Prescriptive study:
In this stage, the demonstrator is prescribed and developed to bring the situation to the desired state. The description of the desired situation is updated using the additional experience gained about the current situation. Finally, a first evaluation is done on the prescription.

Descriptive study-II:
In this stage, the developed demonstrator is further evaluated regarding its applicability and usefulness. The first evaluation aims to find out if the developed demonstrator can be used for this problem. The second evaluation aims to find out how much the demonstrator can fulfil the success criteria formed in the research clarification stage.

2.2.2 Type of research

Studies in each DRM stage can be carried out as one of the following depths:

- Comprehensive: Both a literature review and a new study is carried out
- Review-based: Only literature review is carried out
- Initial: Only the initial steps of a new study are carried out

Essentially each DRM stage shall be carried out as a comprehensive study (i.e., type 7). However, a research project may choose to carry out studies in DRM stages in a less deep manner for various reasons (e.g., resource limitations, sufficient literature exists etc.). Therefore, DRM defines seven types of design research where the study depth of each stage varies. Typically, PhD projects include one or two comprehensive stage. Type 7 is common for research group work or when a problem with a specific scope is addressed. (Blessing & Chakrabarti, 2009)

The PhD student combined literature study and visiting the case company for participant observation and discussions with the engineers and managers in order to generate the initial output of the research clarification stage. From that point on, the goals and the problem definitions have been iteratively updated as new findings found on literature and at the case company. Similarly, keywords for the literature review also updated as new findings has been found.

Descriptive study I has been started as literature review. Due to insufficient literature on lean disturbance management, and to understand the case company deeper, a new study has been carried out by the PhD student.

In terms of prescriptive study, various supports exist, however, the case company is not using them. Furthermore, testing an existing support would have added a new variable; i.e., if one-size-fits all software work in the current settings. Therefore, a support has been developed by the research group, where the PhD student has contributed.

In terms of descriptive study II, after the support has been deployed to the case company, 3 years of data has been collected and analysed. In addition, improvement suggestions were given. Table 2 summarizes the DRM stages followed, which study depth each stage is carried out and by whom.

Table 2. Study depth of each DRM stage

DRM Stage	Study Depth	Carried out by
Research clarification	Review based	Research group
Descriptive Study I	Comprehensive	PhD student
Prescriptive Study	Comprehensive	Research group
Descriptive Study II	Comprehensive	PhD student

2.2.3 Studies

In total four studies have been carried out. The details about each study are given below and summarized as a sequence diagram in Figure 7. Bryman (2016) states that: "… reading the literature is not something that you should stop doing once you begin designing your research. You should continue your search for and reading of relevant literature more or less throughout your research." Consequently, literature review exists in each study; therefore, it won't be mentioned additionally for each study. The reason literature review being prevalent through all studies is that it was simply not possible read all papers related to the topic at once. In addition, as more literature has been reviewed, other related keywords have been found, which then enabled finding new literature.

Study 1 - Hybrid disturbance management

Study-1 focuses on gathering requirements, development, and testing of hybrid disturbance management support. To gather requirements for the support to be developed, it was necessary to understand how the disturbance management meetings and boards are used. 12 interviews and participant observation have been carried for that purpose. After enough information has been gathered, the hybrid disturbance management support has been developed. Lastly, this support has been tested at workshops by presenting it to three different companies and gathering their feedback. The industrial output of study-1 is the hybrid disturbance management support. The research output of study-1 is paper-A.

Study 2 – Towards developing digital disturbance support

Study-2 focuses on how the case company works, how they are using physical pulse board, how the digital disturbance management support should be developed and consequently developing and deploying the digital pulse board. 17 interviews and participant observations have been carried out to understand how the case company works, how they are using physical disturbance management tool, and also to gather requirements for the fully digital (software based) support to be developed. After this, the support has been developed incrementally by presenting and gathering feedback during the way. Thus, the industrial output of Study-2 is the digital disturbance management support. After the support development is complete, it has been deployed to the case company. The research output of study-2 (along with study-3) is paper-B and paper-C.

Study 3 – After deploying the digital disturbance support (Short-term results)

Study-3 focuses on the short-term results of the support deployment at the case company. Problems and barriers that are detected after the introduction of the methodology tried to be mitigated. In addition, small changes were carried out on the digital tool (e.g., changing colours) based on the feedback from the company. Participant observations were continued to be carried out to objectively observe the employees using the digital support, which is important for evaluating if the deployment of the support was successful. 10 Interviews were carried out to get detailed qualitative results from individual employees regarding their personal experiences from using the support and its deployment. In order to capture the results from larger audience, interviews were supported by surveys; 27 employees answered the surveys. The research output of study-3 (along with study-2) is paper-B and paper-C.

Study 4 – Analysing the disturbance database (Long-term results)
Study-4 focuses on the long-term results of the support deployment at the case company. The main activity in this study was to download and analyse the disturbance information that has been registered to the disturbance boards by the employees over three years. The study has been concluded with an interview with a manager both to clarify data when needed and also to verify analyses results. The research output of study-1 is paper-D.

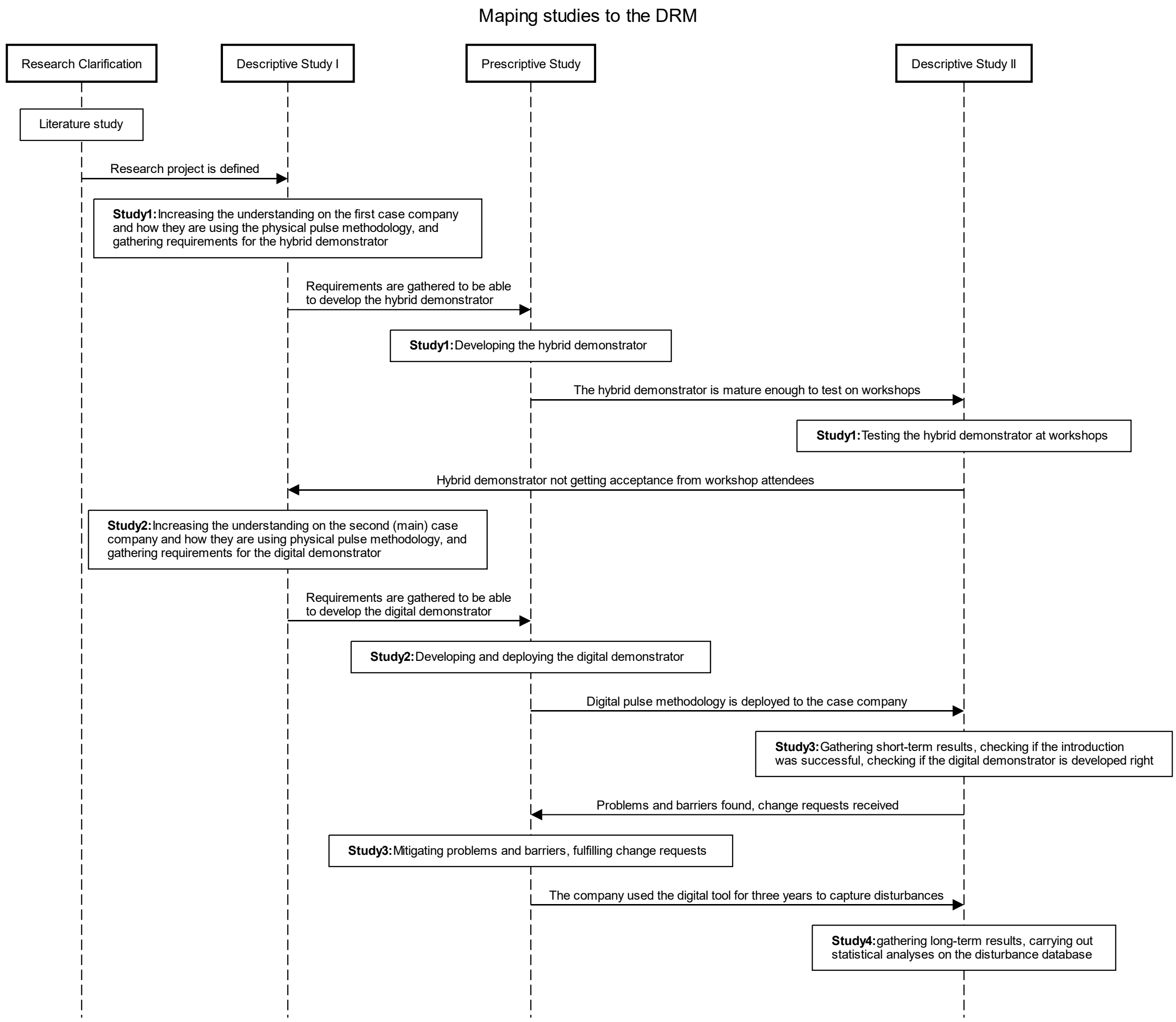

Figure 7. Sequence diagram of mapping studies to the DRM

2.2.4 Applied research methods

Table 3 summarizes the applied research methods for each study. The first column shows the applied research methods in this thesis. How these methods are used will be explained under this heading.

Table 3. Mapping applied research methods to the studies

	Study-1	Study-2	Study-3	Study-4
	Paper-A	Paper-B & Paper-C		Paper-D
Literature review	✔	✔	✔	✔
Interview	✔	✔	✔	✔
Participant observation	✔	✔	✔	
Survey			✔	
Quantitative data analysis				✔
Workshop	✔			

2.2.4.1 Writing style

The aim of this thesis is to give information in its particular subject to the readers. In order to fulfil this aim, this article was written with an easily readable and understandable language, while avoiding "classy writing" (Becker, 1986, as cited in Maxwell, 2013) and "putting tuxedo on brain" (Metzger, 1993, as cited in Maxwell, 2013).

2.2.4.2 Literature review

According to Bryman (2016), the purpose of reviewing the existing literature is to find out:

1. What is already known?
2. What are relevant areas?
3. What methods and strategies have been applied for similar research?
4. Are there any controversies or inconsistencies?
5. Are there any gaps?

Semi-structured literature review (Snyder, 2019) has been used throughout the research project. This means that, (unlike structured literature review) which keywords are used and how many articles have been found have not been registered. As more literature is reviewed, more related keywords have been found. During the literature search, the search phrase was made longer or shorter to get number of results that is possible to browse through. When the search results with many pages, the articles until the page ten have been reviewed. Typically, each page has ten results, which makes around hundred articles. The order of reviewing an article was title, abstract, conclusion, keyword search throughout the article and finally reading the whole article. These steps were followed to make the literature review process more effective by quickly eliminating the non-related articles, so that a wider range of articles can be covered. Typically, articles were reviewed digitally, which allows automatic keyword search throughout the text. Google scholar, ProQuest, Scopus and Chalmers library search engines have been used.

2.2.4.3 Interviews

In the broad sense, interviews (or qualitative interview) can shortly be explained as "one person asking another person questions on a particular topic or issue, and the other responding" (Edwards & Holland, 2013). Interview questions in this research were created, tested and adjusted using thought experiments, and getting feedback from other researchers and pilot tests with the employees. Most of the interviews held at the company premises, and some of them were held via tele- or videoconference over Internet. Interviewees selected using purposeful selection (aka. criterion-based selection, or purposeful sampling) (Light et al, 1990; Patton, 1990; LeCompte et al., 1993, as cited in Maxwell, 2013). Since the number of the primary stakeholder managers was low, all could have been interviewed. However, the number of the non-manager (e.g., operators) primary stakeholders was too high to have interview with all. Therefore, they have been interviewed until reaching the theoretical saturation, which is defined as the time "when addition analysis no longer contributes to discovering anything new about a category" (Strauss, 1987). 27 Interviews were held in a semi-structured fashion using an interview guide, and the audio was recorded using a laptop. Voice (or loud) side-notes were taken (this is a method and term coined by the author of the thesis. Please refer to the paper D for more detail). As suggested in Maxell (2013), interviews analysed by first transcribing them, taking notes/memos while listening and reading the interview material, then putting them into categories that were decided with iterative steps.

2.2.4.4 Participant observation

Musante (2015) defines participant observation as "… a method in which a researcher takes part in the daily activities, rituals, interactions, and events of a group of people as one of the means of learning both the explicit and tacit aspects of their life routines and culture." In addition to learning the current status of the case company, the change over time was needed to be observed. Therefore, a longitudinal design (Bell et al., 2022) on the participant observation was used. Long-term participant observation not only helped collecting data based on observations but also creating rapport with the employees. Two of the co-authors, who carried out the long-term participant observations, were full time employees at two of the case companies. The author of the thesis had a key card that helped him to get inside the company anytime he wants, and also had own desk where he can sit whole day and work. These two facilitated the participant observation activities by eliminating the need to arrange observation sessions with the company; the author could just go and carry out observations at will.

2.2.4.5 Survey

Survey is a method of gathering information from a sample of individuals (Scheuren, 2004). Creswell (2014) states that "survey research provides a quantitative or numeric description of trends, attitudes or opinions of a population by studying a sample of that population" The surveys used in this research were developed using free online program called Google Form, which is a part of Google Docs bundle. The surveys were comprised of both qualitative and quantitative questions. Quantitative questions also had built-in qualitative continuation questions (e.g., "why?") with a free textbox answer space, so that the respondents could also elaborate on their answers. The questions were shown to other researchers and employees in the companies to get feedback on the questions and update them if necessary. Depending on the respondents, the surveys were developed either in English or in Swedish. Surveys that were developed in Swedish were also checked by a native speaker regarding its language.

2.2.4.6 Quantitative data analysis

The data were transferred from the case company database to an Excel file to be analysed. The analyses were performed using the pivot tables in Excel. Before starting the analysis, a missing value analysis was undertaken and missing datasets were removed. We were mainly looking for trends in the data; therefore, analyses were conducted over a period of time. In addition, we were looking for any unexpected and interesting findings by using manual investigations of free text fields and automatic classifications of the associated metadata.

2.2.4.7 Workshop

The demonstrators were presented during the workshops, typically over a use-case. The demonstration was led by the PhD student. The demonstrators were used both by the PhD student and the case company employees. The use-cases were simulated as close to the real scenario.

2.2.5 Validity approach

Maxwell (2013) explains validity as follows, “the correctness or credibility of a description, conclusion, explanation, interpretation, or other sort of account”. He mentions the following two main sources of validity threats in qualitative studies: bias (aka. subjectivity) and reactivity, i.e. effect of the researcher on the individuals and settings studied. Both regarding bias and reactivity (Hammersley & Atkinson, 1995, as cited in Maxwell, 2013) it is impossible to eliminate the variance of the researcher, i.e. researcher’s beliefs, theories, viewpoints, and influences. Instead in qualitative research researchers should make these transparent while avoiding any negative effects (e.g., asking leading questions in interviews). Maxwell gives the following validity test checklist to find validity threats, and if there is any then make them implausible.

Intensive long-term involvement:
This strategy helps increasing the validity by two aspects: long-term involvement and intensive involvement. These give the researchers more chance to test, compare and verify their data, ideas, hypotheses and conclusions.

Rich data
Long-term involvement and intensive interviews are the enablers of the detailed and varied data (i.e., rich data) that gives a picture of what is going on (Becker, 1970, as cited in Maxwell, 2013). In order to make interview data rich, it is necessary to transcribe the interviews. In order to make observation data rich, it is necessary to record and transcribe the observed event (Emerson et al., 1995, as cited in Maxwell, 2013).

Respondent validation
This means systematically requesting feedback from the respondents (e.g., interviewees) about the gathered data and conclusions to validate them by eliminating the possibility of misinterpretations and misunderstandings. However, the respondents’ feedback is not necessarily more valid than the primary data, therefore both should be taken into account.

Intervention
Intervention refers to the aforementioned reactivity. As previously mentioned, instead of eliminating them, which is not possible, the interventions should be made transparent for the reader.

Searching for discrepant evidence and negative cases
Discrepant and negative data should not be just disregarded. Instead, they should be examined together with the supporting data and cases to evaluate whether the conclusions should be adjusted or not. Asking for feedback from others, or letting the readers to decide (Wolcott, 1990, as cited in Maxwell, 2013) are the methods that can be used.

Triangulation
Triangulation means gathering data from varied sources using varied methods thus eliminate the bias that can cause by gathering data using single method or single (individual or group of) source.

Using quasi-statistical data
Instead of using descriptive adjectives (e.g., rare, common etc.), quasi-statistical data (Becker, 1970, as cited in Maxwell, 2013) should be used objectively by making it transparent to the reader (e.g., how many discrepant or supporting instances are there).

Comparison

Comparison is important in order to strengthen the conclusion that it is the presumed cause that led to the current situation in the studied settings. This can be achieved by:

1. reviewing the literature about the settings studied
2. carrying out detailed interviews where interviewees point out and support the aforementioned conclusions
3. bringing forth the experience and knowledge of the individuals about the other settings or the same settings but at an earlier time
4. multi-case or multi-site studies.

2.2.6 Validation and verification approach

Two methods have been used for validation and verification of the results: (1) validation square (Pedersen et al., 2000), and (2) verification by acceptance (Buur, 1990).

2.2.6.1 Validation square

Typically, the validation of engineering research is based on mathematical modelling. However, this type of validation is problematic for engineering research areas that rely on subjective statements. Validation square, as given in Figure 8, (Pedersen et al. 2000) is a tool used to validate such engineering research. It aims to evaluate if correct solutions are given correctly based on qualitative (left side of the validation square) and quantitative (right side of the validation square) measures by six questions divided into each of the four parts of the square. The purpose of going through the four squares of validation square with six questions is to present "circumstantial evidence to facilitate a leap of faith, i.e., to produce belief in a general usefulness of the method with respect to an articulated purpose" (Pedersen et al. 2000).

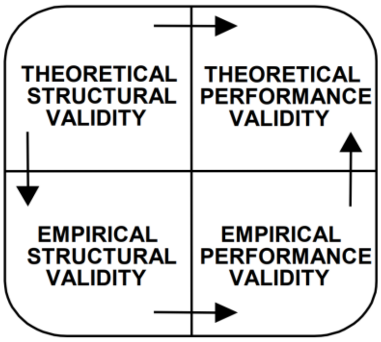

Figure 8. Validation square (Pedersen et al. 2000).

Theoretical structural validity:

1) *Accepting the construct's validity:* Questions the confidence in the constructs used. It checks if the constructs are based on the literature.
2) *Accepting the methods consistency:* Questions the confidence in the way the constructs are put together. It checks if the information flow is openly presented (i.e., which input created which output).

Empirical structural validity:

3) *Accepting the example problems:* Questions the confidence in the example problems (i.e. the case). It checks if the example problems are appropriate to verify the performance of the solutions.

Empirical performance validity:

4) *Performance of the solutions with respect to the example problems:* Questions the confidence in the usefulness of the solutions. It checks if the solutions are tested on representative example problems and the degree that the articulated purpose (e.g., industrial, scientific) is reached.
5) *Accepting that usefulness is linked to applying the solution:* Questions the confidence in that the resulting usefulness is linked to the applied solution. It checks if there are multiple variables that can affect the result, if these variables are tested individually, and if their performance is quantitatively compared to each other and existing other solutions.

Theoretical performance validity:

6) Accepting that the usefulness of the solution is beyond the example problems (case studies): Questions the confidence in generality. It checks if the previous five questions are answered positively, and the existence of further inductions from that point.

2.2.6.2 Verification by acceptance

It is almost impossible to empirically verify theoretical results of engineering design. Since it is stochastic, applying a solution that was successful at a case company to another case raises the probability of success (compared to solutions that are not tested at real settings), but does not guarantee it. In addition, it is impossible to precisely repeat and experiment, since the influencing factors are extremely large. One of the methods Buur (1990) suggests using for such research is verification by acceptance.

Verification by acceptance is based on checking if the proposed solution is accepted and adopted by experienced practitioners. It can be done by presenting, demonstrating, implementing solutions in real settings, and getting opinions of representatives from industry and other researchers.

Similar to the validation square, verification by acceptance does not give the absolute truth, but rather increases the trustworthiness of the research (present "circumstantial evidence to facilitate a leap of faith). The willingness of an expert from industry to accept a prescribed method/solution depends on many variables: current needs, knowledge and experience of the industry representative, complexity of the proposed method/solution, and the (pedagogic) way it is presented.

3 Frame of Reference

This thesis focused on identifying the problems of wall-based lean disturbance management and to mitigate those problems by introducing and evaluating digital lean tools. The case company uses pulse methodology for disturbance management. Thus, the research is framed between lean, disturbance management, and pulse methodology. These constructs are not separate from each other, rather they are subsets of one and other (Figure 9). Since this thesis is carried out in product development department, the product development part of lean (compared to production) is focused.

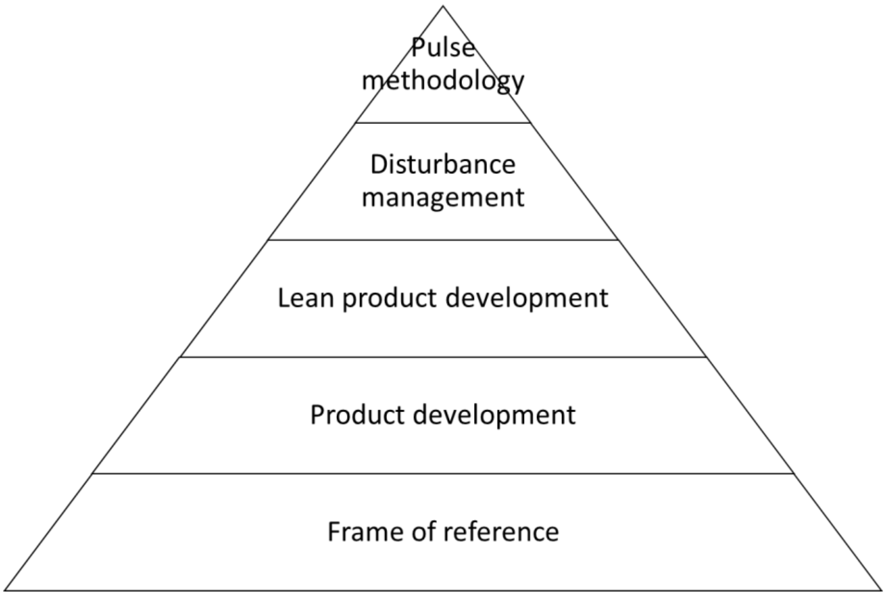

Figure 9. Framing the thesis.

3.1 Product development

Product development is the science of developing products in a structured way. The extent of combining various functional knowledge is considered to manifest the product development capability (Grant, 1996a; Kogut & Zander, 1992). In addition, product cost, product quality, and time to market also shows the performance of product development (Ullman, 2003). Grant (1996b) gives the following two points to be successful in product development:

1. ability to integrate new knowledge by reconfiguring the existing one
2. having access to broad and specialized knowledge base

Hoppmann et al. (2011) also points out the importance of using the knowledge of older products in new product development.

3.1.1 Product development process

Product development process is the structured incremental steps that covers the whole span from idea (concept) to commercialization (market readiness); it starts with a market opportunity/need, and ends with producing/manufacturing, selling and delivering a product (Ulrich & Eppinger, 2012; Otto & Wood, 2001). Ulrich and Eppinger (2012) give the following steps for the product development process:

1. Planning
2. concept development
3. system-level design
4. detail design
5. testing and refinement
6. production ramp-up

Product development process combines divergent and convergent thinking, i.e., iteratively creating many paths and focusing one of them to develop the resulting product (Ulrich & Eppinger, 2012).

In aerospace and defence industries, typically, systems engineering is being followed as a product development methodology. The systems engineering process is typically shown as a V model as given in Figure 10. V model is an iterative process that divides the whole process into two main branches (i.e., arms of the character "V"). The process starts from the upper end of the left branch of V, going towards the bottom of the V, where task/project at hand iteratively and incrementally divided into requirement (i.e., from stakeholder requirements to component requirement). As the second step, travelling from the bottom to the upper corner of the right branch of V, these defined requirements are tested iteratively and incrementally in reverse order (i.e., from testing component requirements (i.e., components test) to testing stakeholder requirements (i.e., acceptance test)).

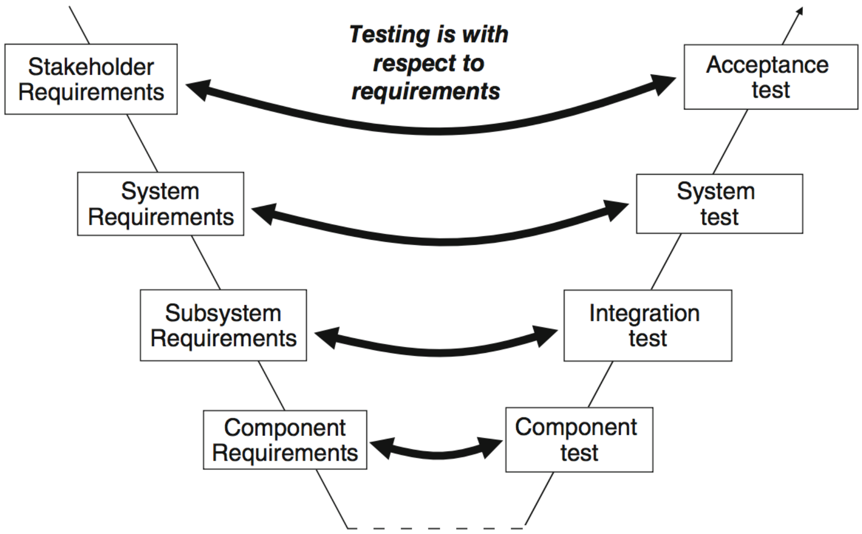

Figure 10. V-model (Dick et al., 2017).

3.1.2 Lean product development

Krafcik (1988) coined the term "Lean production". Lean product development literature starts with the lean manufacturing (or production, which in some sources used interchangeably) literature (Liker, 2004). Lean can be defined as the constant and dedicated strive for eliminating waste (Petersson et al., 2010). It cannot be "implemented"; it is an iterative process towards the state where there is no waste anymore, which is simply not possible (Petersson et al., 2010). Therefore, lean is defined as a journey, not a destination (Hibbs et al., 2009; Chakravorty et al., 2008; Schonberger, 2008).

Morgan and Liker (2006) defines the lean product development system (LPDS) using three sub parts:

1. process
2. skilled people
3. tools and technology

They define these three sub parts as follows. Processes includes each and every necessary task that is used for bringing a product from concept stage to production stage. Skilled people include all the HR activities (recruiting, training, organizational structure etc.) and company culture. These activities not necessarily should be carried out by HR departments. Tools and technology include all the hardware and software oriented tools and technologies that are used to realize a product. The two important points, which are closely connected with this thesis, in tools and technology sub part are:

1. "Adapt technology to fit your people and process", not the other way around.
2. "Align your organization through simple, visual communication"

3.1.2.1 Lean Thinking

Lean thinking consists of five principles (Womack & Jones, 2003):

1. specify value for the customer
2. identify the entire value stream
3. make the value-creating actions flow
4. create a pull system
5. strive for perfection

In order to better explain lean thinking, two examples from real stories presented in the following paragraphs. The first example compares the Toyota way to lean thinking, and the second example compares the prevailing professional life thinking to lean thinking.

Gritton (2008) shares his experience, which constitutes a good example of lean thinking vs. The Toyota way, during the start phase of the first Toyota plant in America that is wholly owned by Toyota. He says that they could just copy everything from the Japanese plant. The Toyota way was created based on the way of working of the Japanese plant. Copying the way of working of the Japanese plant to the new plant could mean employing the Toyota way also in the new plant. However, their Japanese trainers neither want them to copy nor taught them how to copy. Instead the trainers taught them how to think and act (learn, adapt, and improve) in the Toyota way, which is called lean thinking.

The second example is from Liker and Hoseus (2008). The typical way of thinking is that presenting detailed information impresses bosses. Thus, before the visit of a high executive from Japan, Hoseus and his team prepared big information boards with all the information on them. However, the Japanese executive's response to the information boards was "no good!", because they were too complicated. Instead, the executive said, they should be simple and clear that anyone who walks up there can understand the presented information. The value the information boards are supposed to bring to the company is conveying information. Making it complicated hinders conveying the information, thus stops the flow of the value. Hoseus summarizes the learning point of this example as follows: “I remember thinking that this is just the opposite of what we were taught in school, especially college. I was taught to use big complicated words and keep things esoteric. Now, I was being taught to think like a kindergartner”.

3.1.2.2 Waste

Waste (Muda in Japanese), is a fundamental topic in lean, means anything that does not add value to the customer (Petersson et al., 2010). Other sources of waste are unevenness (mura in Japanese) and overburden (muri in Japanese) (Petersson et al., 2010). Focusing on muda, Taiichi Ohno defines the seven categories of waste in lean production (Morgan & Liker, 2006):

1. overproduction
2. waiting
3. conveyance
4. processing
5. inventory
6. motion
7. correction.

Many people in the lean community include an eighth category, underutilized People, to this list (Locher, 2011). Mascitelli (2007) gives ten top sources of waste in product development:

1. “Chaotic work environment – constant interruptions”
2. “Lack of available resources – resource bottlenecks”
3. “Lack of clear prioritization of projects / tasks”
4. “Poor communication across functional barriers”
5. “Poorly defined product requirements”
6. “Disruptive changes to product requirements”
7. “Lack of early consideration of manufacturability”
8. “Overdesigning, analysis paralysis, gold plating”
9. “Too many @!%&* meetings”
10. “Email overload – the “email avalanche”

There is a specific type of waste that is called knowledge waste. “Regardless of how the knowledge was lost, the cost of re-acquiring it is a type of waste” (Sedano et al., 2019). Ferguson (2007) defines it as rediscovering something that was known before. Kennedy et al. (2008) defines it as "paying to create the same knowledge or solve the same problem time after time.” Kiram and Yusof (2020) refers this creating the same knowledge as “relearning”, and defines it as “the acquisition of the same or previously acquired knowledge”. Ward & Sobek (2004) divides knowledge waste into three categories:

1. Scattered knowledge: Knowledge is scattered and employees have to waste time searching for the appropriate knowledge
2. Hand-off: Knowledge is disappeared during hand-off.
3. Wishful thinking: Making decisions without appropriate knowledge and thinking that everything will workout fine by itself

3.1.2.3 Continuous improvement (kaizen)

Unlike some practices in industry, continuous improvement in lean does not mean forming a team to carry out a particular improvement project, or having a kaizen event for a certain amount of time, incorporating changes in a burst. Instead it is a way of thinking by all the employees (comparing to a kaizen team), all the time (comparing to time limited kaizen events). (Liker & Ogden, 2011)

The aim of the improvement is to continuously and iteratively eliminate unevenness, overburden, and waste (mura, muri, and muda in Japanese) from the operations. (Petersson et al., 2010)

There are two types of kaizen: (1) maintenance, and (2) improvement kaizen. Maintenance kaizen can be explained as dealing with the unpredictable. Murphy's law says that, "if anything can go wrong, it will" (Bloch, 2003). Maintenance kaizen refers to the processes that prevent things from having the possibility of going wrong. Improvement kaizen refers to striving for perfection and improving the processes. (Liker & Ogden, 2011)

3.1.2.4 Lean communication

Since the communication is important, one can fall to the pitfall by thinking "the more communication, the better". The pitfall here is making people flood in information, which makes them miss the important information along with the non-important ones. The right way is to have selective communication, i.e. right information goes to the right people at the right time. (Morgan & Liker, 2006)

Morgan and Liker (2006) explain lean communication with the following bulletpoints:

- "If everyone is responsible, no one is responsible."
- "If everyone must understand everything, no one will understand anything very deeply."
- "If all communication is going to everyone, no one will focus on the most critical communication for their role and responsibility."

"If you inundate your people with reams of data, no one will read it."

3.1.2.5 Visualisation and visual communication in lean

Fayyad et al. (2002) defines visualization as "the graphical (as opposed to textual or verbal) communication of information (e.g., data, documents, structure)". Use of visual communication dates back very old times; Roman Empire used colour-coded banners to communicate at battlefield, seaman have used flags to communicate between ships (Mascitelli, 2011). Visualization is the 7th lean management principle in Liker (2011), and it also fits well with various other lean themes (e.g., speed, improvement, involvement, team working, standardization, responsiveness) (Bicheno, 2004; Mascitelli, 2007).

In order to visually communicate effectively, standard state, up-to-date current state, and the gap between the two, which can be stressed using colours (e.g., traffic signals like red, yellow, green), should be present (Liker & Hoseus, 2008). Interaction is also an important point for visualization, which can be defined as "a fundamental component of visualisation that permits user-specified modifications to visualisation parameters" (Fayyad et al., 2002)

Mascitelli (2011) states that it is the best place to begin the lean transformation. Lean companies use visual controls in order to quickly react to changes and enhance the available information (Jackson & Jones, 1996). Some of the examples to this can be given as follows. Visualizing takt time in real time using an electronic board gives employees the possibility to track their performance continuously, compared to checking it with each takt (Petersson et al., 2010). Using visualization together with 5S, standards and deviations from these standards can be identified (Liker & Hoseus, 2008) (e.g., shadow boards (Ortiz, 2006)). Another example can be the use of andon lights, which Liker (2011) defines as "a visual control device in a production area that alerts workers to defects, equipment abnormalities, or other problems using signals such as lights, audible alarms, etc.". Andon lights are used at the workstations, they flash if the workstation cannot reach its planned production quota or cannot keep up with its planned takt time (Summers, 2011). Similarly, tower lights use traffic coloured lights (red, yellow, green) to indicate the status of the workstations (Ortiz, 2006).

3.1.2.5.1 Visual information boards

Visual information boards can be explained with the following keywords: (1) boundary objects, (2) information radiators. Even though the topic of boundary objects dates back to 1989 (Star & Griesemer, 1989), Lindlöf (2014) gives an explanation that is particularly useful for the topic of this thesis. He explains boundary objects as, "… often physical artefacts that mediate communication between individuals or groups of individuals with different perceptions of the topic or content that is communicated". Cockburn (2007) explains information radiators as follows, "An information radiator displays information in a place where by-passers can see it … the information simply hits them as they pass". He states that information radiators should have the following two characteristics: (1) the information on the board should always be up-to-date, (2) the board should be big enough so that by-passers can receive the information with almost no effort. Regarding the residing space for the information radiators, he adds that, the best place is the hallways, not the websites. The reason being that, provided that the hallway that the information radiator is situated is a must-pass route (such as the main and only corridor of an office), people are most likely to see the board while passing by the hallway, comparing to going to a website to find the information, which most of the people will not "afford" unless they really have to.

Visual information boards bring the information, which was locked in managers' offices, to the whole company (Jackson & Jones, 1996). For example, a visual project board brings the information about the status and progress of the projects to the whole company (Mascitelli, 2011); it is highly probable that previously this information has been residing (if not locked) at the project managers' office. Mascitelli (2011) says that they should be situated close to the team, where the managers can see it. Lindlof and Soderberg (2011) add that, if the board is situated close to the team, they can interact with it easier. Being intuitively understandable (Mascitelli, 2011), and providing just-in-time information (right information, at right form, to right people) (Jackson & Jones, 1996) are important points for the visual information boards.

3.1.2.5.2 Obeya

Toyota introduced the obeya (Japanese word for large/big room; also written as oobeya) concept in the early nineties to create effective collaboration in lean management meetings by providing an environment (i.e. obeya room), supported by visualization tools, where previous barriers between the organizational silos are broken down (Terenghi et al., 2014). Aasland and Blankenburg (2012) identify 7 types of obeyas:

1. war room
2. work room
3. meeting room
4. discovery room

5. sharing room
6. workflow room
7. management room

Terenghi et al. (2014) gives an example of virtual obeya and shares the details about their early prototype, which replaces physical A3 papers with digital ones using number of widgets.

The following visual support tools are used in obeya rooms: A3s, graphs, charts (e.g., burndown chart), boards that visualize the progress against the plan etc. Members of the cross-functional team have daily stand-up meeting in the obeya room to discuss the status (i.e., issues and challenges) of the project. Obeya makes the information accessible, thus increases the speed of the PDCA cycle. (Bell & Orzen, 2011)

3.2 Disturbance management

To be able to measure something, it must be defined first (Tsang et al., 1999; De Smet et al., 1997). Similarly, to measure (register) disturbances, it is only logical to define the concept of disturbance first (De Smet et al., 1997). People intuitively have a good idea of what constitutes a disturbance (De Smet et al., 1997). Determining and having a common understanding of what are considered as disturbances is a prerequisite and is essential for handling them (Bokrantz et al., 2016). Same thing applies for using an automated disturbance registration system; a model that precisely define what is disturbance and how they are measured must be defined first (De Smet et al., 1997).

The bottom line is that disturbances are conditions that deviate from desirable/normal, and should be measured as such (Bokrantz et al., 2016). It involves both human and technical operation in automated production system (Toulouse, 2002). Some of the definitions in literature are as follows. According to Antonio & Laura (2012), disturbances are events that are (1) undesirable, (2) unexpected, and (3) observable. Toulouse (2002) also stresses on the observability of disturbances and operators' role in detecting disturbances as follows: "disturbances are noticed through indications of machine malfunction or by defects on the product that are more or less visible and detectable by the operators". Kuivanen (1996) also puts the responsibility on operators: "the invisible ones stay undetected only due to the action of the operators." "A disturbance is an unplanned or undesirable state or function of the system" (Kuivanen, 1996). "A disturbance is a change occurring internally or externally to a production system, which can affect its operational performance, and is either outside its control or has not been planned by the system"; thus, both unpredictable, predictable, and even previously known events are under disturbance umbrella (Matson & McFarlane, 1999). "A disturbance corresponds to a variation in the state or function of the system that requires operator intervention to avoid production shutdowns, material damage, defects in quality, or to return the automated production system to its operating state following an unanticipated shutdown or the appearance of defects in the product" (Toulouse, 2002). "Disturbance can be defined as an unexpected and unplanned event, which causes the deviation between planned MPS and real production flow (production sequence) within the production system" (Golinska et al., 2011) (MPS: Master Production Schedule). "An undesirable or unplanned event that causes the deviation of system performance in such a way that it incurs a loss" (Islam & Tedford, 2012).

As seen from the previous paragraph, there is no agreement on a common definition for disturbance in literature. Golinska et al., (2011) does not count planned events as disturbance. According to Matson & McFarlane (1999), positive changes/deviations are also considered as disturbances. This approach is more similar to the concept of risk in project management.

They state that, "The potential effects could be positive or negative. If negative, then a response may be needed to guard against or reduce the effects. If positive, then a response may be appropriate to maximise the benefit". The main points that differ are including or excluding:

1. external disturbances
2. planned events
3. positive deviations from the planned/expected (i.e., disturbances with positive effects)
4. being expected or not

Regarding the second point, a survey study on 151 companies (80 of them in 2001 and 71 of them in 2014) shows that planned events are neither classified as disturbances nor registered to the same extent as unplanned events (Bokrantz et al., 2016). Furthermore, De Smet et al. (1997) shows that the precise definition of disturbances changes according to the context.

Disturbances should be identified as quickly as possible to avoid changes in planned schedule (Golinska et al., 2011). Typically, major disturbances are easily detected and tackled. Minor disturbances, on the other hand, are harder to detect, and companies often ignore them thinking they are insignificant or that their return-on-investment (spending time to solve them vs. continuing doing the regular task) is too low. When undetected, disturbances can lead to degraded material, and eventually product quality problems (Legat et al., 2013). According to Kuivanen (1996), minor disturbances comprise the largest portion of all disturbances in flexible manufacturing systems, and these less noticeable disturbances are as important as major ones. In terms of reducing and eliminating disturbances De Smet et al. (1997) states that "often the 80/20 rule applies here: the cheapest 20 per cent of possible measures lead to 80 per cent of the improvement." Islam & Tedford (2012) states that, "by monitoring even small problems and analyzing their underlying causes, it might be possible to discover causes for more serious problems and the existence of hazards. Therefore, no disturbance should be overlooked or should be allowed to happen again."

3.2.1 Effects of disturbances

Disturbances lowers the production performance (Ylipää, 2000). They degrade business environment and business performance (Islam & Tedford, 2012), and put organizations at risk in terms of financial, safety and production (Islam 2008). In order to lower the production losses and have a more reliable production, eliminating and preventing disturbances are important (Ericsson, 1997; Ingemansson, 2004). They can cause blocking and idleness (Ingemansson & Bolmsjö, 2004), decrease productivity, increase product cost, reduce profitability (Alsyouf, 2007), reduce production rate, increase defective products, cause unplanned rework and unexpected downtime, delay delivery to market (Islam & Tedford, 2012), and worst of all cause safety and environmental problems (Alsyouf, 2007), accidents and even human loss (Backström & Döös, 1995; Backström & Harm-Ringdhal, 1984; Faverge, 1970; Islam et al. 2006; Islam 2008; Järvinen & Karwowski, 1995; Kuivanen, 1990; Mattila & Kivinity, 1993). If not carefully treated, they may lead to internal/external customer dissatisfaction (Islam 2008), destroying the company image (Alsyouf, 2007), losing market share, and even eventually putting organization out of business (Islam & Tedford, 2012).

3.2.2 Preventing and eliminating disturbances

Preventing and eliminating disturbances are difficult but necessary (Bellgran & Aresu, 2003). Disturbances in both high and low volume production should be handled (Bellgran & Aresu, 2003). Both minor and major disturbances should be handled (Islam & Tedford, 2012). Some of the suggestions in literature for preventing disturbances are as follows. Developing a reliable database and applying statistical techniques (Islam et al., 2008), proper tool management (Monostori et al., 1998), (preventive) maintenance (Toulouse, 2002; Katila 2000), concurrent engineering, forward thinking, using management tools (e.g., risk analysis), focusing on, and having experience and know-how on both product and production system design (Bellgran & Aresu, 2003).

"Disturbance elimination consists of all the measures taken to restore the system to a planned or desirable state" (Kuivanen, 1996). Some of the suggestions in literature for eliminating disturbances are as follows. Information and communication procedures, use of methods and tools, applied working methods, experience, competence, continuous improvement, organizational integration of production and maintenance (Bellgran & Aresu, 2003). Outsourcing the production can be seen as a way of eliminating disturbances; however, even then it is not possible to hand over all disturbances to the supplier (e.g., disturbances may occur during installation at the outsourcing company) (Bellgran & Aresu, 2003).

3.2.3 Classification of disturbances

The aim with classifying disturbances is to, through detailed analysis,

1. reveal major opportunity areas
2. help organizations to be able to prioritize disturbances
3. benchmark similar areas internally and externally

The classification should be done with enough detail so that it is possible to prioritize disturbances. Categories such as "other" or "miscellaneous" should not be used; all disturbances should have and be registered to their particular category. Nevertheless, having too detailed disturbance categories can be problematic as well that the information becomes overwhelming. For example, appropriate detail level for large processes is to have a disturbance category for each key step. (Hansen, 2002)

Based on Lis (1982) for sources and Patig (2001) for effects, Golinska et al. (2011) classifies disturbances as follows:

- Sources:
    1. production resources (e.g., employee absence, breakout of tooling and machines)
    2. production systems' inputs (e.g., material and energy shortage, financial factors, lacking data or information, invalid external services).
- Effects:
    1. production control goal (e.g., changes in customers' order due dates or demand)
    2. production capacity (e.g., limited availability of workforce, machines and tooling)
    3. input (e.g., shortage of raw materials)
    4. information flow (e.g., inappropriate data/information, invalid maintenance/lead-time/inventory data, outdated bill of material).

Islam & Tedford (2012) classified the disturbances in the SMEs they studied as follows:

- Internal:
    1. absenteeism
    2. auxiliary equipment failure
    3. machine malfunction
    4. machine breakdown
    5. material shortage
    6. material handling problem
    7. unexpected defective products

8. unexpectedly high work in progress
9. spare parts shortage
10. unexpected system failure
11. unexpected accidents and/or injuries
12. malfunction of measuring equipment
13. unexpected major hazards
14. tool shortage

- External:
    1. skilled labor shortage
    2. demand fluctuation
    3. competition
    4. delayed supply by regular supplier
    5. government regulatory obstacles
    6. financial obstacles

Islam et al. (2008) suggests recording the following entities:

1. downtime
2. root causes
3. affected areas

in terms of root causes, they suggest the following categories:

1. design fault
2. technological fault
3. operator fault
4. managerial fault
5. supervisory fault
6. quality control fault
7. instrumentation fault
8. machine fault
9. organizational fault
10. external fault.

Tajiri & Gotoh (1992) (as given in Bamber et al. (2003)) classifies disturbances as follows:

- Chronic: Small disturbances that occur repeatedly, and as a result incur large cost. They are difficult to identify and prone to NoD.
- Sporadic: Irregularly occurring large deviations from the normal state. Easier to identify compering chronic disturbances.

Bokrantz et al. (2016) derived the following 21 disturbance factors from Harlin (2000): 1) equipment failure, (2) human error, (3) Failure of peripheral, e.g., external transport system, (4) Failure of software in production equipment, (5) reprogramming, (6) planning error, (7) tool change, (8) Time for changing/refilling of material, (9) set-up/resetting, (10)adjustment, (11) preventive maintenance, (12) cleaning, (13) work meeting, (14) pauses or breaks, (15) Waiting time for incoming product/material, (16) Subsequent stop in output flow from station/machine, (17) shortage of staff, (18) media error, (19) speed loss, (20) Scrap or quality problems of the product, (21) Incidents/near misses

Golinska et al. (2011) gives the following classification for typical disturbances in an automobile plant:

- Material shortage:
    1. delays in external supplies

    2. delays in internal supplies
- Breakdowns:
    1. Machines
    2. information systems
    3. electricity systems
- Reworks:
    1. poor product quality
    2. changes in design
- Non-standard production:
    1. non-standard design
    2. non-standard materials requirements
    3. non-standard delivery times

Bellgran & Aresu (2003) groups the disturbances as follows for a RoRo ship product development and production company. The first grouping is based in the lifecycle phase:

1. basic design
2. design
3. production and installation

The second grouping they give is based on reason:

1. internal
2. changes from ship-owner/yard
3. changes from classification societies
4. changes from suppliers
5. supplier delay.

Disturbances can be classified in terms of consequences as well. It can be qualitative or quantitative. An example to quantitative classification in financial terms is as follows(X is decided by company top management):

1. catastrophic (e.g., ≥ 10$X)
2. critical (e.g., $X to 10$X)
3. significant (e.g., 0.1$X to $X)
4. low significant (e.g., 0.01$X to 0.1$X)
5. insignificant (e.g., ≤ 0.01$X).

Qualitative classification can be in terms of production, safety, and business as follows: (Islam et al., 2008)

- Production
    - Perilous: “Damage to machinery or equipment, major damage occurred, these could stop the whole production/company”
    - Critical: “Particular workstation shutdown, damage to machinery and material (non-recoverable/partially recoverable), production flow partially stopped”
    - Significant: “Machine breakdown (minor damage to machinery), maintenance required, damage to material (possible to rework within control limit), nothing fails”
    - Low Significant: “No effect at present but has potential risk (e.g., slightly misaligned spindle)”
- Safety
    - Severe: “Catastrophic hazard, e.g., death, severe injuries and accidents”
    - Critical: “Critical hazard, major accidents/injuries, injury with permanent after-effects, more than five days sick leave required to recover”
    - Significant: “Consequences are minor, minor accidents/injuries, injury with short sick leave”

    - Alarming: "No immediate effect but risk exists, e.g., injury without sick leave"
- Business
    - Major: "Asset loss, resource loss (including human) market share loss, reputation loss, (decreased quality, late delivery)"
    - Significant: "Increased production cost, lower productivity, increased rework, operator replacement, increased lost time, customer (internal and external) dissatisfaction"
    - Minor or manageable: "Complying with the business strategy (e.g., recruitment of inexperienced worker could deter the production rate)"

3.2.4 Disturbances driving continuous improvement

In order to have continuous improvement in a flow it is important to design it in a way that it is easy to detect disturbances. Such flows are called disturbance driving flows. Making disturbances visible is necessary for succeeding in continuous improvement. Opposite of this is flows that hide disturbances, for example, through having unnecessarily big buffers and capacity. Such flows continue to work even in the presence of most of the minor and major disturbances. Such big safety-net is a relief under high workload, since even in the major disturbances will not affect the deliveries. However, since the disturbances cannot be detected, the flow cannot be improved. Major disturbances can still be detected; however, it would be hard to find the cause. The waste hidden in such flow affects both customers and the company. The Sea of Japan concept in lean can be used to go from a disturbance hiding flow to a disturbance driving flow. The concept is derived from the analogy of sailing on the sea; the sailing ship represents the working company, water level represents the waste (e.g., buffers) that hides disturbances, and the rocky ocean ground represents the disturbances. Continuously lowering the water level down in a controlled way would result better ability to detect disturbances. In addition, waste will be lowered (e.g., through lowering buffers) without negatively effecting neither the company nor the customers. (Petersson et al., 2015)

Continuous improvement efforts that only focus on good ideas has the risk of fading out in time. The energy to come up with the good ideas will diminish, the good ideas will become artificial, which would lead to mere changes rather than improvements. Instead, disturbances should be the base on the continuous improvement work, so that the improvement work becomes long-lasting and sustaining. This way, it is guaranteed that the limited resources reserved for improvement work are used in a place that actually needs it. (Petersson et al., 2015)

As long as a company works with standardisation, there always will be disturbances. If the number of disturbances get lower, then the system should be challenged (i.e., lowering the sea level in the Sea of Japan concept) through, for example, lowering takt time and increasing the frequency of controls. This way new disturbances will arise, which is the fuel of the continuous improvement work. (Petersson et al., 2015).

Continuous improvement work is best suited for minor disturbances. Since they are easier and quicker to solve in comparison to major ones, it is easier to keep a high tempo and more people can take part in the improvement work. Having many minor disturbances is a sign of success for continuous improvement. No improvement is too small to carry out; having very small improvements shows the maturity level of a company in terms of continuous improvement. However, many organizations work only with major disturbances. The problem with only working with major disturbances is that it normally takes long time to fix them and often require specialist competence. The risk is that the continuous improvement activities can get slow down or even totally stop. In order to keep the improvement work fun, it is important to have victories, regardless of its size, as often as possible. Since major disturbances have large impact, they also should be handled through improvement projects (e.g., Kaize, Kaikaku). It is important to work with a combination of both minor and major disturbances in order to have an effective improvement work. (Petersson et al., 2015).

3.2.5 Registering disturbances

Disturbances can be recorded by a quality system (e.g., non-conformities document) (Bellgran & Aresu, 2003), and in most of the cases it can be carried out by operators (Ljungberg, 1998). Agreeing on what factors constitute disturbance is a prerequisite for recording/measuring them (Bokrantz et al., 2016). As Van Goubergen (2010) states, "any measure is only effective if it provides actionable information. Otherwise it is just a waste of time and visualization is just wall paper." As also De Smet et al. (1997) concludes, "registration of disturbances is not an objective in its own right. Disturbances must be registered to control and to improve the primary process"; "the reason for enterprises to measure losses is to find reasons for major losses and use this information as a basis for remedies" (Ljungberg, 1998). Monitoring disturbances systematically guides continuous improvement (De Smet et al., 1997). Last but not least, collecting and analysing disturbance data can help identifying probable potential disturbances and forecasting future trends (Islam et al., 2008).

3.2.5.1 Problems in registering disturbances

Some common problems in collecting and recording disturbances in literature are as follows. Bokrantz et al. (2016) found that companies do not register all factors that they classify as disturbances. In addition, they found that, companies do not classify and/or register planned disturbances to the same extend they do with the unplanned disturbances. This leads to not measuring losses due to planned events and removes possibility of improvement.

De Smet et al. (1997) analysed the cases in (1) Bourlon and Govers (1993) and (2) Meulemans (1993). In the first case, which as De Smet et al. (1997) says certainly not unique, shows that disturbance logs were not accurate; repairmen were registering start and end times of repairing after finishing the task which was making the data inaccurate. Another problem with that case was that the failure cause, which was given by entering a free text to a comment line and choosing a failure code among fifteen predefined failure codes, was not enough descriptive. The failure codes were too general/vague, and comment line entries often were similar to "is down" or "does not work". The following two remedies were used: (1) "a more relevant and extended table of failure codes was developed per machine", and (2) "by giving feedback to the repairmen on the conclusions derived from the data they had entered, they were motivated to do it correctly." In the second case, the problem was measuring the small stoppages. Solving them was quicker than registering them. However, in total they had a large effect on performance. Blocking and starvation was making it difficult to separate effects and causes (i.e., losses cause other losses and propagates throughout the production line).

Ljungberg (1998) mentions the following problems:
(1) data collection systems do not give comprehensive and appropriate picture of losses and their reasons,
(2) foremen and operators show resistance to data collection,
(3) the procedure of filling in the disturbance registration form is not enough easy,
(4) form designer does not understand the complexity of production loses,
(5) data are not compiled and analysed, which then leads to
(6) considerably decreasing operators' motivation to register disturbances, and

(7) some disturbances are not focused enough (i.e., minor stoppages, planned downtime, and cycle time losses)

3.2.5.2 Suggestions for successful disturbance registration

Some of the suggestions in literature regarding registering disturbances are as follows. De Smet et al. (1997) mentions the importance of giving feedback: "If people know for what purposes information will be used, they are more motivated to enter data accurately." They also state that, disturbance registration should not create too much paper work. They suggest using some degree of automation of the registration process, which (1) guarantees data quality, (2) keeps the cost of the registration process at an acceptable level, and (3) supports operational control and improvement activities by fast, accurate, and flexible information. Ljungberg (1998) gives the following suggestions:
(1) data collection method should not take much time,
(2) data should be precise,
(3) foremen and operators should be convinced,
(4) data should provide the info on the extent of disturbances and their reasons,
(5) disturbance registration form should be designed together with the employees who will use them (e.g., operators), which will increase the users commitment to register disturbances,
(6) "forms should be tailor-made to suit the pattern of losses at each machine",
(7) operators should compile the forms regularly with the help of foremen and engineers,
(8) start with a simple model and develop it gradually to a comprehensive model as personnel get data collection experience,
(9) the time to register disturbances, which may take longer until personnel getting used to it, should not take more than 15 minutes per day,
(10) the action of disturbance registration itself is also a loss if done while the machine is operating, therefore should be registered as a loss,
(11) combining automated and manual disturbance data collection methods, which gives precise and detailed information about disturbances,
(12) registering also planned downtime (e.g., planned maintenance, meetings, and education) as disturbance, and finally warns against the following point
(13) "If the operator has to select a reason for stoppages before starting the machine again, the number of codes/reasons has to be limited. If not, the operator will tend to press just any code".

3.3 Pulse methodology

Golinska et al. (2011) have shown that there is a need of simple indicators for a quick scan of the production system that make it possible to identify "potential serious disturbances that negatively affect the ability to fulfil customers' orders on time". Pulse methodology is a solution for the aforementioned problem.

Pulse is a lean method (Medbo & Carlsson, 2013; Gremyr & Fouquet, 2012) for managing disturbances. It comes from Scania (a Swedish truck manufacturer) (Holmdahl, 2010; Kniberg, 2006), and it is commonly used in Sweden (Lindlöf & Trygg, 2012). It is comprised of frequent meetings called pulse meetings and disturbance visualization boards called pulse boards. Holmdahl (2010) refers the use of pulse meetings and pulse boards as multi-project-management as well.

3.3.1 Pulse meetings

Petersson et al. (2015) defines pulse meetings as structured information sharing and decision making meetings where executives and employees act on the basis of frequent and systematic information about how the activities relate to the plan and what has caused possible disturbances. Pulse meeting is a method that has spread widely at least at the concept level (Petersson et al., 2012). Pulse has become the name of short, regular and frequent meetings to report status, which is similar to daily scrum (Tonnquist, 2016). Kniberg (2007) explains a case where they call pulse meetings to 15-30 minutes long corporate level scrum-of-scrums meeting where all members of all teams of all products attend and share the status. Pulse meetings foster interaction and collaboration; this creates a common understanding of the task to be solved and a higher work pace (Bicheno et al., 2006). Pulse meetings are considered to facilitate managing time and resources, and shorten lead times (Gremyr & Fouquet, 2012), and they provide efficient information flow between involved people, teams, and departments (Hölttä et al., 2010).

Pulse meetings are reconciliation meetings. It practically means checking as often as possible how the various activities are in relation to the plan. Through the reconciliation, disturbances can be detected at an early stage. The more frequent the reconciliation, the more and smaller disturbances can be detected. This is desirable because it usually facilitates the work of solving the disturbances. In addition, it helps putting in place necessary measures against disturbances in timely manner to secure the plan. (Petersson et al., 2015)

3.3.1.1 Aim

At these meetings, status of projects is assessed with the help of visualization tools (Gremyr & Fouquet, 2012); i.e., pulse boards that are based on visualization of information and knowledge (Bicheno et al., 2006). The aim is to create a shared understanding on the goals and how to reach them (Bicheno et al., 2006). This way representatives from different functions can access project information regularly (Gremyr & Fouquet, 2012). Gingnell et al. (2012A) tried using pulse meetings in research, and their experience shows that visual support and pulse meetings support each other, and if one is missing the performance drops. Pulse boards are needed to be able to access to the information shared and the result of the topics discussed during the pulse meetings. Pulse meetings are needed continuously to assure that the pulse board is updated and followed (Kristofersson & Lindeberg, 2006).

In addition to spreading information, one of the main purposes of a pulse meeting is to make decisions so that the operations can return to their normal position as soon as possible. In order to facilitate decision making and to increase predictability, decision-making criteria can also be standardized. For example, maximum time lagging behind the planned schedule before asking for overtime work can be standardized. By standardizing decision criteria, the variation in behavior depending on the individuals present at the meeting decreases. (Petersson et al., 2012)

3.3.1.2 Frequency

Pulse meeting is a method of frequent follow-up (of e.g., business performances) and therefore has a link to the lean principle Takt (Petersson et al., 2012). In order to disseminate information and make decisions quickly, pulse meetings should preferably be held daily or at each shift, and in many contexts, pulse meetings are held daily and they are often referred as daily meeting (Petersson et al., 2012). In cases where this is not possible, pulse meetings should be held as often as practically possible (Petersson et al., 2012). The frequency of pulse meetings varies from case to case; it can be daily (Hellerqvist & Svensson, 2014), once a week (Ericsson et al., 2012; Muratov & Machado, 2015; Eibich & Hein, 2013; Ström & Gustafsson, 2013), twice a week (Ström & Gustafsson, 2013), three times a week (Monday, Wednesday, Friday) (Hall & Henriksen, 2016), every second week (Tonnquist, 2016) etc.

3.3.1.3 Length

Pulse meetings are short meetings (Gremyr & Fouquet, 2012; Petersson et al., 2012), which (1) helps making the meeting effective, (2) prevents it taking too much time from main work, and (3) is a prerequisite for being able to hold pulse meetings often (Petersson et al., 2012). Effective meetings also make participants more motivated to use their limited time to attend meetings (Petersson et al., 2012). Suitable length of a pulse meeting depends on how many organizational units will report, but a few minutes per unit may be a benchmark (Petersson et al., 2012). The length varies from case to case; it can be 30 minutes (Vainalis, 2012), one hour (Tonnquist, 2016) (Ström & Gustafsson, 2013) etc.

3.3.1.4 Scope

In order to enable short meetings, all information to be reported must be visualized before the meeting begins, and that only disturbances are discussed at the meeting. However, there are cases where pulse meetings have wider scope. In the case described by Karlsson (2011), not only disturbances but also problems with production flows, product quality, delivery precision, incidents and planned efforts are discussed. But again, an important point to consider here is the definition of the term “disturbance” for the company; i.e., what constitutes disturbances for the company.

3.3.1.5 Agenda

Pulse meetings has standardized agenda (Tonnquist, 2016). In these meetings, ongoing projects are followed-up (Ström & Gustafsson, 2013), disturbances in ongoing projects are discussed (Kristofersson & Lindeberg, 2006), and the attendees go through and plan the work of that day (Hellerqvist & Svensson, 2014). Project managers can report the status of the project in terms of time, cost and resources (Tonnquist, 2016). Having an agreed default agenda helps to make the meetings shorter (e.g., all participants know what will happen so that they are prepared when it's their turn) and makes it easy for anyone to jump in and lead the meeting when necessary (Petersson et al., 2012).

3.3.1.6 Time

The time of day that pulse meetings are carried out also needs to be standardized so that (1) participants can plan their participation in the meeting, and (2) the organization can coordinate meeting times between the different organizational levels (Petersson et al., 2012). It seems that pulse meetings are typically held on mornings (e.g., Hellerqvist & Svensson, 2014; Vainalis, 2012). Result of some pulse meetings in organizations can be input to other pulse meetings, and the order of all pulse meetings should be designed taking this into account (Petersson et al., 2012). Coordinating meeting times ensures that (1) meetings at different organizational levels do not crash, and (2) the time from the first meeting at the lowest organizational level to the last meeting held at the highest organizational level is as short as possible.

3.3.1.7 Place

The place where each pulse meeting is conducted should be as close as possible to where the work is being carried out. The reasons for this are (1) it sends signals that the place where value is created is important, (2) it will be easier to make quick follow-ups based on actual facts in the business, and (3) the time required for the participants to get to and from the meeting will be small. Top management's pulse meetings should also be kept close to where the work is being carried out, even though in many cases their offices located at a far place. It gives the top management a good opportunity to visit the business they lead. In addition, this sends good signals to the employees, i.e., top managers show interest and availability to employees. Such an easy measure as keeping a meeting near the work can help the top management to get close to the business. (Petersson et al., 2012)

3.3.1.8 Attendees

Typical attendees of managerial pulse meetings are all project managers, all line managers, and representatives from the company management (Ström & Gustafsson, 2013). At least one attendee from each project that will be discussed is expected at the meetings; ideally both the project manager and the project owner should attend the meeting (Tonnquist, 2016). To be able to take right and quick decisions in pulse meetings, it is important to have a representative from all stakeholders in pulse meetings (Petersson et al., 2012).

It is a method of making an activity's strategic goals relevant and interesting at all levels of the business. A pulse meeting is an information sharing and decision making meeting aimed at fast and efficient dissemination of information about the situation of the organization and rapid decision making. Therefore, pulse meetings should be held at all organizational levels. In some cases, geographic distances can be considered as an obstacle, but phone calls or video meetings can be a better alternative than leaving remote resources outside. However, participants gathering physically is the preferred way. (Petersson et al., 2012)

3.3.1.9 Other practicalities

At a pulse meeting, the information is reported upwards and it is therefore natural that it is lead by the manager of the respective organizational level where the meeting is being carried out. If necessary, the manager takes decisions that have an impact on the lower levels of the organization. (Petersson et al., 2012)

Conducting pulse meetings standing-up accelerates the pace. The flexibility of the group becomes bigger without fixed places to sit. Participants also experience greater transparency and trust in each other as they stand close to each other. (Bicheno et al., 2006)
The aim with pulse meeting is to create a shared understanding on the goals and how to reach them. In order to create this understanding, the development team must work with visual methods. The methods must be so simple that everyone in the team can learn them in a matter of minutes. (Bicheno et al., 2006)

3.3.2 Pulse boards

Pulse board is a board that is used to visualize/monitor an operation’s performance; the aim is to visualize information to more easily detect disturbances, and to visualize meeting minutes/logs (Petersson et al., 2015). Pulse board is considered as a lean tool (Ström & Gustafsson, 2013; Bicheno et al., 2006). The meeting room where the pulse board is situated is generally called pulse room (Ström & Gustafsson, 2013).

Pulse boards, while managing multiple projects, can be constructed in two principally different ways. One can collect project boards in a room where each project may have its own area on the wall, for example in the form of a whiteboard. Or, one can collect all projects as rows in a matrix (each project has its own line), where the columns are deliveries, different departments of the company, etc. (Holmdahl, 2010). As given in Figure 11, Ström & Gustafsson (2013) gives an example pulse board where the projects are on the vertical axis, departments assessment points and other functions are on the horizontal axis. Colour coded magnets or Post-it notes that represent the status are placed at the intersections of the horizontal and vertical axes. Colour coding pinpoint the bottlenecks (Gremyr & Fouquet, 2012). An example interpretation of the colours are as follows: red means an actual problem, yellow indicates that an actual problem may occur, and green means that there is no problem. (Ström & Gustafsson, 2013)

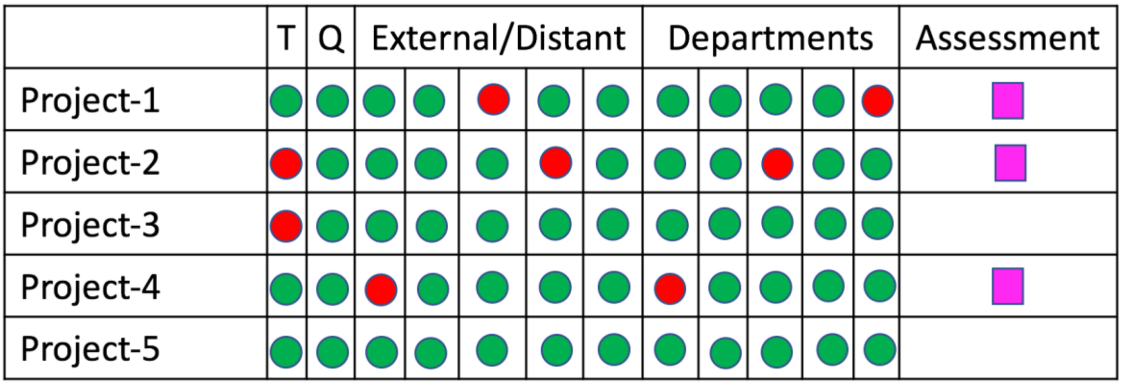

Figure 11. Example pulse board (Ström & Gustafsson, 2013).

According to Bicheno et al. (2006), as depicted in Figure 12, pulse board is a combination of different boards that show different status of the company: goals, synchronization plan, risk analysis, risk management, activity plan, problem log etc. They further describe and explain pulse board as follows. Pulse board provides visual just-in-time information to be used in knowledge work. Figure 12 Shows how pulse boards fit in a visual management system. Shortly, using policies, responsibilities, and goals, long term plans are created; from long term plans, more detailed short-term plans are created; disturbances that arise at the short-term plans are represented on the pulse boards (combination of problem board and problem log in Figure 12); the disturbances create new tasks on the short-term plan to fix the disturbances (or problems) through Kaizen events. The visualization board is also used as an Andon system, where disturbances are directly flagged to act on them. Work overload of individuals can be proactively addressed. Pulse boards visualize information about the project's goals, the current situation of the project, the problems detected, and the plans for the ongoing work. Everything can be compressed into a few pictures and matrices. The images become an aid that facilitates communication between people. Everyone has access to the same image and the same overall information, which enables everyone to contribute. (Bicheno et al., 2006)

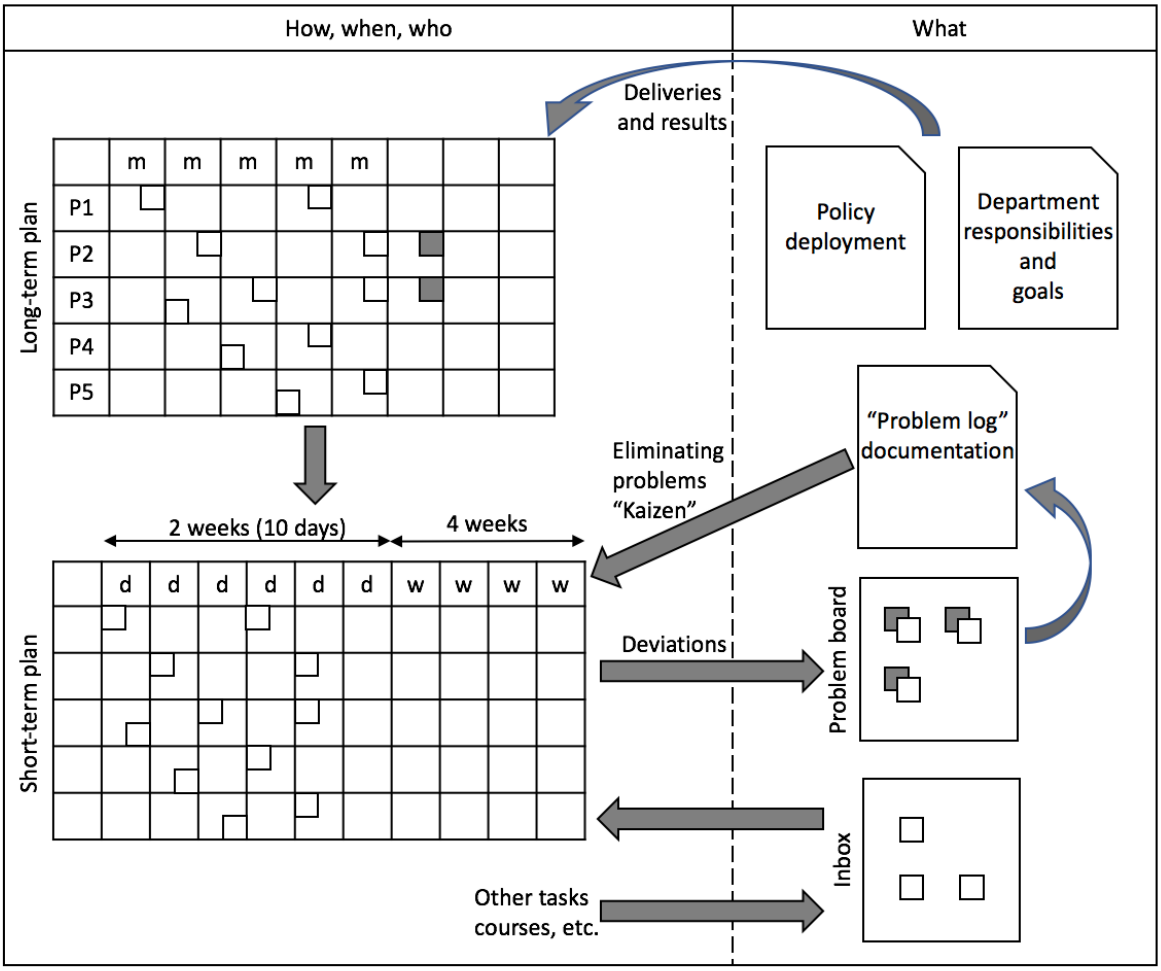

Figure 12. Role of pulse board in a visual control system (Bicheno et al., 2006).

The information to be discussed in pulse meetings should be visualized in some way; an effective visualization enables quick overview and also clarifies the disturbances (Petersson et al., 2012). Figure 13 and Figure 14 show examples of appropriate visualization in manufacturing and production, respectively. Pulse meetings (Nasrin, 2016) and pulse boards (as given in Figure 15 (Petersson et al., 2012)) can be used at healthcare, as well.

	9/2	10/2	11/2	12/2	13/2	Comments
Soft Machining	1400/1400	1349/1400				Material shortage 10/2
Hardening	600/600	600/600				
Hard Machining	200/200	220/220				
Assembly	34/76	73/73				Machine failure 9/2
Quality	64/64	62/63				Test program error 10/2
Logistics	210/210	210/210				

Figure 13. A pulse board example for manufacturing (Petersson et al., 2012).

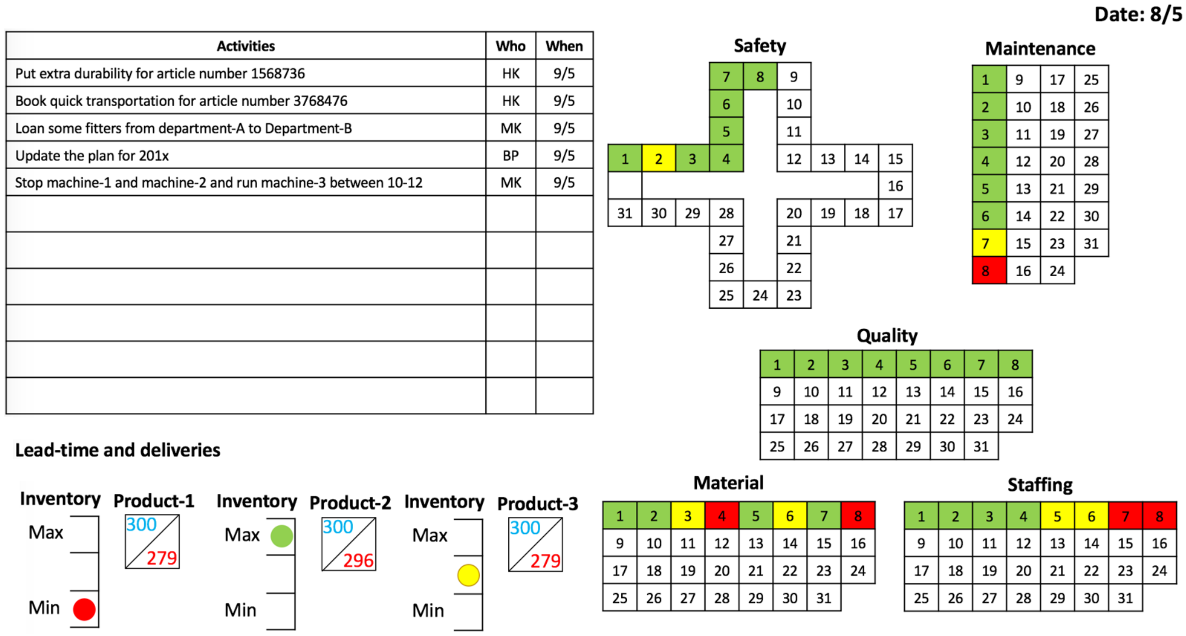

Figure 14. An example pulse board in production (Petersson et al., 2015).

15 / 5					
Patient	**Accepted**	**Care Plan**	**Coordinated Care Plan**	**Planned Leave**	**Status**
Karlsson 28 ♀	10 May	11 May	~~14 May~~ 16 May	~~16 May~~ 18 May	Worsened
Davidsson 39 ♂	10 May	12 May	15 Maj	17 May	Prepare to leave
Danielsson 32 ♀	11 May	12 May	16 May	18 May	Waiting for test result

Figure 15. A pulse board example for Healthcare (Petersson et al., 2012).

3.3.3 Use-cases

Petersson et al. (2012) states that answers to the following questions should be considered while setting up pulse methodology in an organization:

- Which organizational levels will pulse meetings cover
- What functions / positions should be represented?
- What function / position will lead the meeting?
- When will the pulse meeting be held?
- How long will the pulse meeting be?
- What default agenda should apply?
- How should meeting information be visualized?
- Where should the pulse meeting be held?
- Which target parameters should be followed up?
- What functions / positions should be responsible for producing information?
- What should be the standard criteria for decisions?

Different combinations of answers to these questions creates different cases. Cases can vary from each other in other aspects (e.g., design of pulse board) as well. The available information about cases varies. For example, the only information in literature regarding Toyota using pulse methodology is that they started using pulse meetings during the development of the Prius hybrid car, and then they introduced it to the rest of the development organization (Bicheno et al., 2006). Some other cases, of which more detailed information is available, are given below.

Case-1(Scania):
The first case is from the Swedish truck manufacturer, Scania, whom developed pulse methodology (Holmdahl, 2010; Kniberg, 2006). According to their experience, this way of visual multi-project-management lowered their resource needs over time, and that projects are completed within the intended time and budget (Holmdahl, 2010).
Scania in Södertälje carries out follow-up meetings that are called pulse meeting every Monday, where status of more than 100 project are managed in one hour. "A longer meeting once per week gives the teams a chance to step back from the daily flow of activity to think ahead about the upcoming week" (Radeka, 2013). A whole wall-size pulse board is used at the meetings. The data that populates the top management board that is used at the top management meeting come from the project teams and other subsystems; each project team and subsystems have their own boards (and rooms or walls where these boards are situated as in Figure 16) (Radeka, 2013). Columns represents projects, and color-coded magnets represents different status: (Tonnquist, 2016)

- Green: Ok, according to the plan
- Yellow: There is a disturbance in the activity, but a solution is found
- Red: There is a disturbance, and no solution is yet found, escalate and ask for help
- White: No information from project, generally not a good thing

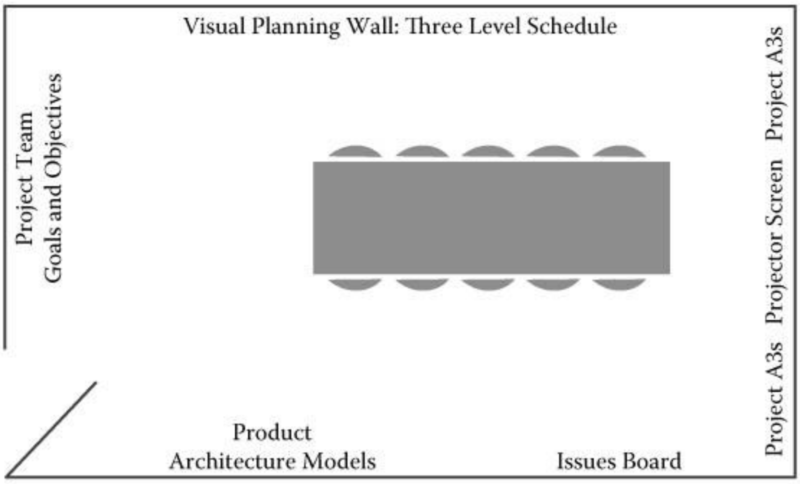

Figure 16. Illustration of an obeya room (Radeka, 2013).

In the meetings, generally the red markings are focused, but status changes are considered as equally important as statuses themselves. In terms of the company culture, the success in projects is a common concern for the entire organization, and it is important that everyone has the same picture of the company status in terms of projects. Project managers and line managers receives the same information and all information comes to surface. This creates an environment that supports better dialog. (Tonnquist, 2016)
The planning system being visual reduces the need for written reports, and improves the quality of communication within and between teams. Outside pulse meetings, one can simply

visit the room, where the board is situated, and read the board to get the updates anytime. Since all the needed project information is on the boards where the meetings are held, attendees do not need to start a laptop or retrieve a project report. (Radeka, 2013)
Pulse meetings focus on disturbances. Teams typically meet daily in front of their boards to answer the following four questions:

1. Did I do what I was supposed to do?
2. If not, why?
3. What will I do today?
4. Do I foresee any problems?

These daily meetings, as PDCA cycles, help teams (1) "rapidly learn what is truly in the way of their work so that they can get more done", and (2) "learn how to adjust their plans so that they can get more capacity from the same pool of resources" (Radeka, 2013).

Case-2:
The case described by Gremyr & Fouquet (2012) is as follows. The company starts every development project with a team meeting where the activities are mapped and the project is planned. This map states the expected deliverables and allows the team members to plan their time. After the project starts, they follow-up the progress and status of all development projects at weekly pulse meetings. The meetings last 30 minutes. They visualize the status and progress on the walls of the meeting room. They use color-coding to visualize the status and progress of all running projects. Different colours represent different project status:

1. on time
2. slightly delayed but there is a chance to catch-up
3. late

In addition, they visualize the bottlenecks of the project, which facilitates prioritization. Staffing of projects is visualized as well. This way employees that are overloaded can be identified and assignments can be re-distributed among team members. The interviewees in this case stated that pulse meetings and the visualization create opportunities for managers to gain more insight into the project work.

Case-3:
This case is given by Ström & Gustafsson (2013) as a suggestion to the case company they did research on. Figure 17 shows a board, in the upper left corner, for planning in a multi-project environment. The board shows the status of the projects. Pulse meetings are held regularly where the attendees get the status of the projects. If you want to convey the status to someone who could not attend the meeting, you can take a photo of the board with a digital camera and email the photo or place it to intranet. The quantitative indications, visual memory of the status, and the trend over time are visualized as follows. In the upper right-hand board in the figure, we see the number of red magnets (problems) at different pulse meetings over time. A column corresponds to a single pulse meeting. The more problems, the higher the stack. This way you can see if the problems increase or decrease per project or for multiple projects over time depending on how the board was designed. The lower part of the figure shows another example of visual follow-up over time. In this example, a red Post-it paper is set to indicate that there is a problem in a department in, for example, a project. When the problem is resolved, a yellow Post-it paper is attached to the right of the red to indicate how the problem was solved. This way, series of problems and solutions will be formed over time. The more problems, the longer row of Post-it papers. This series of papers provides information about the number of problems and how they were solved. (Ström & Gustafsson, 2013)

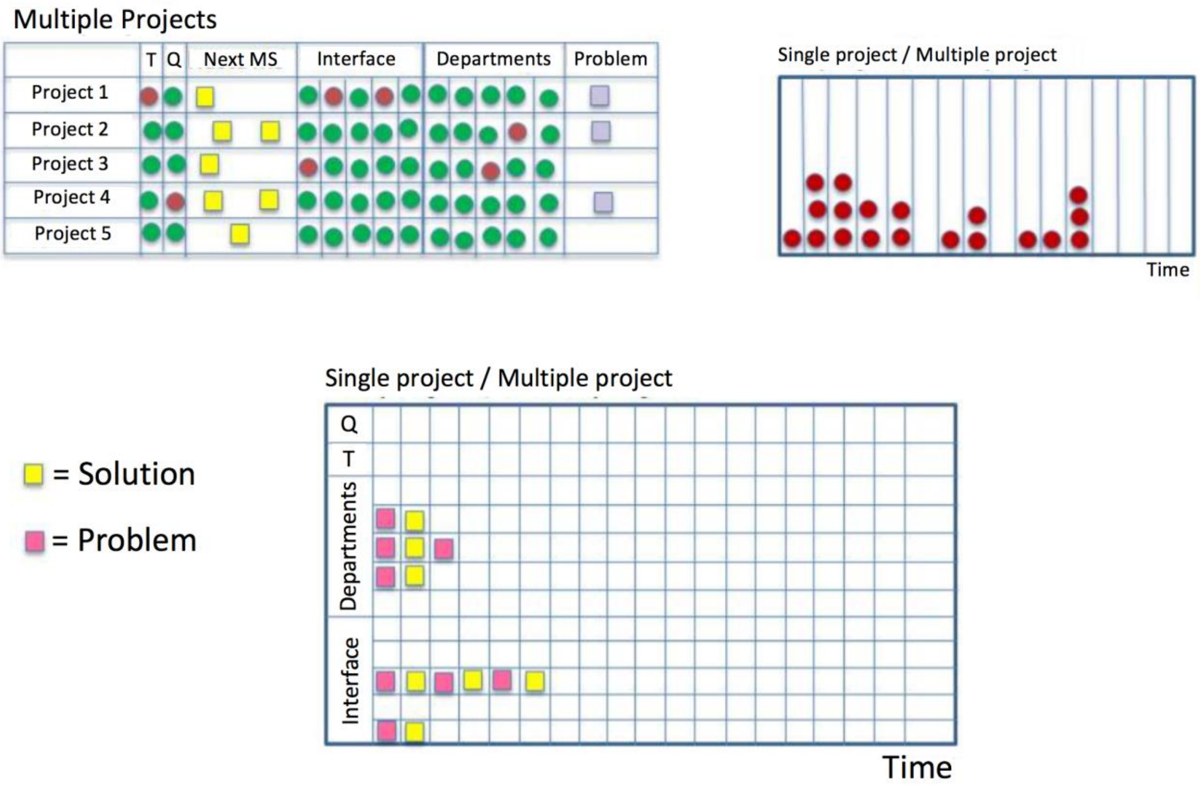

Figure 17. Examples of visual indicators for development projects (Ström & Gustafsson, 2013).

Case-4:

This case is from Mascitelli (2007). In this case, the term "exception" similar to the term disturbance. The board given in Figure 18 is used to show the status of deliverables regarding cost, schedule and performance. He gives examples of what can various disturbances can mean as follows: (Mascitelli, 2007)

- Schedule disturbances: The completion of a task is late more than a week
- Cost disturbances: A task exceeded its budget more than 10%
- Performance disturbances: Not fulfilling a critical product specification

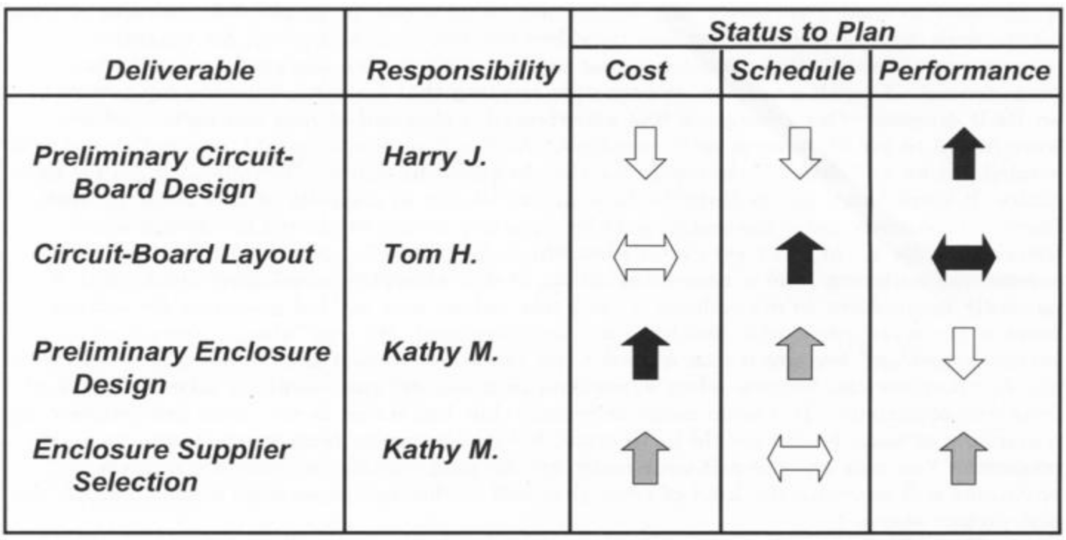

Figure 18. An example of a Stoplight status chart (Mascitelli, 2007).

If the status of a disturbance is red, then additional details and a get-well plan is required to be provided from the responsible employee. No additional action is required from the responsible people of green disturbances. In terms of the yellow status, Mascitelli noticed that employees used it only when the status is very close to being red, and until then they only used green. In order to solve this problem, they begin to use yellow as a transient status. A disturbance is let to stay yellow only for one reporting period; by the next meeting it should either go green or red. Based on this experience, he states that “The actual exception thresholds that you use are up to you, but providing well-defined definitions is critical to finessing the subjective side of status reporting”. They use also arrows in addition to colors on the boards visualizing the trend of the progress: (Mascitelli, 2007)

- Downward arrow: It is estimated that the situation will get worse over the short term
- Upward arrow: It is estimated that the situation will get better
- Sideways arrow: It is estimated that the status will not change until the next meeting

3.4 Summary

Under this heading, frame of reference chapter is summarized with a numbered list (to be able to cross-reference while mentioning the gaps in the literature).

1. Eliminating waste is a lean concept and eliminating knowledge waste is a sub part of it.
2. If the generated knowledge is not captured (so it can be re-used), the same knowledge should be generated again when needed; this is called knowledge waste.
3. Continuous improvement through eliminating waste is described as a never-ending journey in lean; thus, eliminating knowledge waste never finishes but continuously improves.
4. Tools and technology are an important part of lean.
5. Being able to detect disturbances is important for being able to improve.
6. Big buffers create safety nets, but they also prevent detecting disturbances and thus improvement.
7. It is crucial for successful continuous improvement to detect, work with and solve both minor and major disturbances.
8. To be able to detect and register disturbances, first what constitutes a disturbance for that organization should be defined, otherwise, disturbances cannot be captured; it is not possible to capture without knowing what to capture.
9. Operators registering disturbances to a registration system allows controlling and improving process. Some examples to these improvements are: (1) detecting major losses and finding their reason and eventually improving the situation by finding remedies, (2) identifying probable potential disturbances and forecasting future trends. Thus, disturbances guide continuous improvement.
10. In literature, disturbances are typically defined as unwanted changes in the system that affects the system negatively.
11. Negative outcomes of disturbances include low productivity, defective products, rework, blocking, idleness, downtime, longer lead-time, safety and environmental problems, accidents, internal/external customer dissatisfaction that leads to bad company image, and eventually losing market share, and even putting out of business.
12. Applying statistical techniques on a reliable database to prevent disturbances has been proposed in literature. Other actions for preventing disturbances include proper tool management, maintenance, concurrent engineering, forward thinking, using management tools, and increasing know-how in the respective field of product development and production.

13. Classifying and analysing disturbances (1) reveal major opportunity areas, (2) help organizations to be able to prioritize disturbances, and (3) benchmark similar areas internally and externally. The classification should be done with enough detail (not less, which will prevent prioritizing disturbances; and not more, whence information shall become overwhelming). For example, appropriate detail level for large processes is to have a disturbance category for each key step.
14. Numerous disturbances categorizing methods has been proposed in literature (e.g., in abstract level: sources-effects, internal-external, root causes, frequent&minor-rare&major, consequences, production-safety-business).
15. How to register and what to consider while registering disturbances have been given in the literature.
16. Aim, frequency, length, scope, agenda, time, place, attendees, among other practicalities, of pulse meetings has been given in literature.
17. Aim, usage, and structure of pulse boards has been given in the literature.
18. The following parameters should be considered while setting up pulse methodology: the style of the visual tool (variables in columns and rows, meaning of colour coding etc.), the frequency, length, attendees, time, and place of the meetings.
19. Various use cases of pulse methodology have been given in the literature. All these cases, except one, pulse is used as a physical methodology. The digital case, however, is a suggestion of the author; it is not a case of real digital pulse methodology implementation.
20. Disturbance management tools, meetings, and methods other than pulse methodology has been given in the literature.
21. There are commercial digital lean tools available.

3.4.1 Gaps in the literature

Under this heading, the summary of the frame of reference chapter is further analysed for finding out gaps. The summary points, where each gap is derived, are referenced between brackets. The gaps found are as follows:

1. How disturbances can be managed has been given in various use cases (summary point 19). In addition, what to consider while setting up disturbance management methodology that has disturbance management boards and meetings has been given (summary points 16, 17, 19) However, how disturbances can be managed by a digital disturbance methodology and what are the barriers was a gap.
2. Recording disturbances has been suggested in literature (summary point 9). In addition, eliminating knowledge waste through re-using the registered knowledge was suggested in literature (summary points 1 and 2). However, how can registered disturbances can be re-used, what are the barriers, how can they be overcome is a gap.
3. In literature, it was given that to be able to detect and register disturbances, first what constitutes disturbance for that organization should be defined (summary point 8). The literature suggests companies to come up with their own definitions; it does not state which disturbances shall be captured explicitly. Thus, which disturbances shall be registered is a gap.
4. There are examples of digital lean tools (summary point 21), however, particularly how pulse methodology can be digitalized and introduced as a case has not been investigated.
5. Hybrid lean tool has not been prescribed, developed or tested out; thus, it is a gap.

4 Results

In this chapter, summary of each appended paper is given. Only the parts of the papers that contributes to the thesis is summarized under the respective heading. Provided that the papers contribute to the thesis in varying levels, the amount of summary from each paper varies, as well.

4.1 Paper A

Title:	*Exploring the Possibilities of Using Image Recognition Technology to Create a Hybrid Lean System for Pulse Methodology*
Authors:	*Kaya, O., Catic, A., & Bergsjo, D.*
Year:	*2014*
Published at:	*Proceedings of the 12th annual Conference on Systems Engineering Research (CSER 2014)*
Presented at:	*Redondo Beach, CA, USA, March 20-22, 2014.*

4.1.1 Pulse methodology used at the case company

Answers:	RQ-1
Contributes:	Increasing the knowledge on pulse methodology

The company is a Swedish telecommunication company that has around 1800 employees worldwide. The structure of pulse methodology they use is as follows:

- Frequency: Weekly
- Length: 15 minutes
- Time: 15:00 CET (so that EU and USA offices can join the meeting)
- Attendees: product managers and department managers
- Technical solution: Physical board at headquarters + video conference towards other offices where they see the board through a webcam

Attendees in the headquarters join the meeting by gathering around the physical board. Other attendees join the meeting by gathering at a meeting room that has video conference capability. The pulse board forms the agenda of the meeting. The order of products and departments written on the pulse board is used as the meeting structure, i.e., the order of the speakers. Products are given in the Y axis. The meeting starts with the product manager of the product that is written on the top row sharing the status of the product and updating the board accordingly. Other product managers do the same in the order that their products written on the pulse board. After each product manager sharing the product status, department managers share if there are other disturbances regarding the product. Departments are written on the X axis, and the order of sharing status is that the department manager of the department that is written on the leftmost column starts, and rightmost ends. Product managers who reside in the same office with the physical board update the pulse board during the meeting themselves. An assigned meeting coordinator who is by the physical board help distant attendees update the board. The meeting finishes when all product managers and department managers done sharing status. Then, the meeting coordinator takes a photo of the board and shares with the distant offices so that they have a visual on the updated board until the next meeting.

Figure 19 shows the mock-up board made from the company's pulse board. Departments are given in the X-axis, and products are given in the Y-axis, and the disturbances are given in the intersections of these axes. These intersections show the disturbance status at the given product in the given department by a colour-coded magnet:

- Red magnet: big disturbance
- Yellow magnet: small disturbance
- Green magnet: solved or no disturbance

The information regarding the disturbances is given in three separate sections of the boards; left-most section being the most abstract, and right-most being the most detailed one. At the left-most section, the status of the disturbances is visualized by colour-coded magnets. The next section that is on the right-side of the first one, comes the second section, where the disturbances are explained shortly by a summary or title. In addition, date information showing when the disturbances were identified and when the status of the disturbances will be updated next time are also given in this section. Detailed reports regarding the disturbances are attached at the last section.

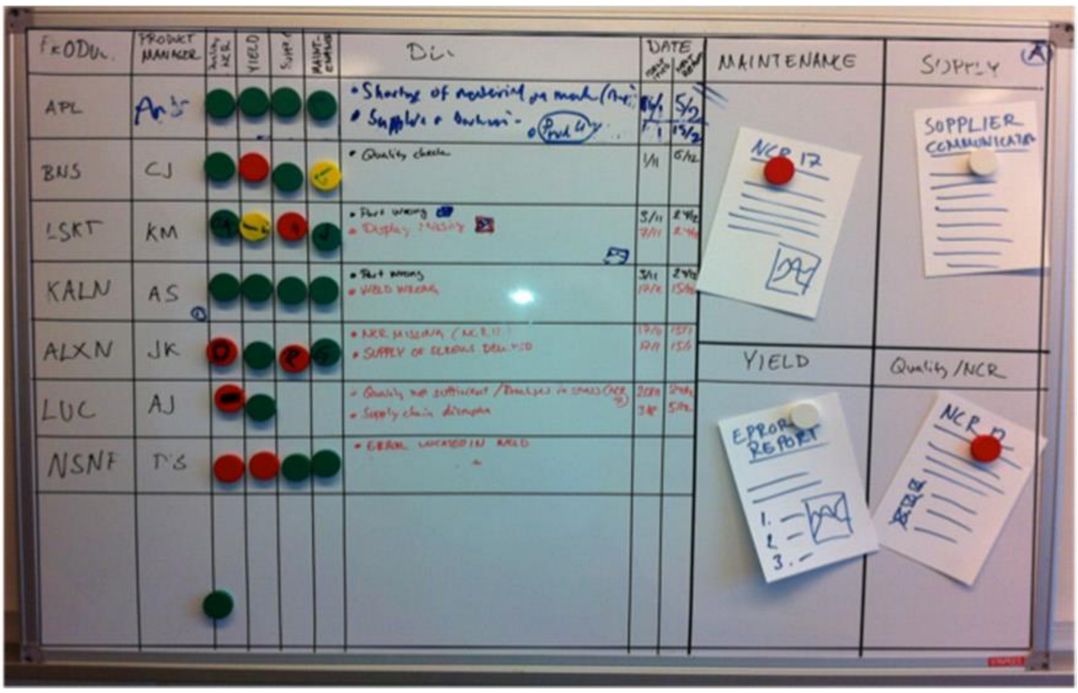

Figure 19. A mock-up board representing the company's board

4.1.2 Hybrid pulse methodology demonstrator

Answers: RQ-2
Contributes: Giving a candidate case for overcoming the barriers

A way to digitalize the methodology without damaging it was thought to be preserving the original pieces as much as possible. Therefore, the hybrid pulse methodology demonstrator was developed, as depicted in Figure 20. It keeps the physical board, the webcam that is directed to the board, the PC that the webcam is connected, the internet connection at the PC and the screens at the distant attendees as it is and enhances the distant attendees' experience by providing them the digital twin of the board. However, it was not approved by the company to be installed and tested in real settings based on three reasons. First reason was that the demonstrator allows information transformation only from physical to digital. Updating the physical board changes the digital board, however, updating the digital board do not change the physical board. Even though the company's current way of working fits with this solution (i.e., distant attendees ask meeting coordinator to update the board), they stated that giving distant attendees possibility to update the board would facilitate the meeting. The second reason was saving the text on the board (disturbance descriptions, dates, reports) as digital images rather than digital text. This limits the possibility to re-use the registered disturbance information (e.g., keyword search, creating statistics). The last reason was that the demonstrator did not perform the image processing with high precision. The company stated that they were sceptical about the robustness of the image processing technology. They further stated that, even though this is not a safety critical system, still the users must trust the system to use it; otherwise, they won't use it.

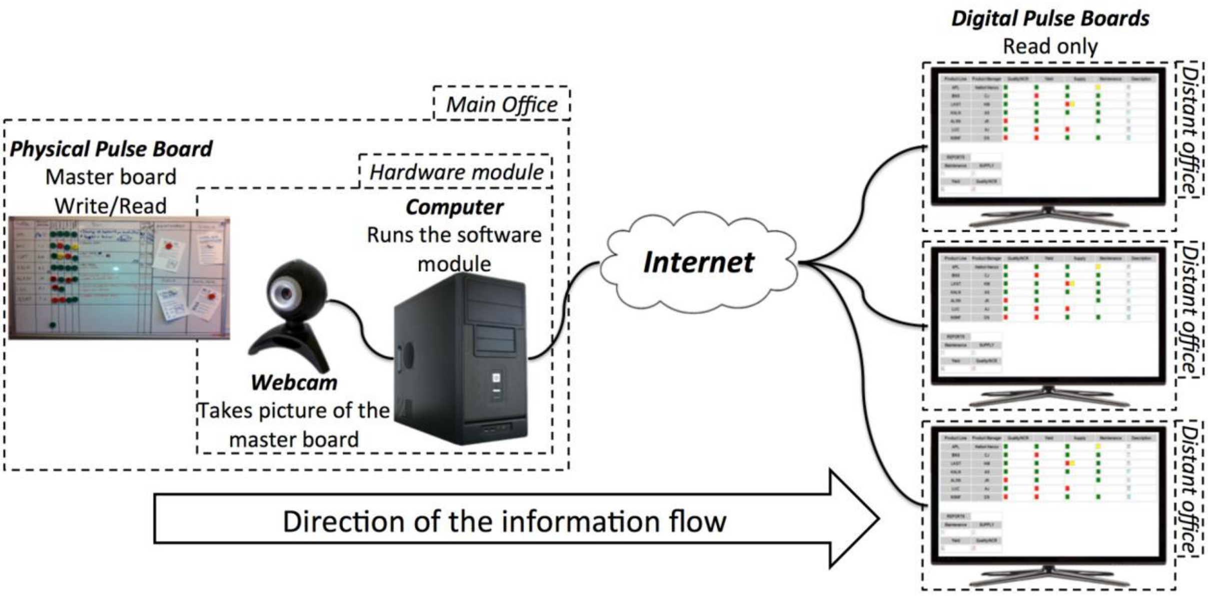

Figure 20. Hybrid pulse methodology demonstrator

The demonstrator worked as follows. The image recognition app is deployed to the PC. The app gets the image from the webcam, analyses, and creates the digital twin of it. The digital twin is created in the form of a webpage, to which the distant attendees can access. The app worked as follows.

As seen in Figure 21, the board has a different line structure at the reports section than the rest of the board. Therefore, the app first divides the image into two parts, and then detects the straight lines in both of them, as in Figure 21a. Cells are identified using the detected lines. The information cells (short description, date, and detailed report cells) are added to the digital twin as a picture. The place and the colour of the colour-coded magnets are detected as follows. First the circles in the image that has the given radius are detected. Then the centre of each image is found. Then this point is compared with the detected cells to define the place of each magnet. The pixel values in the detected circles are analysed to detect the colour of the magnet. Pixels are represented with RGB (red, green blue) value. Using this information, the colours of the magnets are detected.

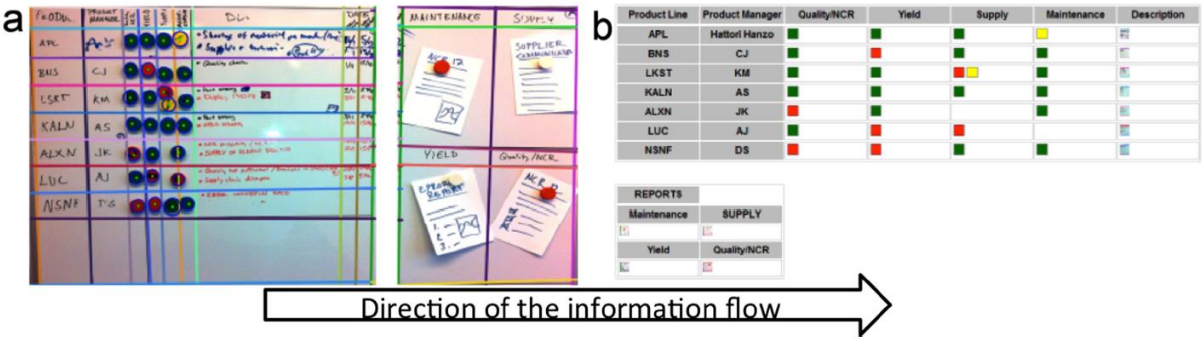

Figure 21. (a) Image recognition application analyzing the image; (b) digital twin of the pulse board.

4.1.3 Workshop results on the acceptance of the demonstrator

Answers:	RQ-2
Contributes:	Giving the reason why the case could not be used as the way to overcome the barriers (failing the user acceptance)

The demonstrator is presented at the premises of three Swedish companies. They agreed on that the hybrid pulse methodology demonstrator combines the simplicity of physical tools with the IT capabilities of digital tools. On the other hand, they pointed out the three following problems:

1. One-way (physical to digital) information transformation: The demonstrator can update the digital boards based on the changes made on the physical board, but not vice versa. It is more accessible then physical boards. However, two-way information transformation (i.e., full interconnectedness as in a fully digital system) is more accessible and can save more time (e.g., keeping the interconnected boards updated)
2. Saving the disturbance description as image: Unlike physical solution where the information is lost after deleted, the demonstrator saves the comments as image to a database. However, it is not possible to do statistical analysis on the image.
3. Robustness of image recognition technology: An example can be given as follows. A possible improvement to the demonstrator is using AI to convert the image to text to enable statistical analysis possibilities. However, this conversation would probably have robustness issue on detecting the text right. However, saving digital text as in fully digital solution is a much more robust solution.

Based on these problems that the companies pointed out, the hybrid pulse methodology and the demonstrator did not get acceptance from the users.

4.2 Paper B

Title:	*Introducing digital pulse as a deviation management methodology for dental product development and production*
Authors:	*Kaya, O., Kero, T., & Bergsjo, D.*
Year:	*2015*
Published at:	*International Journal of Lean Enterprise Research (IJLER)*

4.2.1 Physical pulse methodology at the case company

Answers:	RQ-1
Contributes:	Increasing the knowledge on pulse methodology

The company is a product development and production company within dental implants business. They use pulse methodology in two levels of the organization: (1) departmental, and (2) managerial. The structure of these are as follows:

- Departmental pulse:
  - Frequency: Daily
  - Length: 15 minutes
  - Time: 10:00 (as early as possible when two shifts present)
  - Attendees: Operators and the department manager of the department
  - Technical solution: Physical board (as a pilot at one of the departments)
- Managerial pulse:
  - Frequency: Weekly
  - Length: 15 minutes
  - Attendees: Engineers and department managers
  - Technical solution: N/A

The board is given in Figure 22. There were two main ideas guided the design of the board:

1. The board should not be too detailed that it hinders getting a quick overview
2. The board should not be too abstract that it lacks necessary information

The workstations of the department are given in the X-axis of the board. The disturbances are grouped based on the workstations of the department. Then, disturbances on each workstation is divided into two (in the form of adjacent swim-lanes): (1) machine related disturbances, and (2) flow related disturbances. Individual disturbances were represented by colour-coded magnets. i.e., a magnet in the cell that is at the intersection of workstation-2 column and machine related disturbances row represent the machine related disturbances at workstation-2. Red magnet means an ongoing disturbance, green magnet means a solved disturbance. Solved disturbances are removed from the board at the end of the week. Each magnet also had an ID next to it written with a pen. Then, each disturbance ID is written as a list under the swim-lanes, and a short description of the disturbances is written next to their IDs.

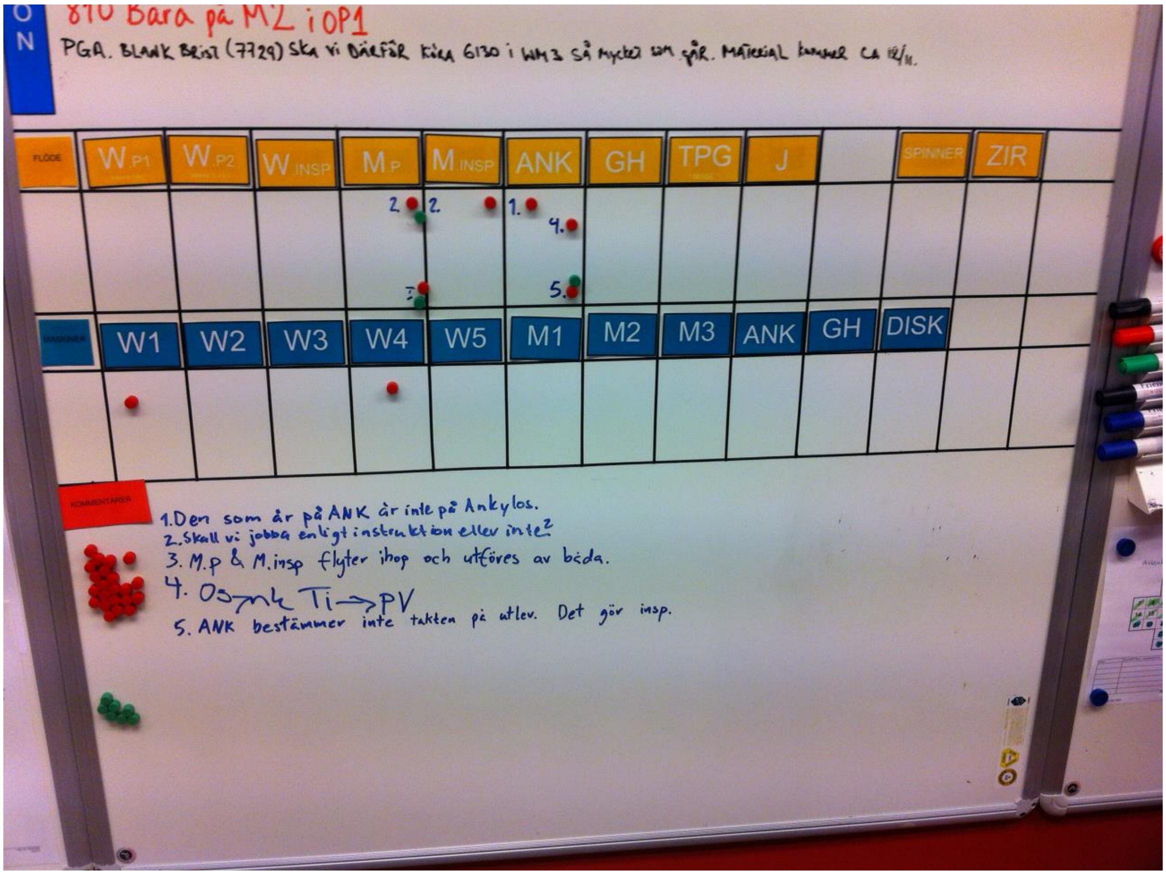

Figure 22. Physical pulse board at the case company

The company described their experience on the pilot pulse board as “better than nothing”. It was providing a meeting log that employees can look and learn about ongoing disturbances outside the meetings. However, it was not possible to re-use the registered disturbance information, because the solved disturbances were deleted at the end of the week. In addition, it did not facilitate the administrative work to escalate critical disturbances from departmental boards to the managerial board. Therefore, instead of deploying physical boards to rest of the departments, digital pulse boards were introduced.

4.2.2 Introducing the digital pulse methodology

Answers:	RQ-2
Contributes:	Making the employees skilful on the digital pulse methodology

As depicted in Figure 23, the digital pulse methodology was introduced to the case company using the following steps:

1. Physical pulse methodology is introduced to the pilot department
2. Standalone digital pulse methodology was introduced to the pilot department
3. Digital pulse boards we connected to the company’s IT infrastructure
4. Digital pulse methodology was introduced to the rest of the departments

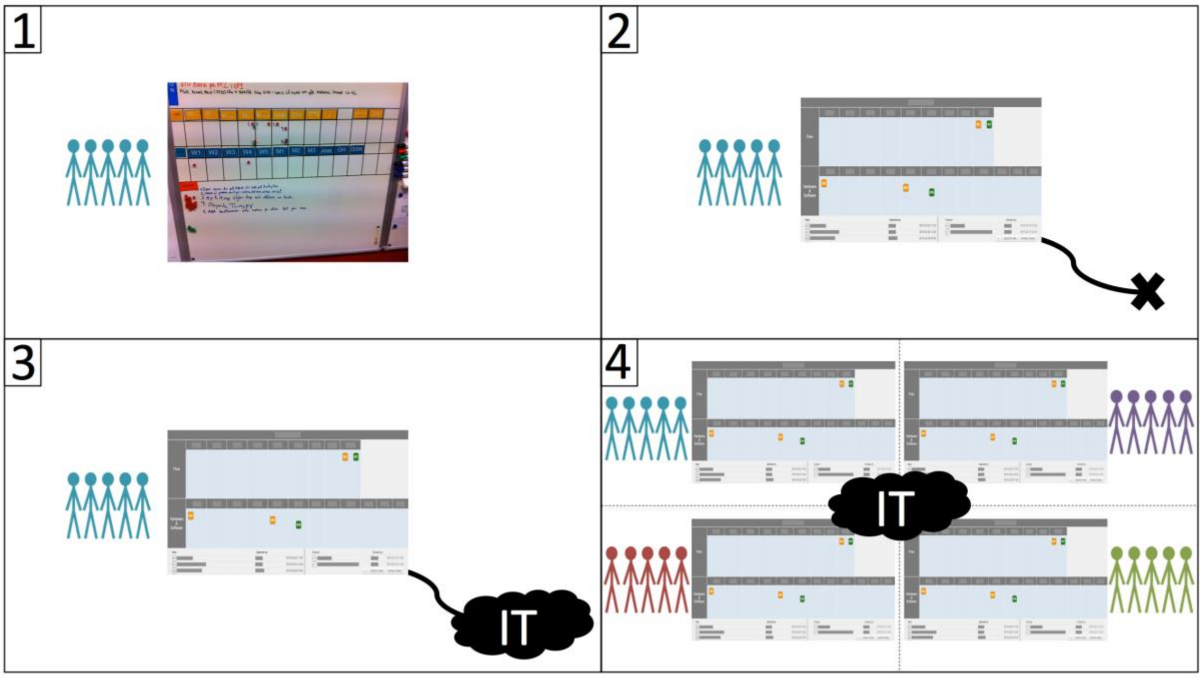

Figure 23. The introduction steps of digital pulse methodology

Accordingly, the following activities were carried out to teach the new methodology to the employees:

1. Physical pulse methodology was taught to the pilot department: 15-minute teaching session, including a question/answer (Q/A) session at the end. The teaching was focused on how and why to use the methodology. The Q/A was about which disturbances should be registered on the board.
2. Digital pulse methodology was taught to the pilot department: After using the physical methodology for three months, the pilot department was introduced with the digital solution. The teaching session took 15 minutes focusing on (1) how to use the digital tool, new processes (escalate, archive, temporary solve, permanent solve, assign severity). The Q/A was about assigning the right disturbance severity.
3. Digital pulse methodology was taught to the rest of the departments: 8 months after introducing the digital methodology to the pilot department, it is introduced to the rest of the company. The rest of the company have not used neither physical nor the digital solution but they have seen them being used in the pilot department. The teaching session took 15 minutes. The teaching sessions focused on how and why to use the digital pulse methodology.

4.2.3 Digital pulse methodology at the case company

Answers: RQ-2
Contributes: Processes that governs the digital pulse methodology

The digital pulse structure of the company is depicted in Figure 24 as an entity-relationship diagram. The company consists of three departments. One of the departments (department two in Figure 24) is divided into two sub departments, because they are located separate locations. Each department has a digital pulse board. Except department two; each of its sub-department has own digital pulse boards instead. The company also had one digital board in the company (top) level. Each board has daily pulse meetings where they gather in front of the board and share status of disturbances. Except the boards coupled with the sub-departments of department two. These sub-departments have one pulse meeting that they gather around one of the boards instead. The placement of the boards is visualised over the company layout in Figure 25.

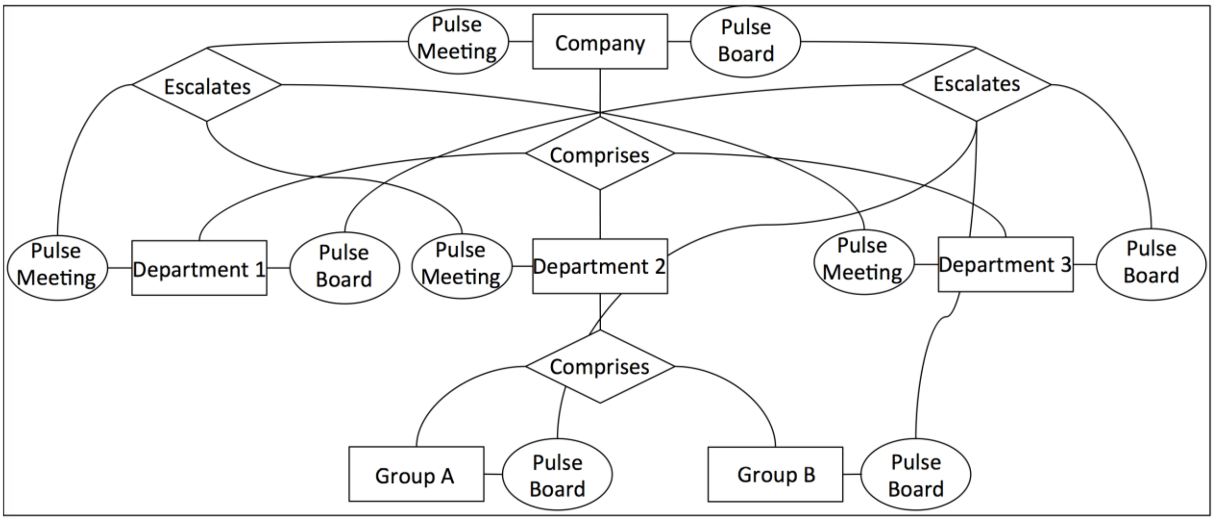

Figure 24. Digital pulse structure of the case company

Department level digital pulse:

- Frequency: Daily
- Length: 15 minutes
- Time: 10:00 (as early as possible, when both shifts are present and all daily orders are received)
- Attendees: Operators and the manager of the department
- Technical solution: Digital board connected to the company's network

Company (top) level digital pulse:

- Frequency: Daily
- Length: 15 minutes
- Time: (As early as possible when all departmental pulse meetings are finished)
- Attendees: Engineers and department managers
- Technical solution: Digital board connected to the company's network

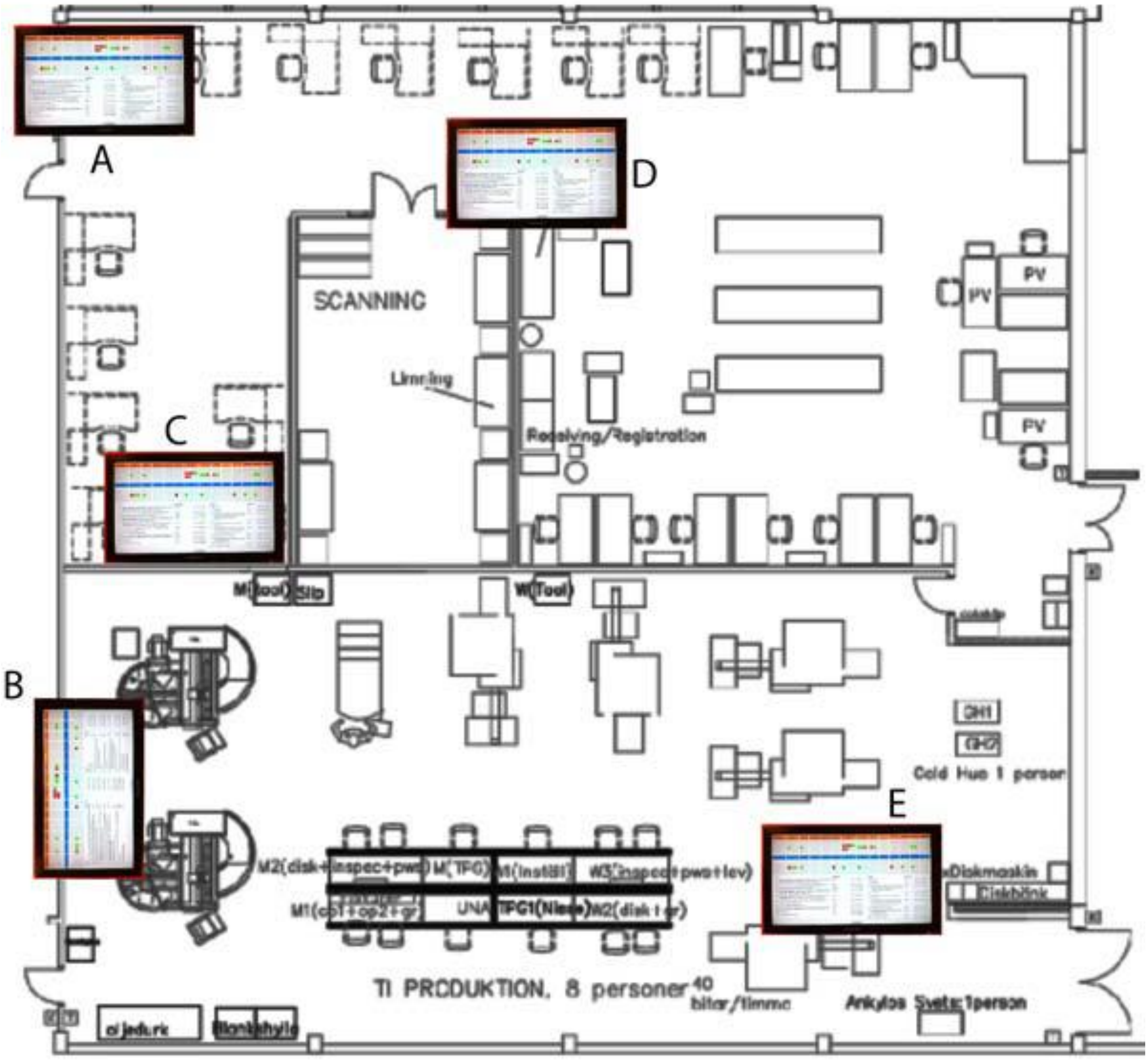

Figure 25. Placement of the digital disturbance boards.
A: managerial, B: workshop-1, C: design, D: order entry/shipping, E: workshop-2

Each pulse board had a different background color as its own visual identity. Figure 26 shows one of the boards, which has grey as background color. Disturbances are typically detected by operators, because they are the employees that carry out the work with the machines. Then, operators logged these disturbances to their department's disturbance board. Critical/stopper disturbances are escalated to the managerial pulse board. Escalation is done by selecting the disturbance on the board and clicking "escalate" button. Then, the disturbance is also visible at the managerial board to be discussed at the managerial pulse meeting. The structure of the board is similar to the physical board that was used at the company as a pilot. Columns represent workstations, and then each column is divided into two swim-lanes (1) hardware and software, and (2) flow.

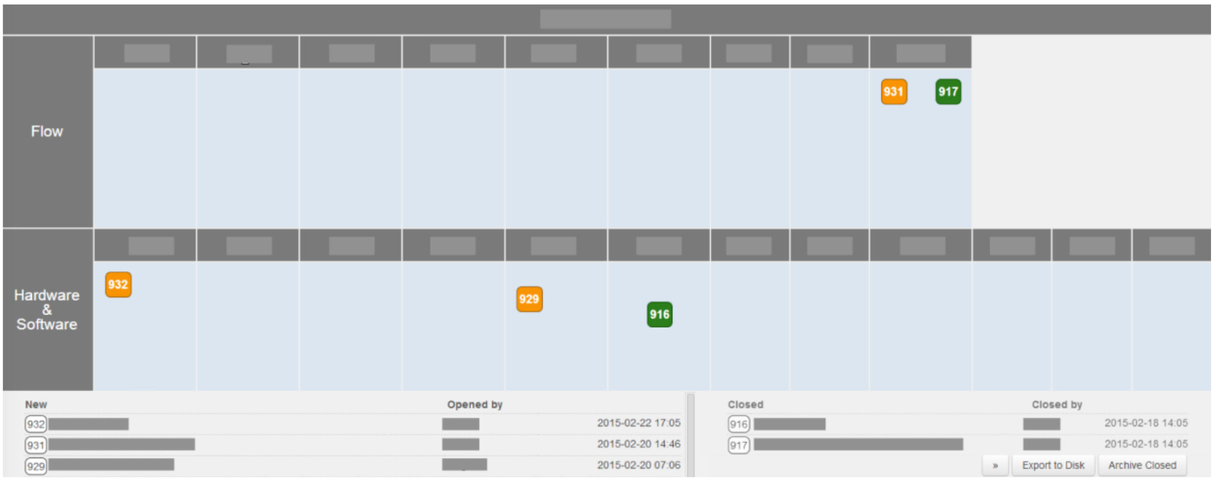

Figure 26. The case company's digital pulse board

The disturbances are visualized (placement and colour) on the board based on four category types, as summarized on Table 4. The first category divides disturbances into (1) hardware and software and (2) flow related disturbances. It is visualized as two adjacent swim-lanes. Category two divides disturbances based on the workstation it is detected at. It is visualized as the columns on the two aforementioned swim-lanes. The third category represents the status of disturbances:

- ongoing
- solved
- archived

Ongoing and solved disturbances are shown on the board. Archived disturbances are removed from the board, and stored in the company database. The disturbances are graded by their severity, which is visualized by colour-coded magnets based on the fourth category:

- Red: critical; stops or slows down the process, affects other departments, requires third-party help
- Yellow: Non-critical; does not affect the process, does not affect other departments, can be solved by operators
- Light green: Temporarily solved, solved by a workaround
- Dark green: Permanently solved, root cause solved

Table 4. Visual disturbance categories

Category-1	Category-2	Category-3	Category-4	
Hardware and software	Workstations	Ongoing	Red	Critical / stopper
Flow		Solved	Yellow	Non-critical
		Archived	Light green	Temporarily solved
			Dark green	Permanently solved

Each disturbance had an owner, who shared the status of it during the pulse meetings. Typically, the operators who detected the disturbance owns it. The exception is the critical/stopper disturbances; department managers owned those disturbances. When both shifts are present and all daily orders are received, departmental pulse meetings were held by gathering around the department pulse board. Operators shared the status of ongoing disturbances in those meetings. The critical/stopper disturbances were escalated to the managerial pulse board. After all departmental pulse meetings are done, managerial pulse meetings were held by department managers and engineers gathering around the top-level pulse board. The topics discussed were:

- critical disturbances
- disturbances that had the risk of becoming critical disturbances
- daily production status
- daily staffing status
- IT releases and launches

Each Friday, department managers archived the solved disturbances using pulse boards. At the Friday departmental pulse meetings, managers used the pulse boards to archive the permanently solved disturbances (by selecting the disturbance and clicking "archive").

4.2.4 Problems with registering disturbances at the case company

Answers:	RQ-1, RQ-2
Contributes:	Barrier about capturing minor disturbances, evaluating the introduction of the digital pulse methodology

After deploying the digital pulse to the company, employees were given teaching sessions on the methodology. In addition, managers continuously helped the operators with the new methodology and answered their questions. However, operators were still having the following problems regarding registering disturbances:

- Deciding what should be put on the board
- Grading the disturbances
- Getting the habit of registering disturbances
- Differentiating temporarily and permanently solved disturbances

Regarding the first problem, some disturbances are trivial or take less time to fix than to register it to the pulse board. During interviews, operators stated that they feel shy about registering such disturbances, because "it feels like whining". Managers have requested all disturbances to be registered to the boards, however, not all of them are registered as in this case. Regarding the second problem, the disturbance severity grading rules did not work for every disturbance. A typical example is the disturbances that are not critical for the department they are detected at but for another department (typically the next the department in the workflow). In such cases, operators graded the disturbances as non-critical, which caused late detection of critical disturbances. Regarding the third problem, operators did not register disturbances to the boards when there is a high workload. In such situations, operators either forgot or neglected to register disturbances. Regarding the last problem, operators were taught the difference between temporarily and permanently solved disturbances. However, since it is the department managers (not operators) close the disturbances (thereby, choose if the disturbance is permanently or temporarily solved), operators could not reinforce this knowledge with practice, and eventually the knowledge became obsolete.

4.3 Paper C

Title:	*Useful deviations for deviation management information systems: From pulse methodology to a generic description*
Authors:	*Kaya, O. & Bergsjo, D.*
Year:	*2016*
Published at:	*11th Annual Systems of Systems Engineering Conference (SoSE16)*
Presented at:	*Kongsberg, Norway, June 12-15, 2016.*

4.3.1 The problems with capturing minor disturbances

Answers:	RQ-1, RQ-2
Contributes:	Analysing why the operators did not capture minor disturbances

The managers have instructed operators to register all disturbances, which includes occurrences of the same disturbance. One of the engineers explained the rationale behind this as follows: “If it is an issue that happens quite frequently, and we don’t collect that data, we won’t know how big the problem is, and we won’t know if it is worth fixing it or not”. However, even being aware of the instruction, operators do not register all minor disturbances. The exception is reoccurring minor disturbances that operators define as “trivial”; operators stated that they report these disturbances. Some of the reasons they gave on not registering minor disturbances were as follows:

- “It kind of clouds the more important things”
- “One can solve this oneself, don’t need to inform all the group”
- “…I did not see anyone else doing it either”
- “…it feels like whining”
- “When I write on the pulse board, for me it stays there. I don’t know what happens to this entry”
- “I don’t know who is interested in to know that my mouse broke. I don’t know, it doesn’t feel important”

From the interviews, following two reasons can be elicited as not being able to capture minor disturbances:

- Thinking minor disturbances are unimportant
- Conforming to the norm of not registering minor disturbances

Another reason of not being able to capture minor disturbances was the managers’ directive to capture all disturbances. The problem was that the definition of minor disturbances was not clear. This led to operators implicitly defining their own threshold to define minor disturbances, below which are thought as trivial disturbances and do not need to be registered. This threshold was high than the managers’, which led to operators not capturing minor disturbances that the managers expected to be captured.

4.3.2 Solving the problems with capturing minor disturbances

Answers:	RQ-2
Contributes:	Overcoming the capturing minor disturbances barrier

The first reason can be solved by the managers explaining reasons why disturbances to be captured, how can they be used, how can capturing them benefit the company. The second reason can be solved when the norm has been changed. Solving the first reason (by conveying the current norm that is capturing minor disturbances being important) and the third reason is a way to change the norm. The third problem can be solved by defining what is disturbance.

A pragmatic definition of disturbance was made, i.e., disturbance was defined as the disturbances that should be captured. A disturbance should be captured if capturing it is/will be beneficial for the company. As a holistic approach, considering the benefits of capturing a disturbance as a span, the two ends of this span can be taken as short-term benefits and long-tern benefits. In the short-term, disturbances are captured to be (1) managed in a structured way, (2) remembered, and (3) followed up in pulse meetings until they are solved. Thus, it is beneficial to capture disturbances that should be remembered because it needs a follow-up to be solved. In the long-term disturbances are captured to utilize the knowledge that was generated by capturing them. Thus, it is beneficial to capture disturbances that generate such knowledge that can be used for the benefit of the company. These disturbances can be grouped under two categories:

- Rare disturbances, which have solutions that can be used to solve similar future disturbances
- Statistically important disturbances, which can be used to elicit statistics that can be used for the benefit of the company

Thus, as depicted in Figure 27, the pragmatic definition of disturbance is the union of these three sets: "disturbances that needs a follow-up to be solved" ∪ "statistically important disturbances" ∪ "rare disturbances".

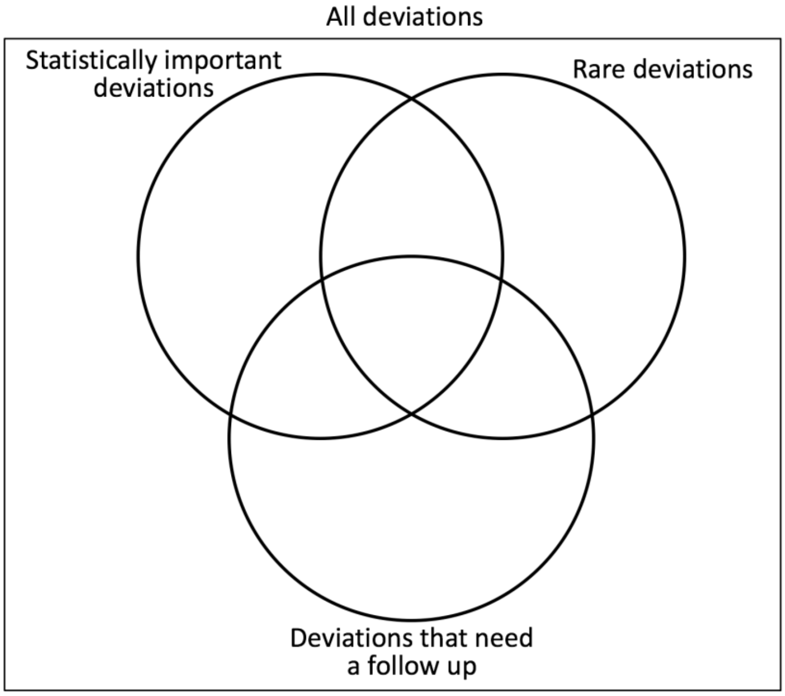

Figure 27. A pragmatic definition of disturbance (i.e., disturbances that are useful to capture)

4.4 Paper D

Title:	*Learning from digital disturbance management in an integrated product development and production flow*
Authors:	*Kaya, O. & Bergsjo, D.*
Year:	*2018*
Published at:	*International Journal of Product Lifecycle Management*

4.4.1 The disturbance database

Answers:	RQ-2
Contributes:	Which data is captured while registering a disturbance to the digital board

The disturbance database is stored in the company's servers, from which the digital disturbance boards fetch data, render, and visualize the open and recently solved disturbances. The data is created by (1) employees registering the disturbances they detected, and (2) updating these entries throughout the disturbance's lifecycle, until it is fully solved. The data collected between January 2014 and March 2017 is used to do the data analysis. The data has the following columns (predefined values, if exists, are shown in parenthesis):

- Unique ID: An integer number assigned automatically to the disturbance when it is created.
- Summary: Short description of the disturbance that is written in free text.
- Reporter: Name of the person who detected the disturbance, written in free text.
- Owner: Name of the person who is responsible for making sure that the disturbance is solved, written in free text.
- Status (new, closed): Status of the disturbance. Can be one of the two predefined values. When a disturbance is created, it automatically gets the "new" tag. When a disturbance is fixed either temporarily or permanently, it automatically gets the "closed" tag.
- Priority (minor, major): The severity of the disturbance. It is decided while registering the disturbance between the two predefined values. Major refers disturbances that slow down, stop the process, or effect other departments. Minor refers to disturbances that neither effect the flow nor other departments.
- Component (machine, flow): The cause of the problem. It is decided while registering the disturbance between the two predefined values. Machine refers to machine and software related disturbances. All the rest belongs to the flow category.
- Resolution (permanently fixed, temporarily fixed): Shows the resolution status of the disturbance. The value is decided after a disturbance is solved based on if it is solved permanently or temporarily by a workaround.
- Keyword: Predefined names of all the workstations, machines, and software in the flow; in total 55 elements.
- Created date: The date and time that the disturbance was created. It is assigned automatically.
- Last modified date: The date and time that disturbance was modified last (the date it was fixed for the fixed disturbances). It is assigned automatically.
- Visibility (on the board, archived): An automatically assigned tag that shows if the disturbance is visible on the board or not (because it was archived).

4.4.2 Analysing the disturbance database

Answers:	RQ-3
Contributes:	Which analyses were carried out to be able to elicit insights from the data

Figure 28 compares major-flow, minor-flow, major-machine and minor-machine disturbances. The data is visualized both in total using a pie chart and by variance over time using a line chart that shows total amount in Y-axis and date in months in X-axis. As seen, minor machine disturbances are more than twice as frequent as major machine disturbances (47% vs. 18%), as expected. On the other hand, minor flow disturbances are almost half the number of major flow disturbances (13% vs. 22%). The interview with the manager helped clarifying this situation; minor flow disturbances typically cost less than minor machine disturbances. Based on this fact, many minor flow disturbances are not registered because their single occurrence incurs insignificant cost. The figure can also be analysed as the comparison of aggregations of minor, major, flow and machine disturbances. Only in 8 out of 39 months, major disturbances occurred more often than minor ones; in the remainder, minor disturbances occurred more often. Minor disturbances comprise 60%, major disturbances comprise 40% of all disturbances. Machine disturbances occurred almost twice as often as flow disturbances (65% vs. 35%). Except for a couple of occasions, machine disturbances were more frequently occurring each month. The aggregation of minor disturbances chronologically follows similar trends with the aggregation of major disturbances. Similar phenomenon applies for the aggregation of machine and flow disturbances, as well.

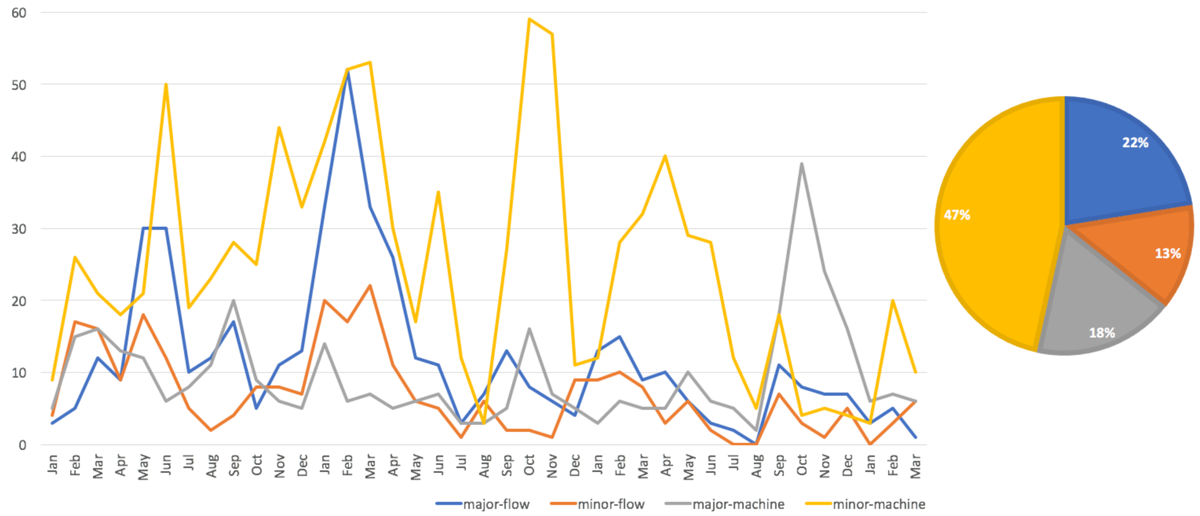

Figure 28. Major-flow vs. minor-flow vs. major-machine vs. minor-machine disturbances.

Figure 29 visualizes the comparison between flow and machine related disturbances. Examples to flow related disturbances can be given as follows: “we sent the case to the customer without the models”, “DHL arrived late around 10:30”, “wrong abutment in bag”. Examples to machine related disturbances can be given as follows: “scanner-5 is down”, “AWO server is down”, “Machine stopped because of X:Y:B-axel stop”. As seen in the figure, two of the flows accounted for 54% (30% + 24%) of all flow-related disturbances, and the remaining 23 flow cells shared the remaining 46% of all disturbances. A total of 69% of all machine-related disturbances were shared between ten instances of a particular machine. Remaining 31% of machine-related disturbances were shared between the remaining 26 machines.

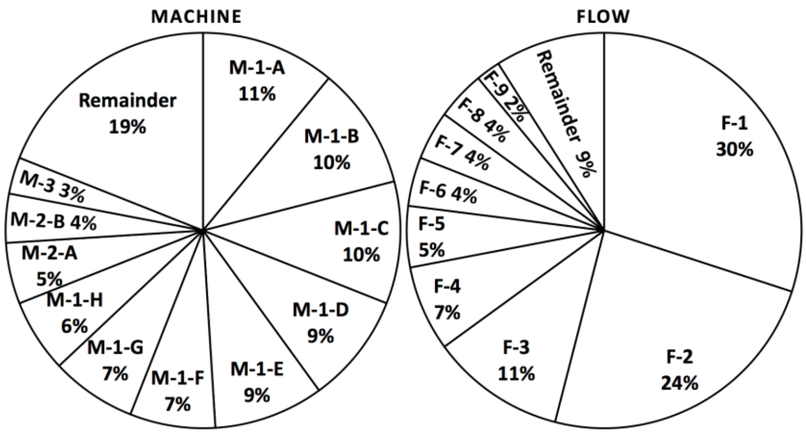

Figure 29. Comparing disturbances in flow and elements

Figure 30 shows the comparison of employees regarding the amount of major, minor and total disturbances they have registered. 14% of all employees registered 50% of all major, 8% of all employees registered 50% of all minor, and 11% of all employees registered 50% of all disturbances.

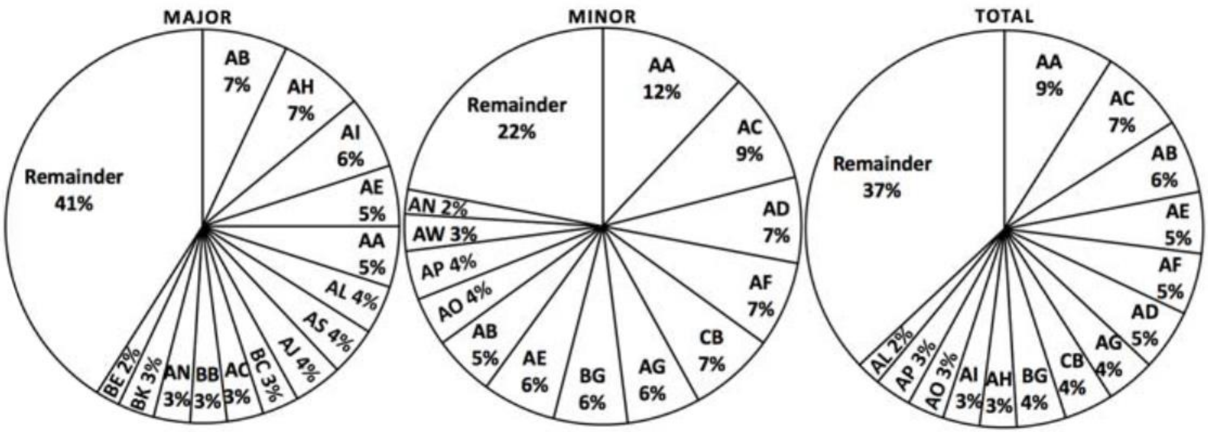

Figure 30. Comparing employees regarding how many minor, major, and total disturbances they registered.

Figure 31 shows the sum of number of appearances of employees in the minor, major, and total disturbance top-ten lists for each year. The figure was generated as follows. First, top-ten lists, which show who had registered most of the disturbances, were generated for each year and for minor, major and total disturbances; 12 lists were generated (minor + major + total = 3, 2014 + 2015 + 2016 = 4; thus, 3*4=12). The 12 lists were aggregated based on the names, which yielded as the Figure 31. The figure can be interpreted as follows. If an employee name were to appear twelve times, he/she would be in the top ten list for each year for minor, major and total disturbances. All employees having an equal number in the figure would mean that top ten lists vary. On the other hand, big differences in the numbers would mean that only same group of employees register most of the disturbances, and that they are the driving force behind the disturbance registration. As seen in the figure, there is great variance in the numbers, which means that same group of employees register most of the disturbances.

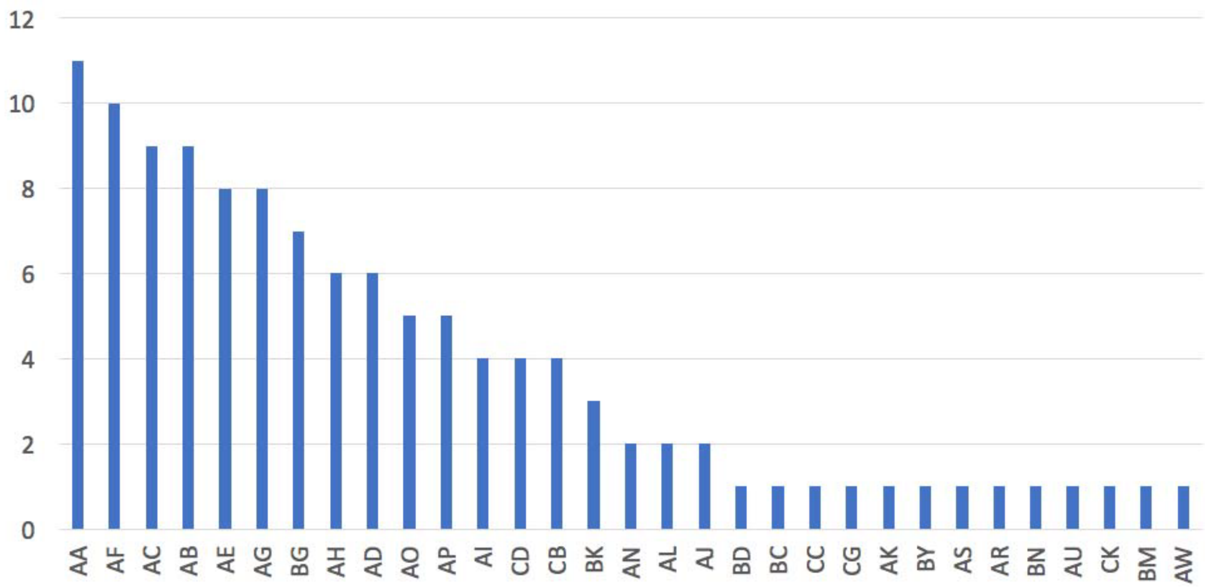

Figure 31. Sum of number of appearances of employees in the minor, major, and total disturbance top-ten lists for each year

Figure 32 shows the weekdays that the disturbances were created and removed. Disturbances were created homogenously throughout the working days, except Friday. Number of disturbances solved varies throughout the working days. As seen, there are some activities in weekends also, when extra work was carried out.

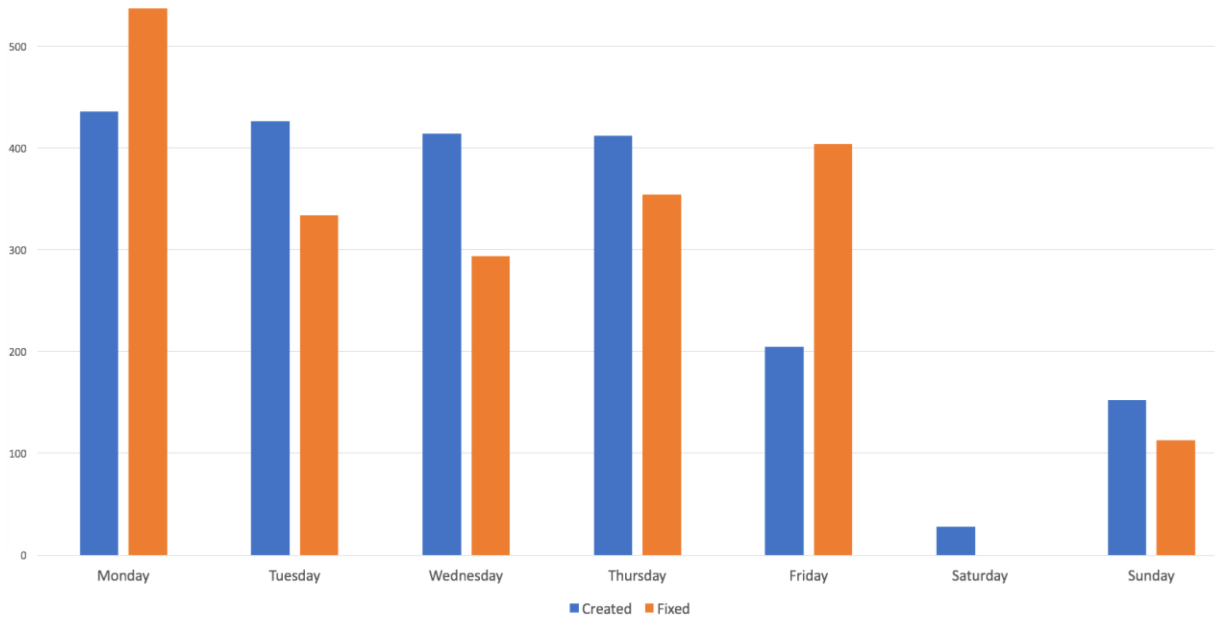

Figure 32. The weekdays that the disturbances were created and removed

Figure 33 shows the average time spent to resolve major and minor machine, and major and minor flow disturbances. In the figure, X-axis shows the months when the disturbances were registered, and the Y-axis shows average days spent to resolve the disturbances for a given month. The average time it took to resolve these four disturbance types was also noted in the figure. Figure 34 shows the minor machine disturbances in longer time span.

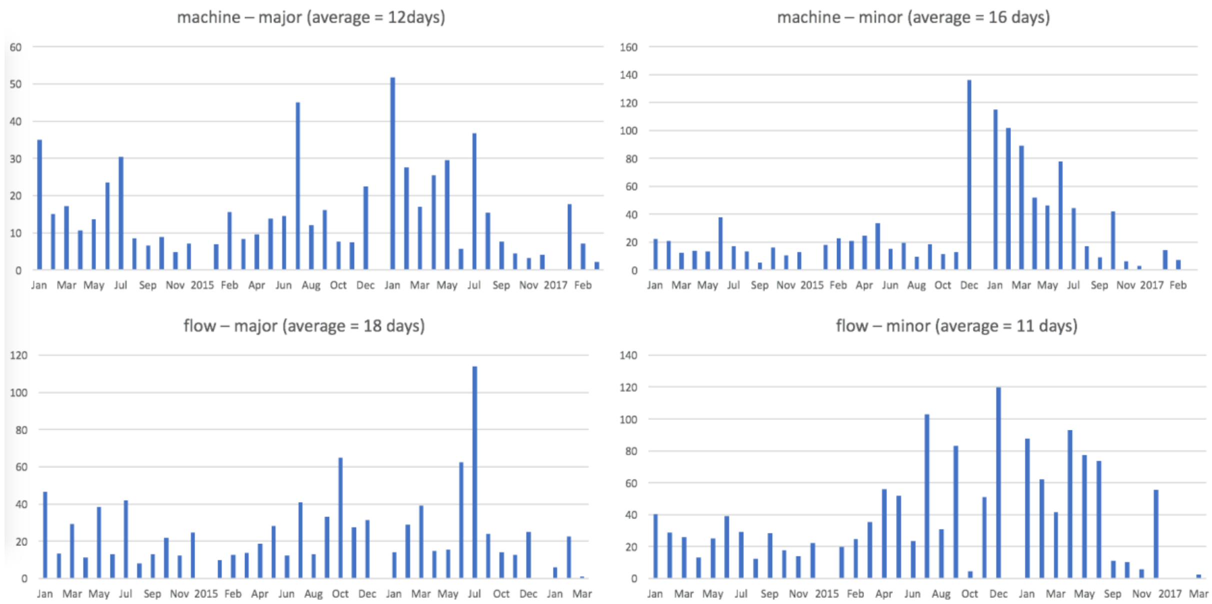

Figure 33. Average time spent to resolve minor machine, major machine, minor flow and major flow disturbances

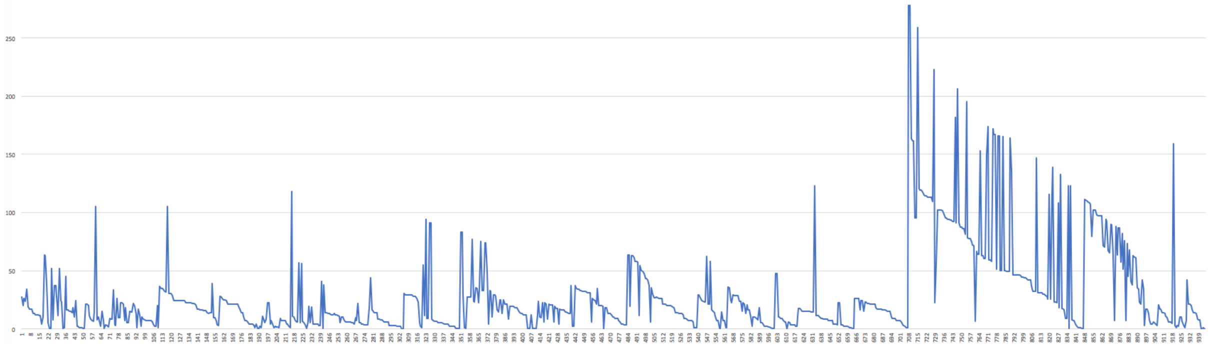

Figure 34. Time spent resolving minor machine disturbances in chronologic order.

Figure 35 shows the number of total disturbances registered over time. Between January 2014 and April 2015, the number of disturbances increased compared to the average number of disturbances taking place in each corresponding month. This can be interpreted as employees getting used to registering disturbances. The general trend between January and June was as follows. First, from January to February disturbances increased; after Christmas, activities were returning into their normal pace, which may be the reason. After that, towards June, disturbances diminished or become stable except for 2014, which may be ignored since it was in-between the aforementioned learning window. Summer months are the times when the minimum number of disturbances occurs. The reason can be that these are the Swedish summer vacation months when activities are reduced to a minimum. It is natural that as activities diminish, the number of disturbances also diminishes.

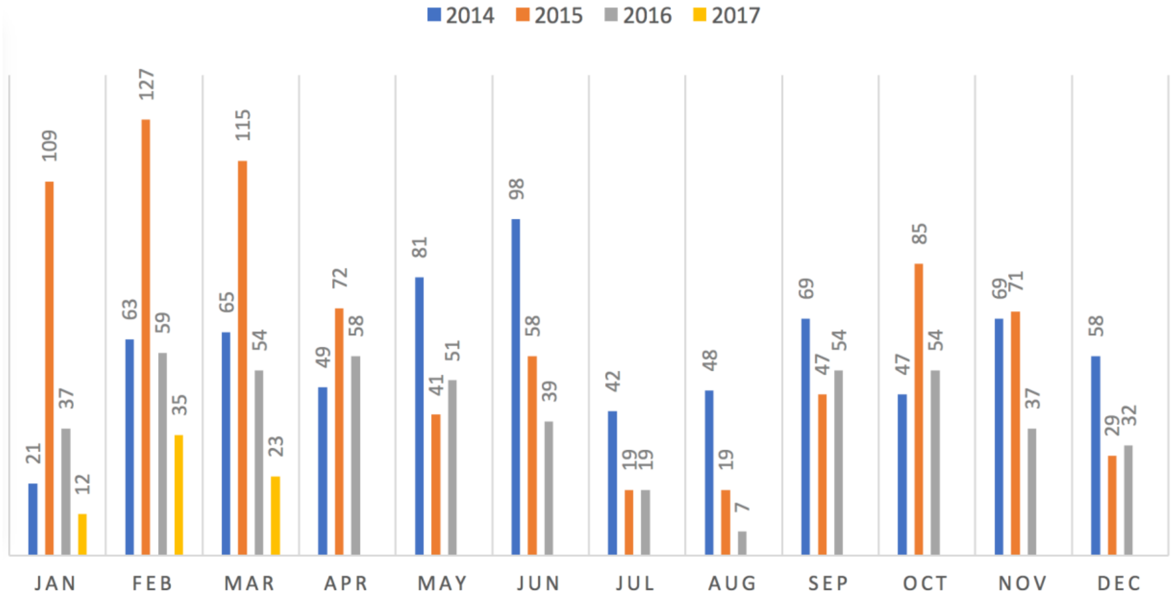

Figure 35. The total number of disturbances registered over months/years

Figure 36 shows both scrap and disturbance per order. The scrap data is stored in a separate database than the disturbance data. The scrap data has been started to be recorded from January 2015. As seen, the scrap rate is much higher than the disturbance rate. Except for August and September 2016, the two values show a similar trend, which is in general downward.

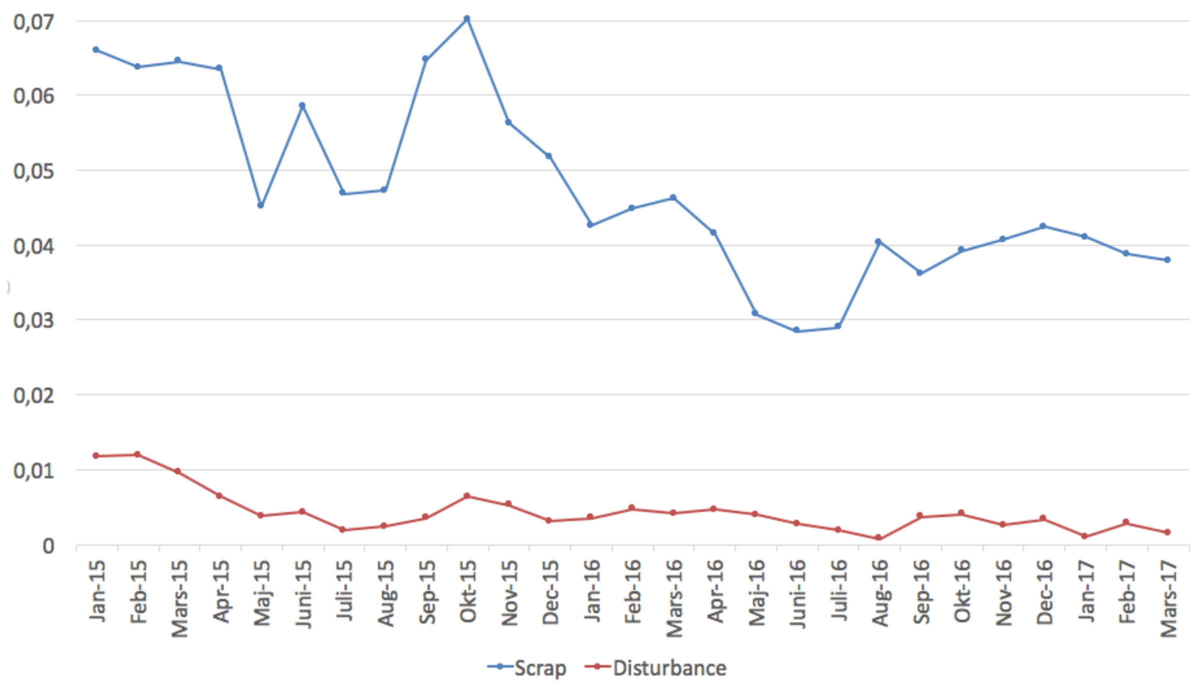

Figure 36. Disturbance and scrap per order received for each month.

4.4.3 Learning from analyzing the disturbance database

Answers: RQ-3
Contributes: The insights generated from analysing the disturbance database

Trend analysis over classifying and comparing disturbances by their severity may show latent problems. Minor vs major disturbances over years in the case company is as follows:

- 2014: 60%–40%,
- 2015: 63%–37%,
- 2016: 54%–46%
- 2017: 60%–40%.

As expected, minor disturbances are more than major disturbances, and the ratio is quite stable over the years. Latent problems can be uncovered by following-up this trend. Ratio of major disturbances increasing over the minor disturbances may be a signal of latent problems, which then triggers for a deeper investigation on the problem. Some example problems can be:

- Operators not registering minor disturbances because they are “trivial”
- Solving minor disturbances are neglected because of focusing on major ones, which causes the minor disturbances becoming major ones and only then being solved

Sorting machines and flow related disturbances according to number of disturbances occurred in each can give an indication on the disturbance related incurred cost to the company by particular machines and flows. This information can guide improvement investments (by investing to the machine/flow that probably incurred the highest cost). As seen from Figure 29, most machine related disturbances occurred at machine-1 and its replicas, and most flow related disturbances occurred at flow-1 and flow-2. This information indicates that machine-1, machine-2, flow-1, and flow-2 may be the best investment options to lower the disturbance cost to the company.

Classifying and sorting employees by the number of minor and major disturbances registered may uncover latent problems. Some examples are as follows. The expected is operators register more minor disturbances then major ones, because minor disturbances occur more often. If certain employees found to be registering equal or more major disturbances than minor ones, it may indicate a problem (e.g., operators ignore registering minor disturbances). Another expectation is that all employees register similar number of disturbances. If over time certain employees always register most or least number of disturbances, then this may indicate a problem (e.g., only a handful employees truly register disturbances). Then as a solution, the company may give coaching and training to improve the situation. Figure 30 shows that some employees registered nine times more disturbances than others. Figure 31 shows that certain employees have been registering the most and least number of disturbances is a trend over the years. These two findings can unravel a latent disturbance registration problem, which then the company can counteract by carrying out coaching and training sessions. This analysis was verified during the follow-up interview with the manager that certain employees known to be more eager to register disturbances.

Classifying registered and resolved disturbances based on weekdays, as in Figure 32, can help finding latent problems. The results were verified during the interview with the manager. In terms of both registered and solved disturbances, Saturday had the lowest amount, as expected, because employees rarely work on Saturdays. Sunday had the second lowest number, as expected, because it is the day when most of the extra work is performed whenever necessary. The number of disturbances resolved throughout the week is rather stable, except for Monday where the number is 50% more than the average of rest of the workdays (Mon-Fri). This is also expected because disturbances that occurred during the weekend are also solved on Mondays. Number of disturbances registered during the workdays are also stable as expected. The exception is Fridays, where the number is 50% less than the average of rest of the workdays. This result was unexpected and can indicate an otherwise latent problem. An example latent problem may be that people may be getting into a weekend mode and overlook registering minor disturbances.

Analysing the trend on the lead-time to solve disturbances may help finding latent problems. The expectation is that the lead-time stays the same or decreases over time. Unexpected results, such as lead-time increasing, may indicate latent problems. In addition, companies aim to continuously improve (e.g., lower lead-time), thus following-up the lead-time trend help companies monitoring their achievement. As seen in Figure 33, the average lead-time is significantly higher in some of the months, which can indicate latent problems. Upon further investigation in the collected data, it was found that those months that few disturbances are registered and if one of them took significantly long time, then it had a big effect on the average of that month.

Sorting number of disturbances registered per year can help finding latent problems. As seen in Figure 35, initially the number of disturbances registered is low. This is expected because employees are getting used to registering disturbances. After that, the number of registered disturbances is stable for a while. Then, the number gets lower as seen from the data from 2017. The reason can be a lower workload, however, as seen from Figure 36, disturbance per incoming order also decreases. This requires a deeper investigation to find the cause. An initial negative interpretation of this can be that employees getting worse at registering disturbances. This latent problem can be solved by coaching or training session. An initial positive interpretation can be that the system (processes, machines, and employees) has improved, but the work/challenge to the system has not. This creates additional slack, which then causes the number disturbances to get lower. This outcome can guide strategic decisions such as challenging the system more. This will then increase the number of disturbances to its prior state, which can be observed in the future data. Thus, by observing the trend in the data, the cycle of (1) improvement, (2) disturbance decrease, (3) challenging the system, (4) disturbance increase, and back to (1) improvement, can be guided.

Analysing re-occurring disturbances may help finding latent problems. Upon analysing the disturbance database, a disturbance that occurred 217 times was detected. This was a minor disturbance, but it incurred a large cost due to frequent occurrence. This information triggers a root cause analysis, which leads to improvement work.

5 Discussion

In this section, the research questions that were given in introduction will be answered, and results and methods used will be discussed.

5.1 Answering Research Questions

Under this heading, each research question will be answered and discussed under its respective subtitle. How the research questions were defined is given in the introduction chapter in detail. How each appended paper contributes to the research questions is given both in the introduction and in the results chapter. In addition to the appended papers, information from the literature and software development related raw material from study-2 and study-3 were used to answer the research questions. A summary of what each research question aims to answer is given in Figure 37.

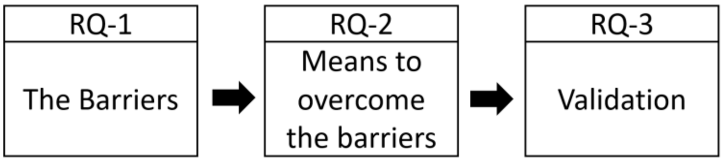

Figure 37. A summary of what each research question aims to answer.

5.1.1 Answer to the first research question

RQ1: What are the barriers towards digitalised disturbance management in lean PPD?

The first research question is about defining the underlying problems for this research work. It aims to increase the understanding of the current state and the problems. To increase understanding on disturbance management, how the case company and other companies manage disturbances was investigated using interviews, observations, and literature study. It was found that companies make use of (1) a physical visual tool to visualize the ongoing disturbances, and (2) frequent short meetings to follow-up the status. In this framework, the style of the visual tool (variables in columns and rows, meaning of colour coding etc.), the frequency, length, attendees, time, and place of the meetings varies (reference: literature summary points 16,17,18,19 in chapter 3.4; case in paper-A chapter 4.1.1; case in paper-B chapter 4.2.1).

Barriers "restricts, impedes, or blocks progress or the achievement of an ultimate objective" (VandenBos, 2007). The ultimate objectives of this research are (1) reaching its aim, and (2) validation of reaching the aim and the hypothesis. "Blocks" to reaching these two "ultimate objectives" are the main barriers of the thesis (which will be further divided into sub-barriers to simplify the problem solving). Thus, the first main barrier is the barrier towards reaching the aim. It is the research challenge, which is derived from the literature, as given in the introduction chapter:

maintaining the leanness of the methodology during digitalization

The first main barrier is further divided into three sub-barriers, using Morgan and Liker's (2006) division of lean product development system, to simplify the problem-solving:

1. process
2. skilled people
3. tools and technology

As given in the introduction, the digitalization was chosen as the way to reach the aim. The processes should be updated to be coherent with the digitized tool, but in the meantime the leanness of the processes should be preserved. This constitutes the first sub-barrier:

maintaining the leanness of the processes during digitalization

The second sub-barrier is about keeping the skilfulness of the people after the digitalizing. Particularly the barrier is after a successful way of introducing the methodology to the company and teaching it to the employees so that the employees become skilful on the digital disturbance management methodology. Thus, the second sub-barrier is:

maintaining the skilfulness of the employees after introducing the digital methodology

It is possible to further divide the tool and technology related sub-barrier. The tool is a single-page (web) application (Scott, 2015; Flanagan, 2006). The parts, which a user can experience and interact with such a tool are: (1) functionality, (2) user interface, and (3) speed and performance; because the rest are hidden from the user (e.g., database) (Simmons, 2023; AWS, 2023). Since a user cannot interact with the rest of the tool, a user can evaluate the leanness of such a tool only based on these three points. Consequently, the three sub-barriers that are defined from these three parts are as follows:

defining the functionality for the digital support while maintaining the leanness of the tool during digitalization

defining the user interface for the digital support while maintaining the leanness of the tool during digitalization

defining the speed and performance for the digital support while maintaining the leanness of the tool during digitalization

The second barrier is the barrier towards the validation of reaching the aim and the hypothesis. The validation is planned to be done by applying the prescribed solution to the case company, capturing disturbances over time, making use of the captured data for the company's benefit, and thereby validating that existence of the prescribed solution prevented the elicited benefit from being wasted. Consequently, the second main barrier is

making sure that the disturbance information is captured to be reused for the benefit of the case company.

This barrier can be further divided into two sub-barriers to simplify the problem solving. Henke et al. (2016) states that "the biggest barriers companies face in extracting value from data and analytics are organizational". Aligned with this thread, in terms of making sure the disturbances are captured, the results show that the employees used the prescribed solution to capture the disturbances. However, as given in the results (paper-B 4.2.4, paper-C 4.3.1), the interviews showed that operators did not register minor disturbances. Minor disturbances bear the information that can be elicited by statistical analyses. Therefore, the first sub-barrier is defined as

capturing minor disturbances

The second sub-barrier is defined as follows. The literature and practitioners point out the pitfall of capturing data just to capture it (i.e., not making use of the captured data) (Burns, 2022). Lean digitalization requires the information to be "displayable, reusable and must be provided to the right person, in the right format, at the right moment" (Negri et al., 2017). Last but not least, real examples of making use of captured disturbance data is needed for the validation. Therefore, a second sub-barrier is defined as:

capturing the disturbance information in a way that it can be reused, while maintaining the leanness.

To summarize, the following barriers are defined:

- maintaining the leanness of the methodology during digitalization
    - maintaining the leanness of the processes during digitalization
    - maintaining the skillfulness of the employees after introducing the digital methodology
    - defining the functionality for the digital support while maintaining the leanness of the tool during digitalization
    - defining the user interface for the digital support while maintaining the leanness of the tool during digitalization
    - defining the speed and performance for the digital support while maintaining the leanness of the tool during digitalization
- making sure that the disturbance information is captured to be reused for the benefit of the case company.
    - capturing minor disturbances
    - capturing the disturbance information in a way that it can be reused, while maintaining the leanness.

5.1.2 Answer to the second research question

RQ2: How the barriers towards digitalised disturbance management in lean PPD can be overcome?

The second research question is about finding out how the barriers towards digital disturbance management, which were identified as the answer to the first research question, can be mitigated. First, the barriers were tried to be mitigated using hybrid pulse methodology case. The idea was to combine the best of both worlds (i.e. leanness and simplicity of physical and IT capabilities of digital world). A demonstrator was developed (chapter 4.1.2). However, it did not get acceptance from the users (chapter 4.1.3). Therefore, the case based on the digital pulse methodology that makes use of fully digital pulse board demonstrator, which got acceptance from the case company to be deployed to their premises, was pursued to mitigate the barriers.

Maintaining the skilfulness of the employees after introducing the digital methodology:
The digital methodology was introduced to the case company as given in paper-B, which is summarized under chapter 4.2.2. The following four problems detected after the introduction (paper-B chapter 4.2.4); the operators did not know/have:

1. the meaning of temporarily and permanently solved disturbance colors on the board
2. how to decide what should be put on the board
3. how to properly grade disturbances
4. the habit of going and writing the disturbances to the pulse boards.

The first problem was detected during the interviews. Even though they were explained the difference between temporarily and permanently solved disturbances during the teaching sessions, some of the operators stated that they do not know the difference. Upon discussing the problem with the engineers and the managers, a possible reason found to be that the operators were not responsible with closing the disturbances. Thus, they could not feed this specific knowledge that they learned during the teaching session with practice, and eventually it became obsolete. As a remedy, department managers reminded the difference between temporarily and permanently solved disturbances to the operators.

The second problem is about capturing minor disturbances. It is one of the main barriers defined under the first research question. How it is mitigated is discussed under its own heading under the second research question.

The third problem was about that the employees knew how to grade the disturbances, but the problem was that the grading rules did now work right for every possible disturbance (e.g., grading a disturbance that is minor for the present department but major for the next department in the workflow). These corner cases can be detected and solved with time as the company gains more experience using the methodology.

The fourth problem was experienced in the early days of using the methodology. Some of the reasons were (1) lacking the habit of using a new methodology, (2) high workload, and (3) stressful situations. In terms of mitigating this problem; the first part is discussed under capturing minor disturbances as mitigating the conformance to the norm of not registering minor disturbances. The second part is mitigated as follows. When operators do not have time to register a disturbance they have detected themselves, they began to either write a post-it note as reminder to register the disturbance later when they have time, or ask their colleagues to register it on their behalf.

These four defined problems were not stoppers; i.e., the employees continued using the methodology even in the presence of these four problems. In addition, as discussed under respective paragraphs, these problems were mitigated. The result of the introduction to enable employees that are skilful at using the digital methodology can be called successful as the employees could use the digital methodology over three years and the collected data could be made use of as given to the answer to the third research question.

Defining the functionality for the digital support while maintaining the leanness of the tool during digitalization:

Since it is hard to verify the leanness of the support objectively, the subjective verification given by the employees (i.e., verification by acceptance (Buur, 1990)) will be used as the benchmark. It is possible to add many, which are possibly unnecessary, functionalities to the tool thanks to being digital, which can make the tool complicated (Maguire, 2016). Therefore, as the result of discussions with the employees, it was decided to add only the functionality that is already present in the physical disturbance board. These functionalities were:

- add
- edit
- remove
- solve
- escalate
- move

The process of assigning an ID to the disturbance, which was done manually for the physical board, was automatized as a part of adding new disturbance. However, two new functionalities were added that weren't present at the physical tool:

- archive disturbance
- download statistics

The reason of having them was to add the long-term disturbance management (i.e., capture disturbances and reuse them) to the digital tool, that wasn't present at the physical tool. Thus, they were necessary functionalities to reach the aim of capturing and reusing the disturbance data. These two functionalities were used only by the managers and the engineers. Thus, the functionalities of physical and digital board were the same for operators. For them the methodology was maintained, and the tool was lean from functionality point of view. The two added functionalities were developed together with the managers and engineers keeping the leanness in mind. Neither managers nor engineers reported any distraction nor any damage to the leanness of the tool; they stated that the tool still feels lean. Possible reasons for such perception are (1) they could see the necessity of these two functionalities, (2) they were involved at the development, (3) these two functionalities are used seldom (once a week or once a month).

Defining the user interface for the digital support while maintaining the leanness of the tool during digitalization:

There are mainly two ways of digitalizing user interface: (1) designing from scratch, (2) keeping as it is. The benefit of the first way is having the freedom of updating the user interface making use of all the capabilities of IT technology in a way that wasn't possible for a physical tool. However, the drawback is that all users will need to familiarize themselves again from the beginning with the new user interface. In their guideline for digitalizing lean, Schumacher et al. (2021) (as cited in Schumacher et al., 2022) states that "Processes and technologies are to be designed in a human-centred way. Employees must be actively involved in decision-making processes." Therefore, as also preferred by the employees, the second way of digitalizing the user interface (using the same user interface design) was chosen. Thus, the methodology and the leanness of the tool was maintained since there is no change made on the user interface.

Defining the speed and performance for the digital support while maintaining the leanness of the tool during digitalization:
According to Navarro & Osiurak (2015), “people prefer to avoid idleness rather than to minimize effort”. Their findings suggest that users choose carrying out a task manually over automatically by an automatic tool if they need to wait idle long time for the automatic tool to finish the task. According to their findings, the “long time” is defined as longer than half the time it takes for the user to carry out the task manually. Example tasks for the tool at hand can be given as follows: escalating a disturbance to managerial board, changing the magnet colour to green to show that a disturbance is solved, writing short description for a disturbance while registering it. Most of these tasks can be carried out using the digital solution with one mouse click or touch on the touchscreen, which is automatically carried out and completed immediately; without any noticeable wait/idle time. The digital tool was fast and responsive mainly because it was a simple (functionality) and small-scale (number of users) application (i.e., it was not process heavy). On the other hand, carrying out some of these tasks manually can take much longer time. For example, escalating disturbances, which requires going to the managerial board and registering the same disturbance to the managerial board and keeping these to clones updated until the disturbance is solved. However, some tasks require writing text, which is carried out by physical keyboard or touchscreen keyboard on the digital tool, or using board-marker on the physical board. Even though readability of computer text typically better than handwriting, the former can take longer time if the user is not familiar with the keyboard layout. However, at a time where big majority of people use a smartphone, which uses a digital keyboard with regular keyboard layout, it can be said that writing text using keyboard is not an issue. Interviews and observations supported this theory. The managers and engineers use computer in their daily work; the operators on the other hand don’t. The operators stated that, even though their daily work does not require working with a computer, they are daily using computers, smartphones, and keyboards in their private lives. Therefore, it is not difficult for them typing a text using keyboard. Typing a text using touchscreen keyboard on the other hand is typically cumbersome and slow. Therefore, a keyboard is connected to each of the digital boards. Thus, it can be said that in terms of speed and performance there is an indication that the tool kept its leanness.

Capturing minor disturbances:
After introducing the digital methodology to the case company, during interviews it was found that operators do not register all minor disturbances (paper-B section 4.2.4). The following three problems are defined as the reason for not registering minor disturbances (paper-C chapter 0). The rationale for these problems and how they were mitigated (paper-C chapter 4.3.2) can be given as follows:

Problem 1: Thinking minor disturbances are unimportant
Rationale: The common thought among operators was that registering minor disturbances was not as important as their main work. Therefore, they did not stop their main work to go and register a minor disturbance. By the time they had time to report a previously detected minor disturbance, they had already forgotten about it. Furthermore, when they could solve a (minor) disturbance quickly, they thought it was not important/necessary to register it.
Mitigation: Operators were trained on the do more (i.e., registering disturbances) to do less (i.e., preventing disturbances, thus sparing the time to solve them) way of thinking. They were

reminded to capture minor disturbances. They were shown hypothetical examples of registering minor disturbances leading to improving the company and simplifying their daily work (e.g., replacing the machine that cause many minor disturbances with a new one). In addition, operators were shown real examples of how the disturbance data has been exploited (which is the answer to the third research question). A clear process of how/when to register disturbances were introduced. According to it, in case of main work needs to be focused and cannot be paused, operators shall write the disturbance on a post-it as a reminder to register it later or tell an available colleague to write/register it. Other times, disturbances shall be registered directly.

Problem 2: Conforming to the norm of not registering minor disturbances
Rationale: Minor disturbances were not collected while using physical tool. This was not an exclusive request from managers; rather a default behaviour from the operators. It did not cause any problems while using the physical tool because it was not possible to do statistical analysis on the data over long time. Thus, digitalizing the tool brought process changes; i.e., minor disturbances shall begin to be collected. However, this was not habitualized by the operators. Many operators stated their reason of not capturing minor disturbances was that the other operators also were not capturing them. Thus, the norm of not capturing minor disturbances that was present while using the physical tool still prevails.
Mitigation: In order to change the behavioural norm, the managers continuously conveyed that the norm has been changed from not capturing minor disturbances to capturing them.

Problem 3: Lacking a definition of disturbance
Rationale: During interviews operators stated that they do not know how minor a minor disturbance can be. When a disturbance is on the major side, then it is natural that it should be registered to the board. However, when a disturbance is on the minor side, then it is not always clear if it should be registered to the board. For example, does a fly that annoys an operator is a minor disturbance and should be registered? It may sound farfetched at first sight, but it may well be a useful minor disturbance. If many operators register a disturbance about a fly distracted them and slowed their work, it may be a sign of a sanitation problem. However, there is also a possibility that it is unnecessary to register such minor disturbance. As a result of this unclarity, operators stated that they do not register minor disturbance because they do not want to seem like they are "whining".
Mitigation: In the disturbance scale of minor to major, it is clear that all disturbances towards the major end of the disturbance scale shall be captured. However, it is not clear if and how long toward the minor end of the disturbance scale should be captured. To clarify this, a definition of "useful disturbances" (i.e., disturbances that can be exploited) is defined in this thesis:

- Disturbances that need to be remembered and followed up (e.g., disturbances that have not been fully solved)
- Disturbances that can be utilized by backtracking their information from the disturbance database (i.e., rare and/or statistically important disturbances).

The second point is still not very clear. The reason is that it is hard to define a generic lower line for the minor disturbances. It is hard to define such line even for the case company. Therefore, this research points out that the companies should decide their lower line by experience of using the tool. This is also supported by Negri et al. (2017), as they stated that definition of value is a big challenge for companies in the new data-driven context: "companies have to understand what value means for them and how to measure it".

Capturing the disturbance information in a way that it can be reused, while maintaining the leanness:

This barrier has two parts that needs to be verified:

1) If the leanness could be maintained
2) If the information captured per disturbance is enough so that it can be reused

The first part shall be verified by verification by acceptance. The second part shall be verified by the elicited results of analyses of the disturbance database (the answer to the third research question).

The more data is captured about an individual disturbance, the more ways to analyze and make use of the disturbance database. However, similar to deciding which functionality to add during digitalization, it is possible to damage the leanness by increasing amount of information to be registered; i.e., "using no more information than is required" (Negri et al., 2017). In such a case, it will be more difficult to register a disturbance, and employees need to spend more time registering disturbances, which can the leanness. Therefore, a balance should be found. Similar to deciding functionalities, mainly the same data required to be registered from employees while registering a database as while they were registering disturbance to the physical board. Which data each registered disturbance had in the digital solution is given in paper D (section 4.4.1). The benefits of digitalization used to automatize the registration. In physical board, the employee who is registering the disturbance needed to write an ID to the disturbance. In digital board this process is automatized, which increases the leanness of the tool by simplifying it and minimizing time spend. In addition, without requiring further manual work, the following additional disturbance information is automatically registered and updated for each disturbance:

- Status (new, closed)
- Date created
- Last modified date
- Visibility (on board, archived)

Up to this point, no additional disturbance information is required during the registration, in contrast, the number of information to be registered is decreased by automatization. Thus, the leanness is maintained, if not increased. In order to distinguish the reporter and the owner the disturbance, the company requested these data to be filled in while registering new disturbances. In addition, they can be useful data to analyse (e.g., finding the employee that registers least number of disturbances). The definition of them are as follows (paper-B chapter 4.2.3; paper-D chapter 4.4.1):

- Reporter: the employee that reported the disturbance
- Owner: The employee who is responsible to solve the disturbance

The interview and survey results showed that employees think that the disturbance registration is still lean. They reported that the disturbance registration did not take much time neither for physical, nor for digital board. Thus, adding the two new data to the disturbance registration did not damage the leanness.

Maintaining the leanness of the processes during digitalization:

Since the board is changed by digitalization, the processes around the board should be changed accordingly to fit the digitized board. While adjusting the processes, the leanness should be preserved. The following changes (as given in paper-B, chapter 4.2.3) have been made on the processes.

Escalate
The escalation procedure has been changed. Previously, while using the physical board, the managers escalated the disturbances by first adding the disturbance to be escalated to the respective managerial board, and second summarizing the disturbance during the managerial meeting. The managers still have to summarize the disturbance at the meeting for the digital solution. The difference is that the procedure of adding the disturbance to the managerial board is automatized. The managers use the escalation function to copy the disturbance to the managerial board by clicking the respective button.

Archive
At the end of each week, managers used to remove the solved disturbances on the physical board. So that the board is avoided to be overpopulated with solved disturbances. This procedure is improved in the digital solution with the “archive” function. This function (as the old procedure) removes the disturbances from the board, in addition, it archives them to the company servers. This way, the disturbance data prevented to be lost at the end of each week. This procedure enables re-using the disturbance information. Lastly, similar to the old procedure, managers carry out the archive procedure at the end of each week.

Grade
Previously only two colors were used to represent disturbances: red representing an unsolved disturbance, green representing a solved disturbance. To be able to prioritize the newly registered disturbances, a new procedure of grading the disturbance is added. The employee that is registering the disturbance should choose between the two colors: red representing major disturbance, and yellow representing minor disturbance. Another procedure regarding the color coding was added to differentiate between temporarily (workaround) and permanently (root cause) solved disturbances. Previously, when a disturbance is solved, its color is changed to green. The current procedure is that the employees should choose between permanently solved (represented by dark green) and temporarily solved (represented by light green).

Download
Since previously the information on the solved disturbances were lost at the end of each week, there was no necessity or possibility to carry out statistical analysis on the historical disturbance data. Since this is possible with the digital solution, a procedure of analyzing the historical data has been added. The procedure involves downloading the disturbance data from company servers to a computer and analyzing it with a help of a tool (MS Excel is used in this case). No strict time to carry out this procedure have been decided during the research project.

In terms of keeping the leanness of the processes after the changes, increasing the number of disturbance status from two to four was a necessity experienced by the company. In addition, there are lean physical tools that use three to four disturbance status. Escalation procedure was simplified to a click (instead of creating a copy disturbance at another board). Archive procedure was simplified to a click, as well (instead of erasing the solved disturbances by hand). Data analysis procedure is a new procedure that takes more time comparing to the other changes. However, it will be used more seldom than the rest. Three out of four changes were simplifications. It can be argued that simplification increases the leanness. The last procedure is carried out only when needed (e.g., once a month or year). Last but not least, the employees stated that they experience that the tool is still lean. They perceived similar leanness level for the digital solution as the physical solution. Thus, there is an indication that the leanness of the processes could be maintained after the digitalization.

5.1.3 Answer to the third research question

RQ3: How can disturbance data collected in a digital solution can be used to increase the decision-making capacity in an organization?

Negri et al. (2017) states that "the big challenge is ensuring that users get the most from the data, i.e. using it to increase the probability of making the right decisions, in the right context and for the right reasons". In this line of thought, the third research question is about finding ways to exploit the disturbance data that was captured by the digital disturbance management tool. It aims to show that (1) disturbance data can be captured by digital disturbance management tool, and (2) analysing the captured data (paper-D section 4.4.2) allows generating new insights to be used for strategic data-driven management (paper-D section 4.4.3). The importance of this research question is manifold.

1. Support the hypothesis:
    a. Reducing knowledge waste: Reducing the knowledge waste caused by physical disturbance management means that disturbances are captured, stored long-term, can be retrieved when needed, and the result of the retrieval can be used (i.e., beneficial). Showing the outcome of analyzing long-term captured disturbance data means that the disturbances have been captured, stored long-term, are retrieved, and the result of the retrieval was beneficial to the company by means of increasing the decision-making capacity.
    b. Maintaining the leanness: To be able to exploit disturbance data, digital disturbance management should be implemented and used over time in the case company to capture disturbance data. Operators willingly used the digital tool over time without problem. This supports that the leanness of the methodology was maintained during the digitalization process.
2. Mitigate a barrier towards digitalization: The answers of the third research question can be used to remedy one of the barriers defined in the second research question as follows. Showing operators possible ways of exploiting the captured minor disturbances would make them understand the importance and eventually capture minor disturbances.
3. Verify that a barrier towards digitalization is overcome: One of the barriers that were defined as the answer to the second research question was "Capturing the disturbance information in a way that it can be reused, while maintaining the leanness". The answer to the third research question can verify If the information captured per disturbance is enough so that it can be reused. Showing ways of analyzing and exploiting the data verifies that the information captured per disturbance is enough so that it can be reused
4. The extent of reaching the aim: The more the captured data can be exploited, the more the knowledge waste is reduced.

The answer to the third research question is as follows.

The digital disturbance management methodology was successfully implemented to the case company (as given in paper-B, chapter 4.2.2) iteratively by testing the implementation first at a pilot department, and upon success, implementing it to the rest. As seen in Figure 35, over three years' time the employees have used the prescribed solution to capture the disturbance data. In addition, employees could use the digital demonstrator successfully for capturing disturbances. This result can be used as the verification by acceptance. Thus, there is an indication that the leanness of the processes and the tool could be preserved, and the users were skilful to capture the disturbances even after the digitalization process.

The captured disturbance data is stored to a database at the case company servers. It is downloaded and analysed using MS Excel. Both qualitative (e.g., analysing free text input) and quantitative (e.g., calculating the number disturbances) analyses were carried out. These analyses are given in paper-D chapter 4.4.2, and insights generated from them are given in paper-D chapter 4.4.3. These analyses can be grouped mainly under two categories: (1) classifying and sorting the disturbance, and (2) Identifying repetitive disturbances. As a result of the first analysis method, latent problems and improvement investment areas were identified. As a result of the second analysis method, seemingly trivial disturbances that feature high total cost when all repetitions are summed up, were identified. The result of the analysis is beneficial for the company by increasing the decision-making capacity as follows. Detecting latent problems provides the opportunity to take countermeasures in time so that the latent problems can be fixed using less resources and with less damage caused to the company (compared to fixing them after they get bigger and easy to notice). The information of improvement investment areas means that the companies have the information on which areas incur how much cost over a given time. Then companies can calculate how much a possible solution would cost to fix these problematic areas. This way return on investment can be calculated. Thus, companies can take the decision on which areas to invest improvement resources using the disturbance data Concrete examples on how the case company data could be used to increase decision making capacity have been given under paper-D part of the results chapter with heading “4.4.3 Learning from analyzing the disturbance database”. Without the prescribed solution, the case company would have access to neither the captured disturbance data, nor the elicited conclusions upon analysing the disturbance data (i.e., they would have been wasted). This validates that the prescribed solution reduced knowledge waste.

5.2 Discussions on the decisions made

Under this heading, various decisions made in the thesis will be discussed.

5.2.1 Defining disturbances – pragmatic vs semantic definitions

De Smet et al. (1997) suggests a pragmatic approach and having a workable definition, rather than debating on semantics. Kaya & Bergsjo (2016) (paper-C) gives the following pragmatic definition: all deviated and unwanted states and actions that needs (1) a follow up, and/or (2) occur rarely, and/or is (3) statistically important”. These disturbances were referred as “useful deviations” in that article; referring to disturbances/deviations that bring benefits to companies when they are registered to disturbance management boards, thus gives the practical definition of disturbances/deviations.

De Smet et al. (1997) also suggest defining disturbances and how they are measured in close collaboration with the people on the shop-floor, because they have the experience with what goes wrong daily, and they will be the users of the disturbance registration system that will be designed based on the defined disturbance model. During the long-term participant observation, the author continuously engaged with the operators and received their opinions on what constitutes disturbance and how can they make use of them if they capture them.

5.2.2 Digitalization – from legacy vs from scratch

Two digitalization ways were tested in this thesis: (1) hybrid (i.e., partly physical and partly digital), and (2) full digitalization. And full digitalization way was chosen for the implementation. Mainly two digitalization ways were considered: (1) from scratch, and (2) from legacy. Both have own benefits and drawbacks. Shortly, digitalizing from scratch gives wider control to the designer: the designer can make use of the digital technology at its best. The main drawback with this way is that the users are used to the legacy tool and the way it works. Thus, introducing a tool from scratch with a new look and new functions is harder (in terms of users learning and getting used to it) comparing the second way (i.e., digitalizing from legacy). Thus, the main benefit of digitalizing from legacy is that the users are already familiar with the tool, and the introduction of this new digital tool is a lot easier comparing the first way. The drawback is that the designer does not have the freedom as in the first way while designing the new tool. To make a smooth transition at the case company, we digitalized the company's pulse board from legacy (comparing to digitalizing from scratch).

5.2.3 Demonstrator – customized vs standard

In a parallel track, another pulse board has been being developed simultaneously. The question that occurs is the possibility of using a single pulse board for both companies. There are no solutions that suit every organization; regardless of how it is developed, it is unique to the organization it is applied (Holmdahl, 2010). Just like consultants cannot transform an organization into lean (i.e., the organization must do it itself), a complete solution (e.g., software) cannot be expected to work for the organization right out of the box (Holmdahl, 2010). The solution should be result of the organizations own work, and the chosen solution should be adapted to the particular conditions of the organization (Holmdahl, 2010). Organizations and their processes are the important parts, IT systems are just enablers; therefore, IT systems should be adapted to organizations, not the other way around (Grieves, 2006). Some vendors provide products with customization options; however, even they will affect the way companies work (Duffy & Andreasen, 1995). Therefore, we have decided to develop separate pulse boards in two separate tracks, however using similar software architecture in the back-end.

5.2.4 Structured vs semi-structured literature review

Structured (or systematic) literature review is one of the most rigorous and accurate method to collect articles. Structured review aims to "identify all empirical evidence that fits the pre-specified inclusion criteria to answer a particular research question or hypothesis". Thus, all relevant data is covered in structured literature review. However, structured review is not feasible nor suitable for all kinds of projects. When the topic to be researched is broad and covers diverse disciplines, semi-structured review fits better. In addition, it is not possible to review every single article that is relevant in such projects, which also makes semi-structured review fit better. (Snyder, 2019)

5.2.5 Methodology introduction – big-bang vs incremental?

Mainly two methodology introduction ways have been considered: (1) big-bang introduction, and (2) incremental iterative introduction. Big bang introduction is particularly appreciated by lean and Agile-Scrum practitioners; they claim that full effect of these methods can be surfaced only when they are introduced with all their aspects on a wide scale. Because of the amount of changes on the processes and the scale of the change on the number of business unit, it bears great risk. Thus, following a big-bang introduction can bring great win but also a great loss. In order to mitigate the risk, this way has not been chosen. In addition, both lean and Agile-Scrum are established methods in comparison to pulse methodology. There are many books and success stories/recipes about them, which can be adopted directly without tests (given the aforementioned risks). However, Pulse is a new methodology; there is neither much experience nor much written/published about it. Therefore, it is not fit for the big-bang introduction.

In the current thesis, Juran and Gryna's (1993) suggestion was followed: "start small and learn from pilot activities" without being rushing to sizeable results. Their approach is referred as "incremental iterative introduction method" in this thesis. The reasons of following this introduction method were to (1) lower the risks, (2) have the possibility of performing build-test-learn-build cycles (as given in Cronje, 2013).

Figure 23 in chapter 4.2.2 summarizes the methodology introduction steps carried out in the case company. First, the physical pulse methodology was introduced to the pilot department. The workshop department had been selected as the pilot group. The reason for this was the department manager's positive attitude towards trying new ways for improvement. Second, digital pulse methodology was introduced to the pilot department. Third, the digital board was connected to the company network. After seeing the success in that pilot implementation, fourth, digital pulse methodology was introduced to the rest of the company.

5.2.6 Choosing the case company

The case company is a product development and production company within dental implants business. They are a separate business unit in a large organization. The unit has around 65 employees. The integrated configuration and production flow works serially in the company as follows. The mouth casts of patients are received from dentists and scanned by the scanning department. Then the abutments are designed using a CAD program by the design department. After the design is approved, it is sent to machining to the workshop department. After the parts are produced, they are sent to verification. Once they are verified, they are packed and shipped to customers.
The case company was chosen based on the following criteria:

- Distance: being close to Chalmers University of Technology, where this thesis has been carried out
- Business: Product and production development which matches the research group and the department that the thesis has been carried out
- Accessibility: that we have contacts inside the company so that we can arrange interviews, observation sessions, or distribute surveys when necessary
- Using lean: Uses at least one physical lean tool
- Experimentability: The company should allow implementing the developed demonstrators to carry out the research.

5.2.7 Choosing the keyword "disturbance"

Selecting the right keyword and framing the research are important points at finding the right literature to read and find out previous research on the topic. Below are some of the keywords that their daily use is similar to the use of "disturbance", but in an academic context their meanings differ from each other.

<u>Deviation</u>: The keyword deviation has been interchangeably used in literature with disturbance. The PhD student has also previously used that keyword in some of the published articles. However, deviation is also used in literature referring the deviating circumstances

(now only towards negative, but also positive), therefore the keyword disturbance is chosen to be used as the main keyword.

Hazard: "a condition that can cause harm, injury, death, damage, or loss of equipment or personnel" (Bahr, 1997)

Failure: "Loss of function when we want the function" (Rees, 1993), or "The event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified" (MIL-STD-721, 1991)

Exogenous Shock: E.g., forest fires tornados, floods that can cause significant organizational loss (Ramanujam & Goodman, 2003)

Latent Errors: "Latent errors refer to events, activities, or conditions that deviate from expectations, and may cause adverse consequences of organizational significance. The principal characteristics of latent errors are: (1) a set of organizational expectations, (2) deviations from these expectations, and (3) absence of direct consequences. We emphasize the absence of immediate consequences because nothing inherent in a deviation can automatically generate adverse consequences. Several enabling conditions and processes are needed to link latent errors with such consequences" (Ramanujam & Goodman, 2003)

Error: "Errors are essentially unintended deviations from rules or procedures (e.g., failure to verify medication before administering it to patients, non-compliance with safety guidelines in a coal mine) that can potentially result in adverse organizational outcomes" (Ramanujam & Goodman, 2003)

Employee Deviance: "…voluntary behaviour that violates organizational norms" (Galperin, 2003)

Workplace/Employee Deviance: "Voluntary behaviour of organizational members that violates significant organizational norms and, in so doing, threatens the well-being of the organization and/or its members." (Robinson & Bennett, 1997)

Organizational Deviance: "an event, activity, or circumstance, occurring in and/or produced by a formal organization, that deviates from both formal organizational design goals and normative standards or expectations, either in the fact of its occurrence or in its consequences, and that produces an unanticipated suboptimal outcome" (Vaughan, 1999)

Organizational Errors: "… the actions of multiple organizational participants that deviate from organizationally specified rules and procedures and that can potentially result in adverse outcomes for the organization." (Goodman et al., 2011)

Mistake: "… deficiencies or failures in the judgmental and/or inferential processes involved in the selection of an objective or in the specification of the means to achieve it" (Reason, 1990)

Issue: "An issue is defined as a threat to the project objectives that cannot be resolved by the project manager." (APM, 2006)

Problem: “concerns that the project manager has to deal with on a day-to-day basis” (APM, 2006)

Risks: “Risks should not be confused with issues. Risks are uncertain in that an event may not occur, whereas issues have already occurred and are therefore not uncertain” (APM, 2006)

5.3 Opposing results from other research

Under this heading literature that opposes to the results of this thesis will be given and discussed.

5.3.1 Automatic vs manual disturbance registration

Forza (1995) states that “one of the main aids in information technology is the ability of some machines to carry out on-line control automatically. It allows immediate signalling of defectiveness and avoids the repetition of defectiveness before production is stopped. It also makes it possible to collect data to be processed subsequently off-line without forcing the operator to spend a lot of time on data entry.” Disturbances can be recorded automatically in real-time. This has been discussed in literature (e.g., Stojanovic et al., 2015); however, this literature has been excluded from this research. The reason being that it requires high investments. Even though the literature on digitalizing manufacturing has travelled far (Mittal et al., 2019), the reality of the industry has not reach there (Leurent & Boer, 2019). This is true especially for small and medium size enterprises due to lack of skills and scarce financial resources (Lorenz et al., 2019). As in this case company, they had not even had a physical disturbance management system (e.g., physical pulse board) in place. Realizing a (pilot) disturbance management system was the first step. Digitalizing it and introducing it to the whole company, as the second step, was achieved by the project of which this thesis is a part of. Another claim of the citation above is that employees spend a lot of time registering disturbances. It is a fact that an automated disturbance registration system will take shorter time for employees to register disturbances (if not no time) comparing a manual system. This difference on spending time can be analysed in terms of employer’s and employees’ perspective in the case company. From the employer’s perspective, this initiative got their approval; thus, they accepted the terms of employees spending time on registering disturbances. In terms of the employees’ perspective, the following points can be discussed. Even if manual registration can be done quickly, employees still need to pause their work momentarily, which can cause inconvenience. Thus, employees’ acceptance on the methodology will give indications on the affect. In order to check the acceptance of the digital pulse at the case company, we had checked if the employees consider/feel that registering disturbances takes too much time. Interview results showed that they do not think that it takes too long time. In addition, they continuously used the system and registered disturbances, which shows that the system got their acceptance. Last but not least, they all are familiar with digital system from their smart phones and other digital tools that they use daily (e.g., PC, ATM, smart TV, tablet etc.), therefore they can use the user interface to register disturbances at a good speed. The only problem that the interview results showed was that in high workload situations, which is found to be rare as the interview results showed, employees did not register disturbances right away. Instead, they kept it in their mind to register later on or asked a colleague to do it for them.

5.3.2 Focusing on the methodology while using digital lean tools

Activity theory discusses that one should not do two tasks simultaneously. First, one of the tasks should be focused and learned so that one can do it even unconsciously. After that, the second one can be focused on. If two tasks are being done simultaneously, then one of them is favoured over the other; the tasks that is not favoured is carried out in a sloppy manner. This is in lined with what lean practitioners suggest; if the lean tool is digital, then the user typically focuses both on following the aspects of the methodology and controlling/navigating the digital user interface. This means that the user will do one of them in a sloppy manner. For example, they will either give poor performance on using the methodology by failing to explain the disturbance good enough with right keywords, or fail using the digital tool by writing the disturbance data but forgetting to save it. We did not find any negative results from the case company using the digital lean tool. For the pilot department, one can say that they have previously used the physical version, therefore, they do not need to focus on the methodology. But other departments had not used the methodology before. The simplicity of the designed user interface, and its similarity to the original physical board (at least for the pilot department) can be the reason of the smooth introduction and usage of the tool afterwards.

5.4 Validity

All appended papers have gone through peer review as a part of publication process. In addition, the PhD student have presented them in various settings to other researchers. For instance, all results and analyses have been presented at Wingquist Laboratory workshops where industrial and academic partners take part at. These activities of sharing and discussing analyses and results with experts served as an external acceptance. Last but not least, a demonstrator is developed, presented and implemented to the case company, from where, feedback has been gathered regarding the actual prescribed solution.

Maxwell (2013) suggests the following validity checklist to identify and tackle the validity threats: (1) intensive long-term involvement, (2) rich data, (3) respondent validation, (4) reactivity, (5) searching for discrepant evidence, (6) triangulation, (7) using quasi-statistical date, (8) doing comparisons. In this chapter, these eight points will be discussed.

- ✓ *<u>Intensive long-term involvement</u>*

In terms of long-term involvement, the case company has been part of the research project over three years. In terms of intensive involvement, the PhD student was present at the case company for participant observation, interviews, updating the code of the demonstrator, and other research related activities. In addition, the PhD student was present at the case company even when there is no research activity planned, doing other work. The reason was to increase the amount being present at the case company to increase the intensively. Some of the benefits of this was ad-hoc discussions, unplanned observations of interesting events, and creating rapport with the employees.

- ✓ *<u>Rich data</u>*

In this research study literature review, interview, participant observation, survey, quantitative data analysis, workshop methods have been used for gathering data. Thus, the gathered data were rich in terms of variety. In order to make these data rich, the interviews have been recorded and transcribed, and observations have been noted down objectively by writing down the observed situation.

- ✓ *<u>Respondent validation</u>*

During interviews, when the interviewees' answer was (1) not clear to the interviewer (who is the author of the current thesis), or (2) it contradicts with the previously gathered data, interviewer rephrased the interviewees' answer and asked it back if that was what they meant.

Taking into account that the answer for this rephrasing and asking back action can have the same validity threat, the interviewer continued this rephrasing and asking process until getting an answer that conforms both of the points mentioned above (i.e., clear and non-contradicting answer).

- ✓ *Reactivity*

Regarding the reactivity, one of the case company engineers being graduated from the same research group as this study is being carried out, him being co-author of one of the articles, and being one of the people that drives this research project in the company forms a possible validity threat in the gathered data. This validity threat may have happened in the sense that the participants may have behaved differently during the observation activities, and may have not gave honest answers during the interviews. This validity threat has been acknowledged. In order to prevent it, the interviews have been carried out by only the author of the thesis (i.e., without the presence of the aforementioned engineer).

- ✓ *Searching for discrepant evidence*

The author actively searched for discrepant evidence, particularly during the interviews. In order to get possible discrepant evidence from the interviewees, the author (as the interviewer) asked questions that would surface possible drawbacks of (1) the methodology and (2) the change arising from the implementation of the methodology to the company. In addition, the research has been published at conferences and journals, and presented to other researchers to get their feedback.

- ✓ *Triangulation*

The data have been gathered using various methods from various sources, which eliminated validity risks of individual methods or sources. These methods and sources were as follows. The empirical data have been gathered using interviews, surveys, participant observations, literature review, workshops, and quantitative analyses of the database. The data gathered from different sources; employees from different departments with different titles. These titles were namely, operator, engineer, middle-manager, and top manager.

- ✓ *Using quasi-statistical data*

This guideline has not been followed. The reason was that, except a couple of respondents, all respondents gave the same answer on quantitative questions. The idea was that, providing quasi-statistical data helps on describing circumstances where respondents divide into 60-90% (or 10-40%) groups, which is hard (in terms of correctness) to explain with qualitative words. Since the gathered results were out of these perimeters (i.e., 90-100% or 0-10%), which can be explained easily (in terms of correctness) with qualitative words. Thus, the author did not have the need to use quasi-statistical data to represent the results. Furthermore, the conferences and journals can have their own ways of writing articles; they may have tendency to use qualitative descriptions in qualitative research, and quasi-quantitative descriptions may be discouraged. No feedback regarding converting some qualitative descriptions into quasi-statistical descriptions have been received from neither conferences nor journals.

- ✓ *Doing comparisons*

To be able to do comparisons, the author (1) reviewed the literature (comparison with existing data), (2) carried out detail interviews where he asked not only "what" but also "why" questions until getting to the root reasons, (3) during these interviews also extracted the information about both the case company at an earlier state and also another company that the interviewee have worked before.

5.5 Validation and verification

Theoretical structural validity:

1) *Accepting the construct's validity:* The gap defined and the constructs used in this thesis are based on the previous research as presented in the frame of reference chapter. The only diversion is the construct defined as "lean disturbance management". It is not a construct that is typically used in the literature. The reason of using such construct is as follows. Disturbance management is not necessarily is a subset of lean. On the other hand, there are lean disturbance management tools that are used in -for example- lean product and production development. Pulse, which is used by the case company, is such a tool. In order to narrow down the research area, the part of the disturbance management that can be considered as the subset of lean is focused. To be able to refer this subset, an alias was needed to be created. Thus, lean disturbance management construct is used. As seen, it is not a construct that is created in this thesis. It existed as a subset of another construct, however, it was not referred before in the literature.
2) *Accepting the methods consistency:* The time flow of the research project (physical, hybrid, digital solutions) is given with the respective reasons of decisions taken each step. These reasons typically are based on literature, feedback from the industry, and internal logical inferences. All these were given in the thesis. In addition, the tested information that is coming from the literature was separated from the untested information that is based on the hypotheses (assumptions). These hypotheses were made open to the reader and was tested in the research project.

Empirical structural validity:

3) *Accepting the example problems:* The reason of choosing the case company (i.e., why it fits for this research project) is given at the discussion chapter, under the respective heading.

Empirical performance validity:

4) *Performance of the solutions with respect to the example problems:* The prescribed solution is developed as a demonstrator. The demonstrator is deployed to the case company. It has been used by the case company throughout the thesis project (i.e., over three years). Both qualitative (interviews, observations etc.) and quantitative (statistical analyses on the disturbance database) test results have been gathered. Thus, the trustworthiness of the prescribed solution is increased. The degree of articulated industrial purpose is reached is shown as a result of a quantitative analysis on the disturbance database (i.e., the number of ways the case company could make use of the knowledge on the disturbance database). The published articles and the scientific contributions that are defined in this thesis can be counted as the degree of reaching the scientific purpose.
5) *Accepting that usefulness is linked to applying the solution:* In terms of checking if there are other variables that could affect the results of the data collection, reactivity (i.e., the results of the e.g., observations and interviews diverges from the routine because of the presence of the researcher (Zahle, 2023)) was discussed under the validity heading. In order to minimize possible affect other variables to the research

flow, all demonstrators were tested at the same department at different occasions, and the results are compared to each other. Finally, the quantitative analysis that was used to analyze the performance of the prescribed solution was done at the disturbance database, which was solely created by the prescribed solution. This indicates that the usefulness is linked to the applied solution.

Theoretical performance validity:

6) Accepting that the usefulness of the solution is beyond the example problems (case studies): The previous fives questions were answered positive, which gives a good basis for generality to this research. Furthermore, the transferability is discussed in detail at discussion chapter, under the respective heading.

Verification by acceptance:

Mainly two types of acceptance were received for the present research, industrial (from the case company), and scientific (from other researchers). After presenting the demonstrator to the case company, first they have accepted to deploy it to the case company. After that, the employees used it over three years. The amount of disturbance data collected and the time frame of the collection shows that the employees used the prescribed solution willingly, which is a type of acceptance from the users. The third acceptance from the case company was accepting the benefits of the prescribed solution after using the tool over three years. The last type of acceptance received is from the research community. The results of the research have been published and presented to other researchers, and their feedback was collected. The results have been well received by other researchers.

5.6 Implications

5.6.1 Transferability

Transferability will be discussed in two parts: (1) transferability of the prescribed solutions and (2) transferability of the answers to the research questions.

5.6.1.1 Transferability of the prescribed solutions

Under this heading if the prescribed solutions can be used at other companies will be discussed. In order to do this analysis more systematic and comprehensive, the target set is divided as follows:

- Companies that use similar methodology as the case company
    - Companies that have been using a board
    - Companies that have not used any board
- Companies that use a different methodology than the case company
    - Companies that find the method in this thesis better than their present one
    - Companies that are content with their method or find their method better than the one prescribed in this thesis

One of the starting points of the prescribed demonstrator was that companies should not adjust their way of working according to the tools; in contrast, the tools should be adjusted according to the companies'. Following the same philosophy, it can be said that the prescribed solutions can be used at other companies that use similar methodology with the case company. Provided that the user interface is adjusted according to those companies' physical disturbance boards. If they haven't used any board before, then even the same user interface designed in this thesis can be used without any change.

In terms of the companies that use different methodology than the case company; aforementioned philosophy still can be used. Thus, if a company uses a methodology that fits its needs, then they should continue using their methodology. The intriguing question here if any of those methods better than the others. And the follow-up question is, then can it be reasonable to change the company's way of working according to the tool to be bought. It is quite difficult to choose a best method/tool. Typically, there are no silver-bullet methods; rather, there are methods that fits to particular companies/needs. Therefore, a second philosophy -that was mentioned in the frame of reference- can help here: focus improvement resources on the necessary areas (such as captured disturbances). Improvement investments on the non-problematic areas not only takes the resources and focus away from the areas that should be improved, but also may give a much lower return on investment. Therefore, unless companies think that their present method does not meet their needs, the same method should continue to be used. And, if the company notices that the method they are using is not meeting their need (i.e., Companies that find the method in this thesis better than their present one) then these companies can use the prescribed solutions in this thesis.

5.6.1.2 Transferability of the answers to the research questions

The transferability of the answers to the research questions will be discussed under this heading.

<u>*RQ1:*</u>
The information on how pulse methodology works in general is given combining the case company and the literature, therefore it is transferable. Six of the defined barriers were given using the literature. Therefore, they are transferable. Three of those six barriers were tool related, which are also transferable since all digital applications have user interface, functions and performance. On the other hand, other barriers may exist for other digital tools that makes use of other technologies (e.g., virtual reality, artificial intelligence). One barrier that was discovered from the case company is also transferable since it is important to capture minor disturbances to be able to do statistical analyses, and clarifying the lower limit of minor disturbances need to be done by all companies.

<u>*RQ2:*</u>
The way tool and technology related barriers overcome can be transferable since it is suggestions given in literature is followed. In terms of the barrier about introducing the methodology to the company and teaching it to the employees, it is transferable to another case where the employees have equal or higher digital tools familiarity. I.e., introducing the digital tool to employees that are not familiar with digital tools may require more to be successful. In terms of overcoming the capturing minor disturbances barrier, defining the lower limit of minor disturbances require experience and it may be company specific. In terms of barriers about deciding the data columns and processes, literature guideline was followed. The solution given in this case may perfectly work for another similar company; or companies may follow the same methodology to create their solutions.

<u>*RQ3:*</u>
If similar methods used to analyse a disturbance database, similar learnings should be acquired as the result. Therefore, this result is transferable to other settings. However, additional learnings are possible to be acquired if additional analysis methods employed.

5.6.2 Sustainability

The three pillars of sustainability are: (1) environmental sustainability, (2) economical sustainability, and (3) social sustainability. This thesis has implications on two of these pillars: environmental and social sustainability

5.6.2.1 Environmental sustainability

Environmental sustainability refers to sustaining the habitat on earth. The world is a sustainable place where everything continues its existence in harmony with the rest. Thus, it can be interpreted as unless disturbed, the environmental sustainability works automatically. Therefore, environmental sustainability can be considered as to minimize the effect of humans to the nature. There are companies that have big negative effects on the nature, such as throwing toxic waste to nature. These companies tend to think that any action they would do to prevent affecting the nature negatively will cost them money. Therefore, companies that prioritize profit over sustainability of environment will continue polluting the nature. Against all these companies, Gordon (2001) shows that lean and environmental sustainability can work together; companies can actually increase their profits with the measure they would take against affecting the sustainability of the environment badly. This is in lined with the do more to do less philosophy.

The hybrid solution makes use of white board, webcam, web-app, and a computer that is connected to the company's network. The digital solution makes use of a digital screen, web-app and a computer that is connected to the company's network. As seen, both solutions use physical products and electricity. Defining carbon footprint of both solutions is difficult. There are many factors that should be considered; some of them are as follows:

- the energy class and the size of the screen used
- if the screen and webcam are open throughout the day or only when needed
- are there separate screens for each department or are they sharing same TV?
- the electricity source that the company is using (recyclable or fossil)
- If recycled products used at manufacturing the physical products

As seen, it is difficult to reach an overall conclusion. However, it is possible to come to conclusions on specific parts. One of such part is data storage. Storing the history of how previous disturbances have been solved via hybrid and digital solutions is better at sustainability compared to for example doing it with papers. Based on their literature review, Kabzhassarova et al. (2021) also mentions positive correlation between environmental sustainability and digitalized lean.

5.6.2.2 Social sustainability

The aim of the social sustainability is to provide liveable and equal living standards to every member of this and next generations. Thus, the thing to sustain the social sustainability is the quality of living. A useful model, The WACOSS (Western Australian Council of Social Service Inc.) gives the five principles of social sustainability (WACOSS, 2008; Baron & Gauntlett, 2002):

1. Equality
2. Diversity
3. quality of life
4. interconnectedness
5. democracy and governance.

Data transparency is an important lean principle (Schumacher et al. 2021, as cited in Schumacher et al, 2022). It can be claimed that both hybrid and digital solutions that are prescribed in this thesis contributes to social sustainability by increasing the equality in the company via providing data transparency. The data on each department and the managerial disturbance board is accessible to all employees in the prescribed solutions. Thus, all employees, if they want, can reach the data on the disturbance status of the whole company. Sony (2018) also supports that digitalized lean increases data accessibility by horizontally integrating the departmental systems.

In addition, the social sustainability is increased by equalizing the workload between departments. The information on the managerial disturbance board in the case company shows both current workload and available workforce for each department. Using this information, the department managers can help each other by sending temporary workforce to each other in the managerial meeting. This increases the social sustainability by equalizing the workload between the employees. As a result of their literature review, Kabzhassarova et al. (2021) also supports that digitalized lean maintains work pressure at an allowable limit, and increases employee health and well-being. The latter was not investigated in the case company, but it can be considered as a result of normalizing workload, which in turn prevents workload peaks and keeps it at an acceptable level.

5.6.2.3 Economic sustainability

Economic sustainability refers to economic growth that does not negatively affect other two pillars of the sustainability.

The proposed solution guides companies to do the right improvements. By doing so, it helps companies have a high return on investment. In the meanwhile, it does not negatively affect neither social sustainability nor environmental sustainability. Thus, it can be said that the proposed solution increases economic sustainability. Various publications also state that digitalized lean increases economic sustainability by increasing operational and process performance (Tortorella & Fettermann, 2018; Dombrowski et al., 2017; Mayr et al., 2018). Similarly, Dahmani et al. (2021) states that integrating lean and digital technology contributes to circular economy.

5.6.3 Business and societal implications

Typically, production moves to the markets where the workforce is cheaper. This benefits the company, but harms the country economy they leave. Sweden is one of the markets with the most expensive workforce. One way for Swedish companies to compete with competitors that benefits cheap workforce is by optimizing the production. The prescribed solutions in this thesis can increase the efficiency in Swedish production, which in turn helps keeping the production in Sweden. Keeping the production in Sweden means decreasing unemployment rate by increasing the job opportunities, strengthening the country’s economy by exports.

5.7 Contributions

This thesis has been carried out in Chalmers Wingquist Laboratory, which aims to carry out research ideas by developing demonstrators and implementing them in real company settings. Thus, this thesis aims to contribute both to science and industry.

5.7.1 Industrial contributions

Industrial contributions include outcome of this thesis and outputs from the project this thesis belongs to, that benefit the industry. Thus, the industrial contributions include (1) systems that have been introduced/applied to the case company, and (2) theories, results, conclusions, experiences that were published in the articles, which may benefit other companies. These contributions are as follows:

- ***Action:*** Hybrid pulse methodology and a demonstrator for it were developed. ***Effect:*** It has not been used by the case company. However, how it was developed, how and why it can be used was given in the publication; thus, other companies may implement and use it.
- ***Action:*** Digital pulse methodology and digital pulse board were developed. **Effect:** Both methodology and tool details have been published so that other companies can implement and try it out.
- **Action:** Digital pulse methodology was deployed to the case company in 2013 and by 2018 (as the year this thesis has been published) it still has been in use. Five digital pulse boards have been installed and have been used by around sixty users. **Effect:** The boards had increased accessibility; read/write actions can be done from distance. Knowledge waste regarding the disturbances was mitigated. Statistics about the disturbances were captured with the aim of guiding improvement work and finding latent problems. How disturbances had been solved was captured with the aim of creating a continuously extending solution database.

5.7.2 Scientific contributions

Scientific contributions of the present thesis are given below in bullet points and cross-referenced with the gaps given in frame of reference. The scientific contributions of the present thesis are as follows:

- How disturbances can be managed by digital pulse methodology was given (gap 1).
- Disturbance data has been collected over three years. How the data can be analyzed and how the results of the analyses can made use of is given (gap 2).
- Barriers to digitalizing physical pulse methodology and how can they be mitigated is given (gap 1, gap 2).
- Giving which disturbances to capture (i.e., what constitutes disturbance for digital disturbance management) (gap 3).
- Giving successful case of digitalizing and introducing the disturbance methodology to an integrated product development company within dental implants business (gap 4)
- Hybrid pulse methodology was coined based on a case company and a demonstrator for it was developed. The demonstrator is presented to three companies. It did not receive acceptance due to the technology it uses (i.e., image recognition) was not considered robust, and that the demonstrator did not allow two-way information conversion (gap 5).

5.8 Future Work

Two future-work were defined. They will further widen the knowledge on the topics that the present thesis has also contributed.

Disturbance database can be used to guide improvements and investments. In the present thesis, the guiding metrics that were used to define improvement and investment areas were the number of disturbance occurrence at a particular machine or flow. However, using monetary terms as the guiding metrics would give more robust and precise results. How this can be done also discussed in paper-D under the improvement suggestions heading in the discussion chapter. Thus, the first future work is calculating the incurred cost of each disturbance.

Disturbance management (or disturbance handling as Bellgran & Aresu (2003) refers it) includes foreseeing and preventing disturbances (Bellgran & Aresu, 2003). In this thesis, a possible way of preventing disturbances is mentioned by re-using the registered disturbance data, finding the machine or flow that caused the highest number of disturbances (or incurred the highest cost), and investing in it to improve. Though, this is a reactive prevention method. Proactive prevention methods can be machine maintenance and continuous improvement on the processes, which are not part of this thesis. However, a fitting future work can be adding systems to foresee disturbances (as given in Bellgran & Aresu (2003)). This can be done by feeding the compiled disturbance data to a neural network, and using it to predict upcoming disturbances.

6 Conclusion

This thesis focused on identifying and mitigating problems of physical lean disturbance management by introducing and evaluating digital lean tools. The aim was to generate knowledge about reducing the knowledge waste in physical lean disturbance management. The hypothesis guiding this thesis was that digitalization can reduce the knowledge waste in lean disturbance management while maintaining the leanness of the methodology. Lean disturbance management was defined as solving disturbances systematically (i.e., capturing, highlighting, following up, solving, storing, and re-using) using lean in this thesis. These activities generate knowledge and data that can be re-used in generating new insights to be used for data-driven decision making in management (e.g., process improvements, improvement investment decisions such as buying new machines etc.). However, they are not captured today by lean disturbance management tools that are typically physical.

Three research questions were defined focusing on barriers, means to overcome the barriers, and validation. In total seven barriers were defined, which are grouped under two categories: maintaining the leanness during digitalization, and making sure that the disturbance information is captured to be reused for the benefit of the case company. The defined barriers were mitigated. As a result, the prescribed lean digital disturbance management system has been deployed to the case company and disturbances has been captured by the employees over three years. The collected data has been analysed for validation. The aim has been fulfilled by, as a result of the disturbance data analysis, eliciting concrete examples on how the case company data could be used to increase decision making capacity. These elicited examples include: identifying latent problems, guiding improvement work and investments, and exposing seemingly trivial repetitive disturbances that incur a high cost over time.

There are two main contributions of this thesis. First, giving a successful case of digitalization of lean in industrial settings. Second, showing that knowledge waste in physical lean disturbance management can be reduced by combining digitalization and lean.

The following two future work were defined that will further widen the knowledge on the topics that the present thesis has also contributed: calculating the incurred cost of each disturbance, and feeding the compiled disturbance data to a neural network and use it to foresee and proactively prevent disturbances (e.g., via maintenance).

7 References

Aasland, K., & Blankenburg, D. (2012). An analysis of the uses and properties of the Obeya. In Engineering, Technology and Innovation (ICE), 2012 18th International ICE Conference on (pp. 1-10). IEEE.

Aasland, K., & Blankenburg, D. (2012). An analysis of the uses and properties of the Obeya. In Engineering, Technology and Innovation (ICE), 2012 18th International ICE Conference on (pp. 1-10). IEEE.

Abuhav, I. (2011). ISO 13485: A complete guide to quality management in the medical device industry (1st ed.). Boca Raton: CRC Press.

Alieva, J., & von Haartman, R. (2020). Digital Muda-the new form of waste by industry 4.0. In Proceeding International Conference on Operations and Supply Chain Management (OSCM) (Vol. 13, No. 3, pp. 269-278).

Alsyouf, I. (2007), “The role of maintenance in improving companies’ productivity and profitability”, International Journal of Production Economics, Vol. 105 No. 105, pp. 70-78.

Anon (1985) Quality and Value for Money, National Economic Development Council, London.

Association for Project Management (APM). (2006). APM body of knowledge (5th ed.). High Wycombe, Buckinghamshire: The Association.

Amazon Web Services (AWS). (2023). What’s the Difference Between Frontend and Backend in Application Development?. Retrieved November 18, 2023, from https://aws.amazon.com/compare/the-difference-between-frontend-and-backend/#:~:text=The%20frontend%20is%20what%20your,application%20data%20for%20your%20users.

Backström, T., & Döös, M. (1995). A comparative study of occupational accidents in industries with advanced manufacturing technology. The International Journal of Human Factors in Manufacturing, 5, 267–282.

Backström, T., & Harms-Ringdhal, L. (1984). A statistical study of control systems and accidents at work. Journal of Occupational Accidents, 6, 201–210.

Bahr, NJ. (1997). System safety engineering and risk assessment: a practical approach. Taylor & Francis, Washington, DC

Bamber, C.J., Castka, P., Sharp, J.M. and Motara, Y. (2003). Cross-functional team working for overall equipment effectiveness (OEE). Journal of Quality in Maintenance Engineering. Vol. 9 No. 3, pp. 223-238.

Baron, L., & Gauntlett, E. (2002). WACOSS Housing and Sustainable Communities Indicators Project. Retrieved from http://www.regional.org.au/au/soc/2002/4/barron_gauntlett.htm

Barringer, H. P., & Weber, D. P. (1995). Where is my data for making reliability improvements?. In Fourth International Conference on Process Plant Reliability, Gulf Publishing Company, Houston, TX.

Bauch, C. (2004). Lean product development: making waste transparent (Doctoral dissertation).

Baxter, D., Gao, J., Case, K., Harding, J., Young, B., Cochrane, S., & Dani, S. (2008). A framework to integrate design knowledge reuse and requirements management in engineering design. Robotics and Computer-Integrated Manufacturing, 24(4), 585-593.

Beck, K., Beedle, M., Bennekum, A.V., Cockburn, A., Cunningham, W., Fowler, M., Grenning, J., Highsmith, J., Hunt, A., Jeffries, R., Kern, J., Marick, B., Martin, R.C., Mellor, S., Schwaber, K., Sutherland, J. & Thomas, D. (2001). Manifesto for agile software development. http://www.agilemanifesto.org/

Becker, H. S. (1986). Writing for social scientists: how to start and finish your thesis, book, or article. Chicago: University of Chicago Press

Becker, H. S. (1970). Sociological work: Method and substance. Chicago: Aldine

Bell, E., Bryman, A., & Harley, B. (2022). Business research methods. Oxford university press.

Bell, S., Orzen, M. A. (2011). Lean IT: Enabling and sustaining your Lean transformation. New York; Boca Raton: CRC Press.

Bellgran, M., & Aresu, E. (2003). Handling disturbances in small volume production. Robotics and Computer-Integrated Manufacturing, 19(1-2), 123-134.

Bellgran, M., Gullander, P., & Harlin, U. (2002, October). Towards improvement of production efficiency and effectiveness from a life-cycle perspective. In Proc. of 33rd Int. Symposium on Robotics.

Bellgran, M., & Säfsten, E. K. (2009). Production development: design and operation of production systems. Springer Science & Business Media.

Bicheno, J. (2004). The new Lean toolbox: Towards fast, flexible flow (3rd ed.). Buckingham: PICSIE Books.

Bicheno, J., Anhede, P., Hillberg, J., & Lindberg Howard, M. (2006). Ny verktygslåda för Lean: För snabbt och flexibelt flöde (New tool box of Lean: For fast and flexible flow). Göteborg: Revere.

Biong, H., Ulvnes, A. M. (2011). If the supplier's human capital walks away, where would the customer go?. Journal of Business-to-Business Marketing, 18(3), 223-252.

Bittencourt, V., Saldanha, F., Alves, A. C., & Leão, C. P. (2019). Contributions of lean thinking principles to foster industry 4.0 and sustainable development goals. Lean engineering for global development, 129-159.

Blessing, L., Chakrabarti, A. (2009). DRM, a design research methodology. Dordrecht; New York: Springer. doi:10.1007/978-1-84882-587-1

Blessing, L., Chakrabarti, A., Wallace, K. (1995). A design research methodology. In Proceedings of the 10th International Conference on Engineering Design (ICED'95) (Vol. 23, pp. 50-55).

Bloch, A. (2003). Murphy's law. Penguin.

Bokrantz, J., Skoogh, A., Ylipää, T., Stahre, J. (2016). Handling of production disturbances in the manufacturing industry. Journal of Manufacturing Technology Management, 27 (8), pp. 1054-1075.

Bolisani, E., Pailoa, M. and Scarso, E. (2013). Knowledge protection in knowledge-intensive business services. Journal of Intellectual Capital, 14(2), 192-211.

Bourlon, E., Govers, G. (1993), "Een performantiemeetsysteem ter ondersteuning van een onderhoudsprogramma" (A performance measurement system supporting a maintenance programme), Master's thesis, Department of Industrial Management, K.U.Leuven, September

Brennen, J.S., Kreiss, D. (2016), "Digitalization", in Jensen, K.B., Rothenbuhler, E.W., Pooley, J.D. and Craig, R.T. (Eds), The International Encyclopedia of Communication Theory and Philosophy, Wiley-Blackwell, Chichester, pp. 556-566

Brito, L. M. P., de Oliveira, P. W. S., & de Castro, A. B. C. (2012). Knowledge management in a public institution for technical assistance and rural extension of northeastern Brazil. Revista de Administração Pública, 46(5), 1341.

Bryman, A. (2016). Social research methods. Oxford university press.

Burns, K. (2022). Why 'Data for Data's Sake' Creates Risks for Business. CPO Magazine. https://www.cpomagazine.com/cyber-security/why-data-for-datas-sake-creates-risks-for-business/

Buur, J. (1990). A Theoretical Approach to Mechatronics Design. Institute for Engineering Design. Doctoral Thesis, Technical University of Denmark

Chakravorty, S. S., Atwater, J. B., & Herbert, J. I. (2008). The Shingo Prize for operational excellence: rewarding world-class practices. International Journal of Business Excellence, 1(4), 418-433.

Christopher M, Peck H. (2004). Building the resilient supply chain. Int J Logistics Manage 15(2):1–14

Cockburn, A. (2007). Agile software development: The cooperative game. Upper Saddle River, NJ: Addison-Wesley.

CPA Leadership Institute. The Paperless Office. Retrieved May, 12, 2010 from www.cpaleadership.com

Creswell, J.W. (2014). Research design: Qualitative, quantitative, and mixed methods approaches. 4th ed. Sage publications.

Cronje, J. (2013). What is this thing called "design" in design research and instructional design. Educational Media International, 50(1), 1-11.

Cross, N. (2006). Designerly ways of knowing. Springer London.

Dahmani, N., Benhida, K., Belhadi, A., Kamble, S., Elfezazi, S., & Jauhar, S. K. (2021). Smart circular product design strategies towards eco-effective production systems: A lean eco-design industry 4.0 framework. Journal of Cleaner Production, 320, 128847.

Dale, B. G., Plunkett, J. J. (1991). Quality costing (1st ed.). Boston, MA: Springer US. doi:10.1007/978-1-4615-3870-7

Dale, B.G., Plunkett, J.J. (1995), Quality Costing, 2nd ed., Chapman and Hall, London.

De Smet, R., Gelders, L., & Pintelon, L. (1997). Case studies on disturbance registration for continuous improvement. Journal of Quality in Maintenance Engineering, 3(2), 91-108.

Demian, P., & Fruchter, R. (2009). Effective visualisation of design versions: visual storytelling for design reuse. Research in Engineering Design, 19(4), 193-204.

Deutsch, M., & Gerard, H. B. (1955). A study of normative and informational social influences upon individual judgment. The journal of abnormal and social psychology, 51(3), 629.

Dick, J., Hull, E., Jackson, K. (2017). Requirements engineering (4th ed.). Cham: Springer International Publishing.

Dirgo, R. (2006). Look Forward Beyond Lean and Six Sigma: A Self-perpetuating Enterprise Improvement Method. J. Ross Publishing.

Dixon, N. M. (1992). Organizational learning: A review of the literature with implications for HRD professionals. Human Resource Development Quarterly, 3(1), 29-49.

Dombrowski, U., Richter, T., & Krenkel, P. (2017). Interdependencies of Industrie 4.0 & lean production systems: A use cases analysis. Procedia Manufacturing, 11, 1061-1068.

Dorf, R. C. (1999). The technology management handbook. Boca Raton, Fla: CRC.

Duffy A.H.B, Andreasen M.M. (1995). Enhancing the evolution of design science. Proceedings of international conference on engineering design (ICED), Prague, Czech Republic.

Durst, S., & Wilhelm, S. (2011). Knowledge management in practice: insights into a medium-sized enterprise's exposure to knowledge loss. Prometheus, 29(1), 23-38.

Edwards, R., & Holland, J. (2013). What is qualitative interviewing? (p. 128). Bloomsbury Academic.

Eibich, W., Hein, M. (2013). Global Sustainable Production - A case study of manufacturing units in differently industrialized countries. Master's thesis. Linnaeus University.

Ejsmont, K., Gladysz, B., Corti, D., Castaño, F., Mohammed, W. M., & Martinez Lastra, J. L. (2020). Towards 'Lean Industry 4.0 ′–Current trends and future perspectives. Cogent Business & Management, 7(1), 1781995.

Emerson, R. M., Fretz, R. I., & Shaw, L. L. (1995). Writing ethnographic fieldnotes. Chicago, IL: University of Chicago Press.

Ericsson, J. (1997). Störningsanalys av tillverkningssystem: Ett viktigt verktyg inom Lean Produktion (Disturbance Analysis of Manufacturing Systems: An important tool in Lean Production). PhD thesis, Lund University (in Swedish).

Ericsson, E., Lilliesköld, J., Gingnell, L. (2012). A survey of quality measurements in product development. International Journal of Engineering and Technology, 4(3), 258.

Faverge, J.-M. (1970). The operator’s reliability and safety in industry. Ergonomics, 13, 301–327.

Fayyad, U. M., Wierse, A., & Grinstein, G. G. (Eds.). (2002). Information visualization in data mining and knowledge discovery. Morgan Kaufmann.

Feigenbaum, A. V. (1991). Total quality control (3., rev. ed.). New York: McGraw-Hill.

Feld, W. M. (2001). Lean manufacturing: Tools, techniques, and how to use them. Boca Raton, Fla; Alexandria, Va: St. Lucie Press.

Ferenhof, H., Durst, S., & Selig, P. (2015). Knowledge waste in organizations: A review of previous studies. Brazilian Journal of Operations & Production Management, 12(1), 160-178.

Ferenhof, H. A., Durst, S., & Selig, P. M. (2016). Knowledge Waste & Knowledge Loss-What is it All About?. NAVUS-Revista de Gestão e Tecnologia, 6(4), 38-57.

Ferguson, R. (2007). Implementing Lean Software Development: From Concept to Cash. Software Quality Professional, 9(3), 45.

Flanagan, D. (2006). JavaScript: The definitive guide. 5th ed., O'Reilly.

Forza, C. (1995). Quality information systems and quality management: A reference model and associated measures for empirical research. Industrial Management & Data Systems, 95(2), 6-14. doi:10.1108/02635579510082502

Galperin, B. L. (2003). Can workplace deviance be constructive?. In Misbehaviour and dysfunctional attitudes in organizations (pp. 154-170). Palgrave Macmillan UK.

Garvin, D. A. (1993). Building a learning organization. Harvard business review, 71(4), 78-91.

Gil-Vilda, F., Yagüe-Fabra, J. A., & Sunyer, A. (2021). From lean production to lean 4.0: a systematic literature review with a historical perspective. Applied Sciences, 11(21), 10318.

Gingnell, L., Ericsson, E., Lilliesköld, J. (2012A). Improved visual planning in a research environment. Paper presented at The 15th QMOD conference on Quality and Service Sciences,Poznan, Poland, 2012 (September 5-7). Poznan.

Gingnell, L., Ericsson, E., Sörqvist, L. (2012B). Swedish Lean Product Development Implementation. In ASQ World Conference on Quality and Improvement, May 21-23 2012, Anaheim, CA.

Grieves M. (2006). Product lifecycle management: driving the next generation of Lean thinking. New York: Mcgraw-Hill. Chicago. p. 39.

Gritton, P. (2008). “Foreword”. Foreword. Toyota culture: The heart and soul of the Toyota way. New York, NY: McGraw-Hill.

Golinska, P., Fertsch, M., & Pawlewski, P. (2011). Production flow control in the automotive industry - quick scan approach. International Journal of Production Research, 49(14), 4335-4351. doi:10.1080/00207543.2010.536180

Gordon, P. J. (2001). Lean and green: Profit for your workplace and the environment. San Francisco: Berrett-Koehler Publishers.

Grant, R. M. (1996a). Prospering in dynamically-competitive environments: Organizational capability as knowledge integration. Organization Science, 7(4), 375-387.

Grant, R. M. (1996b). Toward a knowledge-based theory of the firm. Strategic management journal, 17(S2), 109-122.

Gremyr, I., & Fouquet, J. B. (2012). Design for Six Sigma and Lean product development. International Journal of Lean Six Sigma, 3(1), 45-58.

Hall, M., Henriksen, S. (2016). Identifiering av mätetal för att öka effektiviteten inom inköp. Master's thesis. Högskolan Väst.

Hammersley, M., & Atkinson, P. (1995). Ethnography: Principles in practice (2nd ed.). London, England: Routledge.

Hansen, R.C. (2002). Overall equipment effectiveness: A powerful production/maintenance tool for increased profits. New York, NY: Industrial Press.

Harlin, U. (2000). Towards strategic disturbance management in advanced manufacturing systems. Licentiate thesis, Chalmers University of Technology, Gothenburg.

Hellerqvist, H., & Svensson B.M. (2014). A tool to forecast needed resources in product development projects at Scania's axle and gearbox assembly. Chalmers University of Technology, Göteborg.

Hibbs, C., Jewett, S., & Sullivan, M. (2009). The art of Lean software development: A practical and incremental approach. O'Reilly Media, Inc.

Highsmith, J. (2002). Agile software development ecosystems. Addison-Wesley Longman Publishing Co., Inc..

Holmdahl, L. (2010). Lean product development på svenska. Göteborg: Lars Holmdahl.

Holsapple, C.W., Whinston, A.B. (1996). Decision support systems: a knowledge-based approach. West, St. Paul, MN.

Hoppmann, J., Rebentisch, E., Dombrowski, U., Zahn, T. (2011). A framework for organizing Lean product development. Engineering Management Journal, 23(1), 3-15.

Hölttä, V., Mahlamäki, K., Eisto, T., & Ström, M. (2010). Lean information management model for engineering changes. World Academy of Science, Engineering and Technology, 42, 1459-1466.

Huber, G. P. (1991). Organizational learning: The contributing processes and the literatures. Organization Science, 2(1), 88-115.

Impact. (2020). Fast-Tracking Your Digital Transformation. https://www.impactmybiz.com/ebook/fast-trackingyour-digital-transformation/

Ingemansson, A. (2004), "On reduction of production disturbances in manufacturing systems based on discrete-event simulation", PhD thesis, Lund University, Lund.

Ingemansson, A., Bolmsjö, G. S. (2004). Improved efficiency with production disturbance reduction in manufacturing systems based on discrete-event simulation. Journal of Manufacturing Technology Management, 15(3), 267-279.

Islam, A. (2008). Risk management in small and medium-sized manufacturing organization in New Zealand, PhD Thesis, Department of Mechanical Engineering. The University of Auckland

Islam, A., & Tedford, D. (2012). Risk determinants of small and medium-sized manufacturing enterprises (SMEs) - an exploratory study in new zealand. Journal of Industrial Engineering International, 8(1), 1-13. doi:10.1186/2251-712X-8-12

Islam, A. M., Tedford, J. D., & Haemmerle, E. (2006). Strategic Risk Management Approach for Small and Medium-Sized Manufacturing Enterprises (SMEs)---A Theoretical Framework. In Management of Innovation and Technology, 2006 IEEE International Conference on (Vol. 2, pp. 694-698). IEEE.

Islam, M. A., Tedford, J. D., & Haemmerle, E. (2008). Managing operational risks in small- and medium-sized enterprises (SMEs) engaged in manufacturing–an integrated approach. International Journal of Technology, Policy and Management, 8(4), 420-441.

Jackson, T. L., Jones, K. R. (1996). Implementing a Lean management system. Portland, Or: Productivity Press.

Juran, J. M., & Gryna, F. M. (1993). Quality planning and analysis: From product development through use (3.th ed.). New York: McGraw-Hill.

Jüttner U. (2005). Supply chain risk management. Understanding the business requirements from a practitioner perspective. IntJ Logistics Manage 16(1):120–141

Järvinen, J., & Karwowski, W. (1995). Analysis of self-reported accidents attributed to advanced manufacturing systems. The International Journal of Human Factors in Manufacturing, 5, 251–266.

Kabzhassarova, M., Kulzhanova, A., Dikhanbayeva, D., Guney, M., & Turkyilmaz, A. (2021). Effect of Lean4. 0 on sustainability performance: a review. Procedia CIRP, 103, 73-78.

Kagermann, H. (2015). Change through digitization—Value creation in the age of Industry 4.0. In Management of permanent change (pp. 23-45). Springer Gabler, Wiesbaden.

Kagermann, H., Riemensperger, F., Hoke, D., Helbig, J., Stocksmeier, D., Wahlster, W., & Schweer, D. (2014). Smart service welt: recommendations for the strategic initiative web-based services for businesses. Berlin: Acatech-National Academy of Science and Engineering.

Kan, S. H., Basili, V. R., & Shapiro, L. N. (1994). Software quality: An overview from the perspective of total quality management. IBM Systems Journal, 33(1), 4-19. doi:10.1147/sj.331.0004

Karlsson, J. (2011). Arbetsmiljö för underhållstekniker vid DynaMate AB: Kartläggning och förbättringsförslag vid underhåll av bearbetningsmaskiner. Master's thesis. Luleå university of technology.

Katila, P. (2000), "Applying total productive maintenance – TPM principles in the flexible manufacturing systems", technical report, Institution for Material and Production Technology, Luleå University of Technology, Luleå.

Kaydos, W. (1991), Measuring, Managing and Maximizing Performance, Productivity Press, Portland, OR.

Kennedy, M., et al. Ready, Set, Dominate: Implement Toyota's set-based learning for developing products and nobody can catch you, 2008 (Oaklea Press, Richmond).

Kiram, M. K., & Yusof, M. M. (2020). Lean IT Transformation Plan for Information Systems Development. International Journal of Advanced Computer Science and Applications, 11(8).

Kniberg, H. (2006). Scrum and XP from the trenches (version 1.1). Crisp.

Kniberg, H. (2007). Scrum and XP from the trenches (version 2.2). Crisp.

Kogut, B., & Zander, U. (1992). Knowledge of the firm, combinative capabilities, and the replication of technology. Organization Science, 3(3), 383-397.

Kolberg, D., & Zühlke, D. (2015). Lean automation enabled by industry 4.0 technologies. IFAC-PapersOnLine, 48(3), 1870-1875.

Krafcik, J. F. (1988). Triumph of the Lean production system. Sloan management review, 30(1), 41-51.

Kristofersson A., Lindeberg C. (2006). Lean product development in Swedish industry - an exploratory study [master's thesis]. [Stockholm]: Stockholm School of Economics.

Kuivanen, R. (1990). The Impact on Safety of Disturbances in Flexible Manufacturing Systems. In W. Karwowski & M. Rahimi (Eds.), Ergonomics of Hybrid Automated Systems II (pp. 951– 956). Amsterdam: Elsevier.

Kuivanen, R. (1996). Disturbance control in flexible manufacturing. International Journal of Human Factors in Manufacturing, 6(1), 41-56.

Kumar, U., Galar, D., Parida, A., Stenström, C., Berges, L. (2013). Maintenance performance metrics: A state-of-the-art review. Journal of Quality in Maintenance Engineering, 19 (3), art. no. 17094787, pp. 233-277.

LeCompte M. D., Preissle J, Tesch R. (1993). Ethnography and qualitative design in educational research. 2nd edition. San Diego: Academic Press.

Legat, C., Lamparter, S., Vogel-Heuser, B. (2013). Knowledge-based technologies for future factory engineering and control. Studies in Computational Intelligence, 472, pp. 355-374.

Leurent, H., & Boer, E. D. (2019). Fourth industrial revolution beacons of technology and innovation in manufacturing. In World Econ. Forum.

Light R. J., Singer J, & Willet J. (1990). By design: conducting research on higher education. Cambridge, MA: Harvard University Press.

Liker, J.K. (2004). The Toyota Way: 14 management principles from the world‟ s greatest manufacturer McGraw-Hill.

Liker, J. K. (2011). The toyota way: 14 management principles from the world's greatest manufacturer. New York: McGraw Hill Professional

Liker, J. K., & Hoseus, M. (2008). Toyota culture: The heart and soul of the Toyota way. New York, NY: McGraw-Hill.

Liker, J. K., & Ogden, T. (2011). Toyota under fire. McGraw-Hill Professional.

Lindlöf, L. (2014) Visual Management - on Communication in Product Development Organizations. Göteborg : Chalmers University of Technology (PhD thesis at Chalmers University of Technology)

Lindlof, L., & Soderberg, B. (2011). Pros and cons of Lean visual planning: experiences from four product development organisations. International journal of technology intelligence and planning, 7(3), 269-279.

Lindlöf, L., & Trygg, L. (2012). Task visualization in product development-improved communication for development teams. In The R&D Management Conference 2012, May 23-25, Grenoble, France.

Lis, S. (1982). Rytmicznosc procesu produkcji, zakłócenia i ich kompensacja (Production process rhythm, distortion, and compensation). Warszawa: PWE.

Ljungberg, Õ. (1998). Measurement of overall equipment effectiveness as a basis for TPM activities. International Journal of Operations & Production Management, 18(5), 495-507. doi:10.1108/01443579810206334

Locher, D. A. (2011). Value stream mapping for Lean development: A how-to guide for streamlining time to market. Hoboken: Productivity Press.

Loebbecke, C., & Picot, A. (2015). Reflections on societal and business model transformation arising from digitization and big data analytics: A research agenda. The Journal of Strategic Information Systems, 24(3), 149-157.

Lorenz, R., Buess, P., Macuvele, J., Friedli, T., & Netland, T. H. (2019). Lean and digitalization—contradictions or complements?. In Advances in Production Management Systems. Production Management for the Factory of the Future: IFIP WG 5.7 International Conference, APMS 2019, Austin, TX, USA, September 1–5, 2019, Proceedings, Part I (pp. 77-84). Springer International Publishing.

Luhn, A. (2016). The learning organization. Creative and Knowledge Society, 6(1), 1-13.

Maguire, K. (2016). Lean and IT—working together? An exploratory study of the potential conflicts between lean thinking and the use of information technology in organisations today. Understanding the lean enterprise: Strategies, methodologies, and principles for a more responsive organization, 31-60.

Maidique, M. A., & Zirger, B. J. (1985). The new product learning cycle. Research policy, 14(6), 299-313.

Mascitelli, R. (2007). The Lean product development guidebook: Everything your design team needs to improve efficiency and slash time-to-market. Northridge: Technology Perspectives.

Mascitelli, R. (2011). Mastering Lean product development: a practical, event-driven process for maximizing speed, profits and quality. Technology Perspectives.

Matson, J.B., McFarlane, D.C. (1999). Assessing the responsiveness of existing production operations. International Journal of Operations and Production Management, 19 (8), pp. 765-784.

Mattila, M., & Kiviniity, J. (1993). Job characteristics and occupational safety of manufacturing jobs at different level of automation. The International Journal of Human Factors in Manufacturing, 3, 243–252.

Maylor, H. (2010). Project management (4.th ed.). New York; Harlow, England, Financial Times Prentice Hall.

Mayr, A., Weigelt, M., Kühl, A., Grimm, S., Erll, A., Potzel, M., & Franke, J. (2018). Lean 4.0-A conceptual conjunction of lean management and Industry 4.0. Procedia Cirp, 72, 622-628.

Maxwell, J. A. (2013). Qualitative research design: An interactive approach. 3rd edition. Thousand Oaks: SAGE Publications.

Mittal, S., Khan, M. A., Romero, D., & Wuest, T. (2019). Smart manufacturing: Characteristics, technologies and enabling factors. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 233(5), 1342-1361.

Musante, K. (2015). Participant observation. Handbook of methods in cultural anthropology, 251-292.

Henke, N., Bughin, J., Chui, M., Manyika, J., Saleh, T., Wiseman, B., Sethupathy, G. (2016). The age of analytics: competing in a data-driven world. McKinsey Global Institute Research.

McQuade, E., Sjoer, E., Fabian, P., Nascimento, J. C., & Schroeder, S. (2007). Will you miss me when I'm gone?. Journal of European industrial training.

Medbo, L., Carlsson, D. (2013). Implementation of Lean in SME, experiences from a Swedish national program. International Journal of Industrial Engineering and Management, 4 (4), pp. 221-227.

Meissner, A., Müller, M., Hermann, A., & Metternich, J. (2018). Digitalization as a catalyst for Lean production: A learning factory approach for digital shop floor management. Procedia Manufacturing, 23, 81-86.

Metternich, J., Müller, M., Meudt, T., Schaede, C. (2017). Lean 4.0. Zwischen Widerspruch und Vision, ZWF 112 (5) 346–348.

Metzger, M. (1993). Playing school or telling the truth?. Harvard graduate school of education alumni bulletin.

Meulemans, S. (1993), "Storingsanalyse op een afvullijn en voorstellen tot verbetering van het rendement" (Failure analysis of a bottling line and proposals for efficiency improvements), Master's thesis, Department of Industrial Management, K.U.Leuven, September (in Dutch).

MIL-STD-721. (1991). Military Standard Definitions of Terms For Reliability and Maintainability, Springfield, VA: National Technical Information Service of the U.S. Department of Commerce.

Monostori, L., Szelke, E., & Kádár, B. (1998). Management of changes and disturbances in manufacturing systems. Annual Reviews in Control, 22, 85-97.

Morgan, J. M., & Liker, J. K. (2006). The toyota product development system: Integrating people, process, and technology. New York: Productivity Press.

Mrugalska, B., & Wyrwicka, M. K. (2017). Towards lean production in industry 4.0. Procedia engineering, 182, 466-473.

Munthe, C. I., Uppvall, L., Engwall, M., & Dahlén, L. (2014). Dealing with the devil of deviation: managing uncertainty during product development execution. R&D Management, 44(2), 203-216.

Muratov, A., Machado, M. (2015). Impact of Scania and MAN Merger on Swedish Automotive Suppliers – Special Focus on Sourcing Strategy, Relationship Changes, and Strategic Response Mechanisms. Master's thesis. Jönköping international business school.

Nasrin, R. (2016). A Case Study: Analysis of applying Lean in a public state agency and in a health care system.

Navarro, J., Osiurak, F. (2015). When do we use automatic tools rather than doing a task manually? Influence of automatic tool speed. The American journal of psychology, 128(1), 77-88.

Negri, E., Powell, D., Terzi, S., Cattaneo, L., Rossi, M. (2017). Lean Thinking in the Digital Era. 14th IFIP International Conference on Product Lifecycle Management (PLM), Seville, Spain. pp.371-381, ff10.1007/978-3-319-72905-3_33ff. ffhal-01764207f

Nonaka, I., & Takeuchi, H. (1995). The knowledge-creating company: How Japanese companies create the dynamics of innovation. Oxford university press.

OMB Historical Budget Tables. (2010). Nasa budget as percentage of federal budget & GDP. retrieved from: https://www.lpi.usra.edu/exploration/multimedia/NASABudgetHistory

.pdf. Last accessed 2018.03.03.

Ortiz, C. A. (2006). Kaizen assembly: Designing, constructing, and managing a Lean assembly line. Boca Raton, FL: Taylor & Francis.

Otto, K., & Wood, K. (2001). Product design: techniques in reverse engineering and new product design. Prentice-Hall.

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). Engineering design: A systematic approach. Berlin; London: Springer.

Patig, S., 2001. Flexible Produktionsfeinplanung mit Hilfe von Planungsschritten (Flexible production planning with the aid of planning steps). PhD thesis. University of Magdeburg.

Patton MQ. (1990). Qualitative evaluation and research methods. Newbury Park: Sage Publications Inc.

Pedersen, K., Emblemsvag, J., Bailey, R., Allen, J., & Mistree, F. (2000, August). The'Validation Square'-Validating Design Methods. In ASME Design Theory and Methodology Conference. New York: ASME.

Pereira, A. C., Dinis-Carvalho, J., Alves, A. C., Arezes, P. (2019). How Industry 4.0 can enhance Lean practices. FME Transactions, 47(4), 810-822.

Petersson, P., Johansson, O., Broman, M., Blucher, D., & Alsterman, H. (2010). Lean-Turn deviations into success. Part Media, Bromma.

Petersson, P., Olsson, B., Lundström, T., Johansson, O., Broman, M., Blucher, D., Alsterman, H. (2015). Lean gör avvikelser till framgång! (3rd ed.). Part Development AB.

Petersson, P., Olsson, B., Lundström, T., Johansson, O., Broman, M., Blucher, D., Alsterman, H. (2012). Ledarskap gör Lean till framgång!. Part Development AB.

Pfohl, H. C., Köhler, H., & Thomas, D. (2010). State of the art in supply chain risk management research: empirical and conceptual findings and a roadmap for the implementation in practice. Logistics research, 2(1), 33-44.

Pinho, C., & Mendes, L. (2017). IT in lean-based manufacturing industries: systematic literature review and research issues. International Journal of Production Research, 55(24), 7524-7540.

Powell, D., Romero, D., Gaiardelli, P., Cimini, C., & Cavalieri, S. (2018). Towards digital lean cyber-physical production systems: Industry 4.0 technologies as enablers of leaner production. In Advances in Production Management Systems. Smart Manufacturing for Industry 4.0: IFIP WG 5.7 International Conference, APMS 2018, Seoul, Korea, August 26-30, 2018, Proceedings, Part II (pp. 353-362). Springer International Publishing.

Powell, D., Riezebos, J., & Strandhagen, J. O. (2013). Lean production and ERP systems in small-and medium-sized enterprises: ERP support for pull production. International journal of production research, 51(2), 395-409.

Powell, D., Romero, D., Gaiardelli, P., Cimini, C., Cavalieri, S. (2018). Towards digital Lean cyber-physical production systems: Industry 4.0 technologies as enablers of Leaner production. In IFIP International Conference on Advances in Production Management Systems (pp. 353-362). Springer, Cham.

Progess Data RPM. (2022) Anomaly Detection & Prediction Decoded: 6 Industries, Copious Challenges, Extraordinary Impact. Available online: https://www.progress.com/docs/default-source/datarpm/progress_datarpm_cadp_ebook_anomaly_detection_in_6_industries.pdf?sfvrsn=82a183de_2

Rachinger, M., Rauter, R., Müller, C., Vorraber, W., & Schirgi, E. (2019). Digitalization and its influence on business model innovation. Journal of Manufacturing Technology Management.

Radeka, K. (2013). The mastery of innovation: A field guide to Lean product development. Boca Raton, FL: CRC Press.

Ramanujam, R., Goodman, P.S. (2003). Latent errors and adverse organizational consequences: A conceptualization. Journal of Organizational Behavior, 24(7), 815-836. doi:10.1002/job.218.

Reason J. (1990) Human error. Cambridge, UK: Cambridge University Press.

Rees, R. (1993). Re-defining failure. Reliability Review, 13, 11-22.

Robinson, S. L., Bennett, R. J. (1997). Workplace deviance: Its definition, its manifestations, and its causes. Research on Negotiation in Organization, Vol. 6 (pp. 3-28). Greenwich, CT:JAL.

Romero, D., Flores, M., Herrera, M., & Resendez, H. (2019). Five management pillars for digital transformation integrating the lean thinking philosophy. In 2019 IEEE International conference on Engineering, technology and Innovation (ICE/ITMC) (pp. 1-8). IEEE.

Rossi, A. H. G., Marcondes, G. B., Pontes, J., Leitão, P., Treinta, F. T., De Resende, L. M. M., Yoshino, R. T. (2022). Lean tools in the context of industry 4.0: literature review, implementation and trends. Sustainability, 14(19), 12295.

Sassanelli, C., & Terzi, S. (2020). Evaluating manufacturers' smart readiness and maturity exploiting lean product development approach. In Proceedings of the 6th European Lean Educator Conference: ELEC 2019 6 (pp. 291-299). Springer International Publishing.

Scheuren, F. (2004). What is a Survey?. Alexandria: American Statistical Association.

Schiffauerova, A., & Thomson, V. (2006). Managing cost of quality: Insight into industry practice. The TQM Magazine, 18(5), 542-550. doi:10.1108/09544780610685502

Schumacher, S., Hall, R., Bildstein, A., & Bauernhansl, T. (2022). Lean Production Systems 4.0: systematic literature review and field study on the digital transformation of lean methods and tools. International Journal of Production Research, 1-23.

Schumacher, Simon, Roland Hall, Simon Rapp, and Andreas Bildstein. 2021a. Ganzheitliche Produktionssysteme 4.0: Anforderungen an die Gestaltung von Methoden und

Werkzeuge in Ganzheitlichen Produktionssystemen. Stuttgart: Fraunhofer IPA. http://publica.fraunhofer.de/documents/N-633 925.html.

Schonberger, R. J. (2008). Best practices in Lean six sigma process improvement. John Wiley & Sons.

Scott Jr, E. A. (2015). SPA Design and Architecture: Understanding single-page web applications. Simon and Schuster.

Sedano, T., Ralph, P., & Péraire, C. (2019). Removing software development waste to improve productivity. In Rethinking productivity in software engineering (pp. 221-240). Apress, Berkeley, CA.

Senge, P. M. (2006). The fifth discipline: The art and practice of the learning organization. Crown Pub.

Simmons, L. (2023). Front-End vs. Back-End: What’s the Difference?. computerscience.org. Retrieved November 18, 2023, from https://www.computerscience.org/bootcamps/resources/frontend-vs-backend/

Smith, R., Hawkins, B. (2004). Lean Maintenance: Reduce Costs, Improve Quality, and Increase Market Share. Elsevier, Amsterdam and Boston, MA.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. Journal of business research, 104, 333-339.

Sony, M. (2018). Industry 4.0 and lean management: a proposed integration model and research propositions. Production & Manufacturing Research, 6(1), 416-432.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social studies of science, 19(3), 387-420.

Stojanovic, N., Dinic, M., & Stojanovic, L. (2015). Big data process analytics for continuous process improvement in manufacturing. In 2015 IEEE International Conference on Big Data (Big Data) (pp. 1398-1407). IEEE.

Strauss, A. L. (1987). Qualitative analysis for social scientists. Cambridge University Press.

Ström, M., Gustafsson, G. (2013). Affärsmodell för Lean produktutveckling hos två underleverantörer (Business model for Lean product development at two subcontractors). Swerea IVF AB.

Summers, D. C. S. (2011). Lean six sigma: Process improvement tools and techniques. Boston: Pearson Prentice Hall.

(QCCEC - ASQC) Quality cost – cost effectiveness committee, American society for quality control. (1971). Quality costs – what & how. (2.th ed.). Milwaukee, Wisconsin.

(OGC) Office of Government Commerce (2009). Managing successful projects with PRINCE2 (5th ed.). London: TSO.

(PMI) Project Management Institute. (2013). A guide to the project management body of knowledge (PMBOK guide) (Fifth ed.). Newtown Square, Pennsylvania: Project Management Institute, Inc.

Tajiri, M., Gotoh, F. (1992). TPM Implementation: A Japanese Approach. McGraw-Hill, New York, NY.

Tavares, L. (2002), “Administracio´n Moderna del Mantenimiento”, Procesados por el Club de Mantenimiento & Mantenimiento Mundial, available at: www.mantenimientomundial.com

Terenghi, F., Cassina, J., Kristensen, K., Terzi, S. (2014). Virtual obeya: A new collaborative web application for running Lean management workshops. In Engineering, Technology and Innovation (ICE), 2014 International ICE Conference on (pp. 1-7). IEEE.

Thomke, S., & Fujimoto, T. (2000). The Effect of “Front-Loading” Problem-Solving on Product Development Performance. Journal of Product Innovation Management, 17(2), 128-142.

Tonnquist, B. (2016). projektledning (6th ed.). Stockholm: Sanoma utbildning.

Tortorella, G. L., & Fettermann, D. (2018). Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. International Journal of Production Research, 56(8), 2975-2987.

Tortorella, G., Sawhney, R., Jurburg, D., de Paula, I. C., Tlapa, D., & Thurer, M. (2021). Towards the proposition of a lean automation framework: Integrating industry 4.0 into lean production. Journal of Manufacturing Technology Management, 32(3), 593-620.

Toulouse, G. (2002). Accident risks in disturbance recovery in an automated batch-production system. Human Factors and Ergonomics in Manufacturing & Service Industries, 12(4), 383-406.

Tsang, A.H.C., Jardine, A.K.S., Kolodny, H. (1999). Measuring maintenance performance: a holistic approach. International Journal of Operations & Productions Management. Vol. 19 No. 7, pp. 691-715.

Ullman, D. (2003). The mechanical design process. 3rd edition, McGraw-Hill Higher Education, New York.

Ulrich, K. T. & Eppinger, S. D. (2012). Product Design and Development, Boston, Massachusetts, USA, McGraw-Hill Education.

Unruh, G. and Kiron, D. (2017). Digital transformation on purpose. MIT Sloan Management Review. Available at https://sloanreview.mit.edu/article/digital-transformation-on-purpose/ (accessed July 17, 2020).

Vainalis, R. (2012). Change Management with Lean approach-How the benefits from Lean can be applied in Change Management. Master’s thesis. Chalmers University of Technology.

Valamede, L. S., & Akkari, A. C. S. (2020a). Lean 4.0: A new holistic approach for the integration of lean manufacturing tools and digital technologies. International Journal of Mathematical, Engineering and Management Sciences, 5(5), 851.

Valamede, L. S., & Akkari, A. C. S. (2020b). Lean manufacturing and Industry 4.0: a holistic integration perspective in the industrial context. In 2020 9th International Conference on Industrial Technology and Management (ICITM) (pp. 63-68). IEEE.

Van Goubergen, D. (2010). OEE: the good, the bad and the ugly. Industrial Engineering Solutions Conference, Institute of Industrial Engineering, Cancun, 5-9 June.

VandenBos, G. R. (Ed.). (2007). APA Dictionary of Psychology. American Psychological Association.

Vaughan, D. (1999). The dark side of organizations: Mistake, misconduct, and disaster. Annual Review of Sociology, 25(1), 271-305. doi:10.1146/annurev.soc.25.1.271

Vinnova (2012). Visualisering och IT i produkt och produktionsutveckling (VIS-IT). Retrieved from: https://www.vinnova.se/p/visualisering-och-it-i-produkt-och-produktionsutveckling-vis-it/. Last accessed: 2018-07-15

Ward, A. C., & Sobek II, D. K. (2014). Lean product and process development. Lean Enterprise Institute.

Waters D. (2007). Supply chain risk management. Vulnerability and resilience in logistics. Kogan Page, London

Westerman, G., Calméjane, C., Bonnet, D., Ferraris, P. and McAfee, A. (2011), “Digital transformation: a road-map for billion-dollar organizations”, MIT Center for Digital Business and Capgemini Consulting, Cambridge, MA and Paris.

Western Australian Council of Social Service Inc. (WACOSS). (2008). WACOSS Model of Social Sustainability. Retrieved from http://www.wacoss.org.au/Libraries/State_Election_2013_Documents/WACOSS_Model_of_Social_Sustainability.sflb.ashx

Wiendahl, H. P., Thies, J. M., & Zeugträger, K. (1996). Construction and start-up of complex assembly systems. CIRP Annals-Manufacturing Technology, 45(1), 17-21.

Wiendahl, H.P. and Winkelhake, U. (1988). Permanent automatic supervision of assembly lines. Developments in Assembly Automation, March, pp. 289-300.

Wingquist Laboratory. (2017). Implementation strategy. Retrieved from: http://www.chalmers.se/en/centres/wingquist/research/Pages/Strategy.aspx

Wingquist Laboratory. (2014). Research implementation strategy. retrieved from: http://www.chalmers.se/en/centres/wingquist/research/Pages/research-and-implementation-strategy.aspx

Wolcott, H. F. (1990). Writing up qualitative research. Newbury Park, CA: Sage.

Womack, J. P., & Jones, D. T. (2003). Lean thinking: Banish waste and create wealth in your corporation. London: Free Press Business.

Ylipää, T. (2000). High-reliability manufacturing systems. Licentiate thesis, Chalmers University of Technology, Gothenburg

Zahle, J. (2023). Reactivity and good data in qualitative data collection. European Journal for Philosophy of Science, 13(1), 10.

8 Appended Papers

Paper A
Kaya, O., Catic, A., & Bergsjo, D. (2014). Exploring the possibilities of using image recognition technology to create a hybrid lean system for pulse methodology. Proceedings of the 12th annual Conference on Systems Engineering Research (CSER 2014), Redondo Beach, CA, USA, March 20-22, 2014. Procedia Computer Science, 28, 275-284.

Paper B
Kaya, O., Kero, T., & Bergsjö, D. (2015). Introducing digital pulse as a deviation management methodology for dental product development and production. International Journal of Lean Enterprise Research, 1(4), 351-372.

Paper C
Kaya, O., & Bergsjö, D. (2016). Useful deviations for deviation management information systems: From pulse methodology to a generic description. In System of Systems Engineering Conference (SoSE), 2016 11th (pp. 1-6). IEEE.

Paper D
Kaya, O., & Bergsjö, D. (2018). Learning from digital disturbance management in an integrated product development and production flow. International Journal of Product Lifecycle Management, 11(4), 295-325.