THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

On Brownfield Factory Layout Planning

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ABSTRACT

As manufacturing companies strive to increase productivity and decrease waste, to stay competitive in an increasingly global and digitalised context, their production system must improve. Improvements to production systems can be achieved in many ways, including increased levels of automation, improved product and process flows and improved scheduling. Changes to the production system often also imply the need to redesign it. This is often done within a project structure, as it is a unique and temporary endeavour. Layout planning is a part of the production system design process in which the positions of workstations, machines, and other parts of the system are decided. This can have a major impact on the overall efficiency of operations.

In an industrial setting, factory layout planning is often carried out in brownfield settings, where investment requires changes to areas of the facility already in use. Because every facility and production system is unique, so is each factory layout planning project. They all have different conditions, knowledge, availability and quality of data, lead-times, driving forces and many other factors. Classifying brownfield factory layout planning as a wicked problem; any solution which assumes existing data is both accurate and sufficient to deliver an optimal answer will fail when implemented, as real layout needs to be adapted to a multitude of different factors, requirements and restrictions during development. These factors are not fully understood until the problem is being solved.

The long-term vision of this thesis is to reduce the number and severity of errors in the area of brownfield factory layout planning in the manufacturing industry. Its aims are formulated as a step towards realising the long-term vision of identifying how the research community has handled brownfield factory layout planning and what challenges operational stakeholders encounter during a brownfield factory layout planning process. These aims are addressed using mixed-methods research applied in four different industrial studies; their results are combined and presented in this thesis.

The findings show that a large portion of the factory layout planning conducted in industries is in the brownfield setting and most often on parts of facilities. This allows planners to make the most of what already exists, for the sake of economic and environmental sustainability. On the other hand, the research community has focused more on layout planning solutions for full facilities and with little involvement of expert users. Involving expert users and effective utilisation of new technologies has shown promise in taming the wicked problem aspects of brownfield factory layout planning. A new mindset and new approach to brownfield factory layout planning could be the start of an improved process with lower risk and improved solutions, thus yielding higher stakeholder satisfaction.

Keywords: Production systems, manufacturing systems, factory layout planning, digitalisation, decision support, Industry 4.0

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Gothenburg, November 2019

APPENDED PUBLICATIONS

Publication 1: **Nåfors, D.**, Lindskog, E., Berglund, J., Gong, L., Johansson, B., and Vallhagen, J., "Realistic virtual models for factory layout planning", 2017 Winter Simulation Conference (WSC), Las Vegas, NV, 2017, pp. 3976-3987.

Contribution: Daniel Nåfors was the first author of the paper and a member of the research project. Daniel designed and conducted the study with co-authors Erik Lindskog, Jonatan Berglund and Liang Gong. Björn Johansson supervised and guided the research.

Publication 2: **Nåfors, D.**, Bärring, M., Estienne, M., Johansson, B., and Wahlström, M., "Supporting Discrete Event Simulation with 3D Laser Scanning and Value Stream Mapping: Benefits and Drawbacks", Procedia CIRP, Volume 72, 2018, pp. 1536-1541.

Contribution: Daniel Nåfors was the first author, and involved in the research project hosting this study. With Maja Bärring, he supervised the simulation project and Master's thesis involved in this study.

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Contribution: Daniel Nåfors guided and supervised the research design and thesis-writing process for the two Master's students (Amanda Dalstam and Marcus Engberg, who executed the study).

Publication 4: **Nåfors, D.**, Berglund, J., and Johansson, B., "Brownfield Factory Layout Planning: The Applicability Gap", submitted to Journal of Technology Management.

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ADDITIONAL PUBLICATIONS

Publication 1: Bergman, B., Norman, A., Carlsson, C., **Nåfors, D.**, and Skoogh, A., "Forming Effective Culturally Diverse Work Teams in Project Courses", 13th International CDIO Conference Proceedings, Calgary, Canada, 2017, pp. 508-518.

Contribution: Daniel Nåfors was the coordinator and administrator for the course that was the basis for the paper. He aided in execution of the study and supported the writing of the paper.

Publication 2: Bärring, M., **Nåfors, D.**, Henriksen, D., Olsson, D., Johansson, B., and Larsson, U., "A VSM Approach to Support Data Collection for a Simulation model", 2017 Winter Simulation Conference (WSC), Las Vegas, NV, 2017, pp. 3928-3939.

Contribution: Daniel Nåfors was a member of the research project and supervised the study conducted by the Master's students. He supported the first author in the writing process.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
CAD	Computer aided design
DES	Discrete event simulation
FLP	Facility layout problem
HMD	Head-mounted display
IT	Information technology
SLP	Systematic layout planning
SME	Small and medium-sized enterprises
RGB	Red green blue
VR	Virtual reality
VSM	Value stream mapping

LIST OF FIGURES

1

INTRODUCTION

This chapter gives a background to the research area and positions this licentiate thesis within it. The vision, aim, and research questions are then formulated and the research activities introduced. This chapter concludes with an outline of the thesis and introduction to the rest of it.

1.1 BACKGROUND

An effect of increased globalisation and digitalisation is that manufacturing companies are required to increase productivity and decrease waste to stay competitive. The productivity of a manufacturing company's production system depends on a variety of things, such as level of automation, product and process flow, scheduling, supplier arrangements and many more. Changes to the production system often come with a need to redesign the existing system, or design a completely new one (Jung et al., 2017). The process of designing production systems is often structured as a project, with many factors and problems needing consideration (Schuh et al., 2011). Layout planning is one part of the process; this is when the positioning of workstations, machines and other production system elements is decided (Heragu, 2008). The layout issue typically relates to the location of different facilities within a plant, such as machines, workstations and departments. The positioning of these facilities is called the "facility layout problem" and can make a major contribution to the overall efficiency of operations, reducing total operation costs by 2-15% if handled well (Tompkins et al., 2010).

As observed already in the 1950s, layout work is mostly performed in the setting of existing facilities, making improvements to an existing system or making better use of the facility (Immer, 1950). That observation still holds true, as new facilities rarely are built but layouts in existing ones still are improved. Hence, layout planning in factories is often conducted in brownfield settings where, for example, investment in a new machine might force a layout change to an already area of the facility that is already in use. In such a setting, the availability and quality of data can vary, as different companies have very diverse prerequisites. Companies which rarely invest in new machines or workstations and have had their production in the same facility for a long time may have outdated drawings, while those which often make changes to their facilities and layouts may have up-to-date drawings available. Every brownfield factory layout planning project may be considered unique, with conditions specific to that project and where knowledge of the problem and challenges is acquired as more work towards a solution is done.

1.2 RESEARCH GAP AND PROBLEM FORMULATION

Considering brownfield factory layout planning as a unique and novel problem that is better understood as it is being worked on, any solution which assumes existing data is both correct and sufficient to deliver an answer would likely encounter issues when applied in a real context; there, data may be incorrect or missing and solutions found in more of an ad-hoc manner. Much research into the topic of facility layout planning differs fundamentally from current industrial practice, indicating a gap between what is researched and what actually happens. Manufacturing industries often conduct factory layout planning in project structures, working as a team to try and identify a good solution. Meanwhile, there has been much research into algorithmic solutions which can generate an optimal solution based on high-quality data, more suited toward greenfield projects than brownfield ones.The manufacturing industries involved in the research for this thesis are unlikely to have sufficient data for an optimal solution in a brownfield factory layout planning setting; this creates the need for other solutions, solutions that can provide data and a stronger understanding of the problems and challenges. Industry conducts brownfield factory layout planning in various ways and encounters and solves different challenges in the process. These different challenges lead to errors, some more critical and costly than others. To reduce the number and severity of these errors, there is a need to show how and why brownfield factory layout planning should be implemented. This will help industry make the right decisions.

1.3 VISION

The vision of this research is to reduce the number and severity of errors in the area of brownfield factory layout planning in the manufacturing industry.

This will be achieved by researching, firstly, the challenges in the area to understand the improvement potential and, secondly, how to seize that potential. With the Fourth Industrial Revolution underway, new working methods have been enabled. These need to be integrated so that manufacturing can reap the benefits.

1.4 AIM

The aim of this thesis is to identify challenges related to brownfield layout planning in manufacturing, specifically those encountered by operational stakeholders. The scope is also broader than just the planning phase of the project; it also includes installation and operation. To reach that aim, an understanding of what the brownfield context means for factory layout planning also needs to be established. To this end, the following two research questions have been formulated.

RQ 1) What signifies brownfield factory layout planning?

As a lot of layout planning is performed in existing factories, a broader understanding of the brownfield term is beneficial. Two brownfield layout planning scenarios can differ vastly from each other, therefore this research question explores the area in order to facilitate an improved understanding of the brownfield term in the factory layout planning setting.

RQ 2) What challenges do operational stakeholders encounter during a brownfield layout change process?

In order to support a problem-solving approach and motivate industries to consider changing ways of working and adapting new solutions, the challenges encountered during the brownfield layout change process must be further understood. This research question generates an understanding which can guide future endeavours in the area, helping solutions target identified issues.

1.5 DELIMITATIONS

The research presented in this thesis is concerned with the development of layouts for the factory floor, such as where machines and workstations should be positioned. The focus lies on identifying the challenges faced during this change process by the stakeholders (those responsible for planning and those who will conduct activities in the affected area). Because this thesis has focused its research on large Swedish manufacturing companies, smaller companies and those in other countries may not encounter the exact same challenges. However, the target is the manufacturing domain so the outcome should still apply across the board, albeit with some modifications. Due to the time required to identify a need, decide on a change, plan it, implement it and finally follow up on the outcome, the focus of this thesis is the planning stage of factory layout planning. The installation and implementation phases are excluded from its scope. For this reason there is no feedback loop from planned to actual outcome, showing whether the layout change met expectations.

1.6 RESEARCH ACTIVITIES

The research in this thesis was part of a group of research projects, starting at different times and with varying lengths and focus areas. Thus, it is more interesting to look at the specific activities. Aside from the general literature study for each industrial study, a specific literature study was carried out in two parts. There were also four industrial studies, each presented in its own paper. The summary of the research activities in this thesis and their respective timing is presented in Figure 1, which starts in the middle of September 2016 and ends in early May 2019.

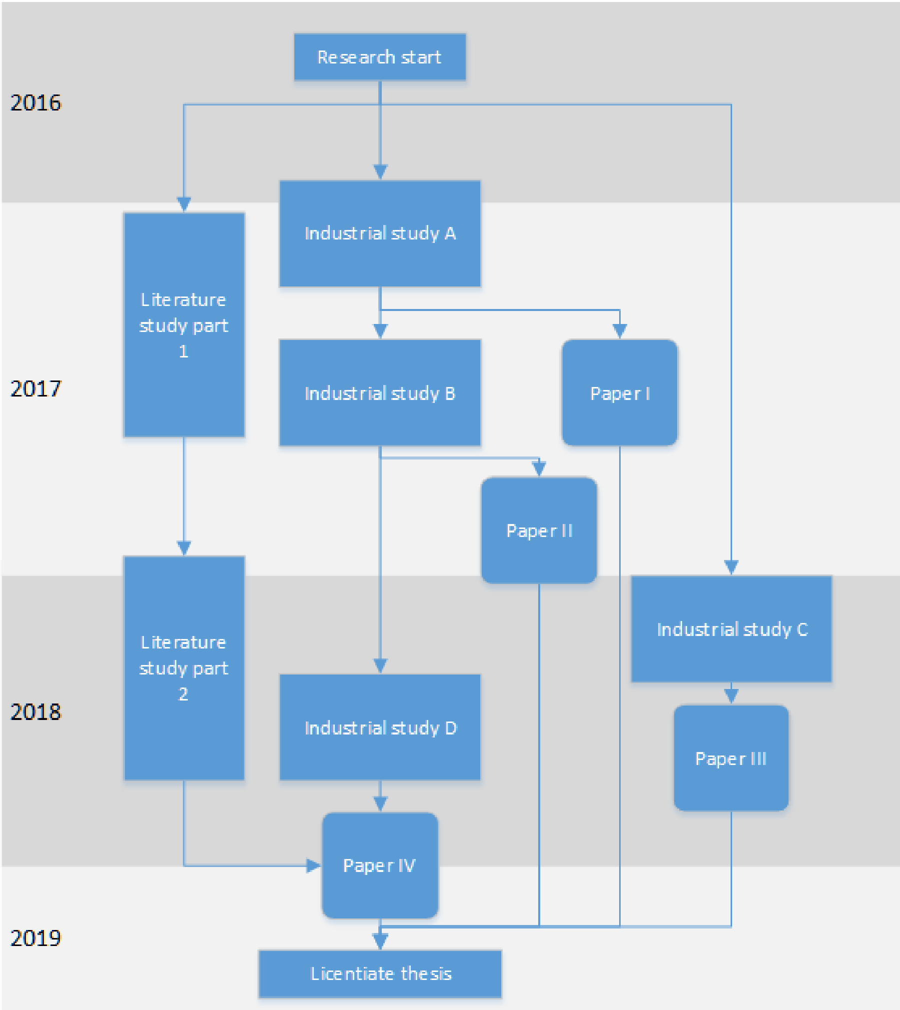


Figure 1: Summary of the research activities in this thesis.

1.7 RESEARCH CONTEXT

The research in this thesis has been carried out with several large Swedish manufacturing companies active in different business areas. The production systems included in the research consisted of a mix of human operators and machines, with various degrees of automation throughout each production system.

1.8 THESIS STRUCTURE

This thesis is structured in six chapters, the content of which are presented in Table 1.

Table 1: An overview of the structure of this thesis.

CHAPTER	CONTENT
1. INTRODUCTION	The first chapter of this thesis introduces the background of the research topic by explaining the interest in brownfield factory layout planning. It presents the research gap and problem formulation, along with the vision and aim of this research and the research activities performed.
2. FRAME OF REFERENCE	The theoretical foundation of the thesis and a brief overview of relevant background and concepts is presented in this chapter.
3. RESEARCH APPROACH	This chapter presents the research design and methods used, the author's philosophical worldview, and how the approach is used to provide knowledge on the research questions posed.
4. SUMMARY OF APPENDED PAPERS	This chapter summarizes the four appended papers of this thesis in a shorter manner, with the intention of giving the most important parts from each. The chapter's summary in the final section summarizes and connects the appended papers to the research questions.
5. DISCUSSION	The discussion chapters provides both discussion on the research performed, as well as on the contribution and quality of the research, the state of brownfield factory layout planning today, and some discussion on future research directions.
6. CONCLUSION	This chapter presents the conclusions drawn from the research presented in the thesis.

2

FRAME OF REFERENCE

This chapter presents the frame of reference for the thesis. It starts with production system design, and an introduction of the recent development in the area. Following that introduction, the terms "greenfield" and "brownfield" are explained, after which a theoretical base on factory layout planning is presented. This leads in to a section on wicked problems before the chapter is wrapped up by presenting the technical tools used as decision support in the research performed in this thesis.

In order to connect and guide the content that is presented in this chapter, Figure 2 is presented. This figures visualizes how the sub-chapters production systems, "brownfield" and "greenfield", factory layout planning, and technical tools as decision support relate both to each other and the research questions. Each sub-chapter presents information related to each topic as necessary to further set the context for this thesis.

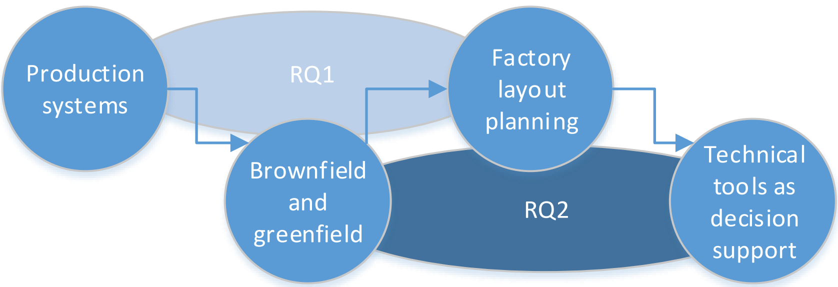


Figure 2: A summary and connections of the concepts used in the thesis and their relation to the research questions.

2.1 PRODUCTION SYSTEM DESIGN

A system comprises several elements, designed to fulfil different functions based on the objective and purpose of the system and interacting with each other to carry out a function (Frezzini et al., 2011; Kauffman, 1980). Each system has a boundary, which can be set at different levels, with everything inside that boundary regarded as a system and everything outside it as external and unaffected by the system. A production system is the transformation of material into a product or service (Bellgran and Säfsten, 2010). In this case, the transformation process (by which an input to the system becomes an output) is production; material, resources, labour, and capital are combined to create services and/or products (Jonsson and Mattsson, 2009). This transformation process involves a number of areas: technology, humans, energy and information, all of which must be organised and managed effectively if the transformation process is to be possible (Bellgran and Säfsten, 2010). The elements of a production system, such as facilities, humans, equipment, software and procedures are all interrelated (Löfgren, 1983; Chapanis, 1996).

A production system is a sub-system to the larger system denoted manufacturing (Bellgran and Säfsten, 2010). Manufacturing is a series of interrelated activities and operations involving the design, material selection, planning, production, quality assurance, management and marketing of products, while manufacturing production (shortened to production) is the act or process of physically making a product (CIRP, 1990). In a production system, there can be different sub-systems such as a parts production system, in which parts are produced and an assembly system, in which parts are assembled into a product (Bellgran and Säfsten, 2010). This hierarchical perspective on the production system is shown in Figure 3. The decision-making process is an additional dimension which ca be added to the production system description (Bellgran and Säfsten, 2010). In this process, capital management, business management and production management can be added to the system (Sandkull and Johansson, 2000).

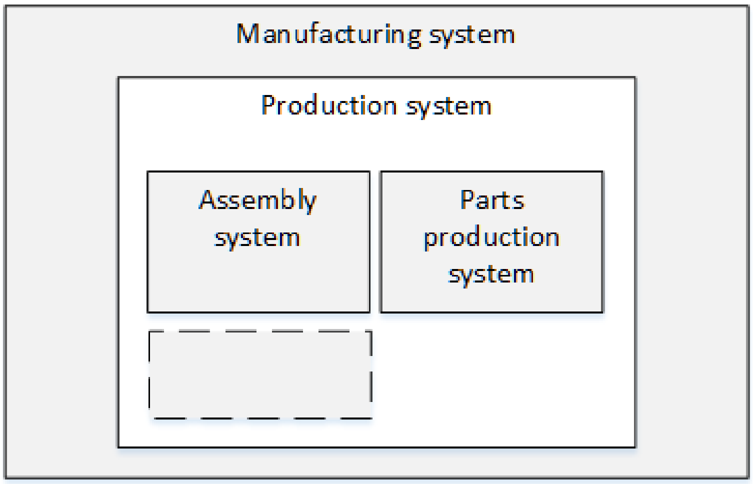


Figure 3. The production system viewed in a hierarchical perspective, adapted from Bellgran and Säfsten (2005).

The production system could be regarded as having its own life-cycle as shown in Figure 4, starting with the planning of system design and ending with the system phase-out (Bellgran and Säfsten, 2010). For reasons of environmental responsibility, it is increasingly expected that products will be re-used. The same expectation might be placed upon the production system, with it expected to support multiple generations of products and production systems when it is designed (Bellgran and Säfsten, 2010). This leads to new production system being designed and realised alongside the old ones and makes awareness of a production system's current position in its life-cycle essential (Bellgran and Säfsten, 2010).

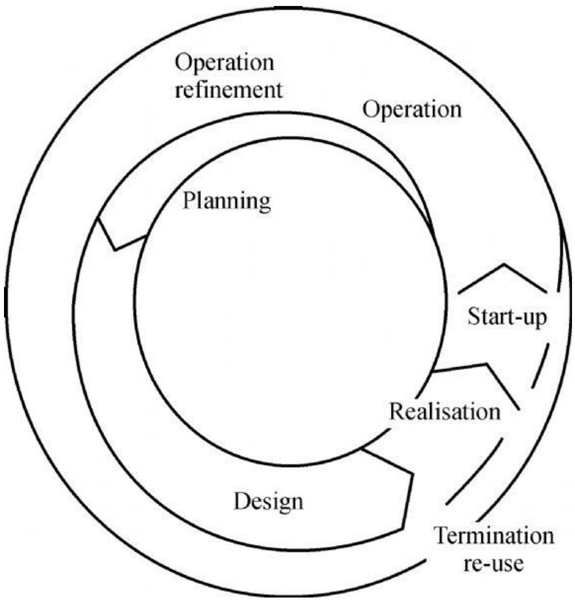


Figure 4. The life-cycle of a production system (Wiktorsson, 2000).

Production systems are often changed as a result of new or changed products or product families. These might be developed due to such things as new legislation, altered market requirements or technological development (Bellgran and Säfsten, 2010). Changes to the production system will also affect the factory layout and the stakeholders in the production system.

To date, there have been three industrial revolutions. The first was mechanisation, the second was mass-production in assembly lines and the third was automation using information technology. The Fourth Industrial Revolution has been predicted and goes by various other names; commonly Industry 4.0 (Industrie 4.0 in Germany), or Smart Manufacturing (in the United States). The next industrial revolution is expected to be heavily focused on data, the integration of information and communications technology and increased automation of systems in combination with human operators (Thoben et al., 2017). Via technical advancements, this revolution is also expected to improve flexibility, speed, productivity and quality of the production system within a fully integrated, automated and optimised production flow. Optimising resource use and an ability to adapt quickly to changing conditions are key ingredients in the realisation of future manufacturing (Lu et al., 2015). Kang et al. (2016) identifies several core technologies and sub-technologies identified for the coming industrial revolution. One of these is cyber-physical systems (CPS), connected systems which can interact via Internet-based protocols. These systems can predict failures, carry out self-configuration and adapt to changes by analysing data (Rüßmann et al., 2015). As many changes are expected on a system-wide level, it is reasonable to expect that the layouts of factories all over the world will also be changed as the next industrial revolution is realised.

2.2 GREENFIELD AND BROWNFIELD

The terms “greenfield” and “brownfield” stem from the field of urban development, in which “greenfield” can be defined as “denoting or relating to previously undeveloped sites for commercial development or exploitation” (Oxford Dictionaries, 2019) and “brownfield” as “denoting or relating to urban sites for potential building development that have had previous development on them” (Oxford dictionaries, 2019). Relating these terms to production systems, greenfield projects have “wide possibilities and no historical limitations” (Vallhagen et al., 2011) while brownfield projects consider “rebuilding or reorganising an existing site” (Vallhagen et al., 2011). In the field of product development, “brownfield” can mean reusing available assets, considering limitations in the design and solution phases due to existing structures (Pakkanen et al., 2016).

The design of manufacturing systems applies to both greenfield and brownfield scenarios, however true greenfield opportunities are rare (Vaughn et al., 2005). Greenfield production systems come with no preliminary conditions, allowing for optimal design according to current best practices. However, production sites are most often already up and running (Bader et al., 2018). Larger projects in brownfield settings may be on the same scale and require the same effort as greenfield ones, but they come with more limitations in terms of requirements, considerations and constraints (Vaughn et al., 2005). Existing system resources, such as machines, people and culture are typical constraints on manufacturing system design in brownfield settings (Vaughn et al., 2005), while in greenfield settings these can almost be excluded. This also applies to the dimensions of the production area, which in a brownfield setting are fixed and constrain any layout solution (Stäbler et al., 2016). Brownfield settings also have established social systems, group norms, management behaviour and management workforce relations (Wall et al., 1986). The historical relationships between management and labour force can be a very important factor when adopting human resources management in small and medium-sized manufacturing organisations. This process might therefore be expected to be easier in a greenfield than a brownfield scenario (Duberley and Walley, 1995). Investing in the necessary IT for smart manufacturing or Industry 4.0 is also considered much more difficult in brownfield production systems than greenfield ones (Davis et al., 2012). All these special circumstances and challenges relating to brownfield scenarios will require future engineers to have strong analytical skills and the ability to find brownfield solutions, as probably the most critical competency in a future production system will be an ability to deal with both old and new in parallel (Erol et al., 2016). Some of the differences between greenfield and brownfield settings are presented in Table 2.

Table 2: Summary of some of the differences between greenfield and brownfield settings

CATEGORY	GREENFIELD SETTING	BROWNFIELD SETTING
OCCURRENCE	Once per object lifetime	Multiple times per object lifetime
SOLUTIONS	Optimal designs	Adapted designs focused on working
SOCIAL PRECONDITIONS	Societal norms No workplace culture or other preconditions	Societal norms Workplace culture Management/workforce relations Management behaviour Social systems and group norms
PHYSICAL PRECONDITIONS	Ideal shape and area No existing resources or machines Media to be designed	Constrained shape and area Existing resources and machines Existing media connections Reusing available assets

2.3 FACTORY LAYOUT PLANNING

Layout planning is one of the main areas to address in the process of designing production systems (Tompkins et al., 1996). The problem of planning a factory layout can be divided into two categories: design and optimisation (Heragu, 2008). Optimisation problems are mathematical in nature and offer solutions to an optimal theoretical layout, while the design type of layout planning is subjective in nature and based more on previous experience. Research has focused on the optimisation-type problems (often called the “facility layout problem”), with multiple algorithms developed over the years. This has been summarised by Drira et al. (2007) and several other more recent literature surveys and reviews (such as Hosseini-Nasab et al., 2017; Ahmadi et al., 2018). While there is much research into the optimisation problem, there is little help for factory layout planning which takes into account all the different considerations, compromises and challenges faced by industry. However, Systematic Layout Planning is a method developed to provide practical help with this; it offers hands-on systematic procedures, methods and tools to use when planning layouts (Muther, 1973). Even so, it is not fully adapted to today’s factories, which are becoming more and more digitalised and connected. Other approaches throughout history include Immer’s Basic steps (Immer, 1950), a three step method for converting flow lines to machine lines, Reed’s Plant Layout Procedure (Reed, 1961), a ten step procedure that also consider future expansion needs, and Apple’s 20 step Plant Layout Procedure (Apple, 1977).

Tompkins et al. (1996) divided layout planning procedures into two types: 1) construction layout methods, which involve planning in empty factories and 2) improvement procedures, in which updated layouts are generated based on existing production systems. Schenk et al. (2010) define three separate levels for executing layout planning projects:

- *Level 1:* systematisation of the planning principles in accordance with the planning activities and project definition;
- *Level 2:* implementation of ideal layout planning in accordance with the project development planning activities;
- *Level 3:* implementation of real layout planning in accordance with the project development planning activities and taking real restrictions into account.

These three levels of executing layout planning generate three different types of layouts: 1) ideal, 2) approximate and 3) real layouts (Schenk et al., 2010). The ideal layout is the best possible layout solution, created without constraints or restrictions, while the approximate layout is an interim step which pays particular attention to building parameters (Schenk et al., 2010). The real layout is one which takes all restrictions into consideration, adapted from the ideal layout by taking into account a multitude of separate factors, requirements and restrictions, such as planning information during development (Schenk et al., 2010). Because the real layout considers a vast array of factors, requirements, and restrictions, it is the one most likely to be implementable in a real factory setting. Figure 5 shows an example of an ideal and a real layout.

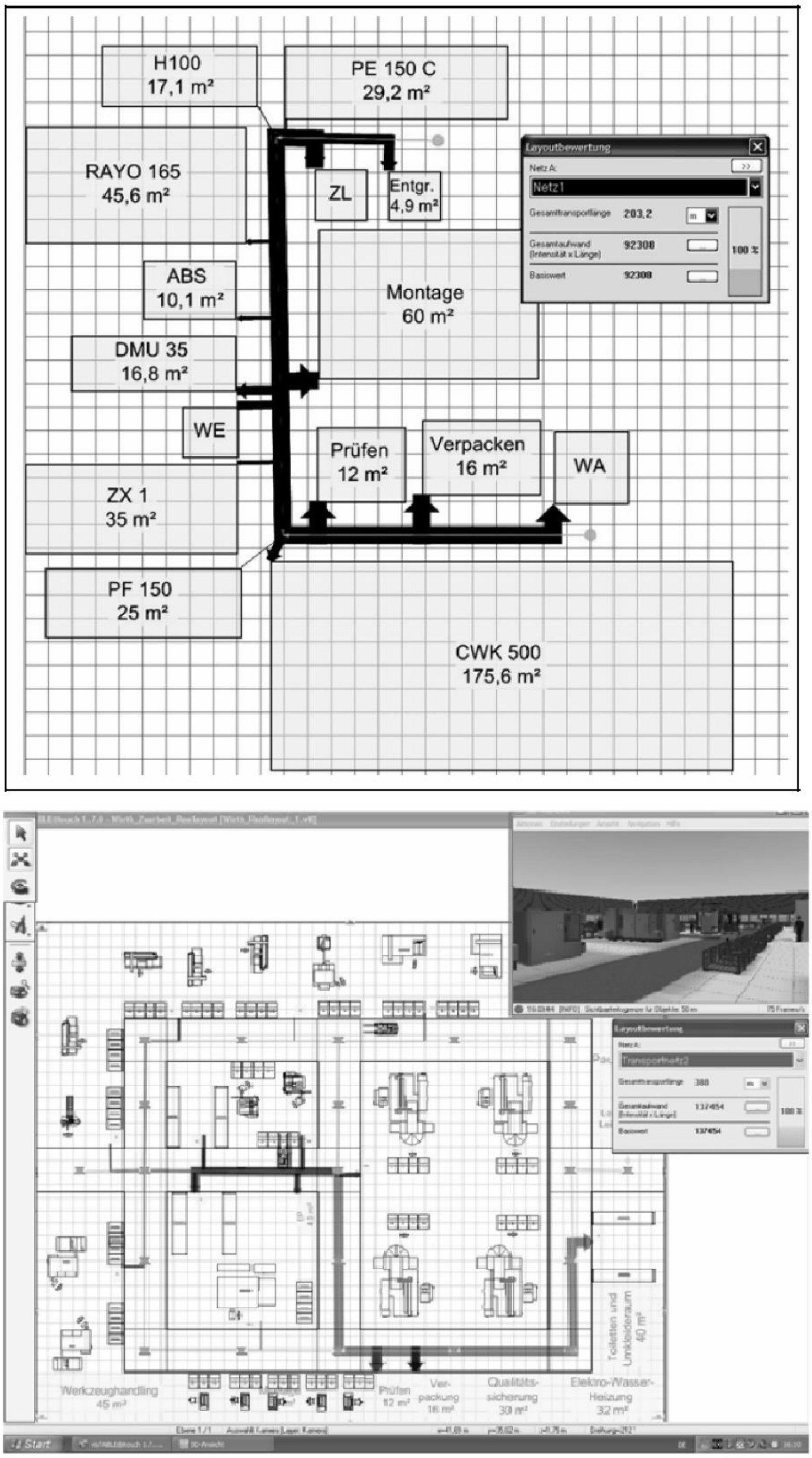


Figure 5. Ideal layout in the top and real layout in the bottom (Schenk et al., 2010)

2.4 WICKED PROBLEMS

Collective intelligence (the creativity and resourcefulness which a group or team can bring to a collaborative problem) is a natural property of socially shared cognition and a natural enabler of collaboration (Conklin, 2005). This intelligence can be challenged by so-called forces of fragmentation, which make collaboration difficult or impossible (Conklin, 2005). Fragmentation can be defined as when project stakeholders all are convinced that their version of the problem is correct, even if based on tacit assumptions (Conklin, 2005). In the factory layout planning context, there is a relationship between the real production system, the virtual representation of it and the mental model of it (Vallhagen et al., 2011). This could be the cause of the above-mentioned type of fragmentation. Other types of fragmentation include social complexity and technical complexity (Conklin, 2005). Social complexity is a function of the number of people involved and affected by a project and their diversity (Conklin, 2005). In a factory layout planning setting, this complexity can vary. However, bringing in, say, a maintenance engineer can yield important feedback to the layout planning process while also presenting new challenges. Technical complexity considers the number of technologies involved in a project, the number of possible interactions between them and the rate of technical change (Conklin, 2005).

Conklin (2005) states that complaints such as, "how am I supposed to get my work done with all these meetings?" and "we always have time to repeat it, but never time to do it right" is the kind of organisational pain cause by fragmentation. Such organisational pain leads to frustration, likely due to misunderstanding the nature of the problem. This is because the problem might not be just any problem, but actually a wicked one (Conklin, 2005). Conklin (2005) presents six characteristics to distinguish wicked problems:

1. You do not understand the problem until you have developed a solution.
2. Wicked problems have no stopping rule.
3. Solutions to wicked problems are not right or wrong.
4. Every wicked problem is essentially unique and novel.
5. Every solution to a wicked problem is a "one-shot operation".
6. Wicked problems have no given alternative solutions.

Fragmentation may be caused by wicked problems; these require appropriate tools and methods if they are to be dealt with efficiently (Conklin, 2005). Tame problems (the opposite of wicked problems) can be solved by traditional linear processes which produce a workable solution within an acceptable timeframe (Conklin, 2005). Such problems may have a well-defined and stable problem statement, a definite stopping point and a solution which can be evaluated objectively as right or wrong (Conklin, 2005). Conklin (2005) also suggests six ways to tame wicked problems, with each solution corresponding to the characteristic described above:

1. Lock down the problem definition.
2. Assert that the problem is solved.
3. Specify objective parameters with which to measure the solution's success.
4. Cast the problem as "just like" a previous problem which has been solved.
5. Give up on trying to get a good solution to the problem.
6. Declare that there are just a few possible solutions and focus on selecting from among these options.

2.5 TECHNICAL TOOLS AS DECISION SUPPORT

This section gives a brief frame of reference for the technical tools used as decision support in the research. In the decision-making process, data provides support to make an informed decision (Koščielniak and Puto, 2015). While there is a plethora of tools which could act as decision support, this section presents the three technical tools used to provide this data: 1) discrete event simulation, 2) 3D laser scanning and 3) virtual reality. These tools were chosen due to their familiarity and helped identify the challenges faced during the brownfield factory layout planning process.

2.5.1 Discrete event simulation

Discrete event simulation (DES) is a type of simulation often used to simulate production systems performance, for example airports or car production facilities (Banks et al., 2005; Klingstam and Johansson, 2000; Johansson et al. 2003). DES models are based on logic, which states that independent change through triggered events is controlled as the model is being executed. These triggered events are scheduled to occur at a discrete time which, in turn, can trigger other events. DES models are based on such events and so nothing is simulated unless such an events occurs. This gives the models time to jump from event to event. This makes it possible for well-built DES models to simulate very long time spans and offer good decision support which might otherwise be hard to obtain.

2.5.2 3D laser scanning

3D laser scanning is a technology stemming from such fields as terrain mapping. It can be applied to gather unbiased spatial data in a non-contact way (Gregor et al., 2009). 3D laser scanners are mainly divided into either time-of-flight scanners or phase-shift scanners. Time-of-flight scanners are suitable for outdoor use (such as construction sites) because they capture data from objects over 100 meters away (Dassot et al., 2011). Phase-shift scanners are better suited to indoor use (such as most production systems), because they normally capture data from objects within 100 meters at higher resolution (Dassot et al., 2011). 3D laser scanners operate by emitting laser beams which reflect from a surface in the direction of measurement. By measuring the distance travelled by the laser beam and combining that with the direction in which it was sent, a measurement point in 3D space can be acquired (Klein et al., 2012). 3D laser scanners often have a 360-degree field of view in the horizontal plane and around 300-320 degrees in the vertical plane, as shown in Figure 6 (Dassot et al., 2011). By systematically controlling the direction of measurement, the combination of millions of measurement points in 3D space can generate a detailed and neutral spatial representation of the scanned environment. Using the built-in camera, these measurements can also be complemented with RGB data to provide enhanced visual properties. This kind of systematic data capture is known as a “scan”. 3D laser scanning has been applied in the context of production systems in many ways, for example in combination with DES (Lindskog et al., 2012).

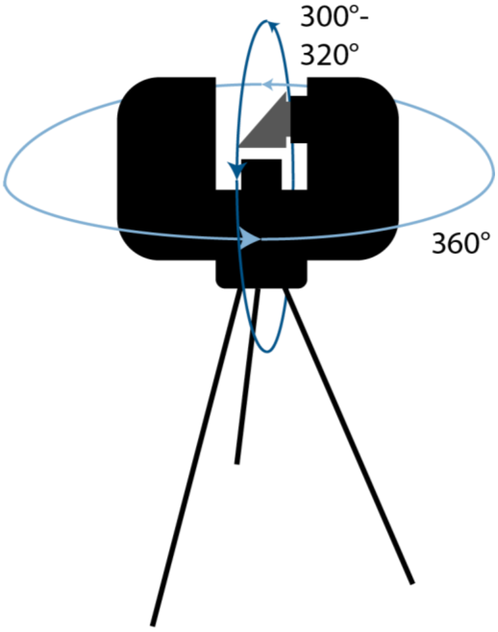


Figure 6: Visualisation of a 3D laser scanner and its field of view.

2.5.3 Virtual reality

Virtual reality (VR) can be defined as the computer-generated simulation of a three-dimensional image or environment, which can then be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors (Oxford Dictionaries, 2019). VR has been developed since the first system in 1968, which presented stereoscopic 3D views while tracking head movement (Sutherland, 1968). Two important characteristics are used to differentiate VR systems: 1) immersion, the user's sensation that the virtual environment is real and 2) presence, the user's sensation of being part of the virtual environment (Magenat-Thalmann and Thalmann, 1999; Liebert, 2001). Immersion can be affected by such things as feedback lag time, field of view, spatial audio, tactile feedback and force feedback (Lu, Shpitalni, and Gadh, 1999), while presence can be affected by such things as virtual representations of the user. VR systems can be classified based on their level of immersion, ranging from non-immersive systems such as desktop systems, to fully immersive VR systems using a head-mounted display (HMD) (Korves and Loftus, 1999).

VR has shown potential in the production field as a collaborative tool for exchanging data and information, which can facilitate better understanding and improved decision-making through immersive experience and visualisation (Choi, Jung, and Noh, 2015). Immersive VR systems have produced positive results in collaborative factory planning scenarios, which visualise multiple users' viewpoints (Wiendahl and Harmschristian Fiebig, 2003), and recent development show promising results in using VR to support layout planning (Gong et al., 2019).

3

RESEARCH APPROACH

Research, the systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions (Oxford Dictionaries, 2019), is often thought of as an organised, linear process. However, in practice the process is often under much less control (Williamson et al., 2002), but should be conducted such that people can understand, reproduce, and evaluate its quality (Trochim et al., 2016). Research can be divided into two strictly seoparate types: 1) basic research, focused on building fundamental theory and 2) applied research, focused on exploring real-life problems (Williamson et al., 2002). This thesis fits the description of applied research in the field of production systems. This chapter explains the systematic way in which the research in this thesis has been conducted.

A research approach is based on three interconnected components: 1) philosophical worldviews, 2) research design and 3) research methods. Jointly, these form a plan to conduct research (Creswell, 2013). The combination of these three components is critical when planning research; research needs to be designed properly if it is to be relevant to a given worldview. Research methods should also translate the designed research into practice. An important part of research is theory-building.

3.1 THEORY-BUILDING

Theory-building can be carried out in two essentially disparate ways: via inductive or deductive reasoning. Inductive reasoning starts with a specific observation, after which theory-building is initiated. It is the more open-ended and exploratory of the two (Trochim et al., 2016). Deductive reasoning, on the other hand, is an approach which starts with something generic and moves toward more specific theories. It is often applied when testing hypotheses (Trochim et al., 2016). This research was initiated as several challenges and problems appeared while the process of factory layout planning was being studied. This triggered a need for further research into the area, as the well-researched methods of factory layout planning were absent from the part of the manufacturing domain being studied. As the research on this topic progressed, more studies were warranted by a need to understand challenges in various settings and different cases and using both deductive and inductive reasoning, depending on the specific case and theory.

3.2 PHILOSOPHICAL WORLDVIEW

The choice of methods and methodologies during research are affected by the underlying assumptions the researcher makes about reality, or the researcher's philosophical worldview (Crotty, 1998). These assumptions are fundamental to the researcher's interpretation and understanding of the research question and the findings are interpreted (Crotty, 1998). In order to formulate a research problem or research question, existing literature or experience of a practical problem may be used as sources. A major motivation for applied research may be the opportunity to solve a problem of personal significance to the researcher (Trochim et al., 2016).

This research is targeted at the manufacturing domain, in which the author of this thesis has a personal background and previous experience. Prior to starting his Ph.D. studies, his experiences of studying and working within the manufacturing field were gained mainly nationally in Sweden, but also internationally in Wales. Alongside undergraduate studies in Automation and Mechatronics and subsequent studies for a Master's degree in Production Engineering, many hours were spent working in a production system, garnering much valuable experience and insight. After gaining the Master's degree, a year working in a global engineering company with customers and production sites all over the world gave further insight into the challenges facing industry. All the experience and insight gained prior to the Ph.D. grew into to a personal desire to improve and make processes more effective and to reduce wasted time and effort. This provided a curiosity about proving knowledge and insights and shaping future factory-related processes.

Epistemology relates to the assumptions regarding what creates acceptable, valid and legitimate knowledge (Burell and Morgan, 1979). There are four main epistemologies or philosophical worldviews: 1) postpositivist, 2) constructivist, 3) transformative and 4) pragmatic. Pragmatism, as presented by Creswell (2014), is a problem-centred, pluralistic worldview focused on real-world practice and the consequences of actions. This implies that the consequences of actions and concepts are relevant when they can support those actions. In research, a pragmatic worldview causes the researcher to focus on identifying solutions which can support future practice in a given field and use all available approaches to understand and solve the problem (Rossman & Wilson, 1985). The pragmatic researcher commonly mixes quantitative and qualitative assumptions during research, choosing the methods and techniques which best meet the relevant needs and purposes (Creswell, 2014).

The author of this thesis identifies as a pragmatic researcher. As the research in this thesis is mainly applied and focused on providing valuable knowledge to the manufacturing domain, it is appropriate to cite the pragmatic theory which says a statement is true if it can provide value when put to practical use and that valuable knowledge is created mainly by the process of identifying practical problems and using whatever methods are suitable. In practice, this meant that a combination of qualitative and quantitative research approaches were applied, as further explained in section 3.3. This mixed-methods research approach has the benefit of collecting data in the most appropriate way to explain or answer the problem, rather than deciding beforehand which method to apply (Creswell, 2014).

3.3 MIXED-METHODS RESEARCH APPROACH

The research approach is the plan for how the research questions should be addressed. It can be either quantitative or qualitative, or use a mixture of the two (known as mixed-methods research). In quantitative research, relationships between certain identified variables and data are examined in order to test objective theories. In qualitative research, open-ended data is gathered in order to explore and understand the problem. The mixed-methods approach combines both quantitative and qualitative research to gain the strength of both approaches while minimising their respective drawbacks. This research method is aligned to the pragmatic worldview and meant to give a more complete understanding of the problem being investigated by the research (Creswell, 2014). In this research, the mixed-methods research approach has been used to further explore the research questions. As the vision is broad and includes all types of errors in the area of brownfield factory layout planning, this approach is well suited as it can capture many different kinds of aspects. For the industrial studies conducted, this has mainly taken the form of action research.

3.4 RESEARCH DESIGN

The research design section covers the research design and data collection methods used in the studies upon which this thesis is built.

3.4.1 Action research

Action research can be broadly defined as an approach in which the researcher collaborates with a client to diagnose a problem and develop a solution (Bryman and Bell, 2007). This makes it well-suited to working in industrial scenarios, where the initial problem might not be clearly defined. A typical action research approach is cyclical, with the plan, action, results and reflection steps conducted as shown in Figure 7 (Oosthuizen, 2002). By applying the action research process in this manner, the next study can build upon the results and reflections of the previous one. This process also allows the researcher to be part of the studied group in varying ways and apply different data collection methods pragmatically, depending on which is best-suited (Oosthuizen, 2002).

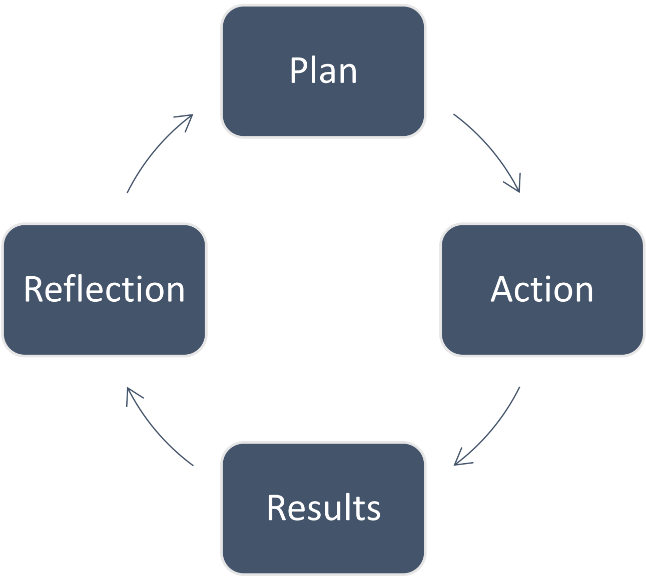


Figure 7. The cycle of action research, based on Oosthuizen (2002).

3.4.2 Participant observation

Participant observation is a qualitative method of collecting data. It is used to collect data on events or situations and allows the researcher to gain insight into the specific context, behaviours and relationships (Mack et al., 2005). Conducting research as a participant can be classified into four different levels of observation: 1) complete observer, 2) observer-as-participant, 3) participant-as-observer and 4) full participant (Kawulich, 2005). The complete observer role is when the researcher is covert and unknown to the studied group, while its counterpart of full participant is when the researcher is a member of the group but concealing their research role from the group (Kawulich, 2005). The observer-as-participant can participate but focuses on collecting data via observation, while the participant-as-observer interacts extensively with the group (Kawulich, 2005).

3.4.3 Interviews

Interviews as a data collection method may be divided into three separate types, depending on design and execution (Bryman and Bell, 2007). They may be *structured, semi-structured* or *unstructured*.

A *structured interview* follows a fixed sequence, but yields results which are less qualitative (Bryman and Bell, 2007).

A *semi-structured interview* uses an interview guide with a list of questions prepared for specific topics which need to be covered, whilst leaving some latitude for the interviewee in their replies (Bryman and Bell, 2007). Such an interview need not adhere exactly to the outlined schedule and can deviate to include other questions, depending on what replies are given by the interviewee (Bryman and Bell, 2007).

In an *unstructured interview*, the interviewer uses almost no prepared questions on specific topics; instead, the interviewer more freely pursues points they deem worth following up (Bryman and Bell, 2007). An unstructured interview resembles a conversation rather than a typical interview (Bryman and Bell, 2007).

Semi-structured and unstructured interviews have a greater focus on qualitative data, such as the interviewee's point of view (Bryman and Bell, 2007).

3.4.4 Research carried out

The research in this thesis has applied mixed-methods research differently in the four performed studies. The data collection methods have varied depending on the questions and scope of each study. Data collection has been conducted both qualitatively and quantitatively, via literature reviews, interviews and participant observations, as explained for each paper below and summarised in Table 3.

In *Paper I* used action research and participant observation applied to gather data. Three researchers were involved in different participant roles during the workshop: one researcher had the role of participant-as-observer (due to technical difficulties controlling the model during parts of the workshop), while the other two focused almost solely on recording data by taking notes and recording audio. These two researchers were present in the room and their role as researchers and observers was known to the study group. Thus, the role of complete observer was not entirely fulfilled. However, there was little or no interaction with the group and this also made the observer-as-participant description a poor fit.

In *Paper II*, the role of participant-as-observer was used again because the researcher had the advantage of being acquainted with the software. In this study, observations came mostly from when the study was being conducted and the experimental stage of model-building. These observations were combined with data from semi-structured interviews to form the study results.

Paper III used an interview study to gather data in the form of semi-structured interviews. The interview guide was based on the results of a literature study, which gave the necessary initial contextual and technical information. The interview results were later coded using magnitude coding to further analyse and summarise the data that had been gathered. This study also incorporated a benchmarking study to facilitate improved understanding.

Paper IV comprised semi-structured interviews and a literature study. The literature study aimed at both quantitatively and qualitatively analysing how published literature approached brownfield factory layout planning. The study was also complemented with a mixture of semi-structured and structured interviews, with the interview guide mostly comprising structured interview questions mixed with more open ones.

Table 3. Summary of the data collection approaches used in each paper.

PAPER	QUALITATIVE	QUANTITATIVE
I	Participant observation	
II	Participant observation semi-structured interviews	
III	Semi-structured interviews	Interview coding
IV	Semi-structured interviews	Literature review

3.5 RELIABILITY AND QUALITY IN RESEARCH

Three prominent criteria are often used to evaluate the quality of research: reliability, replication and validity (Bryman and Bell, 2007). Reliability concerns whether the results of a study are repeatable and is often associated with quantitative researchers (Bryman and Bell, 2007). Replication means that another researcher should be able to replicate a study that has been conducted. In other words, the study procedure must be highly detailed so as to allow replication (Bryman and Bell, 2007). Validity, often considered the most important criterion, concerns the integrity of the conclusions generated by the research (Bryman and Bell, 2007). Bryman and Bell (2007) explain four type of validity:

- *Measurement validity*, which considers whether a devised measure of a concept really reflects the concept as intended.
- *Internal validity*, which considers whether a conclusion which relies on a causal relationship between multiple variables is genuine and not caused by something else.
- *External validity*, which considers whether the results of a study can be generalised beyond the context in which those results were generated.
- *Ecological validity*, which considers whether social scientific findings apply to people's natural social settings, or whether the data gathered does not fully reflect people as it would, had the researcher not intervened.

These validity concepts, adapted to the setting of qualitative research, can be defined and explained as follows: *credibility*, which considers how believable the findings are, *transferability*, which considers whether the findings apply to other contexts, *dependability*, which considers whether the findings apply at other times and *confirmability*, which considers whether the researcher has allowed their values to affect the study significantly. The reliability and quality of this research will be discussed in Chapter 5.

4

SUMMARY OF APPENDED PAPERS

This chapter summarises each appended paper in three parts; background, information on the study, and outcome. At the end of the chapter, each paper's outcome is linked to the researched questions posed. All figures are from the published papers unless otherwise specified.

Paper I	**Nåfors, D.**, Lindskog, E., Berglund, J., Gong, L., Johansson, B., and Vallhagen, J., "Realistic virtual models for factory layout planning", 2017 Winter Simulation Conference (WSC), Las Vegas, NV, 2017, pp. 3976-3987.
Paper II	**Nåfors, D.**, Bärring, M., Estienne, M., Johansson, B., and Wahlström, M., "Supporting Discrete Event Simulation with 3D Laser Scanning and Value Stream Mapping: Benefits and Drawbacks", Procedia CIRP, Volume 72, 2018, pp. 1536-1541.
Paper III	Dalstam, A., Engberg, M., **Nåfors, D.**, Johansson, B., and Sundblom, A., "A Stepwise Implementation of the Virtual Factory in Manufacturing Industry", 2018 Winter Simulation Conference (WSC), Gothenburg, Sweden, 2018, pp. 3229-3240.
Paper IV	**Nåfors, D.**, Berglund, J., and Johansson, B., "Brownfield Factory Layout Planning: The Applicability Gap", submitted to Journal of Manufacturing Technology Management.

4.1 PAPER I

Paper I reports from a project named "3D-SILVER" which aimed to aid decision support tools by visualising layouts and simulating ergonomics. This paper is from the end of the project, where the layout visualisation tools were applied to a real case via an industrial study. The industrial study aimed to investigate and evaluate the usefulness of a realistic virtual factory model in a brownfield factory-layout planning scenario. In this scenario, eight new multi-operation milling machines were to be installed in an already utilised area of roughly 600 square meters inside an existing factory. The machine area was served by four operators who were responsible for keeping the machines running as much as possible, while trucks would supply raw materials to the area. The new machines were to be placed on separate foundations to ensure product quality, meaning that the first step (once the layout was finalised) was to start with the foundations for each machine.

In this study, a combination of point cloud data, 3D CAD model data, and 2D CAD model data was combined to create a realistic and accurate model of a planned future state at a Swedish manufacturer. The model was then used in two different ways in structured workshops, either displayed on a projector screen or visualised in immersive virtual reality.

4.1.1 Industrial study

The industrial study was divided into four steps as shown in Figure 8. The starting point was using 3D laser scanning to objectively and neutrally generate a point cloud of the area. This was then used in the factory layout planning. This was followed by the creation of a realistic layout model of the future state for viewing on a projector screen, with the point cloud data combined with 3D CAD model data and 2D CAD drawing data. Upon completion of the previous step, an identical model was created for use with an HMD setup in immersive virtual reality. The final step was to hold layout evaluation workshops at the company, with the researchers observing what kind of feedback and discussions the company stakeholders focused on while using the two models.

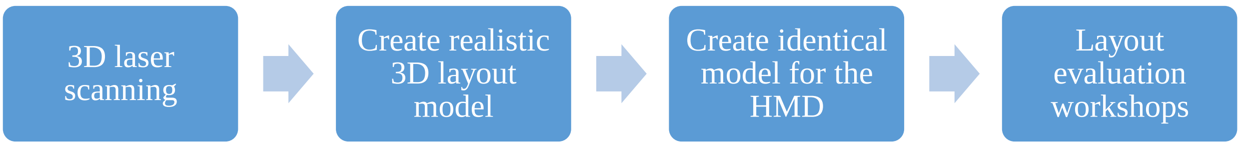
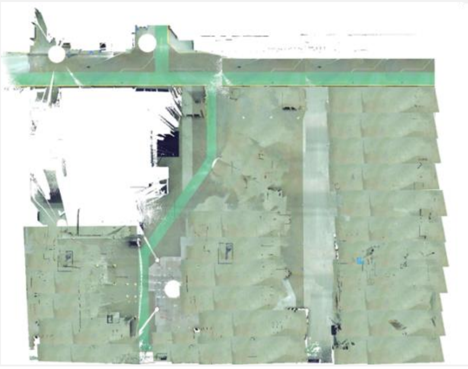
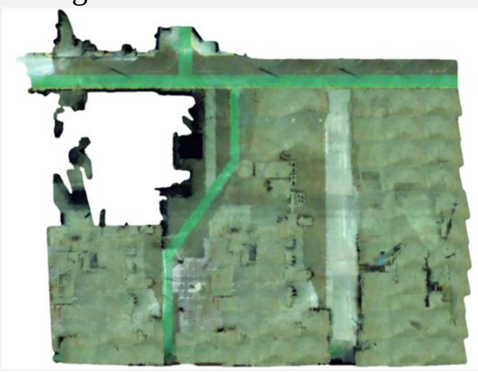


Figure 8: The industrial study process used.

Step 1 – 3D laser scanning

The relevant area of the factory was digitised using a 3D laser scanner with a built-in RGB sensor. A total of eight scan positions were used, resulting in a combined point cloud of 226 million points, with each point having a coordinate in space (x, y, z) and a colour (r, g, b) from the RGB sensor. As the area was in use at the time of scanning, equipment and materials which would not remain in the area in the future scenario were digitally removed. This was done in dialogue with on-site production engineers. The remaining point cloud was divided manually into suitable pieces, such as a roof component and a component for each wall. To achieve a highly stable framerate in the HMD later on, certain components (such as the floor and walls) were simplified and meshed. This reduced the data size significantly, as shown in Table 4. Meanwhile, the roof component had its point density reduced. A side-effect of this is that the visual quality is altered. Visualising all points gives a high degree of detail but when the number of pixels displayed is in excess of the number rendered, the components become transparent on close inspection. Simplified meshes show fewer details but remain opaque.

Table 4: Sample of the floor model before and after simplification and meshing.

FLOOR	Scan data 	Triangle mesh 
VERTICES	67,036,944	24,295
DATA SIZE	1,013 MB	21 MB

Step 2 – Create realistic 3D layout model for a projector screen

The second step of the industrial study process in this paper was to create the realistic 3D model of the future layout for viewing on a projector screen. This was created in Autodesk Navisworks. To increase the model's representation of the expected future step, it was realised in three iterations. A meeting was also held with members of the industrialisation project to ensure no equipment was missing in the layout and that it matched their expectations. The initial model comprised the following components:

- 2D CAD layout drawing of the area, created by the industrialisation project team.
- 3D CAD models of the machines and other equipment to be installed in the area.
- 2D CAD model of the planned walkway in the area.
- A point-cloud model of the digitally cleaned shop floor area, divided into several components.
- A point-cloud model of existing equipment set to remain in the area.

The changes and additions to the layout as realised by the industrialisation project team from each iteration are presented in Table 5. These were implemented in the model after each iteration.

Table 5: Changes and additions to the layout.

ITERATION	CHANGE/ADDITION
FIRST	Addition of two pallets in front of each machine Addition of one pallet lift per machine
SECOND	Repositioning of three machines Repositioning of pallet rack
THIRD	Rotation of pallets Addition of one work bench per two machines Changing of the tool measurement model Addition of a coordinate-measuring machine and a washing machine

Step 3 – Create identical model for the HMD

The final model from the previous step was replicated in Unity (with some slight changes) for viewing in an HMD. To save data, the floor and walls were replaced with triangle meshes made from the point-cloud data. Customised scripts were also added to enable interaction in the model, such as navigation and repositioning of interactable objects. The interactable objects in this model were a pallet lift and a cart.

Step 4 – Layout evaluation workshops

A succession of three workshops was held on the host company's premises. These followed the overall structure from Lindskog et al. (2016), as summarised in Figure 9. The participants varied between workshops, however the project leader, process planner and the three researchers were always present. One researcher controlled the realistic 3D layout model projected onto a screen for workshop participants, while the other two made written observation notes to support the audio recording. When the other model was used during the second half of the second and third workshops, one participant wore the HMD and controllers (enabling them to interact with the model), while the other participants viewed a representation of the HMD display on a projector screen.

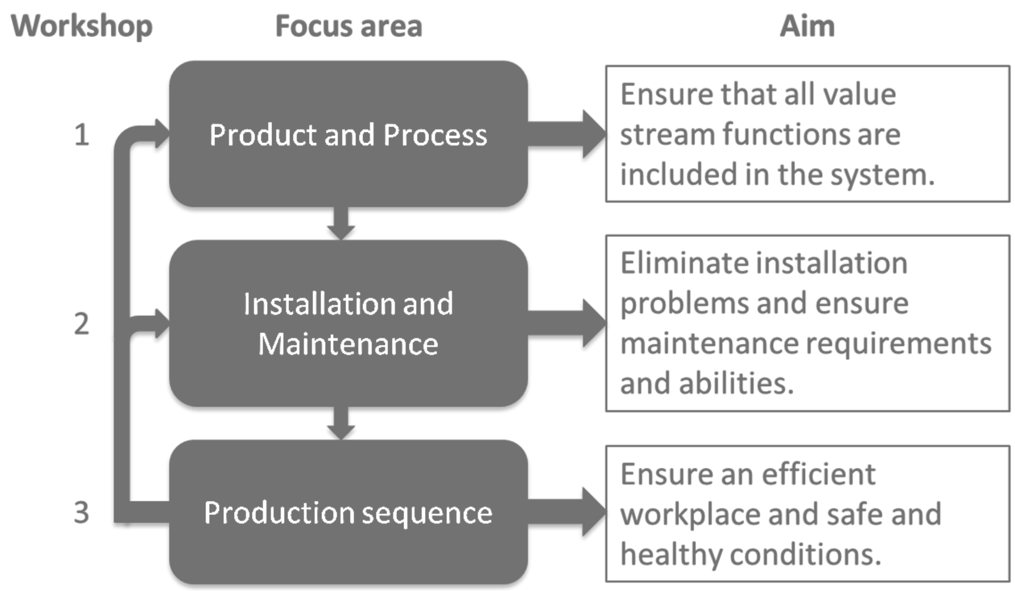


Figure 9: Structure of the three layout evaluation workshops (Lindskog et al. 2016).

4.1.2 Outcome

Several problems or risks were identified during the three workshops, which had not been raised during the model-building iterations earlier in the study. Some of these were solved during the workshop by implementing changes and additions to the layout proposal directly in the software; others require more work. Some of these issues include: lack of an incoming and outgoing material area, not enough fixture wagons, the positioning of machines being less than satisfactory, not enough workbenches. When viewing the model using an HMD, the user could better perceive proportions and distances and gained a better feel for the area. For example, a table model was too small throughout the entire study, but was not realised until the very end when an operator wore the HMD. Based on knowledge gained from experience, the operator could instantly tell that the table would be too small for the necessary products and work.

This study also showed a problem with 2D CAD drawings, as it was impossible to perfectly align the neutral and objective 3D laser-scanned point cloud representation of the area with the hand-made drawing of the area. If the walls were aligned, some pillar positions were off, and vice-versa. When the walls were aligned between the point cloud and 2D CAD drawing, one of the pillars was over 30cm off, as shown in Figure 10. This would cause potential problems during layout installation and operation.

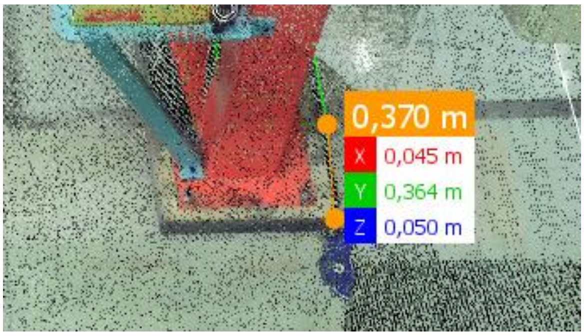


Figure 10: Difference between the point cloud and 2D CAD drawing when the walls were aligned.

4.2 PAPER II

Paper II reports from a research project called "The space industry of tomorrow", in which Chalmers and RUAG Space AB approached the challenges of the new market in the space industry dubbed "new space". This new market brings significantly higher volumes and changes in customer requirements, as it contains a completely different customer segment than previously. This study aimed to investigate the potential benefits and drawbacks of making a discrete-event simulation (DES) model based on data from value-stream mapping (VSM) and 3D laser-scanning. This combination has seen little exposure in research and is thus a novel idea, while also serving as decision support for the industrial side.

The production system in this study was a clean room consisting mostly of workbenches and human operators, plus special machinery for various tasks (such as ovens for heat testing and a vacuum chamber for compliance testing). There were no trucks or AGVs in the production system; the operators conducted all transportation either by hand or with a cart. The production system was divided into three separate product units with some overlap, producing engineer-to-order products in very small runs.

4.2.1 Industrial study

The industrial study used in this paper consisted of three main steps: 1) data collection, 2) model building and 3) model validation. After the model validation, two semi-structured interviews were held; one with the product unit manager of the modelled part of the production system and one with an experienced operator.

Data collection

The starting point of the industrial study was to carry out a VSM in order to understand the production system's various flows and convergences. For the production system that was to be modelled (the one most affected by the new market), the VSM resulted in eight sub-flows which converged into a final assembly flow. Due to the number of sub-flows, convergences, and production of engineer-to-order products, the VSM method applied was specially developed for this case, as presented in Bärring et al. (2018). The shortest sub-flow is the VSM shown in Figure 11, with two administrative processes, three storage buffers and five production processes. The total flow, including all sub-flows and the final assembly flow, consisted of over

150 process steps.

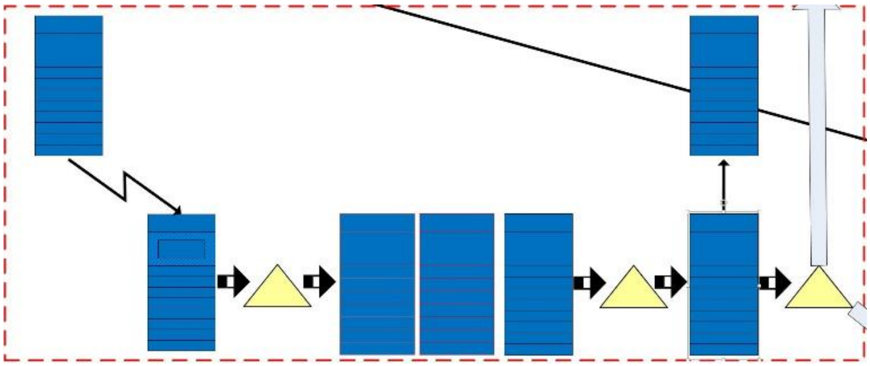


Figure 11: VSM of the shortest sub-flow. The square boxes are processes, while the yellow triangles represent storage buffers.

The production facility was digitised using 3D laser scanning technology. Over 50 scan positions were used to produce a point-cloud model of the roughly 1,800 square meter facility, consisting of over 500 million measurement points. An example of the spatial data resulting from this 3D laser scanning is shown in Figure 12. The data was divided into various pieces representing different parts of the factory, while the roof was removed to support top-view visualisations.

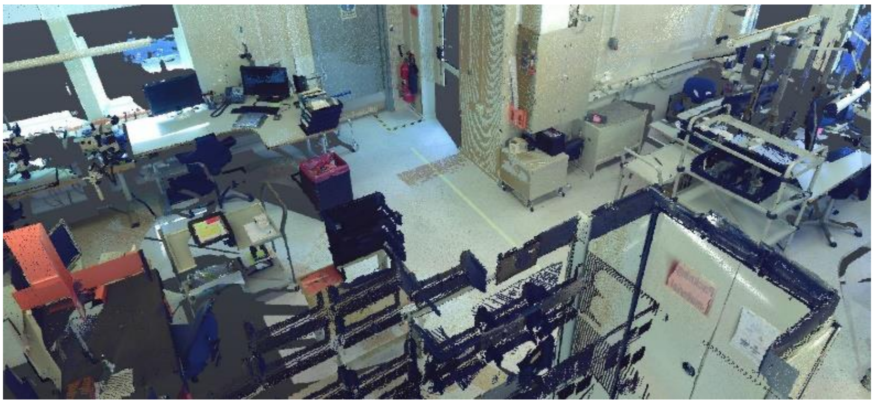


Figure 12: Visualisation of the spatial data gathered via 3D laser scanning.

Model building

The DES model used in this study was built in two separate steps. First, all the resulting data from the VSM plus additionally gathered data not included in the VSM was used to build a logic model of each individual sub-flow. Each process step in each sub-flow was modelled according to the VSM and in most cases connected by an operator moving the product from one process to the next. When the logic of each sub-flow was correctly represented in the simulation model, the sub-flows were connected to create the entire flow of the simulated product. Once the full flow was achieved, the point cloud model was imported so each process step could be accurately positioned with the proper spatial relations. The pathing of operators was also modelled so that there were no collisions between the simulated operators and the point-cloud model. An example of this is shown in Figure 13, in which operators (marked by red arrows) can be seen walking through doorways in the simulation model.

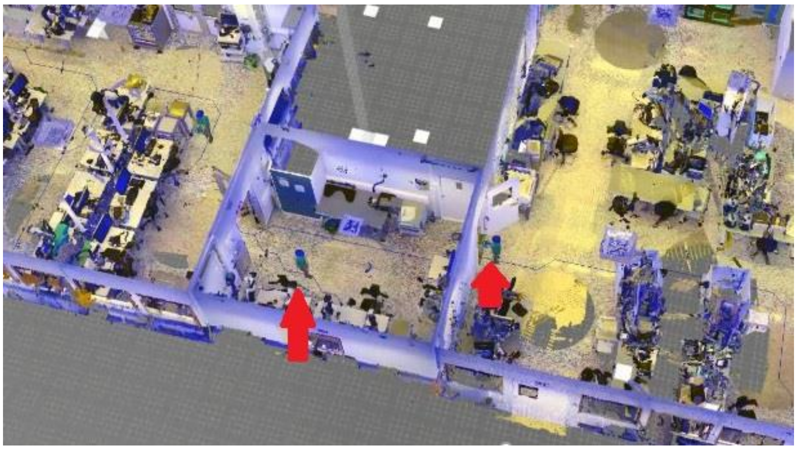


Figure 13: Visualisation of the simulation model showing operators (marked by red arrows) walking through doorways instead of walls.

Model validation

Two separate methods were used to validate the simulation model. In the first one, the product unit manager responsible for the modelled production flow and an experienced operator assessed the flow and movement of products and operators in the model, while it ran in real-time. Their task was to identify deviations from their expectations based on their daily work. Once the model was validated as described above, the product unit manager checked the data for all the processes in the VSM, including such factors as batch size, process step, and process times. Once both these validations were concluded, the model was considered complete.

4.2.2 Outcome

The outcome of this industrial study consists of results from the semi-structured interviews combined with the papers based on authors' experiences from the study. The VSM strongly supported structuring the DES model by breaking the production system down into more manageable sizes which could be individually modelled and tested. However, some data required for the simulation model was missing. 3D laser-scanning gave an accurate, photo-realistic visualisation of the production system, which was very useful in aligning the mental models of the model builder and industrial stakeholders. For example, the operator could almost instantaneously point out the position where a certain process should be conducted. These realistic visualisations also seemed to enhance trust in the simulation model and analysis of its results. The down side to this was that it might lead to reduced scepticism about the model. The way this study incorporated the large point-cloud model into the DES model led to a performance loss, as the amount of rendered data had a noticeable effect on how quickly the model could be simulated. Future DES models using point-cloud data would benefit from only using it when its realistic visuals are beneficial (for example, when accurately positioning objects, deciding operator and truck pathing, or validating the flow).

This study indicated great potential in the combination of VSM, 3D laser-scanning and DES. While VSM and 3D laser-scanning do not give all the data required to build a highly accurate DES model, they can make model-building quicker and more accurate. Using accurate and realistic point-cloud data can also ensure that changes in the DES model will fit and work as planned, when implemented in reality.

4.3 PAPER III

Paper III was produced as part of a Master's thesis focused on how the virtual factory could be implemented at a case company. The virtual factory is a digital platform in which data from the production system is consolidated and presented visually in the form of relevant and precise information for the user or user group (Yang et al., 2015). It can help users observe events and their effects in the production system, thus providing different stakeholders with an understanding (Becker et al., 2005).

This paper presents a methodology to identify needs at the case company while benchmarking available virtual factory technology from industry leaders and academic literature. Ultimately, the paper proposes a stepwise implementation of the virtual factory concept tailored to the case company's needs in order to support fact-based decision-making.

4.3.1 Industrial study

The industrial study applied in this paper consisted of three phases of data-gathering, followed by triangulation of this data to create the implementation plan using an exploratory approach. The three phases of data-gathering were: 1) a literature study, 2) an interview study and 3) a benchmarking study.

The literature study provided initial contextual and technical information on the current trends. It also resulted in the framework for measuring the maturity of virtual factories in six steps, adapted from the framework proposed by Bjarnehed and Dotevall (2018) and shown in Figure 14.

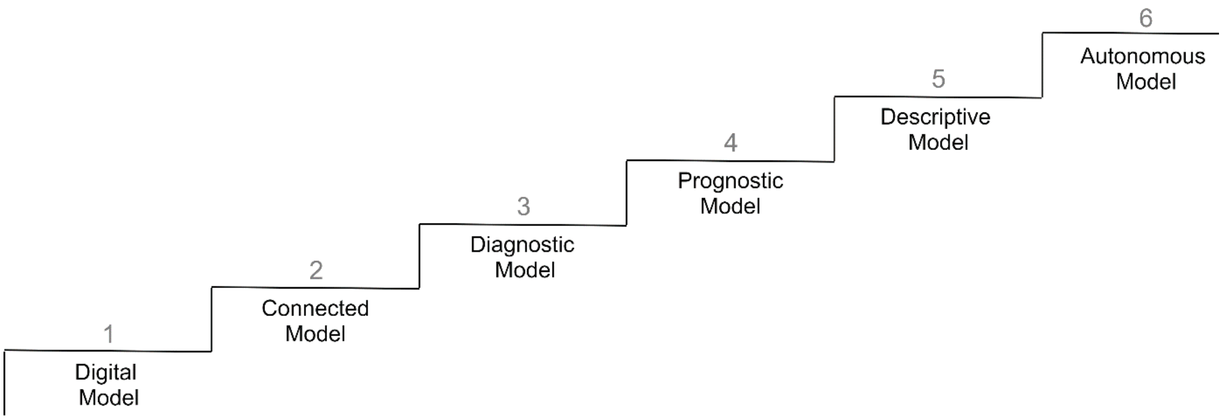


Figure 14: The maturity of the virtual factory divided in to six steps.

The literature study was followed by an interview study to identify the needs at the company. A total of 25 semi-structured interviews were held, based on a questionnaire comprising five main sections: 1) introduction, 2) information, 3) technical readiness, 4) acceptance and 5) summary. This structure aided the review and analysis of the qualitative interview results. Using magnitude coding, the results were coded to assess the level of technical readiness and acceptance; ranging from no technical readiness to full technical readiness and from no acceptance to full acceptance.

The benchmarking study focused on identifying available technologies from industry leaders, to facilitate understanding of which strategies and tools other companies were using. Three companies were benchmarked via a study visit, including a meeting with a subject-matter expert from the benchmarked company.

4.3.2 Outcome

The needs identified at the case company (gathered from the interviews) were divided into two subcategories: 1) technical needs and 2) organisational needs. The technical needs concerned the functionality of the virtual factory, while the organisational needs reflected the use and implementation of the virtual factory and provided insights into the interviewees' expectations and experience. A total of 29 technical needs were identified, with simulation of production flows being the one most frequently expressed. The full table of identified technical needs and how many interviews they were expressed in is presented in Table 6.

Table 6: Identified expressed technical needs and their respective frequency.

EXPRESSED NEED (LABEL)	FREQ.	EXPRESSED NEED (LABEL)	FREQ.
Simulation of production flows (A)	16	Reusability of base model (P)	3
Visualization to educate (B)	10	Path planning and collision tests (Q)	3
What-if analysis (C)	10	Online based model (R)	3
Common information platform (D)	8	Traceability of sources of errors (S)	3
Factory layout design (E)	8	Simulating staffing in production (T)	2
Economical investment decision aid (F)	8	Work environment and ergonomics (U)	2
Resource allocation/optimization (G)	7	Integration of CAD-model (V)	1
Evaluation of available capacity (H)	7	Evaluation of product quality (W)	1
Factory layout representation (I)	7	Accurate virtual measurements (X)	1
Cost calculations for products (J)	7	Virtual FAT and SAT (Y)	1
Simulate process parameters (K)	6	Traceability of machine changes (Z)	1
Product-production feasibility (L)	4	Simulation of product assembly (AA)	1
Production logistics planning (M)	4	Optimize operator movement (AB)	1
Planning of maintenance (N)	3	NC-programming support (AC)	1
Commissioning for installation (O)	3		

The organisation needs culminated in a distribution of the interviewees' acceptance and technical readiness, as shown in Figure 15. This distribution showed that all but one interviewee had full acceptance of the virtual factory concept, while one interviewee showed neutral acceptance of it. The technical readiness varied from no knowledge about virtual factories to full knowledge, with the average being slightly above "some knowledge". Future research should therefore focus on decreasing the spread of virtual factory knowledge and increasing the average level of knowledge, as the acceptance level was already high.

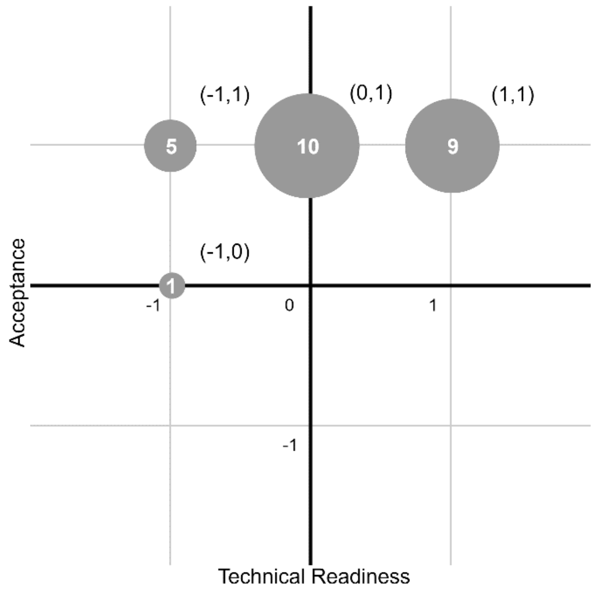


Figure 15: Technical readiness and acceptance among the interviewed persons.

Other findings from the organisational side included the importance of pilot projects with key individuals. However, individual key users should be prevented from getting too involved so as to ensure a wider range of users. A stepwise implementation of modules and functionality throughout the virtual factory's implementation was deemed significant in enabling value-adding activities. Standardised work procedures and local full-time personnel responsible for the virtual environment were also deemed important, plus the accessibility of in-house competences. Several points about the virtual factory's system architecture were also considered important: communication between different software systems; modularisation of the simulation environment to offer different tools for different users; ease of use; ease of access; an online-based environment and the possibility to view production environments from different locations.

The three benchmarked companies had various levels of virtual-factory maturity and were marked as: step 0 (no virtual-factory model at all), step 1 (digital factory) and step 4 (prognostic model). Which step they occupied varied internally however, as some parts of the individual companies had a more mature virtual factory than others. An example of this was the company positioned at step 4, which had a prognostic 2D model for a highly specialised unit within the company that was fully connected to the real factory. That model was able to predict maintenance actions, depict theoretical output and help optimise plant performance. However, such a mature virtual-factory model was not present throughout the company. It was focused on spreading and replicating the model to other departments which were not as far along with their virtual-factory models.

A standardised way of working with human-centred virtual-factory development (working systematically to keep the model updated) can help realise the value of a virtual factory. For example, one of the case companies regularly 3D-scanned its production system to keep its virtual model updated and reliable. This study showed that the potential of the virtual factory relies on the knowledge possessed by the end user, making training highly important to the success of the concept.

All the needs expressed at the case company fell into the first four maturity steps of the virtual factory shown in Figure 16. This does not necessarily mean that those steps could be completely ignored, as they may become highly important in the future. One outcome of the study was the implementation plan of how the case company could reach each step in sequence, relative to its expressed needs. The technical needs labelled in Table 4 are linked to each maturity step, as presented in Figure 16. The focus of this mapping was to ensure that the virtual factory would serve as a decision aid. In the long term, if the virtual factory were to be deemed a supporting function with which employees could regularly interact, then it should be viewed as the original and the real factory as a copy of it.

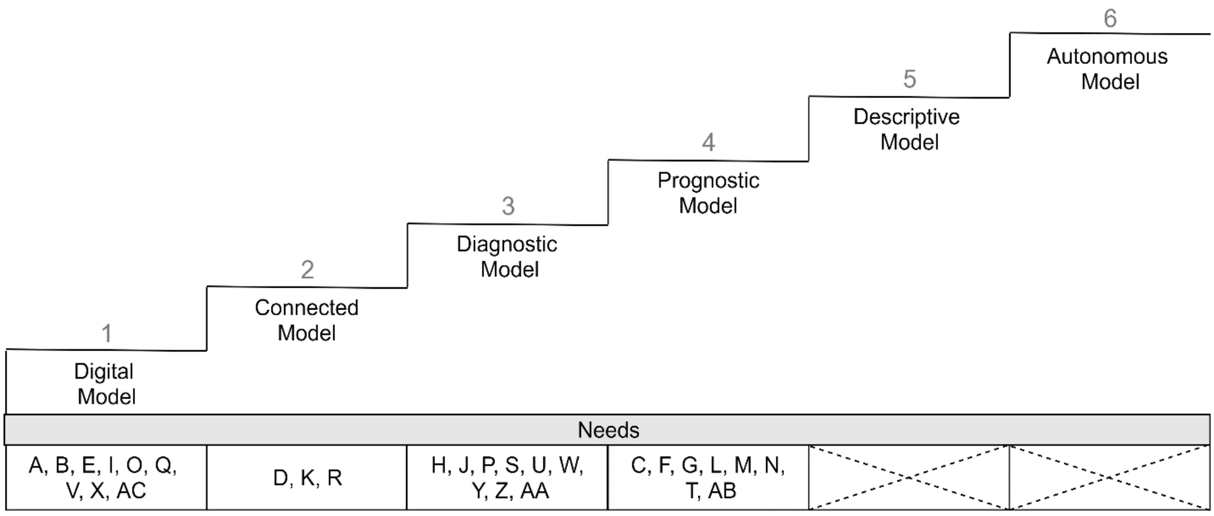


Figure 16: Identified technical needs mapped to the virtual factory maturity steps.

4.4 PAPER IV

Paper IV is based on a literature study spanning 2017 and 2018, focusing on the factory layout planning topic and facility layout problem approaches applied to it. The purpose of this paper was to summarise the field with viewpoints other than those in existing reviews and surveys. This was because existing reviews and surveys often stemmed from the optimisation problem category of factory layout planning, rather than design. Also, because its aim was to add viewpoints from industrial settings within this field, based on previous industrial studies and interviews conducted in this study. The main long-term purpose of the paper was to guide future research into factory layout planning towards helping industry and offer the beginnings of a link between academia and industry in this field.

4.4.1 Industrial study

The study applied in this paper comprised two parts: 1) a quantitative literature review and 2) a more qualitative approach via semi-structured interviews with industry representatives combined with findings from industrial studies. The literature review took place in two steps. The first started in June 2017, searching in SCOPUS from 2008 for any of the keywords (production, manufacturing, factory or facility) in combination with “layout” and either “planning” or “problem”. The abstracts of the identified papers were then read to determine whether the article was a good fit or not. This was continued until 40 papers had been identified which were read during the first step of the literature review and relevant referenced papers identified, downloaded, and stored, following the same process as before in a snowballing process.

The second step of the literature review started in June 2018, with the papers from the snowballing process and another search returning an additional 49 papers. This method was applied to reach a broader spectrum and find papers which would otherwise have been hard to identify. Prior to reading these papers, a review guide was created based on what was learned from the first literature review step and previous industrial studies. This was applied first to the 49 papers from the second step, then to the 40 papers from the first step. The review guide provided a method for assessing each paper and consisted of the following questions:

- Is the paper not a survey or review? IF YES, continue.
- Is the research exclusively greenfield, or could it be brownfield?
- Does the research consider the full facility/factory or any given part of the facility/factory?
- Is it a real case or not? IF YES, then continue.
- Does the method applied involve expert users from the case?
- Is the developed layout implemented in the study? IF YES, then continue.
- Is the layout followed up after implementation?

After concluding the literature study, semi-structured interviews were also held with representatives of four separate factories in Sweden. These interviews focused on identifying the following:

- How many layout planning projects the person had been involved in at the company.
- How many layout planning projects were full and partial factory/facility.
- The extent of the layout planning projects in terms of area, workstations, machines and stakeholders.
- The extent of involvement of stakeholders in the layout planning projects.
- The lead-time of the layout planning projects.
- Which problems and challenges they encountered during the planning, installation, and operation phases relating to the layout planning projects.

4.4.2 Outcome

The literature review resulted in 89 papers, 73 of which were not a survey or review paper. Key findings showed that about 71% of the possible papers planned layouts for the full facility and that 37% studied a real case. Of the papers in which a real case was studied, 33% involved one or more expert users in the layout planning process. The extent to which the expert users were involved and influenced the layout planning process varied in each paper, but the degree of that involvement was mostly low. The developed layout suggestion was implemented in two papers of all the ones included in this study; one of those papers also followed up and assessed whether or not the implemented layout achieved its targets. The review also showed that much of the research was into optimisation problems, a fact which often precluded decision-makers, shop floor personnel, maintenance personnel and other stakeholders from the layout planning process. Table 7 presents a summary of the literature review conducted in this study.

Table 7: Summary of the literature review performed.

		Percentage uses number of non-survey/review			*Percentage uses the number of real cases studied*		
SUM	Is not a survey or review	is or could be brownfield	Plans full facility	Studies a real case	Involves expert users	Is implemented	Assesses results after implement-ation
89	73	71	52	27	9	2	1
100%	82%	97%	71%	37%	33%	7%	4%

The interviewees involved in the semi-structured interview study had a combined experience of 35 years in their roles, in which they had been responsible for leading and working with layout planning in their company's factories. The interviewees had been involved in a total of 60 layout planning projects, three of which were in completely new or rebuilt facilities. The remaining 57 were brownfield, of which 48 were restrained to a part of the facility. The extent of the projects varied; the smallest were a single machine or a few workstations, while the largest considered up to 30 machines or up to 150 workstations. The number of stakeholders affected was as low as five, or as many as 100 depending on the scope of the project. The lead-time of the projects varied from one week up to 36 months, involving everything from a few key stakeholders and up to the entire affected department. Table 8 provides a summary of the projects, broken down into greenfield and brownfield projects as well as whether the project was a full or partial facility project.

Featuring prominently among the problems and challenges brought up by the interviewees were: communication with various stakeholders (such as affected personnel), suppliers and installation. Reactions from affected personnel was something which needed to be managed, as it could yield positive as well as negative side effects. Cooperation within the project group was deemed important and also highlighted was a problem with drawings being outdated, inaccurate or lacking detail. The interviewees also mentioned that many things were missed in the planning stage and identified during installation and operation. This had forced adaptation of the layout to the real world when it was supposed to be in full operation which, in turn, led to delays and irritation.

This study showed a clear gap between academia (which emphasises full facility layout planning) and industry (which is heavily focused on partial-facility brownfield layout planning projects). The problems and challenges the interviewees mentioned also had many similarities to the wicked problem. For those reasons, future research might focus on bridging the gap via more research on partial-facility layout planning in brownfield settings, while also helping industry tame the wicked problem elements of layout planning projects.

Table 8: Summary of data gathered via interviews with persons working with layout planning.

	AMOUNT	FULL FACILITY	PARTIAL FACILITY	PERCENTAGE OF PROJECTS
PROJECTS	60	16%	84%	
GREENFIELD	3	1	2	5%
BROWNFIELD	57	9	48	95%

4.5 KEY RESULTS AND FINDINGS

This section connects the summarized papers to the research questions of this thesis, paper by paper and research question by research question. Table 9 shows how the different papers contributed to the research questions in focus in this thesis.

Table 9: Each papers contribution to the research questions. Circle size roughly corresponds to contribution level.

	Paper I	Paper II	Paper III	Paper IV
RQ1	●	●		●
RQ2	●	●	●	•

4.5.1 What signifies brownfield factory layout planning?

Three of the appended papers show different brownfield aspects, which together with the theoretical background from section 2.2 provides input to this question. Each appended paper's contribution is presented in the corresponding section below.

Paper I

Due to the brownfield setting of this study, multiple constraints and requirements limit possible layout solutions. For example, there were some existing foundations in the floor which were to be re-used for the new machines; also, the pillars were not positioned exactly as intended. There were also existing pathways to be considered and re-used, existing adjacent machinery which was to remain in place but still function properly, an existing truck path which was to remain, a set production area specified for this project and existing electrical prerequisites to consider during the planning stage. Alongside these physical aspects, there was an established social system and workforce relationship, as the machine operators and maintenance personnel were already employed at the company.

Paper II

The cleanroom environments in this study affect any possible future changes. There was an area with a higher level of cleanliness and two areas with a lower level of cleanliness, plus an airlock between the two. This, and the physical shape of the areas, limited where different processes could be carried out. Some of the rooms with sensitive equipment were also to remain in place due to their physical properties. By implementing point cloud data into the simulation model in this study, it was possible to use the brownfield setting as a benefit during the validation stage, since both operator and manager could visually identify correctness and flaws.

Paper IV

The experienced interviewees in this study mentioned several challenges which could be related strictly to brownfield settings. For example, drawings being outdated and lacking detail, plus having to adapt any solution to the available electrical, water and sewage installations. Pre-existing installations also constrained the new solutions, as did the ability to install the new solution with minimal effect on operation. Another aspect was the social aspects of the brownfield settings, as communication and reactions from personnel affected the projects. As a step towards improving this and finding better solutions, more people could be brought into the process and help find an optimal solution, but at the cost of it being difficult to find one that was acceptable. Difficulties installing the layout also affected the projects, as the layout had to be adapted to the actual brownfield settings; this could lead to unforeseen consequences.

4.5.2 What challenges do operational stakeholders encounter during a brownfield layout change process?

All appended papers show different challenges and problems in the area. Each papers contribution is presented in the corresponding section below.

Paper I

The industrial study conducted in Paper I highlighted a number of direct and indirect issues. For example, the mismatch between the drawing and the neutral and objective point cloud showed how the 2D hand-made drawings might be insufficient. The project team also learned more about the layout as the study went on, making changes and alterations after visualising it better and including more people. The issue with the table being too small was not detected until the very end of the study when an operator wore the HMD and moved around in the model. This highlighted how difficult it can be to fully grasp scale and perspective. The study also showed that many things are missed and expected to be solved ad-hoc during installation and operation, such as workbenches, cleaning supplies for operators and the addition of other equipment such as coordinate-measuring machinery and the washing machine.

Paper II

The main contribution to the second research question from Paper II comes from the qualitative experiences shown by the interviewees when expressing that the model would be beneficial for quickly and accurately evaluating layout changes. The ordinary way of evaluating layout changes (using 2D drawings) could be time-consuming and difficult for stakeholders to grasp easily. The way the operator involved in this study instantly could recognise spatial properties and identify flaws in the model points indicates that neutral and objective point cloud data would be beneficial, instead of (or additional to) 2D drawings.

Paper III

Paper III’s biggest contribution to the second research question comes in the form of the needs expressed and their connection to the virtual factory. Several of the technical needs that were expressed connect to brownfield factory layout planning. These include: simulation of production flows, visualisation to educate, what-if analysis, factory layout design and economical investment decision aid. Many of the factors relate directly to this particular planning area, showing that the company wants the virtual factory to be a strong aid in its layout planning process. The way the case company viewed the virtual factory, combined with the extent of technical readiness, adds to this research question, because the technical solutions applied in Papers I and II require the application of a degree of technical readiness. This paper also shows how simply having a virtual factory model (even at step 1) could address many of the technical needs and provide some support to the factory layout planning process.

Paper IV

The interview study presented in Paper IV yielded several insights into the problems and challenges encountered by those responsible for layout planning during a brownfield layout planning project. Among the most-emphasised challenges were communicating with the various stakeholders and issues with drawings. Realising that something had been missed, or identifying improvements during or after installation was also emphasised as a challenge, as adapting the layout to the real world was a difficult step.

5

DISCUSSION

This chapter starts with a discussion of my research journey. This is followed up with a discussion on the current practice of brownfield factory layout planning, the quality in the conducted research, the effects of the research approach, and the contribution of the results both for industry and academia. The chapter is concluded with discussions on the three aspects of sustainability and recommendations for future research, along with a discussion on how that research could be approached.

5.1 MY RESEARCH JOURNEY

As foreseen in Williamson et al. (2002), this research journey has not been a straightforward one leading to the conclusions of my licentiate thesis. In September 2016 when I started my Ph.D. journey, my focus was on how we could involve 3D scanning technology in factory layout planning scenarios and what effects it might produce. The technology was rather novel for the area, but had shown plenty of positive effects when put to smart use in other areas. It was not until after the first two studies (Industrial Study A and Industrial Study B from Figure 1) that I discovered a much larger area of highly interesting and somewhat unexplored territory. That was when I started to understand the gap presented in this thesis, between academia (from the papers on the topic I had been reading for some time) and industry (from the studies). Many impressive solutions have been developed over the years, but none of the industrial contacts had used any of them. This led me to wonder why, and when just talking to the industrial practitioners my impression was that they were not particularly interested in the algorithmic solutions. It spurred the investigation sections of Papers III and IV and led me onto the present research path.

5.1.1 Research approach

Being a pragmatic researcher, I have tried my best to take the perspective of the industrial side of brownfield factory layout planning. That is why such a large emphasis is placed on the brownfield part to begin with, as that is the setting for most of the factory layout planning performed today as well as in line with my expectations for the future. As a pragmatist, focus has been on whatever works in solving a particular problems, hence the choice of methods have been varied. The usage of participant observation for example has been, to my knowledge, the best way to guide the industrial practitioners in new ways of working while attempting to keep a low profile, thus the observer-as-participant role. A full observer role has been tough to implement in the performed studies as the participants needed some guidance in the process. By applying the observer-as-participant role, the results cannot be completely unbiased. Me and my fellow researchers taking part in the study have however done our best to keep any bias out of the results by gathering and analysing data separately before discussing results to draw conclusions.

This research has also consisted of many semi-structured interviews where several of the interviewees has had interaction with the research group's work before. In practice, this means that some of the interviewees has seen our groups work with point clouds and VR prior to the interview, and perhaps even been a part of a study before. This may induce some bias in what challenges and solutions they consider, however such a statement would be true for any interviewee. The purpose of this research has not been to conclude any one, optimal way of working. Rather, the purpose is to see how and where the brownfield factory layout planning process can improve in general, with the specifics varying for each implementation.

Applying action research means to collaborate in both diagnosis of problem and development of solution (Bryman and Bell, 2007). Doing this in a cyclical manner, where the researcher is the one reflecting on the results and implementing new knowledge into the next cycle, allows the researcher to apply data collection in pragmatic ways (Oosthuizen, 2002). An effect of this approach is that the researcher builds up a lot of qualitative knowledge, and skills in this case, as the solutions are being applied in different ways and improved for each cycle. Thus, every cycle and case has non-identical prerequisites both from the case setting but also from the researcher's knowledge and skills. The impact of the researcher on each unique case is therefore hard to specify, but important to bear in mind. For example, as my skill in programming has increased, I am able to show the industrial participants in workshops more detailed and animated VR models, something that I was unable to produce at the first industrial study I performed.

5.2 CURRENT PRACTICE OF BROWNFIELD FACTORY LAYOUT LANNING

The term "brownfield" has been endowed with various meanings and significances in different countries, (Adams et al., 2010). Similarly, the brownfield setting for layout planning may have varied meaning and significance for factory layout planning. It could benefit the project (as shown in Paper II) but also constrain solutions. It is possible that the brownfield setting is a major contributor to the wickedness of factory layout planning, as there are many limitations to consider when working on a solution. As mentioned in one of the interviews in this research, a better solution can be found by involving more people. However, this also makes it tougher to find an acceptable solution as more opinions must be considered. "Brownfield" is a very broad term and can mean almost anything. Moreover, the extent to which a brownfield will affect any project varies according to both the site in question and how much the project chooses to take on board; similar to the taming of wicked problems as presented by Conklin (2005).

Brownfield factory layout planning is very close to the design problem category defined by Heragu (2008), as it is based on previous experience and highly subjective in the way it's currently conducted in the industrial setting. The exact method used by the companies involved in this research has varied. However, the use of hand-made 2D drawings as a basis for layout planning has been a common thread among them. Which stakeholders were involved also varied majorly. Sometimes the layout would be developed by just one or two members; in other cases, multiple stakeholders were involved, such as maintenance personnel and machine operators. As stated in one of the interviews, more people means more opinions, which makes it more difficult to find a good solution. Such a statement corresponds somewhat to one of the ways to tame a wicked problem explained by Conklin (2005).

5.2.1 Wicked problem

Defining brownfield factory layout planning as a wicked problem based on the previous section and the experiences gained through this research feels like an obvious choice. When I was first introduced to wicked problems by my co-supervisor, it immediately felt like an accurate description of this type of planning. For example, during the first industrial study, every iteration yielded new knowledge of new problems and challenges, plus new solutions. Problems and challenges which would likely have manifested themselves during installation or operation and solutions which would likely have been conceived when their implementation was no longer feasible. If brownfield factory layout planning is considered a wicked problem, it might also explain the variance in methods and approaches used by industry as well as why optimisation approaches may be hard to apply in real cases. Not all problems, factors, considerations, and compromises are known in these scenarios; hence, any optimisation model would produce a result based on input which is likely to change or only a subset of the complete data. Since knowledge of each unique and novel wicked problem is gained by attempting to solve it, the logical next steps would be to try and build as much knowledge as possible by including stakeholders and to use appropriate technology and methods allowing for an efficient process.

5.3 QUALITY IN RESEARCH

Quality in research, as defined in Section 3.5, is an important criterion for any research. For the research in this thesis, the most important concept is that of validity. The validity of this research may be assessed based on four concepts adapted for qualitative research: 1) *credibility*, 2) *transferability*, 3) *dependability* and 4) *confirmability*.

The *credibility* of this research should be equally as high as was the case for applying established research methods in the industrial context. To date, none of the findings have produced any shocking revelations. However, this may be because the research was strongly focused on rather new concepts, such as using 3D laser scanning, virtual reality and the virtual factory concept.

So far, the *transferability* of this research, which considers how well the findings apply to other contexts, has been high. The research transferred the findings from one study to the next; transferring them in different ways to the next study, next case and next company. However, those contexts were all major Swedish companies, so the question remains as to how well the findings might transfer to, say, smaller companies or companies in other countries.

Naturally, the *dependability* of this research will be hard to prove. Conducting the same research in the same context with the same subjects might yield slightly different results, as the research subjects will have been changed by their involvement in this research. Asking one of the subjects about the challenges of their layout planning process, before and after conducting a study with them, would likely yield different results. Nevertheless, the research process has been well-documented, so another researcher should be able to follow the trail from data to analysis and reach similar conclusions.

The *confirmability* of this research, which considers whether the researcher's values have majorly affected the study, may be evaluated by documenting the rationale for the decisions made whilst the research was being conducted. For example, all of the 89 papers printed and reviewed in Paper IV are still sitting in folders in the researcher's office with his notes. Interview notes and the like are also stored, so it is possible to go back and assess whether the researcher's values had much of an impact on the interpretations.

Another important aspect to note is that this research likely only covers a subset of all the issues and challenges organisations face during the brownfield layout-change process. Even though some of the issues are similar and may share the same underlying cause (such as misalignment of mental models), each case can yield more knowledge. Additional cases would likely yield further challenges and issues. The summarised findings of this thesis are final at the time of print, but do not represent an exhaustive list.

5.4 ACADEMIC AND INDUSTRIAL CONTRIBUTION

This thesis contributes to both the academic community and the industrial setting. By using the results of this thesis, the academic community may steer research toward taming the wicked problems of brownfield factory-layout planning; an area quite prominent in industry. The answers to the second research question offer a good starting point for such research. This thesis has also presented a gap in research by examining the field from a different standpoint and showing that much research remains if we are to cover the complete process, including planning, installation and operation.

The industrial contribution comes mainly from the collaboration between academia and industry, upon which this research is built. It shows that working together can benefit both sides; helping industry forward and helping academia target real problems. This research has also presented several ways to help industry tame the tricky aspects of brownfield factory-layout planning, or at the very least acknowledge them. While the road ahead is long in order to spread knowledge to more industries, the start is promising.

5.5 ASPECTS OF SUSTAINABILITY

A very common definition of sustainable development is the one from the Brundtland Commission (1987); "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainability is often divided into three pillars, and while the origin and reason for this division is unclear (Purvis et al., 2018) the pillars still help in talking about sustainability. The three pillars are economic, environmental, and social sustainability. It is my firm belief that solutions originated from research should be improving one or more of these aspects without making any negative impact on the others. As shown in for example Andersson et al. (2011), developing solutions that incorporate multiple aspects of sustainability can be beneficial and lead to more holistic solutions. The methods applied in the studies included in this licentiate thesis have intended to help companies find better brownfield factory layout planning solutions in a multitude of regards. By relying on accurate and neutral 3D laser scanned data, the risk for problems during the installation phase should be reduced, thus lowering the expected cost of delays and unexpected issues. Reducing the risk of mistakes has a slight benefit for all three pillars of sustainability, however the implications are mainly economic. Neither of the studies showed any negative impact on either of the pillars of sustainability, however it seems like the social part is the biggest benefactor. Going to a less abstract model and incorporating immersive visualizations allows more stakeholders to take part and give feedback in the development process. While not explicitly measured, it seems like change acceptance increases while at the same time layout plans become more complete, as many details were added due to stakeholder feedback. As such, the body of work in this thesis mainly impacts social sustainability in a positive way without having a negative impact on neither economic nor environmental sustainability.

5.6 FUTURE RESEARCH

This thesis has produced a number of directions for future research. Such research can now focus on solving the issues identified, perhaps by examining which issues have been solved in other fields. When, how, or why solutions from other fields might apply to this field is something which could be examined, especially in collaboration with researchers from other fields. Future research should also place greater emphasis on following up the implementations of the layout suggestions that have been developed and understanding their effects. Challenges with no obvious readily available solution and research into how these might be alleviated or solved is also of interest for future research. Ultimately, with the next industrial era, how companies should work with brownfield factory layout planning is a very important topic, as new technologies offer new opportunities and solutions.

Another interesting point for research to look at in collaboration with industry is the financial implications of companies continuing to work as they currently do, versus yet-to-be-developed ways. This is an important step in convincing decision-makers and helping motivate industry to implement the changes. Examples of things to look at based on this research could be the financial implications of conducting and using 3D laser scanning and/or virtual reality in brownfield factory layout planning scenarios. Do the benefits outweigh the costs and, if so, by how much? What kind of requirements does it put on the organisations? When and how should it be used? These are just examples based on the research that has been conducted; there are likely many other solutions to test. An example of quantifying the value of 3D laser scanning could be by intervening when a company has completed a layout plan, adding the 3D laser scanning layer and then giving the company another look at their planned layout. The changes which occur afterwards could be attributed to the 3D layer and, if possible, an estimated cost saving attributed to each change.

Finally, as per the definition of digitalisation by Garner IT Glossary (2019): "*the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business*", brownfield factory layout planning can be connected to innovation by using digital technologies. This connection could be further researched, so as to provide industry with a recipe to innovate its processes and find new and valuable opportunities.

6
CONCLUSION

Brownfield factory layout planning represents a significant proportion of industrial layout planning, yet sees a comparatively low level of research interest. Most research focus on the planning of full facilities, while the industries seem to do so very rarely as the partial factory layout planning approach is more common. As companies must strive to make the most of what already exists for the sake of economic and environmental sustainability, effective utilisation of existing factories instead of new builds is highly important. Hence, research into the brownfield area generally and factory layout planning area specifically, could be highly impactful. As the brownfield setting poses a wide variety requirements, considerations, and constraints on any project, it is important to identify and consider these effectively, so as to find an appropriate solution.

The research presented in this licentiate thesis has shown that there are industries facing many challenges and difficulties when conducting layout planning in brownfield settings. There are problems with ingoing data leading, difficulties involving and communicating with stakeholders, difficulties surrounding mental models and challenges adapting the planned layout to the real world which impact the entire factory layout planning process in several ways. Planning and preparing becomes more challenging, installation and operation may encounter more issues and the entire project may take longer time as uncertainties increase. Considering brownfield factory layout planning as a wicked problem (in which knowledge and understanding of the problem increases the more it is tackled), it is reasonable that the involvement of more stakeholders and more detailed planning should lead to new challenges. As indicated by the studies, the challenges differ for each case. However, if properly implemented, the next industrial revolution, Industry 4.0, could alleviate some of those problems and help tame their wicked aspects by utilizing new technology in efficient ways where more stakeholders can be involved in the layout planning process. The studies in this research have focused on the implementation of technical solutions, such as 3D laser scanning and immersive Virtual Reality, with a slight focus on changing companies' way of working by showing and involving them in alternate ways of working. A new mindset and approach to factory layout planning on the part of companies could be the starting point of a new, much-improved process with lower levels of risk and improved solutions with greater stakeholder satisfaction.

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