THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Brownfield Factory Layout Planning using Realistic Virtual Models

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ABSTRACT

To stay competitive in an increasingly digitalised and global context, manufacturing companies need to increase productivity and decrease waste. This means their production systems must improve; something they can achieve in a multitude of ways. For example, increasing the level of automation, improving scheduling and improving product and process flows. Often, these production system improvements entail redesigning the system to incorporate these ensuing changes; a unique and temporary endeavour that is often structured as a project. One part of the production system design process is layout planning, in which the positions of operators, workstations, machines and other parts of the system are decided. This planning process can have a major impact on the overall efficiency of operations.

In industrial settings, factory layout planning is often conducted in brownfield settings. In other words, in operational facilities. Since every production system and facility is unique, so is every factory layout planning project. Each such project has different preconditions, existing knowledge, availability and quality of data, lead-times, expectations and driving forces, to name just a few. If factory layout planning were treated as a design problem (more subjective than mathematical in nature), it would be hard to produce a mathematical solution for an optimal layout that would also work in reality. Instead, if a layout is developed and adapted to all real constraints and factors while it is being developed, the result would more likely be installable and work as expected.

The long-term vision of this thesis is of a future in which sustainable manufacturing industry continues playing a vital role in society, because its contribution is more than just economic. A future in which the manufacturing industry is appreciated and engaged with by the local community; in which high performance is connected to the successful adoption and efficient use of digital tools in developing and improving existing brownfield production systems. This thesis aims to ensure that manufacturing industry adopts realistic virtual models in its brownfield factory layout planning processes. It does this by identifying and describing common challenges and how they may be reduced by developing and using realistic virtual models. This leads to improvements in the planning, installation and operational phases of production systems.

The findings of this thesis show that brownfield factory layout planning represents a significant proportion of industrial layout planning. Its challenges lie mainly in the areas of data accuracy and richness. There are difficulties in grasping scale and perspective, communicating ideas and gathering input in the layout planning phase. By applying 3D laser scanning to provide accurate data and virtual reality to provide immersion and scale, realistic virtual models have been created. These reduce or eliminate the challenges stated above and allow more employees to be involved in the layout planning process. This, in turn, results in the identification of flaws in the layout and improvements in the early stages, rather than during or after installation. There is also an overall improvement to brownfield factory change processes, with costs that pale by comparison to the total cost of layout changes.

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

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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).

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Publication 3: 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.

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Publication 5: Bully, C., Gery, J., **Nåfors, D.**, Gong, L., Despeisse, M., Johansson, B., and Billesø, M.B., “Increasing Eco-Efficiency Awareness for Ship Loading Process Using Virtual Reality and Gamification”, Advances in Transdisciplinary Engineering, Vol. 13, pp. 167-178.

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TABLE OF CONTENTS

1 Introduction ... 1
- 1.1 Background ... 1
- 1.2 Vision ... 2
- 1.3 Purpose and aim ... 2
- 1.4 Research questions ... 2
- 1.5 Delimitations ... 3
- 1.6 Target audience and structure of the thesis ... 3

2 Frame of reference ... 5
- 2.1 Production systems ... 5
- 2.2 Greenfield and brownfield ... 8
- 2.3 Factory layout planning ... 9
- 2.4 Technological tools as decision support ... 11

3 Research approach ... 15
- 3.1 Theory-building ... 15
- 3.2 Philosophical worldview ... 16
- 3.3 Mixed-methods research approach ... 17
- 3.4 Research design ... 17
- 3.5 Reliability and quality in research ... 20

4 What type of research has been done in the area? ... 21
- 4.1 Methodology ... 21
- 4.2 Results ... 23
- 4.3 Synthesis ... 25

5 Summary of appended papers ... 27
- 5.1 Paper I ... 28
- 5.2 Paper II ... 31
- 5.3 Paper III ... 35
- 5.4 Paper IV ... 37
- 5.5 Paper V ... 42
- 5.6 Paper VI ... 44

6 Following up on the research questions ... 49
- 6.1 Contributions of the appended papers ... 49
- 6.2 RQ1 - What are the challenges for relevant stakeholders in brownfield factory layout change processes? ... 49
- 6.3 RQ2 - How might 3D laser scanning and virtual reality be applied when addressing the challenges in brownfield factory layout change processes? ... 51
- 6.4 RQ3 - What are the effects of using 3D laser scanning and virtual reality in brownfield factory layout change processes? ... 57

7 Discussion ... 59
7.1 My research journey ... 59
7.2 Research results ... 61
7.3 Aspects of sustainability ... 63
7.4 Academic and industrial contribution ... 64
7.5 Research quality ... 64
7.6 Future steps to realise ... 65
8 Conclusions ... 67

PAPER I
PAPER II
PAPER III
PAPER IV
PAPER V
PAPER VI

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

Figure 1: A summary and connections of the concepts used in the thesis and their relation to the research questions. 5
Figure 2: The production system viewed in a hierarchical perspective, adapted from Bellgran and Säfsten (2009). 6
Figure 3. The life cycle of a production system, adapted from Wiktorsson (2000). 7
Figure 4: Three phases of a factory layout’s lifecycle. 11
Figure 5: Visualisation of a 3D laser scanner and its field of view. 12
Figure 6. The cycle of action research, based on Oosthuizen (2002). 17
Figure 7: Visualisation of the six studies and how they connect sequentially. The knowledge gained from one study builds into the next, so the knowledge and insights from Study 1 underpin Study 6. 19
Figure 8. Literature review process. 22
Figure 9: Maturity of the virtual factory divided into six steps. 28
Figure 10: Technical readiness and acceptance among the interviewees. 30
Figure 11: Identified technical needs mapped to the virtual factory maturity steps. 31
Figure 12: The industrial study process used in Paper II. 32
Figure 13: Structure of the three layout evaluation workshops (Lindskog, Vallhagen, et al., 2016). 34
Figure 14: Difference between the point cloud and 2D CAD drawing after alignment of the walls. 34
Figure 15: VSM of the shortest sub-flow. The rectangular boxes represent processes, while the triangles represent storage buffers. 35
Figure 16: A visualization showing a part of the spatial data gathered via 3D laser scanning. 36
Figure 17: Snapshot of the running simulation model showing operators, marked by red arrows, walking through doorways instead of taking the shortest path through walls. 36
Figure 18: The floor model (left) and corresponding height map (right) of Industrial Study A. 39
Figure 19: Machine model (left) used to generate models of machinery that were unavailable in 3D CAD (right) via scaling based on 2D drawings. 39
Figure 20: Security installations in the 3D laser scanned facility (A) prior to cleaning and (B) after cleaning. Following the removal of point cloud data, there are visible holes where the data used to be as can be seen in (B). 41
Figure 21: Example of the final model as it would be seen when visualized in immersive VR. The forklifts and operators move around and conduct simulated tasks in the model which consists of a combination of both point cloud and 3D CAD data. 43
Figure 22: General process applied in the studies conducted between 2012 and 2019. 45
Figure 23. Overview of how industrial companies might utilise 3D laser scanning and virtual reality today, showing what they should be able to do independently and where expert assistance may be required. 52
Figure 24. The complete point cloud (top) is segmented by removing one piece at a time (left) until only the required dataset remain;, in this case a separate machine (right). 53
Figure 25. Sample first stage of a realistic 3D model. Point cloud data is combined with more accurate 3D CAD models of machines and a red volumetric representation to the left. 54
Figure 26. Immersive VR view of a realistic 3D model. 55

Figure 27. Evaluating spatial installation constraints by moving the CAD model of an installation through the point cloud model of the facility. 56
Figure 28. Relationship between mental models, virtual models and reality. 58

1

Introduction

This chapter gives a background to the research area and positions this thesis within it. The vision, aims, and research questions are then formulated. The delimitations are introduced, and the chapter concludes by giving an outline of the thesis and defining its target audience.

1.1 BACKGROUND

As globalisation and digitalisation increases, manufacturing companies need to improve productivity and decrease waste to remain competitive. The productivity of a manufacturing company's production system depends on a wide variety of things. Among other things, these include scheduling, process flow, level and efficiency of automation and supplier arrangements. Often, changes to the production system involve either redesigning the existing system or designing an entirely new one (Jung, Choi, Kulvatunyou, Cho, & Morris, 2017). This process of designing production systems is often structured as a project, considering many different factors and problems (Schuh et al., 2011). One part of this design/re-design process is layout planning, in which the positioning of workstations, machines, and other elements of the production system is decided (Heragu, 2008). Positioning the elements that make up the production system within a facility may be termed the "facility layout problem" and can majorly impact the overall efficiency of operations. Indeed, a good layout can reduce total operating costs by 2-15% (Tompkins, White, Bozer, & Tanchoco, 2010).

In the middle of the 20th Century, most layout work was conducted at existing facilities and entailed making better use of the facility or improving existing systems (Immer, 1950). That observation still seems accurate, as new facilities are seldom built while layouts in existing factories are being improved. Thus, brownfield settings are where layout planning in factories is often conducted. Investment in, say, a new machine may force a layout change to an area of the facility that is already in use. In such settings, the availability and quality of data may vary since different companies have diverse prerequisites. Companies that rarely invest in new machines or workstations and have used the same layout for a long time may have outdated drawings which no longer reflect reality. Meanwhile, companies that often make changes to their facilities and layout would be more likely to have up-to-date drawings. Every factory layout planning project in a brownfield setting may be considered unique, with conditions specific to that project and in which improved knowledge and understanding of the specific challenges and problems is acquired only as a solution is worked out.

If projects for changing brownfield factory layouts are deemed a unique and novel challenge, best understood whilst in progress, a solution that assumes existing data and knowledge to be correct and sufficient would likely encounter issues when applied in a real context. In such a context, data may be incorrect or missing and, hence, a solution would likely not be implementable without adaptation. Much of the research into facility layout planning differs fundamentally from current industrial practice. This indicates a gap between what is being researched and how industry conducts its layout planning. On the one hand, manufacturing industries often conduct factory layout planning as projects, with a team working to try and develop a suitable solution. On the other hand, there has been much research into algorithmic solutions that can generate an optimal solution based on high-quality data more suited to greenfield projects than brownfield ones. The manufacturing industries involved in this thesis' research do not have the necessary data for developing an optimal solution in context of brownfield factory layout planning. These industries need solutions that can provide data alongside a better understanding of the problems and challenges they face. They conduct brownfield factory layout planning in various ways, encountering and solving different challenges in their processes. The challenges encountered are not always identified or perfectly managed, leading to errors; some more critical and costly than others. To reduce the number of errors and their ensuing impact, there is a need to show how and why brownfield factory layout planning should be conducted using realistic virtual models. Using models of planned changes that are accurate and visually easy to understand will help industry make the right decisions.

1.2 VISION

The vision of this thesis is for a future in which sustainable manufacturing industry continues to play a vital role in society, contributing in ways other than just economically; a future in which the manufacturing industry is appreciated and engaged with by the local community. In this future, high performance is connected to the successful adoption and efficient utilisation of digital tools to develop and improve existing brownfield production systems.

1.3 PURPOSE AND AIM

The purpose of this thesis is to ensure the manufacturing industry adopts realistic virtual models in its brownfield factory layout planning processes. Achieving this requires an understanding of how to use realistic virtual models and the effects of using them. Therefore, to achieve its purpose, this thesis aims to describe a method developed by applying action research on how to use realistic virtual models. It also describes the effects of following this method when it comes to improving the planning, installation, and operational phases of production systems-

1.4 RESEARCH QUESTIONS

Based on the purpose and aim, three research questions were formulated. The first research question investigates the area of layout changes in brownfield settings. It supports a problem-solving approach that will motivate industry to consider changing its work procedures and adopt the suggested solutions.

RQ 1) What are the challenges for relevant stakeholders in brownfield factory layout change processes?

3D laser scanning is a tried and tested technology which may be used in brownfield factory layout change processes to provide neutral, realistic and accurate models of existing facilities. Alongside virtual reality (to provide immersion and scale), the second research question follows on from the first by investigating how and when to apply these two technologies and, thus, potentially impact the layout change process.

RQ 2) How might 3D laser scanning and virtual reality be applied in addressing the challenges in brownfield factory layout change processes?

The third research question evaluates the effect of potential improvements. This might motivate manufacturing companies to change their work procedures.

RQ 3) What are the effects of using 3D laser scanning and virtual reality in brownfield factory layout change processes?

1.5 DELIMITATIONS

The research presented in this thesis is concerned mainly with the development of layouts for the factory floors of manufacturing industry. For example, deciding where people should work and travel, and where workstations, machines and storage areas should be positioned. The focus is on supporting this process through technological solutions. These will alleviate the challenges faced by stakeholders throughout the change process, from planning to operation. The research focuses on Swedish manufacturing companies, whilst companies in other regions may encounter different challenges. However, the target of this research is the entire manufacturing domain, so its general findings should remain applicable, albeit with slight modifications. Due to the time required for a layout change to go from idea to planning, to installation and finally operation, this research has focused on gathering as much information as possible from the available cases and then generating knowledge, rather than conducting a large volume of cases.

1.6 TARGET AUDIENCE AND STRUCTURE OF THE THESIS

The target audience for this thesis is researchers and practitioners of differing backgrounds and experiences. There are some important factors to consider when targeting these two groups. Practitioners (in this case, those working with layout changes in industry), prefer solutions that are usable, not too costly and which give proven results. For researchers, the method of getting there is significantly more important than the outcome. Moreover, layout changes in industry affect more than just the bottom line; producing more involves more than just monetary investment in new machines. It is a change process which, in various ways, affects all stakeholders and which can impact the mood and attitude of employees. This can lead to different outcomes depending on how the change has been managed. It makes the engineering process of problem-solving somewhat more challenging as multiple factors affect how a layout change is experienced and the result it produces. This thesis targets practitioners from engineering backgrounds, while the appended papers target researchers. The three research questions have been approached in a somewhat linear fashion. This author has learned more and improved during his PhD journey and, as such, the quality of the work should naturally be stronger towards the end. This thesis is structured to reflect the author's research PhD journey and should be viewed as a learning process. The content of each of this thesis' eight chapters is presented in Table 1.

Table 1: Overview of the structure of this thesis.

CHAPTER	CONTENT
1. INTRODUCTION	The first chapter introduces the background to the thesis by explaining the author's interest in brownfield factory layout planning. It presents the vision, purpose and aims of this research, alongside the research questions, delimitations and research activities.
2. FRAME OF REFERENCE	The second chapter provides a theoretical foundation to the thesis and a brief overview of relevant background and concepts, such as production systems, layout planning and operations management.
3. RESEARCH APPROACH	The third chapter explains and defends the research approach used, including the author's philosophical worldview, research design and methods and knowledge generation.
4. WHAT TYPE OF RESEARCH HAS BEEN DONE IN THE AREA?	The fourth chapter presents and analyses the findings of a literature review on the research topic, plus interview data to give a more thorough background to the research area.
5. SUMMARY OF APPENDED PAPERS	The fifth chapter presents and summarises the results of the empirical studies and connects them to the research questions posed in this thesis.
6. FOLLOWING UP ON THE RESEARCH QUESTIONS	The sixth chapter covers each research question and the knowledge they have produced, so as to connect the contributions of the papers summarised in Chapter 5.
7. DISCUSSION	The seventh chapter provides discussions on the research process and results. It also discusses the academic and practical contributions of this work and makes proposals for future work.
8. CONCLUSION	The eighth chapter summarises the thesis and presents its conclusions.

2

Frame of reference

The frame of reference chapter aims to give the reader the background information required to better understand the rest of this thesis by defining important areas such as production systems, brownfield, factory layout planning, and the technological tools used in this research to support decision making. These categories are of high relevance to the research performed.

To both connect and guide the content that is presented in this chapter, Figure 1 is presented. This figure visualises how the individual 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. As can be seen in this figure, factory layout planning is a central concept for all research questions and the central element of this thesis. Each of the sub-chapters presents necessary information on each topic as required to further set the context for this thesis.

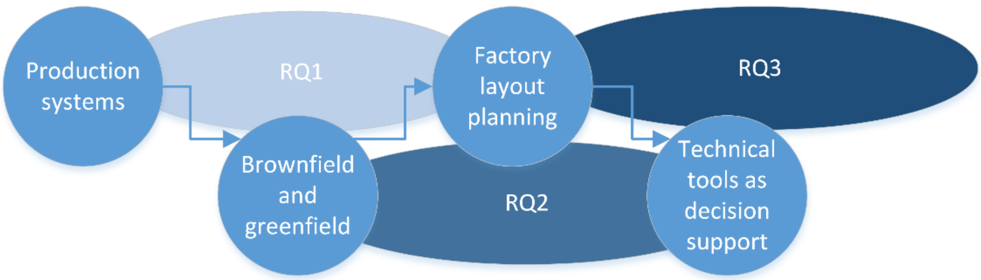


Figure 1: A summary and connections of the concepts used in the thesis and their relation to the research questions.

2.1 PRODUCTION SYSTEMS

A system, as in production systems, comprises several elements, where each element is designed to fulfil different functions based on the objective and purpose of the system while interacting with each other to carry out a function (Frezzini, Sachan, & Azimi, 2011; Kauffman, 1980). Systems have boundaries that can be set at different levels, with everything inside the set boundary being regarded as a system and everything outside it regarded as external, and unaffected by the system. In the case of production systems, it regards the transformation of material into either a product or a service (Bellgran & Säfsten, 2009). The transformation process by which an input to the system becomes an output is where resources, labour, material, and capital are combined to create these services or products (Jonsson & Mattsson, 2009). This transformation process involves several areas that all needs to be organised and managed effectively in order for the transformation process to be efficient or even possible, namely technology, humans, energy and information (Bellgran & Säfsten, 2009). In production systems, the elements (such as humans, equipment, facilities, and procedures) are all interrelated (Chapanis, 1996; Löfgren, 1983).

Manufacturing system is a larger system that consists of other sub-systems including production system (Bellgran & Säfsten, 2009). Manufacturing involve design, planning, material selection, quality assurance, marketing and management of products which all are interrelated, and should not be confused with manufacturing production (shortened to production) which simply is the act or process of physically making a product (CIRP, 1990). Within a production system there can be multiple different sub-systems, for example an assembly system which assembles parts produced in a parts production system into a product (Bellgran & Säfsten, 2009). A hierarchical perspective on the production system as it is viewed within the manufacturing system is shown in Figure 2. An additional dimension that can be added to the description of a production system is the decision-making process (Bellgran & Säfsten, 2009) where capital management, business management and production management can be considered sub-systems (Sandkull & Johansson, 2000).

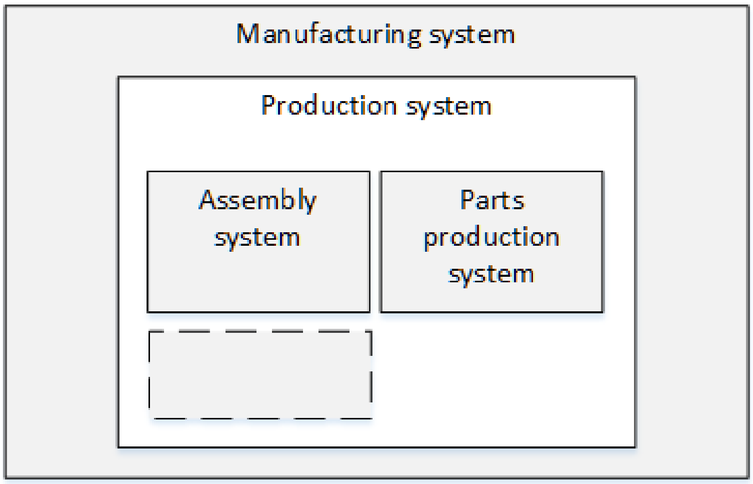


Figure 2: The production system viewed in a hierarchical perspective, adapted from Bellgran and Säfsten (2009).

A production system can be regarded as having its own life cycle starting with the planning of production system design and ending with the system termination or re-use as visualised in Figure 3 (Bellgran & Säfsten, 2009). As shown in this figure, re-use as an alternative for termination is increasingly expected in the same sense that products are expected to be re-used or recycled for environmental reasons. A production system should be expected to support multiple generations of products when it is designed (Bellgran & Säfsten, 2009). Hence, new production system needs to be designed and realised alongside the old ones, and an awareness of a production system’s current position in its life-cycle becomes essential (Bellgran & Säfsten, 2009).

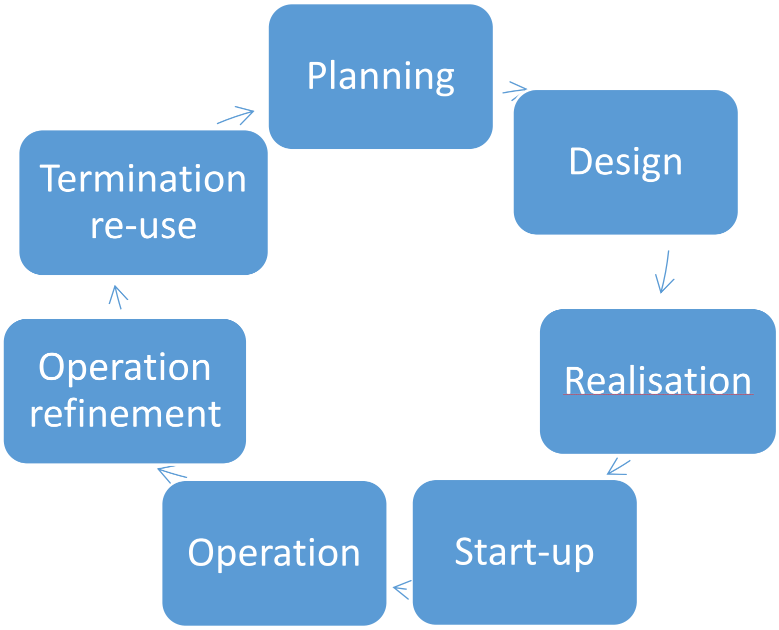


Figure 3. The life cycle of a production system, adapted from Wiktorsson (2000).

New or changed product families or individual products often lead to changes in production systems, due to for example new legislations, market requirements, or recent technological development (Bellgran & Säfsten, 2009). These changes to production systems will also affect the layout of the factory in which the production system resides physically, as well as the stakeholders in the production system such as operators, maintenance engineers, and logistic personnel.

Production systems are heavily influenced by industrial revolutions, as they bring significant improvements that also drive changes. To date, there have been three industrial revolutions; first mechanisation, followed by mass-production in assembly lines, and most recently automation using information technology. Currently ongoing is the fourth industrial revolution, which 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 fourth industrial revolution is predicted to be heavily focused on data, increased automation of systems in combination with human operators, and the integration of information and communications technology in manufacturing (Thoben, Wiesner, & Wuest, 2017). As an effect of technological advancements, this revolution is also expected to improve flexibility, speed, productivity and quality of the production system when fully implemented by utilizing a fully integrated, automated and optimised production flow. Future manufacturing needs to optimise resource use and be able to adapt quickly to changing conditions (Y. Lu, Morris, & Frechette, 2015). There are several core technologies and sub-technologies as identified by Kang et al. (2016), such as cyber-physical systems. These systems are connected and can interact via internet-based protocols, predicting failures, adapting to changes by analysing data, and perform self-configuration (Rüßmann, 2015). Since the fourth industrial revolution is predicted to imply many changes on a system-wide level, it is reasonable to expect that the layouts of factories all over the world will also be changed once this revolution is being more and more 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 University Press, 2021b) and “brownfield” as “denoting or relating to urban sites for potential building development that have had previous development on them” (Oxford University Press, 2021a). Outside of the field of urban development, such as in the field of product development, the brownfield term can relate to reusing available assets and considering limitations due to existing structures (Pakkanen, Juuti, & Lehtonen, 2016). When it comes to production systems, greenfield production system projects generally have broad possibilities with few or no historical limitations, while brownfield production system projects often regard the rebuilding or reorganization of an existing site (Vallhagen, Stahre, & Johansson, 2011).

The process of designing manufacturing systems applies to greenfield scenarios as well as brownfield scenarios, although the greenfield opportunities are rare in comparison (Vaughn, Fernandes, & Shields, 2002). A greenfield production system comes with near no preliminary conditions, which allows for an optimal design according to the current best practices, however in most production system change projects, the production sites are already up and running (Bader, Wolff, Vossing, & Schmidt, 2018) meaning that the change project would be more akin to a brownfield than a greenfield one. Large projects in the brownfield setting can be of the same scale and require as much effort as a greenfield one, such as to build a completely new factory, but comes with more limitations in terms of the requirements, considerations, and constraints put on the project and solution (Vaughn et al., 2002). The existing resources in the system, for example the people, machinery, and the culture are typical such constraints that impact the design of manufacturing systems in the brownfield setting (Vaughn et al., 2002). In the greenfield setting, many of these constrains can be almost completely excluded. A similar reasoning can be applied to the dimensions, both shape and size, of the production area. In a brownfield setting, these are generally fixed and constrain any possible production system layout solution (Stäbler, Weber, & Paetzold, 2016), while in a greenfield setting the size and shape of the facility as well as external logistical connections can be mostly designed to fit the purpose. Another factor to highlight is that of established social systems, group norms, management behavioural aspects and the management workforce relation in brownfield settings (Wall, Kemp, Jackson, & Clegg, 1986). Historical relationships between the labour force and management can be a significant factor, specially in small and medium-sized manufacturing organisations. The process of adopting human resources management can therefore be expected to be easier in a greenfield setting than in a brownfield setting (Duberley & Walley, 1995). Another important factor is that of IT investment, which has become more important with the rise of smart manufacturing and Industry 4.0. IT investments is considered much more difficult in brownfield production systems than greenfield ones (Davis, Edgar, Porter, Bernaden, & Sarli, 2012). In summary, these special circumstances and challenges relating to brownfield settings requires engineers to have strong analytical skills in order 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, Jäger, Hold, Ott, & Sihn, 2016). A summary of some impactful differences between greenfield and brownfield settings are presented in Table 2.

Table 2: Summary of some of the potential differences between greenfield and brownfield project settings. A project can be a mixture of both greenfield and brownfield setting in the different categories.

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 outside of local ones	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

One of the main areas to address in the production system design process is the process layout planning (Tompkins et al., 1996). The problem of planning a factory layout can be divided into two categories: design and optimisation (Heragu, 2008). The optimisation type of problem is mathematical in nature and offer solutions to an optimal theoretical factory layout. This type of problem has seen much interest in academia, often called the facility layout problem, and has seen multiple algorithmic solutions developed over the years as summarised in for example Drira, Pierreval, and Hajri-Gabouj (2007), and more recently Ahmadi, Pishvaee, and Akbari Jokar (2017) and Hosseini-Nasab, Fereidouni, Fatemi Ghomi, and Fakhrzad (2018), with the latter showing that the most frequently applied meta-heuristic approaches have been genetic algorithms and simulated annealing. While there has been much research on the optimisation type of layout problem, there has been comparatively little interest in developing help for factory layout planning that considers all the different compromises and challenges faced by industry in brownfield settings. One method developed to work in these settings however is Systematic Layout Planning, a method that offers hands-on systematic procedures, methods and tools to use when planning layouts in live factories (Muther, 1973). The method however is not fully adapted to the factories and engineering methods of today, that are more digitalised and connected. Historically, there has been other methods such as Immer's Basic steps (Immer, 1950), a method that converts flow lines to machine lines, Reed's

Plant Layout Procedure (Reed, 1961), a ten step procedure that noteworthy also consider future expansion needs, and Apple’s 20 step Plant Layout Procedure (Apple, 1963).

Layout planning procedures can be divided into two separate types: construction layout methods, that involve the planning of empty factories, and improvement procedures, which generate updated layouts based on existing production systems (Tompkins et al., 1996). Another way of separating layout planning projects is to break them down into the following three separate levels as defined by Schenk, Wirth, and Müller (2010):

- *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 respectively generate three different types of layouts, in the corresponding order to the levels previously mentioned: 1) ideal, 2) approximate and 3) real layouts (Schenk et al., 2010). An ideal layout represents the best possible solution, one that is created without constraints or restrictions, while an approximate layout is an interim step that specifically pays attention to building parameters (Schenk et al., 2010). The final type of layout, the real layout, takes all restrictions into consideration and is adapted from the ideal layout by considering many factors, requirements, and restrictions that applies to the real scenario and is therefore the layout most likely to be possible to implement in a real factory setting (Schenk et al., 2010).

2.3.1 Lifecycle of factory layouts

This thesis focuses on the planning part of factory layouts, but it is important to mention the context of which a factory layout exists. It can be broken down to three distinctly different steps as summarized in Figure 4 – planning, installation, and operation. The installation phase is where the plan is realized, where the facility is being prepared for machine installation for example, and where the actual physical changes to the layouts are being performed. Whatever is done in this phase, that in turn is based on the planning phase, will often live on in the operation phase. In the operation phase, the layout comes to life as it is being utilized. This often means that the layout is being adapted to the humans working there and could imply minor changes to things that can be changed, for example the positioning of material and lighting. The give a perspective of time, the planning phase can be around half a year to a year, the installation phase from a weekend to a few months, and the operation phase from a few years to several decades. This perspective highlights the importance of the planning phase as it precedes the often very stressful installation phase and the often very long operation phase. A well-planned layout can therefore, in theory, lead to a minor efficiency increase that can live on for decades, yielding vast returns.

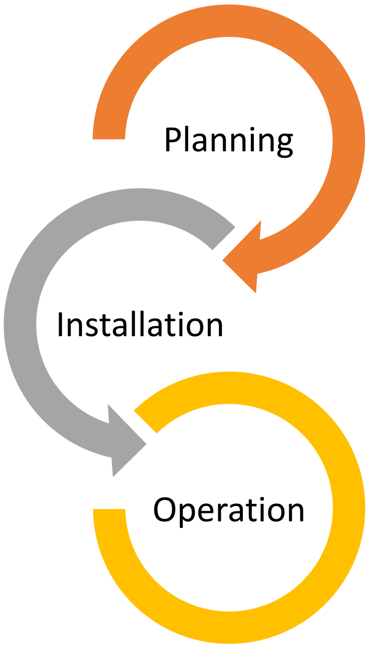


Figure 4: Three phases of a factory layout’s lifecycle.

2.4 TECHNOLOGICAL TOOLS AS DECISION SUPPORT

The work summarized in this thesis has utilized mainly three technical tools in order to provide data, that in turn provides support to make informed decisions in the decision making process (Kościelniak & Puto, 2015). These three tools are discrete event simulation (DES), 3D laser scanning, and virtual reality (VR). There is a plethora of tools that could help in decision support, and these three tools were chosen due to their familiarity. Each of these technological tools is briefly presented in the following sections.

2.4.1 Discrete event simulation

DES is a type of simulation which often is used to simulate the performance of production systems, such as airports or car production facilities (Banks, Carson, & Nelson, 2005; Johansson, Johnsson, & Kinnander, 2003; Klingstam, 2000). DES models are based on logic and is as the name implies, driven by events. These events trigger and change things as the model is being executed and are scheduled to occur at a discrete time and can trigger other events. As DES models are based on the events, nothing is simulated unless an event occur which allows the models to jump from event to event, saving time in running the model. This allows for well-built DES models to simulate long timespans and offer good decision support that otherwise may be difficult to obtain, such as data on years of production with different product variations or machine configurations.

2.4.2 3D laser scanning

3D laser scanning is a measurement technology that can be applied to gather unbiased spatial data in a non-contact way (Gregor, 2013). 3D laser scanner can be divided into either time-of-flight scanners or phase-shift scanners, depending on the specific type of solution applied in the scanner itself. A time-of-flight scanner is typically suitable for outdoor use, for example construction sites, as such scanners can capture data from over 100 meters away (Dassot, Constant, & Fournier, 2011). A phase-shift 3D laser scanner on the other hand is better suited for indoor use, which most often is the case for a production system, as they typically capture data from objects at a closer distance with higher resolution (Dassot et al., 2011). 3D laser scanners operate via the emittance of laser beams which reflect from a surface in the direction of measurement, eventually returning to the scanner. By measuring the distance the laser beam has travelled combined with the direction in which it was sent, a measurement point in 3D space can be acquired (Klein, Li, & Becerik-Gerber, 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 (Dassot et al., 2011) , as shown in Figure 5. 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. By combining these measurement points in 3D space with RGB data acquired from the built-in camera, these measurements can be provided with 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, Berglund, Vallhagen, Berlin, & Johansson, 2012).

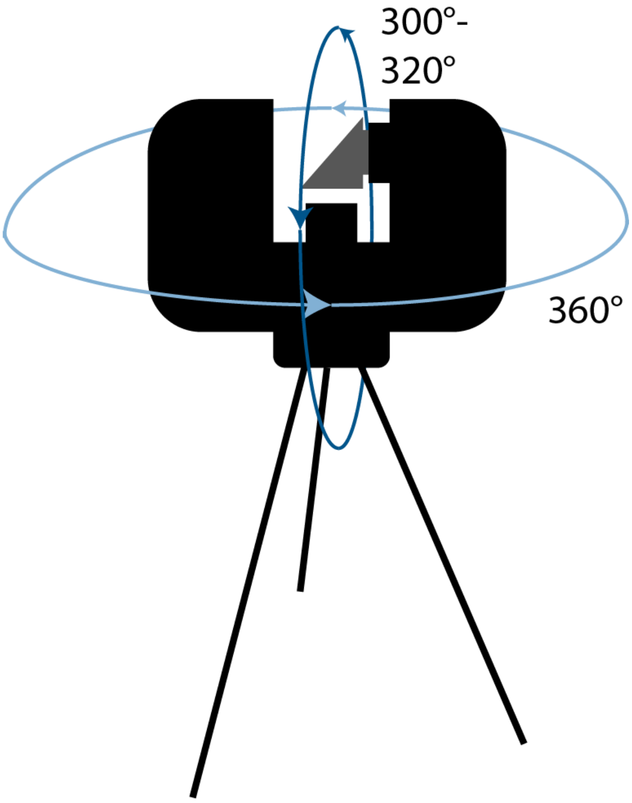


Figure 5: Visualisation of a 3D laser scanner and its field of view.

2.4.3 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 University Press, 2021d). VR was in development already in the 1960s, when a system which presented stereoscopic 3D views while tracking head movement was presented (Sutherland, 1968). VR systems can be differentiated based on two vital characteristics; immersion, the user's sensation that the virtual environment is real and not virtual, and presence, the VR system user's sensation of being part of the virtual environment (Magnenat-Thalmann & Thalmann, 1999; Schuemie, Van Der Straaten, Krijn, & Van Der Mast, 2001). The amount of immersion a user experiences can be impacted by such things as feedback lag time, field of view, spatial audio, tactile feedback and force feedback (C. Lu, Shpitalni, & Gadh, 1999), or anything else that can hint to the user that there is a computer doing calculations in the background. The presence a user experiences 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, via semi immersive systems, such as projection systems, to immersive VR systems (Korves & Loftus, 1999). Immersive VR systems can in turn be categorized into two separate systems depending on the technology and approach used: Cave automatic virtual environment (CAVE), where the environment is projected and directed to multiple walls of a cube in which the user is positions, and VR systems using head-mounted displays (HMDs).

VR has shown positive potential many areas, for example 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, & Noh, 2015). In collaborative factory planning scenarios where multiple users' viewpoints were visualised using immersive VR systems, positive results were identified (Wiendahl & Fiebig, 2003), and recent development show promising results in using VR to support layout planning (Gong et al., 2019). Immersive VR has also been used in urban planning as it allows the user to experience the plans in ways previously impossible, such as standing in places that have no structure to get a good view or by augmenting information (Edler et al., 2019; Jamei, Mortimer, Seyedmahmoudian, Horan, & Stojcevski, 2017; Ma, Wright, Gopal, & Phillips, 2020).

3

Research approach

Research, the systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions (Oxford University Press, 2021c), is often thought of as an organised, linear process. In practice, the process is often much less controlled (Williamson, 2002) but should be conducted so that people can understand, reproduce and evaluate its quality (Trochim, Donnelly, & Arora, 2016). Research may be divided into two strictly separate types: 1) basic research, focused on building fundamental theory and 2) applied research, focused on exploring real-life problems (Williamson, 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; to be relevant to a given worldview, research needs to be properly designed. Research methods should also translate the research that has been designed into practice. An important aspect of research is theory-building.

3.1 THEORY-BUILDING

Theory-building may be conducted in two somewhat disparate ways; inductive or deductive reasoning. Inductive reasoning is the more open-ended and exploratory of the two. It starts with a specific observation and theory-building is then initiated. (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 due to the appearance of various challenges and problems while the factory layout planning process was being studied. This triggered a need for further research into the area, as the well-researched factory layout planning methods were absent in the particular manufacturing domain being studied. As the research into this topic progressed, the need to understand the challenges of various settings and in different cases warranted additional studies. Both deductive and inductive reasoning were used, 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 (their philosophical worldview) (Crotty, 1998). These assumptions are fundamental to the researcher's interpretation and understanding of the research question and how they interpret the findings (Crotty, 1998). Existing literature or experience of a practical problem may be used as sources when formulating a research problem or research question. A major motivation in applied research is the opportunity to solve a problem of personal significance to the researcher (Trochim et al., 2016).

This research targets the manufacturing domain, in which the author of this thesis has a personal background and previous experience. Prior to starting his PhD studies, the author's experiences of studying and working within the manufacturing field were gained mainly at home 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, the author spent many hours working in a production system, garnering much valuable experience and insight. After gaining the Master's degree, a year was spent working in an engineering company with customers and production sites all over the world. This gave the author further insight into the challenges facing industry. All the experience and insight gained prior to this PhD grew into a personal desire to improve processes and make them more effective and to reduce wasted time and effort. This produced a curiosity about proving knowledge and insights and about shaping future factory-related processes.

Epistemology relates to the assumptions regarding what creates acceptable, valid and legitimate knowledge (Burrell & 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 is a pragmatic researcher. As the research in this thesis mainly applies to and focuses upon providing valuable knowledge to the manufacturing domain, it is appropriate to cite pragmatic theory. This says that a statement is true if it can provide value when put to practical use. It further states that valuable knowledge is created mainly by the process of identifying practical problems and then using suitable methods. In practice, this meant applying a combination of qualitative and quantitative research approaches, as elaborated in section 3.3. Such a mixed-methods approach has the benefit of collecting data in the most appropriate way to explain or answer a problem, rather than deciding beforehand which method to apply (Creswell, 2014).

3.3 MIXED-METHODS RESEARCH APPROACH

A research approach is a plan for addressing research questions. It may be quantitative or qualitative, or it may use a mixture of the two (a mixed-methods approach). In quantitative research, relationships between certain identified variables and data are examined to test objective theories. In qualitative research, open-ended data is gathered to explore and understand a problem. The mixed-methods approach combines quantitative and qualitative research, gaining the strength of both approaches whilst minimising their respective drawbacks. This research method is aligned to the pragmatic worldview and is intended to give a more complete understanding of the problem that the research is investigating (Creswell, 2014). In this research, a mixed-methods research approach has been used to further explore the research questions. The vision is broad and includes all types of errors within brownfield factory layout planning. This makes the mixed-methods approach a good fit as it can capture many different aspects. For the industrial studies conducted within this thesis, the approach was mainly manifested in action research.

3.4 RESEARCH DESIGN

This section covers the research design and data collection methods used in this thesis' studies.

3.4.1 Action research

Action research may be broadly defined as an approach in which the researcher collaborates with a client to diagnose a problem and develop a solution (Bryman & Bell, 2007). This makes the approach well-suited to industrial scenarios, in which 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 6 (Oosthuizen, 2002). Using the action research process in this manner, a subsequent study may build upon the results and reflections of the previous one. This process also allows the researcher to participate in the studied group in various ways, applying different data collection methods pragmatically, as dictated by the context (Oosthuizen, 2002).

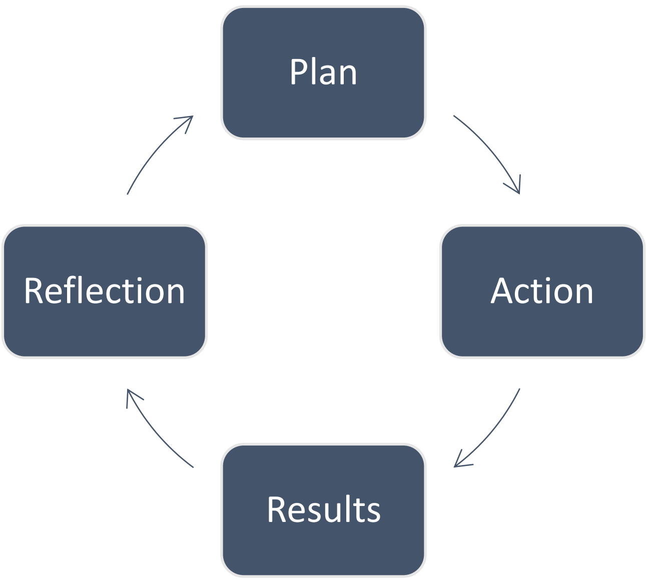


Figure 6. The cycle of action research, based on Oosthuizen (2002).

3.4.2 Participant observation

Participant observation is a qualitative data collection method. It is used to gather data on events or situations and allows the researcher to gain insight into the specific context, behaviours and relationships (Mack, 2005). Participant research may 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. Its counterpart – full participant – is when the researcher is a member of the group but conceals their research role (Kawulich, 2005). The observer-as-participant may participate but focuses on collecting data via observation, while the participant-as-observer interacts extensively with the group (Kawulich, 2005).

3.4.3 Interviews

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

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

A *semi-structured interview* uses an interview guide. This is a list of questions, prepared for specific topics which need to be covered but leaving the interviewee some latitude for their replies (Bryman & Bell, 2007). The interview need not adhere exactly to the schedule and, depending on the interviewee's replies, may deviate to include other questions (Bryman & Bell, 2007).

In an *unstructured interview*, the interviewer uses almost no specific prepared questions; instead, they more freely pursue points deemed worthy of following up (Bryman & Bell, 2007). An unstructured interview resembles a conversation, rather than a typical interview (Bryman & Bell, 2007).

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

3.4.4 Research activities

The research activities underpinning this thesis were conducted over five years (2016-2021) and across multiple research projects, each with different goals, aims and intentions. This made the research activities more interesting. The activities in this thesis were conducted alongside Swedish manufacturing companies active in different business areas. They mainly considered production systems comprising a mixture of humans and machines, with varying degrees of automation. The main activities were six industrial studies in which action research was applied in cycles to build knowledge of the area. This is visualised in Figure 7, where the knowledge gained from each study goes into the next one. This means that insights from the first study become part of the knowledge base underpinning the last one. Study 1 is presented in Paper II, Study 2 is presented in Paper III, Studies 3, 4 and 6 are presented in Paper IV and Study 5 is presented in Paper V.

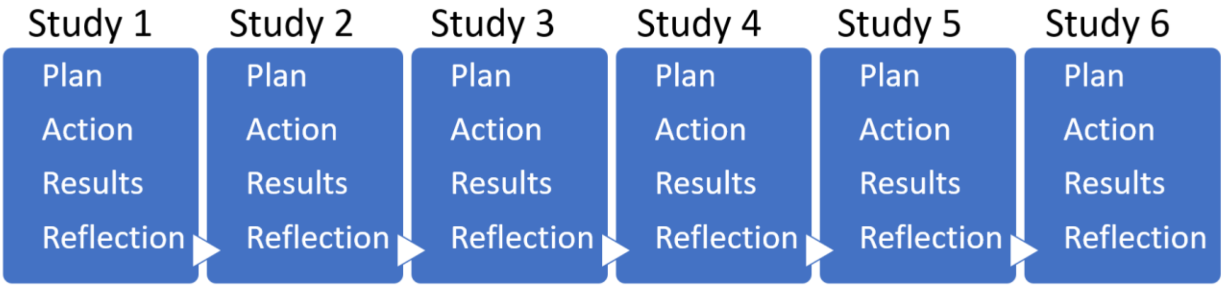


Figure 7: Visualisation of the six studies and how they connect sequentially. The knowledge gained from one study builds into the next, so the knowledge and insights from Study 1 underpin Study 6.

The research in this thesis applied mixed-methods research differently in the studies presented in the appended papers. The data collection methods varied depending on the questions and scope of each study. However, participant observation was a key ingredient for most of them. Data was collected qualitatively and quantitatively, mainly via interviews and participant observations. This is explained below for each paper and summarised in Table 3.

Paper I used an interview study, using semi-structured interviews to gather data. The interview guide was based on the results of a literature study, providing the necessary initial contextual and technical information. The interview results were then coded using magnitude coding to further analyse and summarise the data. This study also incorporated a benchmarking study to facilitate improved understanding.

Paper II used action research and participant observation to gather data. Three researchers were involved in different participant roles during the workshop. One had the role of participant-as-observer (due to technical difficulties controlling the model during parts of the workshop), while the other two researchers focused almost solely on recording data in the form of notes and audio recording. They were present in the room and the study group was aware of their role as researchers and observers. Thus, the role of complete observer was not entirely filled. However, there was little or no interaction with the group, making the observer-as-participant description a poor fit.

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

Paper IV used semi-structured interviews combined with participant observation. More specifically, the role was that of participant-as-observer because the researcher was able to execute the tasks required in the studies. This paper covers three studies, all using the same methods.

Paper V applied participant observation, again using the role of participant-as-observer (for the reasons given above). This was combined with semi-structured interviews, to gather feedback and input afterwards.

Paper VI mainly applied structured and semi-structured interviews plus coding of the interview data. This allowed the previously conducted industrial studies to be followed up, giving a better understanding of the effects achieved. Notably, this study also included industrial studies conducted by other researchers (without the author’s involvement).

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

PAPER	QUALITATIVE	QUANTITATIVE
I	Semi-structured interview	Interview coding
II	Participant observation semi-structured interviews	
III	Participant observation semi-structured interviews	
IV	Participant observation semi-structured interviews	
V	Participant observation semi-structured interviews	
VI	Semi-structured interviews	Structured interviews Interview coding

3.5 RELIABILITY AND QUALITY IN RESEARCH

Three prominent criteria are often used to evaluate the quality of research: reliability, replication and validity (Bryman & Bell, 2007). Reliability examines whether a study's results are repeatable. This criterion is often associated with quantitative researchers (Bryman & Bell, 2007). Replication means that another researcher should be able to replicate a study. Thus, the study procedure must be highly detailed to allow replication (Bryman & Bell, 2007). Validity (often considered the most important criterion) concerns the integrity of the conclusions generated by the research (Bryman & Bell, 2007). Bryman and Bell (2007) explain four types of validity:

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

Adapted to the setting of qualitative research, these validity concepts may 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.
- *Confirmability*, which considers whether the researcher has allowed their values to affect the study significantly.

The reliability and quality of this research will be examined in Chapter 7, Discussion.

4

What type of research has been done in the area?

A literature review was conducted, to investigate the background and existing research into factory layout planning. Instead of focusing on specific solutions applied to specific types of facility layout problem, as in multiple previous reviews in this field such as Ahmadi et al. (2017) or Hosseini-Nasab et al. (2018), the emphasis is on how closely the problem being addressed resembles real scenarios and how far the research reaches into the layout change process. This study aims to research two questions and support knowledge-building on the stated problem:

1. To what extent has research into the topic in the past 10 years been case-based, in-depth and longitudinal?
2. In what settings does industry currently conduct brownfield factory layout planning?

4.1 METHODOLOGY

4.1.1 Literature study

A literature study, or literature review, is a way of gathering information from published works. Robust findings can be produced by applying a systematic method of selecting which literature to review and how to review it. This type of systematic literature review is often aimed at synthesising information from multiple sources on a narrow topic or area. Its purpose is not to report what is known but, rather, to identify what remains unknown or where there is a knowledge gap or deficit (Giltrow, Gooding, Burgoyne, & Sawatsky, 2014). Knowledge gaps may be characterised in different ways. These include a pure knowledge deficit, when no-one has examined specific things, or a controversy, when scholars disagree on, say, definitions (Lingard, 2018).

Application in this study

The literature review was conducted in two parts, following the snowballing process inspired by Wohlin (2014), as illustrated in Figure 8. The initial set of sample papers was gathered in June 2017 by searching in SCOPUS for any of the keywords (“production”, “manufacturing”, “factory” or “facility”) in combination with “layout” and either “planning” or “problem”. To limit the samples to more recent studies, the search was filtered to include only results from the last ten years (2008-). The abstracts of the identified papers were then read to determine whether the articles were a good fit. Those papers deemed to be within scope were then used in a backward snowballing process to generate further papers, see Figure 8. This first part generated 40 papers. These were read and analysed according to a review guide developed to answer the two research questions. The guide aimed to determine the nature and scope of the study presented in a paper and is formatted as a set of questions, nested in four levels:

- Is the paper *not* a survey or review? IF YES, then 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? IF YES, then continue.
        - Does the applied method involve expert users from the case?
        - Is the layout that has been developed implemented in the study? IF YES, then continue.
        - Is the layout followed up after implementation?

The results from the first batch of papers were mostly consistent and conformed to each other. However, they were deemed insufficient to conclusively describe the current state of research. In June 2018, a second iteration was therefore initiated. This used the previously identified papers to produce an additional 49 papers. This took the final count of papers in the literature review to 89.

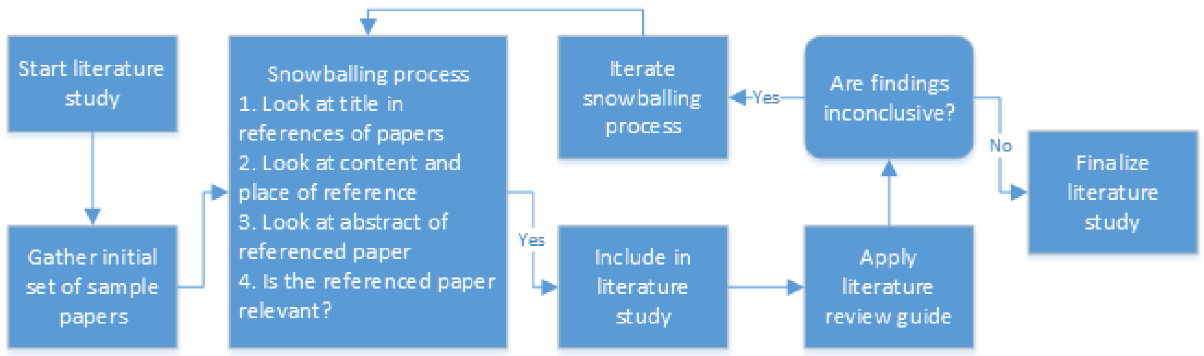


Figure 8. Literature review process.

4.1.2 Semi-structured interviews

Interviews as a data collection method may be split into three separate types, depending on design and execution (Bryman & Bell, 2007):

- structured interviews, which follow a fixed sequence and use the same questions and give results that are more quantitative and less qualitative;
- semi-structured interviews which use a list of questions prepared for specific topics. These must be covered by an interview guide but leave space for the interviewee in the replies;
- unstructured interviews, in which the interviewer does not use any prepared questions on specific topics. Instead, the interviewer more freely follows up on those points they deem worthy. This type of interview is more akin to a normal conversation.

Application in this study

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

- how many of the company’s layout planning projects the person had been involved in;
- how many layout planning projects were full and partial factory/facility;
- extent of layout planning projects in terms of area, workstations, machines and stakeholders;
- extent of stakeholder involvement in layout planning projects;
- layout planning projects’ lead time;
- problems and challenges encountered during planning, installation and operational phases relating to layout planning projects.

4.2 RESULTS

4.2.1 Literature study

Table 4 presents a summary of the literature review conducted in this study. In this table, the first step of the review guide is the second column (“is not a survey or review”). This states whether or not the reviewed paper is a survey. Papers that make it through the second column are then subject to the third (“is or could be brownfield”). This represents whether the research is, or could be, brownfield-related. The fourth column (“plans full facility”) considers whether the paper researched the layout of full facilities or just partial ones. The fifth column (“studies a real case”) covers whether or not the paper researched a real case. If so, the sixth column in the review guide (“involves expert user”) assesses whether the study involved expert users from the case being studied. The seventh column (“is implemented”) represents whether or not the resulting layout from the study was implemented as a part of the paper. The eighth and final column (“assesses results after implementation”) shows whether the studies that contained an implemented layout were followed up longitudinally.

After applying the review guide to the 89 papers in the two-step literature review, key findings showed some 71% of papers covered layout planning for a 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 with each paper. Mostly, their degree of involvement was low. Of all the papers included in this study, the developed layout suggestions were implemented in two. One of them also followed up and assessed whether or not the implemented layout hit its targets.

The review also showed that much of the research deals with the layout optimisation problem. This often removes decision-makers, shop floor personnel, maintenance personnel and other stakeholders from the layout planning process.

Table 4: Summary of the literature review.

		Percentage based on number of non-surveys/reviews			Percentage based on 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 implementation
89	73	71	52	27	9	2	1
100%	82%	97%	71%	37%	33%	7%	4%

4.2.2 Interview results

The interviewees in the semi-structured interview study had a combined experience of 35 years, with responsibility for leading and/or working with layout planning in their respective companies. They had been involved in some 60 layout planning projects, three of which involved completely new or rebuilt facilities. The remaining 57 layout planning projects were brownfield, 48 of those dealing with just part of a facility. The extent of the projects varied; from a single machine up to 30 in some cases and, in the case of workstations, anything from a single workstation up to 150. The number of stakeholders affected by the projects was as low as five, or as many as 100. The lead-time of the projects varied from one week to 36 months. The number of stakeholders involved in the projects varied from a select core of just a few key stakeholders and up to an entire department. Table 5 provides a summary of the projects, broken down into greenfield and brownfield projects and whether the project involved a full or partial facility.

Problems and challenges brought up by the interviewees prominently featured communication with various stakeholders (such as affected personnel, suppliers and installation). The reactions of affected personnel needed managing, as these might yield positive or negative side effects.

Cooperation within the project group was stated as important and a problem with outdated, inaccurate or missing details on drawings was emphasised. The interviewees also stated that many things were missed in the planning stage but then identified during installation and operation. This meant the layout had to be adapted to the real world when it was already supposed to be in full operation. This, in turn, led to delays, loss of revenue and irritation.

Table 5: Summary of data gathered via interviews with those working on layout planning.

	Number	Full facility	Partial facility	Percentage of projects
Projects	60	17%	83%	
Greenfield	3	1	2	5%
Brownfield	57	9	48	95%

4.3 SYNTHESIS

As stated back in 1950 (Immer, 1950), layout planning projects are very rarely of the greenfield type. In the interviewees' experience, brownfield planning situations accounted for 95 % of their project portfolio and they were forthright in stating that true greenfield opportunities were very rare. The literature review identified many solutions using algorithmic approaches. By default, these will be very difficult to apply to brownfield scenarios. This is because the data required to apply an algorithmic solution is often not readily available or of good enough quality, as exemplified by the misrepresentations of reality in 2D CAD drawings. As brownfield settings for layout planning present unique difficulties and prerequisites in each project, they require a different approach to finding a solution.

Due to the lack of data, an iterative problem-solving strategy would appear suitable. This means a new problem may be explored whilst a solution is being worked on, albeit acknowledging that the initial solution will not be the final one. This approach was seen in the participant observation studies. The more that project teams learned about a problem and its related challenges, the more they worked on solving it. A solution would change over time and incorporate aspects not even considered at the beginning, until a point was reached where the solution was considered good enough (or had to be implemented due to time constraints). The literature review concluded that only 36% of the studies conducted on real cases included expert users in the process, possibly leading to unsuitable solutions. However, this would not really be apparent as only 7% of the studies conducted on real cases were implemented as a part of the study and only 4% were then followed up longitudinally (including the installation and operation phases). In one case, the results were followed up very loosely after implementation by just examining a few key numbers. No qualitative data was gathered to support any findings. Researching brownfield layout planning may require longitudinal studies to close the applicability gap between proposed solutions and their applicability in real industrial scenarios. An understanding of what is suitable for use in industry and why, plus its effects, should be highly prioritised so that research produces the intended effect.

4.3.1 A brief discussion

In initiating this study, the author (perhaps somewhat naively) expected to find a substantial proportion of publications studying real cases. As it turned out, much of their work focused on solving and optimising mathematical problems rather than aiding the work of manufacturing companies across the world. There might be many reasons for this. Industry in other countries might not be as open as that studied in this thesis. Or perhaps the financing models simply did not work well for that type of research. However, observing the gap between the research being conducted and the practical cases further reinforces this thesis' focus on practitioners. It would be excellent to develop optimal solutions in conjunction with the design of a new factory but such opportunities are inherently rare. The process of acquiring land, constructing a facility, building an entire production system and then seeing it operate at full speed may take several years. Meanwhile, industries such as the automotive sector push face-lifts and new models perhaps several times per year, often with each one leading to changes in the production system. The number of brownfield projects should thus far exceed greenfield ones, even though greenfield projects would have much larger budgets.

5

Summary of appended papers

This chapter summarises each of the six appended papers in details of the study performed and the outcome of that study. The findings from the studies are connected to the three research questions posed in the following chapter. All figures and tables shown in this chapter are from the published papers unless otherwise specified.

Paper I 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 II **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 III **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 IV **Nåfors, D.**, Berglund, J., Gong, L., Johansson, B., Sandberg, T., and Birberg, J., "Application of a Hybrid Digital Twin Concept for Factory Layout Planning", Smart and Sustainable Manufacturing Systems 4, no. 2 (2020): 231-244.

Paper V **Nåfors, D.**, Johansson, B., Erixon, S., and Gullander, P., "Simulation in Hybrid Digital Twins for Factory Layout Planning", 2020 Winter Simulation Conference (WSC), 2020, pp. 1619-1630.

Paper VI **Nåfors, D.** and Johansson, B., "Virtual Engineering Using Realistic Virtual Models in Brownfield Factory Layout Planning", sent to journal (Sustainability Special Issue, "New and Renewed Manufacturing Paradigms for Sustainable Production") 30/6/21.

5.1 PAPER I

Paper I was produced as part of a Master's thesis focusing on how a virtual factory might 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 as relevant and precise information for the user or user group (Yang et al., 2015). It can help users observe events and their effects on the production system, thus providing understanding to different stakeholders (Becker, Salvatore, & Zirpoli, 2005).

This paper presents a methodology to identify the needs of a 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 and supporting fact-based decision-making.

5.1.1 Industrial study

The industrial study in this paper consisted of three data-gathering phases, followed by triangulation of the data to create an implementation plan via 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 current trends. It also resulted in a six-step framework for measuring the maturity of virtual factories. This was adapted from the framework proposed by Bjarnehed (2018), as shown in Figure 9.

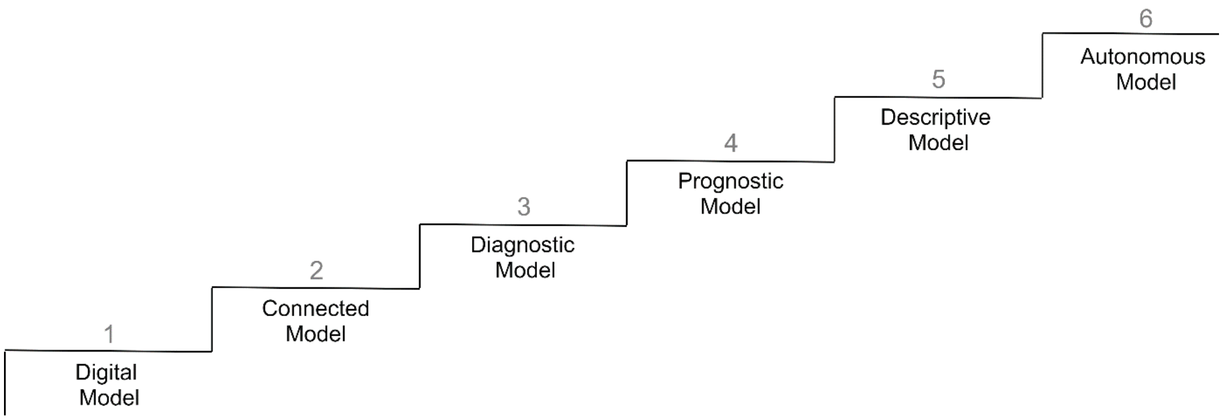


Figure 9: Maturity of the virtual factory divided into six steps.

The literature study was followed by an interview study to identify the company's needs. 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. This ranged 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 and facilitating 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.

5.1.2 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 range of technical needs and number of interviews in which they were identified appears in Table 6.

Table 6: Identified 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
Visualisation 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/optimisation (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	Optimise operator movement (AB)	1
Planning of maintenance (N)	3	NC-programming support (AC)	1
Commissioning for installation (O)	3		

The organisation's needs culminated in the distribution of interviewees' acceptance and technical readiness seen in Figure 10. This showed that all but one interviewee fully accepted the virtual factory concept, while one showed neutral acceptance. The technical readiness varied from no knowledge about virtual factories to full knowledge, with the average being slightly above "some knowledge". Since the acceptance level was already high, future research should focus on decreasing the spread of virtual factory knowledge whilst increasing the average level of knowledge.

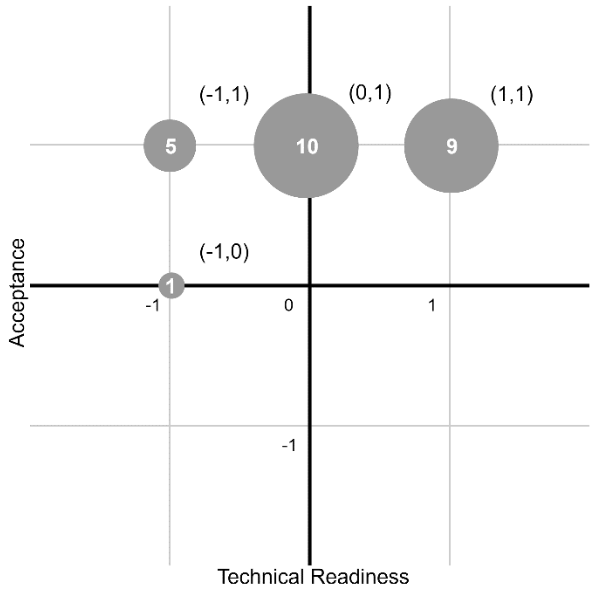


Figure 10: Technical readiness and acceptance among the interviewees.

Other findings from the organisational side included the importance of pilot projects involving key individuals. However, to ensure a wider range of users, individual key users should be prevented from getting too involved. Throughout the virtual factory's implementation, a stepwise implementation of modules and functionality 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, as was the accessibility of in-house competences. Various points about the virtual factory's system architecture were also deemed 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 opportunity 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). However, the step they occupied varied internally, 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 of 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. The focus was on spreading and replicating the model to other departments which were not as far along with their 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 end user's knowledge, which makes training highly important to the success of the concept.

All the needs expressed by the case company fell into the first four maturity steps of the virtual factory shown in Figure 11. This does not necessarily mean those steps could be completely ignored, as they may become highly important in future. One outcome of the study was an implementation plan of how the case company might achieve each step in sequence, relative to its expressed needs. The technical needs labelled in Table 6: Identified technical needs and their respective frequency.are linked to each maturity step, as shown in Figure 11. The focus of this mapping was to ensure that the virtual factory would serve as a decision aid. In the long term, if a virtual factory is to be deemed a supporting function with which employees may regularly interact, then it should be viewed as the original and the real factory as a copy of it.

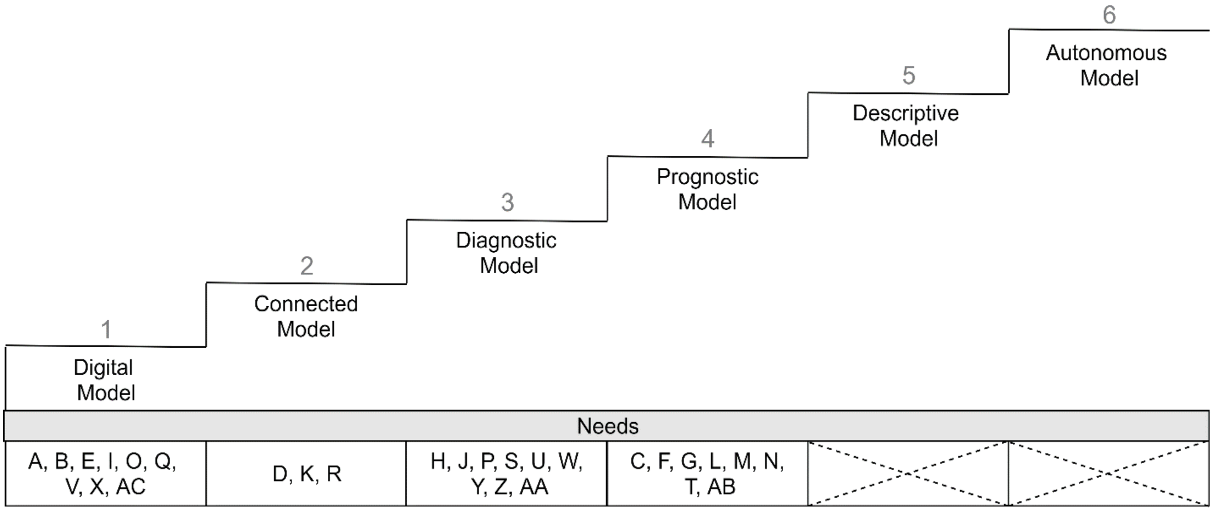


Figure 11: Identified technical needs mapped to the virtual factory maturity steps.

5.2 PAPER II

Paper II reports on 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. This 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 area of roughly 600 m^2 already in use within an existing factory. The machine area was served by four operators responsible for keeping the machines running as much as possible, with trucks supplying raw materials to the area. The new machines were to be placed on separate foundations to ensure product quality. This meant 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, 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.

5.2.1 Industrial study

The industrial study was divided into four steps, as shown in Figure 12. The starting point was using 3D laser scanning to generate a point cloud of the area objectively and neutrally. This was then used in the factory layout planning. A realistic layout model of the future state was then created 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 involved holding layout evaluation workshops at the company. The researchers observed what kind of feedback and discussions the company stakeholders focused on whilst using the two models.

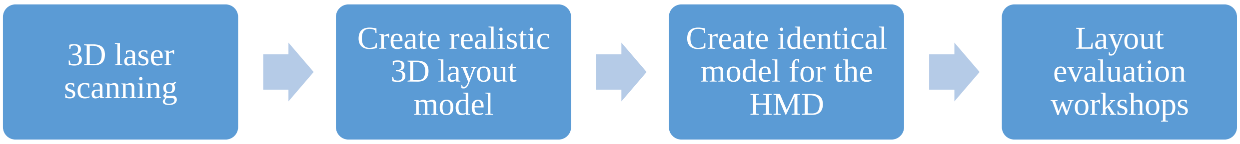
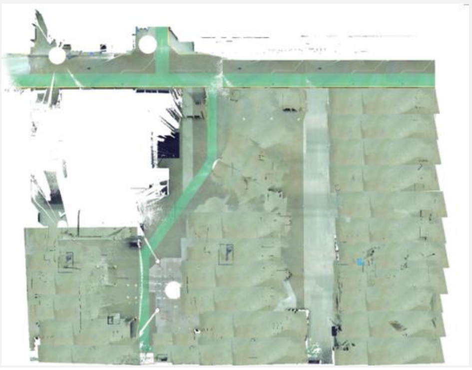
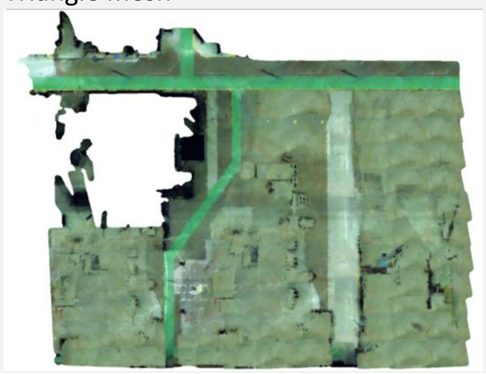


Figure 12: The industrial study process used in Paper II.

Step 1 – 3D laser scanning

The relevant area of the factory was digitised using a 3D laser scanner with 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 there in the future scenario were digitally removed. This was done in dialogue with on-site production engineers. The remaining point cloud was manually divided into suitable pieces, such as a roof component and a component for each wall. To achieve a highly stable frame rate in the HMD later on, certain components (such as the floor and walls) were simplified and meshed. This significantly reduced the volume of data, as shown in Table 7. Meanwhile, the roof component had its point density reduced. A side-effect of this was that the visual quality was altered. Visualising all points gives a high degree of detail but, on close inspection, when the number of pixels displayed exceeds the number rendered, the components appear transparent. Simplified meshes show fewer details but remain opaque.

Table 7: Sample of the floor model from this study 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 – creating a realistic 3D layout model for a projector screen

The second step of the industrial study process in this paper was to create a realistic 3D model of the future layout for viewing on a projector screen. This was created in Autodesk Navisworks and realised in three iterations to enhance the model's representation of the anticipated future step. 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 appear in Table 8. These were implemented in the model after each iteration.

Table 8: 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 – Creating an 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 with 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 series of three workshops was held on the host company's premises. These followed the overall structure from Lindskog, Vallhagen, Berglund, and Johansson (2016), as summarised in Figure 13. The participants varied between workshops but the project leader, process planner and the three researchers were always present. One researcher controlled the realistic 3D layout model which was projected onto a screen for workshop participants, while the other two made written observations 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.

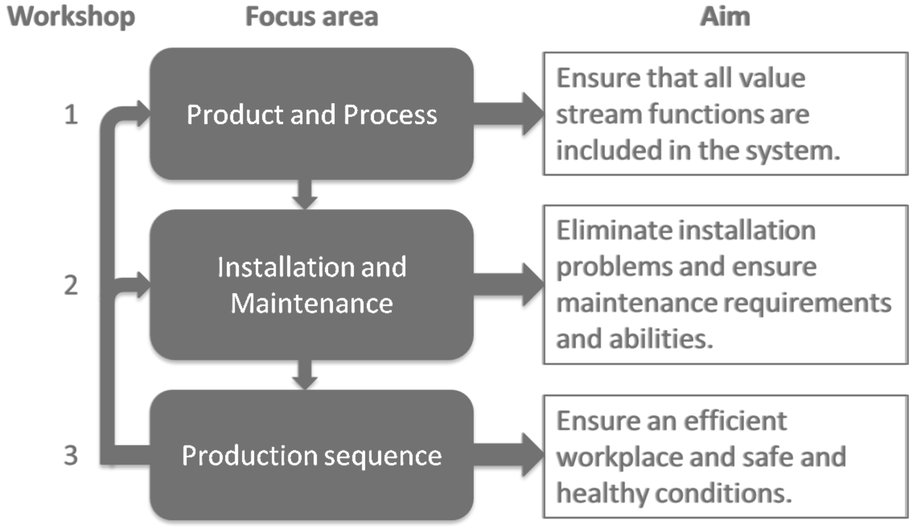


Figure 13: Structure of the three layout evaluation workshops (Lindskog, Vallhagen, et al., 2016).

5.2.2 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 will require more work. Some of these issues include: lack of an incoming and outgoing material area; not enough fixture wagons; positioning of machines being less than satisfactory; and 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, throughout the entire study, a table model was too small. But this was not realised until the very end when an operator wore the HMD. Based on knowledge gained from experience, the operator could tell instantly 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 it. 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 14. This would cause potential problems during layout installation and operation.

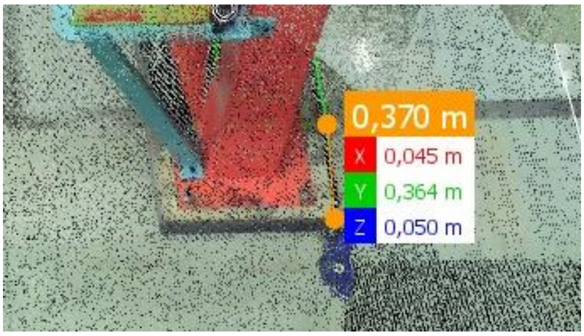


Figure 14: Difference between the point cloud and 2D CAD drawing after alignment of the walls.

5.3 PAPER III

Paper III reports on a research project called "The space industry of tomorrow", in which Chalmers and RUAG Space AB approached the challenges of the new space industry market dubbed "new space". This market brings significantly higher volumes and changes in customer requirements, as it serves a completely different customer segment than previously. This study aimed to investigate the potential benefits and drawbacks of making a discrete-event simulation (DES) models 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 did all the 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.

5.3.1 Industrial study

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

Data collection

The starting point of the industrial study was to carry out a VSM to understand the various flows and convergences of the production system. For the production system being 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 in question was developed especially for this case, as described in Barring et al. (2017). The shortest sub-flow is the VSM shown in Figure 15, 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.

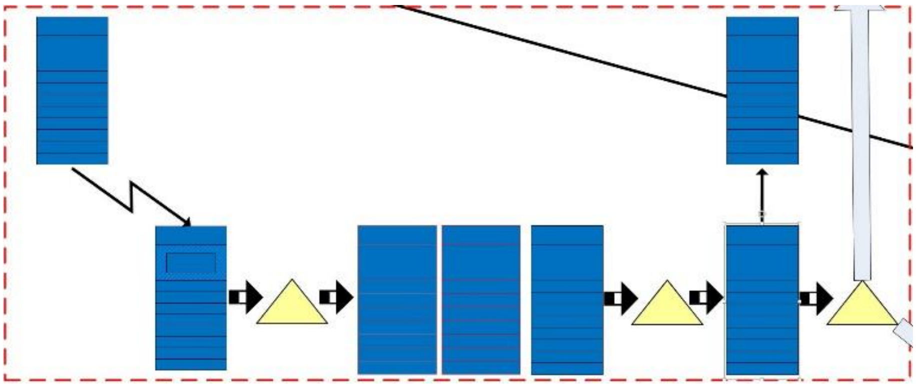


Figure 15: VSM of the shortest sub-flow. The rectangular boxes represent processes, while the triangles represent storage buffers.

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 m^2 facility, producing over 500 million measurement points. An example of the spatial data resulting from this 3D laser scanning is shown in Figure 16. The data was divided into various sections representing different parts of the factory, while the roof was removed to support top-view visualisations.

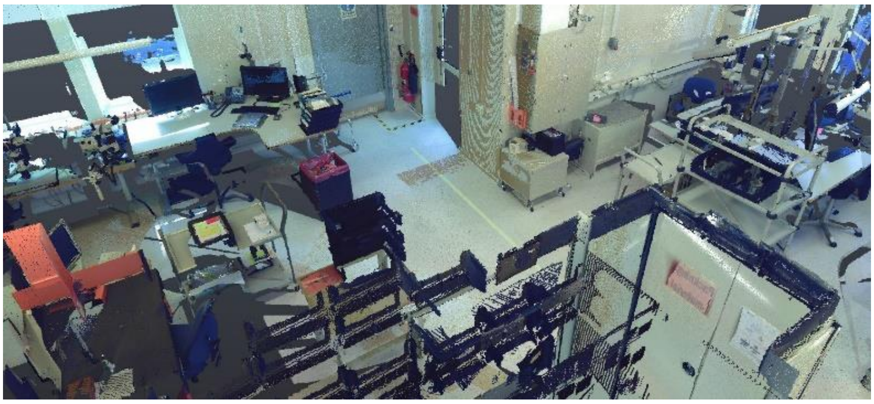


Figure 16: A visualization showing a part of the spatial data gathered via 3D laser scanning.

Model building

The DES model used in this study was built in two stages. Firstly, all the data resulting from the VSM plus additional data not included in the VSM was used to build a logic model of each individual sub-flow. Secondly, each process step of 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 full flow of the simulated product. Once this was achieved, the point cloud model was imported so that each process step could be positioned accurately and with its proper spatial relationships. The pathing of operators was also modelled so that there were no collisions between the simulated operators and point cloud model. An example of this is shown in Figure 17, in which operators (marked by red arrows) may be seen walking through doorways in the simulation model.

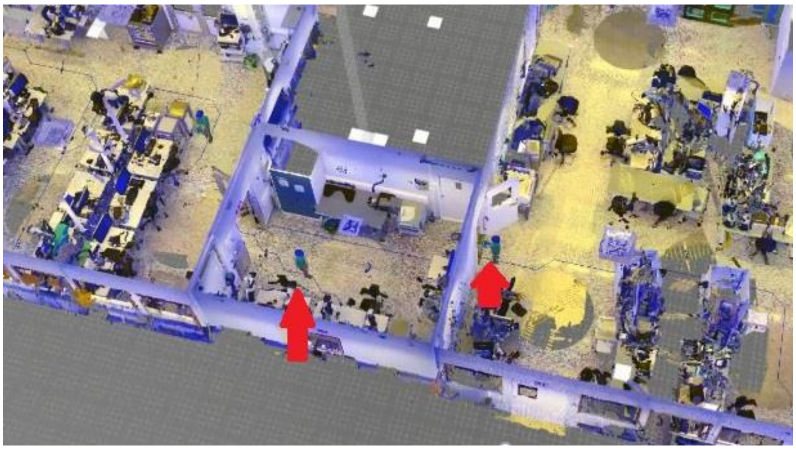


Figure 17: Snapshot of the running simulation model showing operators, marked by red arrows, walking through doorways instead of taking the shortest path through walls.

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 day-to-day work. In the second method, once the model had been validated as described above, the product unit manager checked the data for all the VSM processes, including such factors as batch size, process step and process times. The model was considered complete once both these validations had been concluded.

5.3.2 Outcome

The outcome of this industrial study comprised results from the semi-structured interviews combined with the papers, based on the authors' experiences from the study. The VSM strongly supported structuring the DES model by breaking the production system down into more manageable pieces which could be modelled and tested individually. 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 downside 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 might benefit from using it only when its realistic visuals are beneficial (for example, when accurately positioning objects, determining operator and truck pathing or validating the flow).

This study indicated great potential in combining VSM, 3D laser scanning and DES. While VSM and 3D laser scanning do not yield all the data required to build a highly accurate DES model, they may make model-building quicker and more accurate. Moreover, using accurate, realistic point cloud data ensures that changes to the DES model will fit and work as planned when implemented in reality.

5.4 PAPER IV

Paper IV reports on a research project called "SUMMIT". In this, a consortium of 15 members aimed to increase the sustainability, efficiency and robustness of production systems by utilising the full potential of production data analysis in the design and maintenance phases. In part, the project focused on generating pilot cases for designing digitalised factories and this formed the basis of the three industrial studies summarised in this paper. The production systems in this study consisted mostly of manual assembly; producing complex products in low volumes.

5.4.1 Industrial studies

The three industrial studies part of this research all considered production engineering aspects. However, there were some differences in both the purpose of each study and the research approach to them. Moreover, Industrial Studies A and B were conducted in Sweden while Industrial Study C was conducted in Brazil. Industrial Study A's main challenge was the placement of equipment and machinery, minimising investment costs and maximising use of the existing facility. Industrial Study B's main challenge was sharing the planned future state with the project team, shop floor operators and other stakeholders to gain more feedback before starting installation. Similarly, Industrial Study C's main challenge was evaluating the planned future state with all the stakeholders to determine the feasibility and fit of solutions, while trying to identify improvement areas prior to installation.

To simplify their explanations, these studies may be broken down and summarised under different categories. As people's hybrid digital twin modelling skills increased, less researcher input was required to control the viewing and guide viewers. This is represented by the "Level of researcher control" category, which also affects what level of participant observation was suitable for each study. The three studies also had different volumes of 3D laser-scanned point cloud data, represented by the "Point cloud data" category. The "CAD data" category considered what kind of CAD data was used in the hybrid digital twin model.

Each industrial study consisted of different activities conducted using the hybrid digital twin model, as summarised in the "Activities" category. This category included two point-cloud-specific tasks: 1) cleaning, the process of removing certain things from the point cloud, either for security reasons or due to the data being obsolete in the future state; and 2) objectification, the process of grouping point cloud data representing a certain object. The "Utilisation" category represented what the hybrid digital twin models were used for in each study and the "With whom" category covered which roles used the models in each study.

5.4.2 Outcome

Industrial Study A

The hybrid digital twin model created for this industrial study consisted solely of point cloud data produced by scanning the 950m^2 facility in question. A bounding box was placed around the floor to segment that data out from the rest; this data was then analysed. Figure 3 shows the visualised height deviance analysis for the floor data, with a 10 centimetre difference from highest to lowest point. The project manager and production engineer used a colourised image of the height deviation to identify suitable positions for production equipment requiring flat ground but without the need for floor repairs. Minimising remodelling costs was a high priority, as the facility would only be used temporarily for this equipment. The hybrid digital twin model was combined with CAD models of the production equipment. This allowed simple drag-and-drop puzzling of the equipment, with near-instant evaluation of solution feasibility. The model was viewed on a desktop monitor. However, there were discussions on how more insights into, say, the sense of scale and comfort could be gathered by using immersive VR to experience the model rather than just looking at it. Overall, the data-gathering for the model and analysis of the floor data presented in Figure 18 was done by two people during the course of a day. In summary, a hybrid digital twin would benefit from being controllable by others and by being experienced in immersive VR, rather than just viewed on-screen.

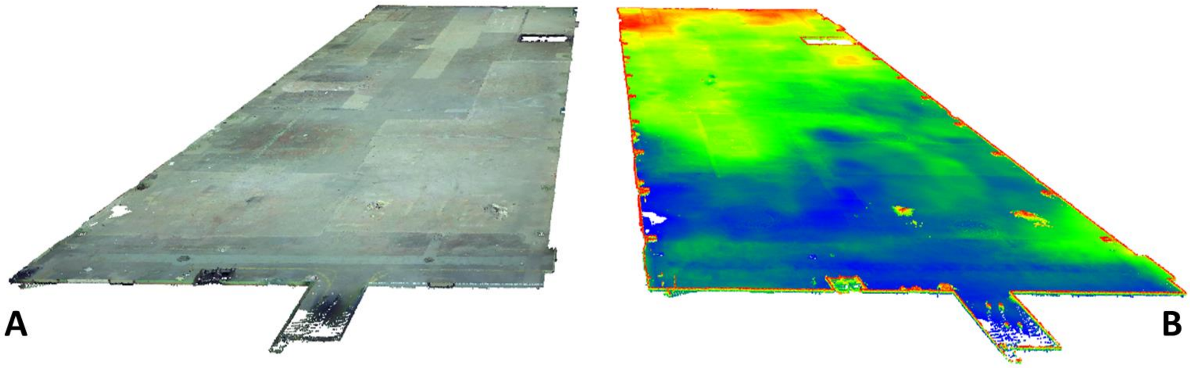


Figure 18: The floor model (left) and corresponding height map (right) of Industrial Study A.

Industrial Study B

Industrial Study B used point cloud data for everything in the hybrid digital twin model. However, some of the data was modified. The relevant area of the facility (some 925m^2) was in use for other production purposes at the time. Nevertheless, it was 3D-scanned alongside a representative machine located in a different part of the factory. By segmenting out the representative machine and re-scaling it, it was possible to generate realistic models of machines intended for use in the future state but which had no 3D CAD model. Based on the 2D CAD drawings from the machine supplier, appropriate scales could be applied to a similar existing machine, as shown in Figure 19. As a benefit, this way of generating models allows for the inclusion of many auxiliary components that are often left out of CAD models, such as trash bins, cleaning materials and waste bins.

Figure 19: Machine model (left) used to generate models of machinery that were unavailable in 3D CAD (right) via scaling based on 2D drawings.

Since the machines were to be delivered fully assembled, the project team working on the production system changes questioned whether the new machines would be able to fit through the doorway into the facility. This could be assessed using path planning software. Setting a start and end path for the machine model allowed the software to evaluate whether there would be any collisions. This was first done using point cloud data for the door frame and the machine. However, that trial indicated that the points representing the machine could travel between the points representing the door frame, with no collision where one might be expected. To solve this, the machine model was meshed into a solid shell through which no points could inexplicably travel. This assessment showed that the machine would fit through the doorway, albeit with a margin of only a few centimetres, if part of the screen mounted on a swivel arm was disassembled. If this proved impossible, emergency solutions would be required, such as dismantling the door frame or making another hole in a wall somewhere. This would occasion additional cost and lead time.

Since the previous study found potential benefits in using immersive VR to view the hybrid digital twin model, the point cloud data was adapted for use in VR. This meant meshing the floor and walls with high-quality textures plus point cloud density adjustments to the rest of the model. These gave a high degree of visual fidelity without compromising performance too much. The hybrid digital twin model was presented in immersive VR via an open workshop. Over 50 operators, maintenance personnel and management at the company were able to experience the model and assess logistics, tool handling and maintainability as they saw fit. Because the model was not sufficiently intuitive, the researchers guided the users in using it. All the workshop participants were asked to complete a survey (as presented in the Methodology chapter) which got 26 responses. In general, the model was positively received and the average response was 3.51 on all agree/disagree statements. A summary of the survey results is displayed in Table 9.

Table 9: Summary of the Likert scale-based statement from the survey performed in Industrial Study B.

Statement	Rating of agreement (scale 1-4, where 4 is high)
I thought the system was easy to use.	3.58
I see immediate benefits in using the system.	3.69
I would find the system useful in my job.	3.23
I would recommend the system to other people.	3.62
This system could provide value to its user (e.g. easier to do the work).	3.57
This system could provide value to our company.	3.65
This system could provide value to our customers (e.g. better quality products).	3.30
This system could provide value to our network (e.g. improve co-operation and communication).	3.41
Average.	3.51

The hybrid digital twin models used in this study were developed by two people over four days and produced increased decision comfort for those involved in the project. It also allowed the stakeholders who would be affected by the changes to share their thoughts and discuss changes, possibly reducing change resistance. One insight from this study was that a hybrid digital twin would benefit from being more standalone; requiring no developer involvement while being visualised so that users might act more freely and naturally. Several survey respondents also chose to leave comments on how the model might be improved. The suggested collision detection, higher levels of detail and adding objects of known scale for better size reference.

Industrial Study C

The hybrid digital twin model in Industrial Study C had two main components in the model: 1) a point cloud model of the empty 2,600m^2 facility which would be used as an assembly plant and 2) a 3D CAD model of the planned layout of that production system. Due to security concerns, parts of the point cloud model had to be deleted, leaving empty spaces in the data, as seen in Figure 20. Once the hybrid digital twin model had been finalised for both desktop viewing and viewing in immersive VR with an HMD, a workshop was held in Brazil for the project manager, project owners and production engineers. Based on insights gained in the previous studies, the developed model now was more intuitive and featured several interactable buttons allowing the user some control of what was displayed in the model. This allowed the researchers to focus on observing. The immersive VR model was controlled by two people responsible for the production layout for a straight hour, as they evaluated reachability and comfort levels in the planned solutions. The plan was for Swedish colleagues to join the workshop via weblink. However, the connection was too poor to transmit video of sufficient quality, frame rate and latency. This led to cancellation of that part and an extra workshop being held in Sweden instead. By using the hybrid digital twin model, increased decision comfort was achieved in the project group, because solutions could be simultaneously assessed as new ones were identified. Various issues were identified, such as misplacement of pillars in the CAD model, working height and visibility in certain assembly areas, and whether products could be comfortably transported from one station to the next. The CAD model was also slightly longer than the facility and would therefore not fit as it stood.

Figure 20: Security installations in the 3D laser scanned facility (A) prior to cleaning and (B) after cleaning. Following the removal of point cloud data, there are visible holes where the data used to be as can be seen in (B).

The hybrid digital twin model used in this study was developed by two people over three days. However, it could have been done quicker had the 3D CAD model been in separate files. As the 3D CAD model received was not supported natively by the VR software, it had to be re-worked and made slimmer to work well. Insights from this study included identifying other solutions for multiple users, making image sharing less reliant on the connection and data transfer rate and a need for a method for dealing with various sources of 3D CAD data in the hybrid digital twin model. Different companies use different software, so it would be preferable to use a standard format and a structured way of delivering components.

5.5 PAPER V

Paper V reports on a research project named Digital Twin for Development and Installation of Production Systems, or DIP for short. The DIP project aims to help small and medium-sized enterprises (SMEs) create spatial digital twins of their factories using 3D laser scanned data and to use that twin for such things as conducting layout planning. The study presented in this paper was conducted at an automotive supplier working with delicate plastic parts that are specially sensitive to scratches. The production system consisted of a mixture of manual assembly, individual human transportation of the product by hand, truck transportation, machining and robot processes.

5.5.1 Industrial Study

The layout planning work in this industrial study comprised three main steps:

- Data-gathering, consisting of 3D laser scanning and subsequent data processing, plus collection of 2D and 3D CAD models and data on forklift and operator movements in the area.
- Model-building, in which the data gathered in the previous step was combined to produce the hybrid digital twin for both desktop and VR.
- Workshops, in which the models were displayed for various stakeholders.

The final model of the layout (which included static planned changes) simulated employees moving around with and without products as would be expected, plus a simulated forklift traffic adjacent to the production area. This model was displayed using VR during several workshops, with and without the researcher's presence. The model was shown to engineers and operators, who could explore the model at true scale in immersive VR using an HTC Vive setup. An example of what the VR user would see within headset is shown in Figure 21.

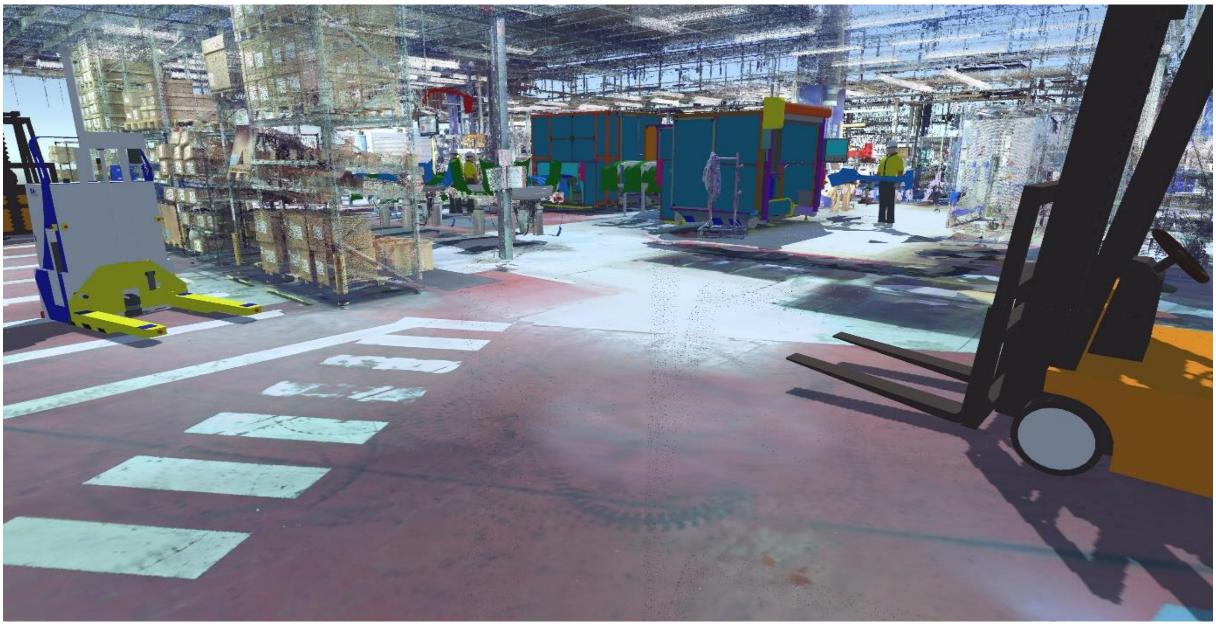


Figure 21: Example of the final model as it would be seen when visualized in immersive VR. The forklifts and operators move around and conduct simulated tasks in the model which consists of a combination of both point cloud and 3D CAD data.

5.5.2 Outcome

The experiences from the industrial study may be divided into three parts, consistent with the three phases of a factory layout: 1) the planning phase, in which the layout is prepared; 2) the installation phase, in which the changes are installed; and 3) the operation phase, in which the layout is used. The following sections summarise these experiences for each phase.

Planning phase

The following effects were identified during the planning phase:

- The company found the 3D environment offered by the hybrid digital twin model to be far more realistic than the previously used 2D CAD drawings. The cross-functional team working on the layout for the related production area in the factory stated that the feedback received for proposals made was far better than usual. They said this was due to the employees who gave feedback (those who would be working in the area) simply having a better understanding of the proposals with which they were presented.
- The point cloud data used in the hybrid digital twin model was considered more precise and trustworthy than the 2D CAD drawings otherwise used in the layout planning process. This yielded more quantity and quality of information, thus making it easier to understand and avoid mistakes.
- Through the VR model, the operators from the affected area could get a feel of the planned layout. As early as the planning phase, they could comment and make valuable improvement suggestions; things which would otherwise only be obtainable post-installation.
- In the VR model, operators could also evaluate the visibility of the forklift traffic from a safety point of view as that traffic was implemented via simulation logic. The altered

positioning of layout elements changed the visibility within the area, making a rough safety assessment possible.
- The movement of ungainly equipment could be evaluated in the hybrid digital twin model by moving it through gates, narrow passages and areas where the roof height was lower. The situation was aided by point cloud data gathered from the 3D scanning accurately representing the facility in 3D space. Such information was not available in the 2D CAD drawing.
- The hybrid digital twin model was greatly appreciated by the company, as highly detailed measurements and installation planning could be done remotely. This saved the engineers from multiple control measurements which might impact operations.

Installation phase

During the installation of the layout, the company noticed several effects of using the hybrid digital twin in their layout planning process:

- While the layout was being installed, much less re-planning was needed than normal.
- The hybrid digital twin model was used in communication with those involved, to explain what should be done and how. This resulted in simpler, more effective communication.
- The hybrid digital twin model was also used to give contractors preparing electrics, improving the flooring and conducting the actual moving of equipment a better understanding.

Ultimately, the installation process went much more smoothly than usual and there were generally fewer errors.

Operation phase

The operation phase of the layout started in 2019 and is still ongoing. Multiple effects of the changed way of working were experienced:

- The operational personnel's understanding of the proposed changes and involvement in the change process increased their engagement. It also anchored the proposal throughout the organisation, leading to a simpler implementation.
- The start-up phase of the layout went more smoothly than usual. This was likely because of a stronger evaluation of the layout and more thorough planning due to the use of an accurate 3D environment viewed on-screen and experienced in immersive VR.

The entire process was considered so beneficial that the company is now working to further implement it throughout the organisation. Another test case has been set up, with the engineers in Sweden planning changes for another of the company's factories (in Belgium) using this way of working. This result points to strong benefits from this method.

5.6 PAPER VI

Paper VI follows up on industrial studies conducted in a multitude of research projects over a period from 2012 to 2019. These were carried out to increase knowledge of the effects of using 3D laser scanning and VR in brownfield factory layout change processes.

5.6.1 Study

The study conducted in this paper consisted of two main parts. Firstly, data-gathering via mixed-structure interviews (structured and semi-structured). Secondly, analysis and compilation of that data, to better grasp the effects of using 3D laser scanning and VR in brownfield factory layout change processes. A total of seven interviews of roughly one hour each were conducted, as follow-up to seven different industrial cases. These interviews were recorded virtually and conducted according to an interview guide developed iteratively with a more experienced interviewer (than the author). They were then tested on a subject matter expert to ensure that the guide covered the most important areas. The recordings were transcribed and the responses colour-coded according to which challenge area they covered. These colour-coded responses were then grouped and further analysed to provide more insights and generalisable findings.

Although the industrial studies were conducted over eight years by different leading researchers, in essence, they all followed a similar methodology. Data was gathered, including drawings, 3D CAD models and point-cloud models via 3D laser scanning. These data sources were then processed and combined into a virtual model. This model was used in meetings and workshops to gather insights to fuel improvements and changes to the planned layout model. In some cases, the virtual model was also adapted for use in immersive VR. This flow is visualised in Figure 22.

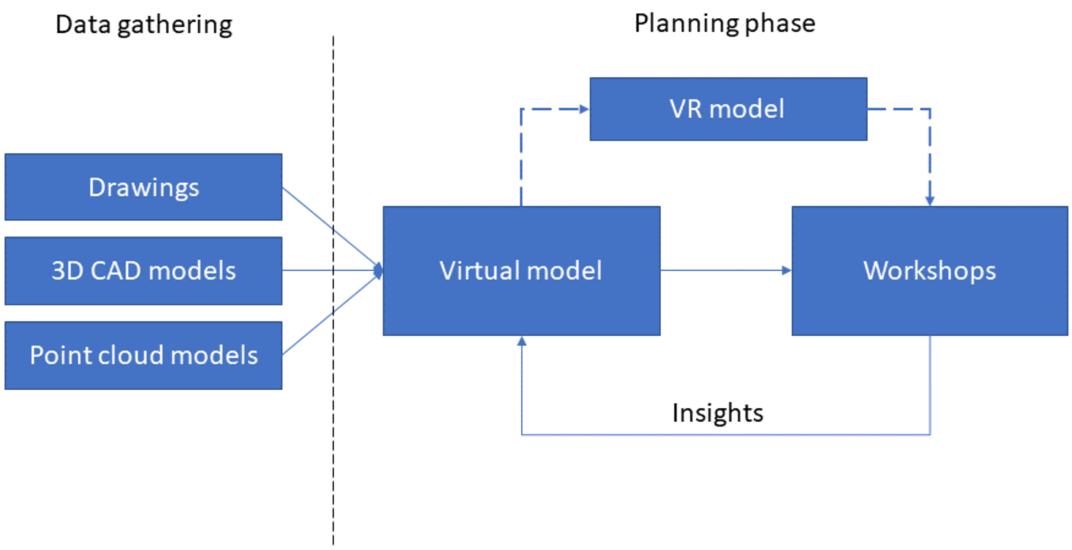


Figure 22: General process applied in the studies conducted between 2012 and 2019.

5.6.2 Outcome

This study had two outcomes. For the first outcome, revisiting all the cases and summarising them as in Table 10 and Table 11 produces some generalisable insights. One such insight is that full factory layout planning is rarely executed, even though the area covered varies significantly. Another insight is that the planning time may vary heavily, according to the case. In Case B, for example, the project grew over time while Case F was conducted in a more familiar environment.

Also noteworthy is the time for installation. This varied from a weekend to as much as two years, depending in part on the business area and on the task. At the one extreme, the case in which the company only had a weekend to make its layout changes, there was no time for ramp-up as full production was expected right away. At the other extreme (two years), production was meant to ramp up alongside installation.

Looking at all the studied cases, the number of people involved in the project work varied, as did the number of stakeholders affected by the changes that were to be implemented. The researchers' involvement focused on supporting the project teams in their work using realistic models. In all cases, this happened exclusively in the planning phase; generally on and off for a few months, except Case D in which the researchers' involvement lasted a week.

Table 10: Summary of the different case conditions.

	Case A	Case B	Case C	Case D	Case E	Case F	Case G
Sequence	1	2	3	4	5	6	7
Task & purpose	Relocation of a machine to a new area	Changing method of production, new technology, change materials, reduce waste	Increased production capacity	New production technology and methods for new products	Installation of conveyors and weight stations to improved quality in production and reduce waste	Adapt production system and change machines due to product change	Build a production system to enable production of certain components as part of contract
Area (m2)	100	6000	2000	600	40	600	5000
Full/separate/part	Part	Part	Part	Separate	Part	Part	Full
Requirements	Existing foundation	Nothing in particular	An installation to be used for a while longer & existing truck traffic lane	Many existing machines and existing logistical system to remain	Adapt changes to existing system, not moving the machines	Utilizing existing high-bay storage and transport isles	Utilize overhead in facility, utilize existing loading bay
Time for planning	Few months	Several years	3-4 months	6-12 months	1 year	6 months	1 year
Time for installation	Short, just moving the parts and assembling again	Few months for machine, ~1 year for robot cells	3-4 months	6 months	1 month	1 weekend	1½-2 years
Ramp-up	None	3-4w for machines	3-4w	Several months	3-4w	None	Alongside installation

Table 11: Layout project related information and researcher involvement at the different industrial studies (3DLS = 3D laser scanning, VR = Virtual reality).

	Case A	Case B	Case C	Case D	Case E	Case F	Case G
Group composition	5 people. Technical manager production development, senior project engineer, production development, DES simulation, layout engineer	15-30 people. Purchasing, layout engineers, logistic, economy, receiving manager, facility, technicians.	6-8 people. CAM-programmers, managers, operators, logistics, safety officer.	~10 people. Operators, purchasing, maintenance, production technicians, process planners	8 people. Flow simulation, project leader, operators, safety officer, automation engineers, maintenance	4. Production engineers, process planners, project leader	10-15 people. Production technicians, layout engineers, CAD engineers, security responsible.
Stakeholders	~20 per shift	200-300 people	30-40 people	20-30 people	14 people	100-110 people	~50 people
Technological tools	3DLS	3DLS	3DLS, VR	3DLS, VR	3DLS, VR	3DLS, VR	3DLS, VR
Involvement	Support project team with realistic models in their work	Support project team with realistic models in their work	Support project team with realistic models in their work	Support project team with realistic models in their work	Support project team with realistic models in their work	Support project team with realistic models in their work	Support project team with realistic models in their work
Time	1 month	On and off throughout planning phase	4-6 months	1 week	3-4 months	3-4 months	4-6 months
Phases	Planning	Planning	Planning	Planning	Planning	Planning	Planning

The second outcome of this study relates to the semi-structured parts of the interview guide (as summarised in Table 12). It focused on the challenges encountered during brownfield factory layout change processes.

All cases encountered data challenges, be that incompleteness, accuracy, or availability of data when it came to planning layouts. In all but one case, the methods and technological tools applied in the studies were found to either solve or greatly reduce the challenge. The remaining feedback indicated there was still a need to go from the neutral 3D laser scanned data to 3D/2D CAD data in order to carry out the installation. Hence, this specific challenge was not significantly less impactful.

Cases B, C, E, F and G all both encountered challenges and sufficiently reduced them relative to the scale and perspective of changes. For example, whether a certain area was too narrow for an operator or whether it would be comfortable enough to walk around in it. The respondents in the same cases also stated that they usually encountered problems gathering input and feedback on the proposed changes and communicating these efficiently to stakeholders. They also reported that these types of challenges were much less of an issue when the researchers were involved.

The respondents in all cases stated that the installation phase went well with no particular issues, although multiple interviewees mentioned difficulty in that they were unable to use the virtual model from the planning phase to support installation. Thus, they still needed to generate 2D drawings.

All respondents in all cases also stated that the entire change project was successful, achieving the anticipated results on time. Some other challenges were mentioned during the interviews such as difficulties learning new ways of working, challenges with computer performance using point cloud models and data security issues. These were specifically due to the point cloud models being very detailed.

One highlighted potential use case for the virtual models which offered major benefit was conducting virtual safety rounds with the safety representative. This would allow the company to find and solve potentially major issues which might impact ramp-up and potentially cause conflict post-installation.

Table 12: Summary of findings from the cases in relation to the three challenge areas. Brackets means that the challenge was identified, and an x inside the brackets indicates that the challenge was solved or much less of an issue using the method and technologies applied in the case study.

Challenge area	Case A	Case B	Case C	Case D	Case E	Case F	Case G
Drawings/models/data	[x]	[x]	[x]	[x]	[ ]	[x]	[x]
Scale and perspective		[x]	[x]		[x]	[x]	[x]
Input/communication		[x]	[x]		[x]	[x]	[x]

6

Following up on the research questions

This chapter relies on input from the previous chapter to follow up the research questions posed and give insight into them.

6.1 CONTRIBUTIONS OF THE APPENDED PAPERS

Table 13 shows the six appended papers and the insights they contribute to each of the research questions. All papers contributed to the first questions, four papers to the second and two papers to the third.

	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
RQ1	●	●	●	●	●	•
RQ2		●	●	●	●	
RQ3					•	●

Table 13. Each paper’s estimated contribution to answering the research questions. The size of the dots represents the significance of the contribution.

The insights gained into each of the research questions are presented sequentially in the following sub-sections, starting with the first research question.

6.2 RQ1 - WHAT ARE THE CHALLENGES FOR RELEVANT STAKEHOLDERS IN BROWNFIELD FACTORY LAYOUT CHANGE PROCESSES?

Each change project is unique and the challenges encountered by relevant stakeholders in the brownfield factory layout change process vary from project to project. However, after studying various of these unique projects, certain challenges become more apparent. The significant commonly faced challenges in this scenario have been boiled down to three: 1) accuracy and completeness of **data**; 2) grasping **scale and perspective**; and 3) gathering **input and communication** issues. Each of these will be explained in more detail, with examples, under the relevant following sections. A fourth common challenge was adapting the planned layout to the real world. However, this challenge may have been caused by the data challenge and is not, therefore, given the same attention as the others.

6.2.1 Data

The data-related challenges encountered by relevant stakeholders in brownfield factory layout change processes and identified in the industrial studies are twofold. The challenges consider both the accuracy of the data (whether or not the measurements can be trusted) and its completeness (whether all relevant details have been included). These challenges are the same for 2D drawings of objects and 3D CAD models of them.

Paper I does not explicitly pinpoint these challenges but, by discussing the technical needs and their connection to a virtual factory, it highlights the fact that there are some challenges the interviewees would like to see addressed. Paper III directly showed the mismatch between the drawings and point cloud data (as seen in **Error! Reference source not found.**), whilst h ighlighting how many objects were missed in the planning phase. These would be solved instead during installation and operation and included adding workbenches, additional machinery for operations and cleaning supplies. Paper IV showed how uneven brownfield factory floors could be (**Error! Reference source not found.**), plus some of the accuracy and detail issues with using a 3D laser scanner to point cloud gather data (**Error! Reference source not found.**). This paper also showed how to reuse point cloud assets to generate more accurate representations of machinery than the less detailed 2D/3D models (**Error! Reference source not found.**). In Paper V , as some objects only constituted an obstacle at certain heights, the project team identified new layout solutions using an accurate representation of the real facility instead of 2D drawings. This enabled better use of space.

6.2.2 Scale and perspective

Another challenge area identified from this body of work was grasping scale and perspective in order to assess layout solutions qualitatively. It can often be difficult to make fair assessments, especially in 2D layouts. As realised late in Paper III's study, the table used in the model was far too small. This was only realised when an operator viewed the model in immersive VR.

Another example came from the study in Paper II, in which the interviewees stated that instantly being able to understand and relate to layout changes was highly beneficial. In this study, the operator was instantly able to recognise the spatial properties of the models and identify potential problems because it looked very familiar. If an object was too small, a passage too narrow, or a workbench too tall, the operator could notice it right away. Similar findings come from the studies in Papers IV and V, in which workshop participants walked around in the immersive VR model and assessed the availability of space and reachability of objects qualitatively. In the interview part of Paper VI, it was also mentioned that it would be possible to carry out further layout assessments in the planning phase (such as safety rounds) which would not otherwise be done until installation or operation. One such specific example mentioned in an interview was that a tool-changing station was too high for the average operator. This was not identified from the 2D drawings or 3D models but was apparent when using immersive VR. This further emphasises the issue of grasping scale and perspective in 2D and 3D.

6.2.3 Input and communication

The third area of challenges identified relates to input and communication. In all studies, having realistic virtual models was appreciated when used for communicating with those outside the project group and when gathering input. A 2D drawing of a planned layout may be difficult and/or time-consuming to understand, as it may not be instantly recognisable or relatable to everyone. Any changes made since previous versions may also be hard to identify and their significance lost.

Finally, when communicating planned changes to the stakeholders whose daily work will be most affected, it is far more intuitive to view a realistic virtual model than an abstract 2D drawing. In the studies, a lot of input and feedback on the layout was gathered in the planning phase, when more stakeholders were invited to view and experience the planned changes. In discussions with the project team, it was often mentioned that feedback and input may only be received once installation is finished, by which time many changes are out of scope.

6.3 RQ2 - HOW MIGHT 3D LASER SCANNING AND VIRTUAL REALITY BE APPLIED WHEN ADDRESSING THE CHALLENGES IN BROWNFIELD FACTORY LAYOUT CHANGE PROCESSES?

More and more knowledge on how 3D laser scanning and VR might be applied in industry was gained following the numerous iterations of action research (as visualised in Figure 7). A general overview of how these technologies might be utilised is shown in Figure 23, with an explanation of each step. Before starting to use these technologies in brownfield factory layout change processes, it is important to answer three questions. The answers to these will help determine a proper implementation; one most likely to work for the unique scenario and lead to positive long-term effects.

1. What is the purpose of using these technologies?

Identifying the purpose helps determine how much workload the company should take itself and how involved they should be in the different steps. Once a company sees sufficient need for the skillset required to carry out some or all of the work, it needs to seize the opportunity and learn from those who are more knowledgeable. For companies wanting to use the technologies again, the drawbacks arise when they realise they should have been more involved and gained more practical knowledge when they had the chance.

2. Who will be involved in the project?

Understanding the participants is important as it may impact the usability of technological solutions. For example, a contractor may not yet have the capability to work with 3D models but may still prioritise it for other reasons. Point cloud data is not commonly used in production system installations, so it may be unreasonable to expect everyone to be able to accept it. However, there are workarounds such as hosting the model online and allowing contractors to take the necessary measurements. Another aspect of identifying those involved in the project is grasping the potential of using VR. Running a VR model with point cloud data of sufficient performance requires not only VR equipment but also a rather powerful computer.

3. How should the data be stored and shared internally and externally?

Just for the layout elements in the industrial studies, the total project data storage requirement was around 20-100GB. This alone can put new demands on the available connection and storage solutions, especially when working in global situations (as in Paper IV). Multiple interviewees in Paper VI also pointed out security issues with 3D laser scanned data, as it represented highly accurate, true facilities. It is hard to control what is gathered by the 3D laser scanner, as some sensitive information may end up being captured. Hence, a requirement might be to only allow data to be worked with offline or in controlled situations, with raw data securely stored as with the study in Paper II.

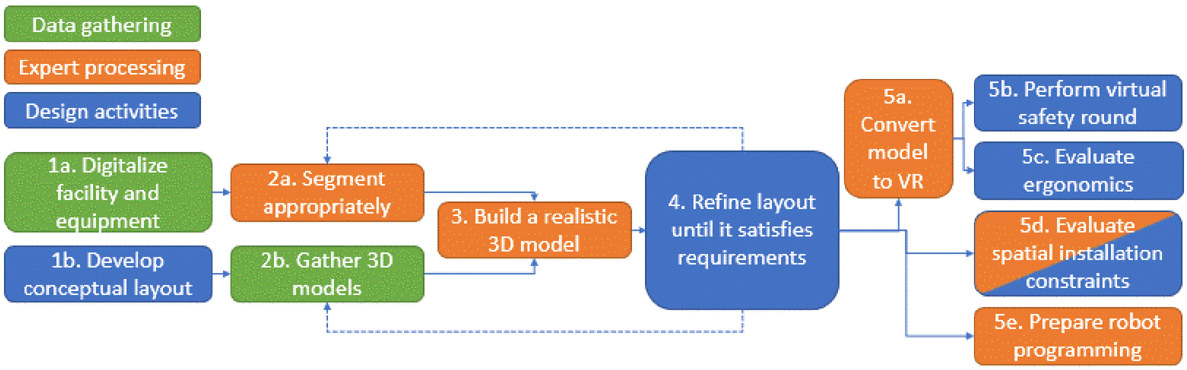


Figure 23. Overview of how industrial companies might utilise 3D laser scanning and virtual reality today, showing what they should be able to do independently and where expert assistance may be required.

1a. Digitalising facility and equipment

The first step (which enables many benefits) is to digitalise the facility and the equipment involved in the brownfield factory layout change process. While most companies may not benefit from owning and maintaining a 3D laser scanner and acquiring the in-house skills needed to do the digitalisation themselves, this service may be purchased at comparatively low cost proportionate to the budget of most such projects.

2a. Conducting appropriate segmentation

Once digitalised via 3D laser scanning, the resulting point cloud (Figure 24, top) must be appropriately segmented to yield the right models for the next step. This may mean segmenting walls, floor and ceiling, followed by segmentation of individual machines (as shown in Figure 24), assembly stations and storage units. This task is learned by doing. So, if a company needs to repeat this process multiple times per year, it might be worthwhile training somebody to do it. Alternatively, an external expert can carry out this task much more efficiently than someone with the wrong tools and no software experience.

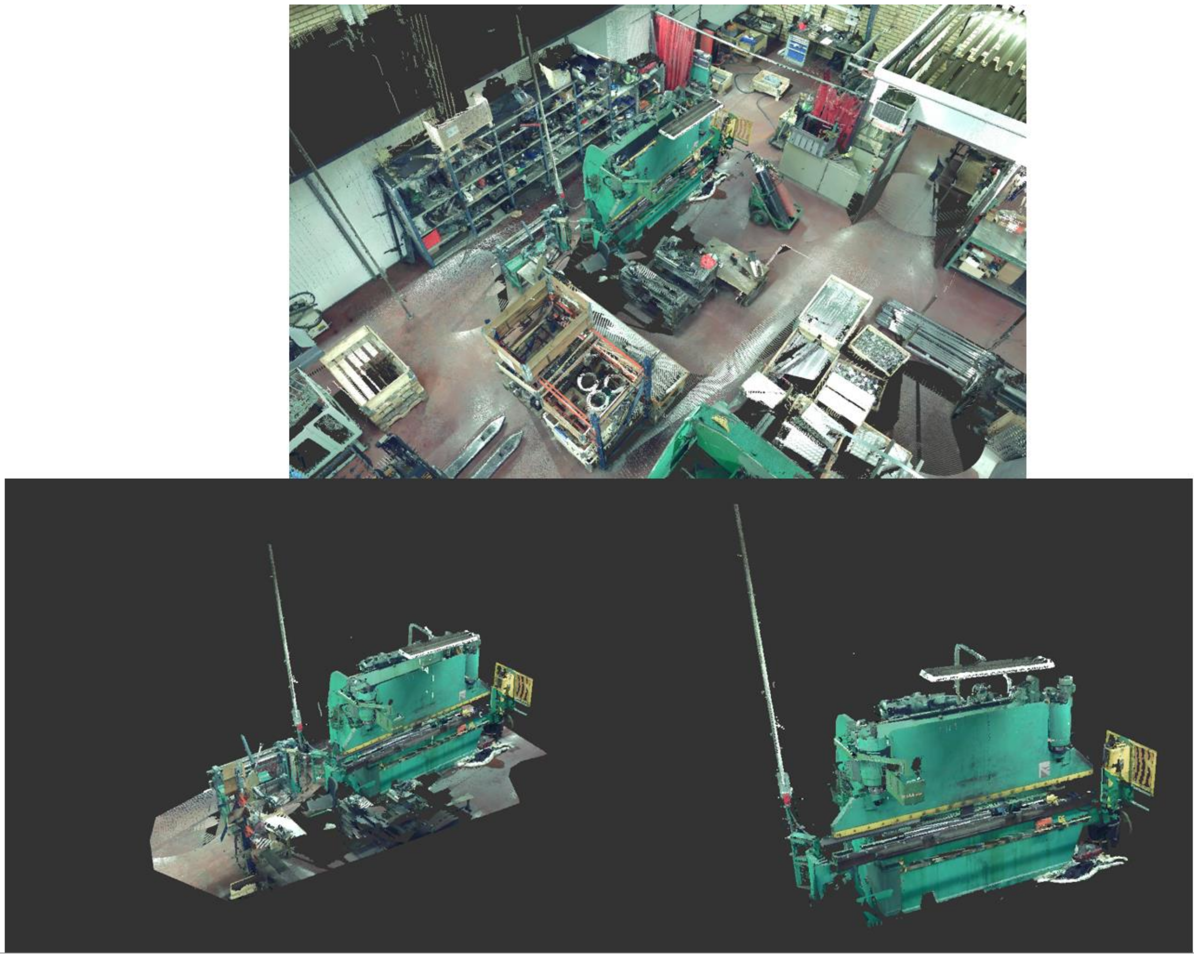


Figure 24. The complete point cloud (top) is segmented by removing one piece at a time (left) until only the required dataset remain;, in this case a separate machine (right).

1b. Developing conceptual layout

As a first step in the change project, multiple conceptual layouts may be developed early on, for use as input later in the process. These layouts may be rough but still include the desired equipment and serve to represent ideas the project team wants to investigate further.

2b. Gathering 3D models

Following the development of conceptual layouts, all components of the new layout (machines, storage racks, assembly stations and so on) should be known. Models of these components need to be gathered in preparation for the following step and should be prioritised as follows.

The main priority of data is neutral and accurate point cloud data gathered via 3D laser scanning. If this is not possible (such as when machines are being made to order), then detailed and accurate 3D models that represent the object as closely as possible should be gathered. If this is not possible either (as when evaluating potential solutions prior to deciding on a supplier), simplified 3D models which at least represent the anticipated volume of the object should be gathered or generated.

3. Building a realistic 3D model

A realistic 3D model should be built by combining input from steps 1a, 1b, 2a, and 2b. This might appear as in Figure 25, which shows a combination of point cloud data, fairly accurate 3D CAD models of machines to be installed and a red volumetric representation of an object for which no better data was available. This model may be used to communicate within the project team and with stakeholders, as it visually represents an area of the facility which stakeholders may recognise. This step may be carried out by an external expert as in step 2a. However, if this step recurs frequently it may benefit the company to have this skill in-house as this allows much more freedom in the next step.

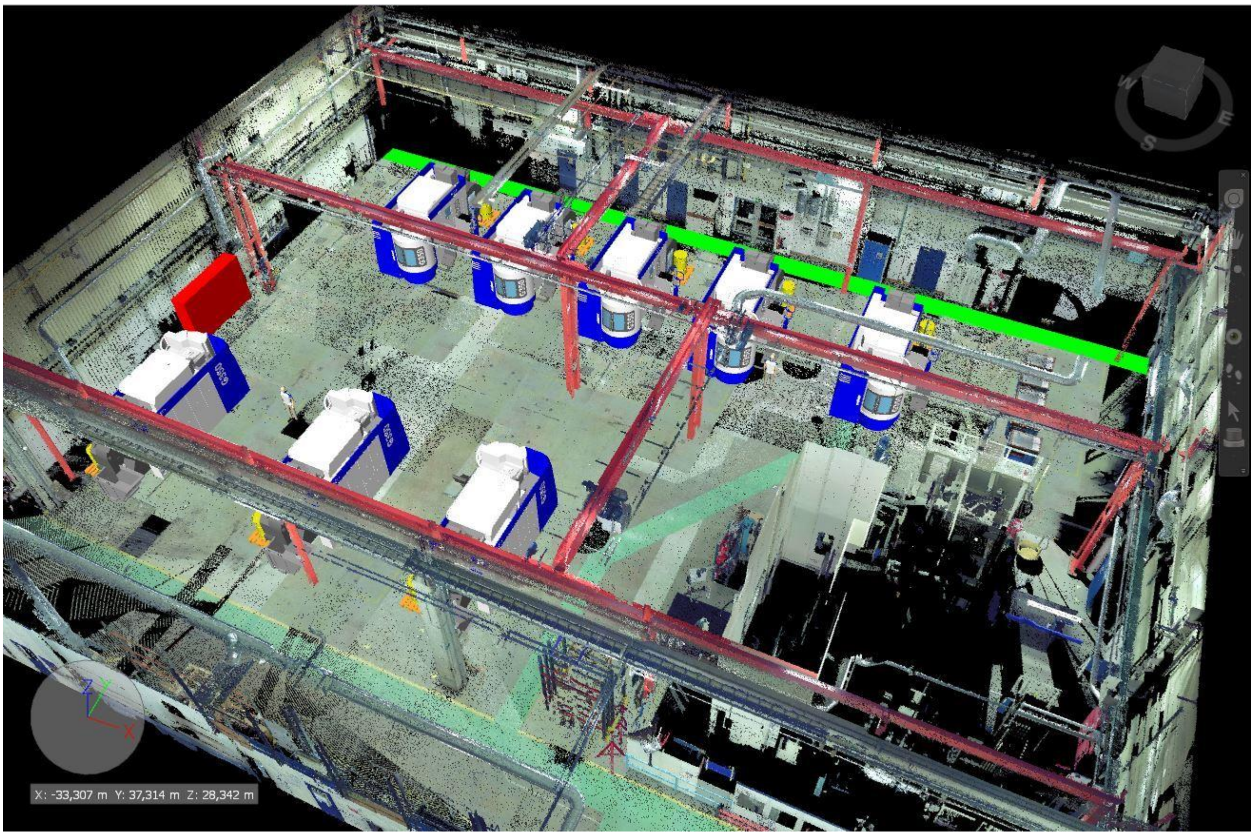


Figure 25. Sample first stage of a realistic 3D model. Point cloud data is combined with more accurate 3D CAD models of machines and a red volumetric representation to the left.

4. Refining layout until requirements are satisfied

Once the realistic 3D model has been established, it may be used in discussions and development work as required. Further segmentation of point cloud data is relatively simple to do, even in this stage. Similarly, should additional 3D models be required, they may be simply gathered and then added to the realistic 3D model. The purpose of this step is to refine the layout until it satisfies the requirements of the specific company. Approval by certain departments or passing certain tests, for example. If no such process is in place, it may be good to apply the workshop structure presented in Lindskog, Vallhagen, et al. (2016), as shown in Figure 13. Depending on the case, once the satisfaction criteria for this step have been passed, multiple potential steps may follow. Two of these may be done by converting the now mature, realistic 3D model to VR. However, two are possible without this.

5a. Converting the model to VR

At the time of writing, making a realistic 3D model viewable in immersive VR is a complicated task with no simple solution. It requires a skilled developer using several different pieces of software to produce the right file format. This needs to contain the right data to produce the anticipated realistic experience. To begin with, the point cloud data format must be changed to work in Unity3D (the platform used in the studies). However, displaying many millions of points at a sufficiently high framerate will tax even the most powerful of systems. Thus, generally flat surfaces such as walls and floors may be meshed. In conjunction with a high-resolution image overlaid on the meshed surface, the results should be of sufficiently high visual quality without costing too much in performance. This process is still experimental and different methods may achieve the same results more efficiently. In addition to the point cloud adaptations, CAD data sometimes also needs adapting. This is mainly because models may come from different software and contain varying amounts of detail, not all of which may be easily handled by Unity3D. Some models may contain incompatible animations or too many details (such as every single screw inside a machine). Finally, programming features such as interactions, commenting and scene-switching to view alternate layouts requires specific experience and expertise in both Unity3D and the C# programming language. These difficulties may be overcome in the future as VR becomes more common and gets used in engineering software. At the moment, however, this step is best made by an in-house or external expert. Figure 26 shows an example of how a realistic 3D model might look in immersive VR, with a mixture of point cloud data, meshed point cloud data and 3D CAD data.

Figure 26. Immersive VR view of a realistic 3D model.

5b. Conducting virtual safety rounds

Hosting a workshop with the safety manager and other key people assessing workplace safety is easy to do with a VR version of a realistic 3D model. Immersive VR technology allows the future state of a layout to be assessed as though it had already taken place, with any problem areas identified prior to installation.

5c. Evaluating ergonomics

As with step 5b, the immersive VR model allows operators, maintenance engineers and other stakeholders who will be working in an area to naturally assess such things as reachability, movements and other ergonomic aspects. They may do this by carrying out the work tasks in this model.

5d. Evaluating spatial installation constraints

The realistic 3D model may also be used to evaluate spatial installation constraints. For example, if the machine arrives at the facility pre-assembled it may be moved through the point cloud model of the facility to check whether it can be taken to its installation location. This is shown in Figure 27, which illustrates a clash with a waste bin at bottom right, plus tight margins to the wall on both sides of the machine and low height clearance to an exit sign. These facts might not have been shown in a 2D drawing. This evaluation can be done manually with limited software skills. However, it may also be done by an expert using dedicated software. This is especially useful in situations where a solution may be difficult to find.

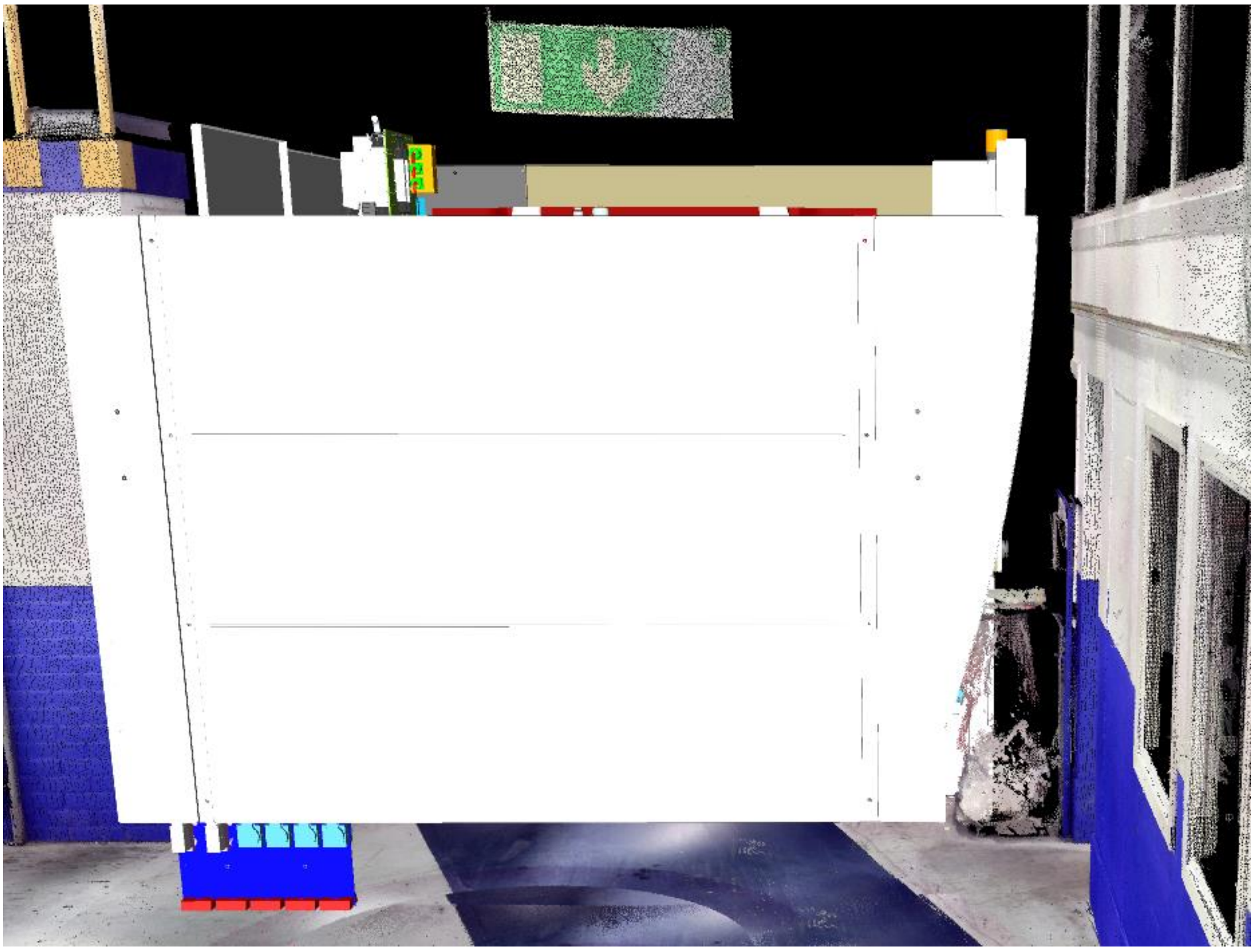


Figure 27. Evaluating spatial installation constraints by moving the CAD model of an installation through

the point cloud model of the facility.

5e. Preparing robot programming

Another use case of the realistic 3D model is preparing robot programming. With an accurate representation of the future state, robot programming can be prepared prior to installation. This assumes the installation phase has been completed accurately. This may shorten the lead time significantly, as robot programming can be time-consuming. Depending on the company, this expertise may be available in-house, or from the robot supplier or automation supplier. Either way, this is a task best done by an expert.

6.4 RQ3 - WHAT ARE THE EFFECTS OF USING 3D LASER SCANNING AND VIRTUAL REALITY IN BROWNFIELD FACTORY LAYOUT CHANGE PROCESSES?

As shown mainly in Paper VI but also Paper V, using 3D laser scanning and VR in brownfield factory layout change processes can help overcome (or noticeably reduce) the impact of the challenges that stakeholders face. Challenges related to working in 2D have generally been overcome, including challenges of abstraction, scale and perspective, lack of detail (such things are only an obstacle in a certain part of the z-axis, for example). This is because industries can work with available volume instead of available floor space in their planning processes. Challenges stemming from data quality have mainly been overcome, although it is still not possible to guarantee the accuracy or exhaustive detail of the 3D CAD models sometimes needed for realistic virtual models. Experience is a good tool in this context and can help bridge the last bit of this challenge.

Regarding input and communication challenges, these can be greatly improved. It may be hard to understand a 2D drawing because the need to be mentally visualised. However, a 3D model or, even better, a realistic 3D model using realistic and accurate data can bridge this gap and allow everybody to see the same thing and apply their thoughts productively, see Figure 28. By reducing the gap between real, virtual and mental models, people are more likely to see and discuss the same thing, rather than multiple mental models coloured by individual experience and interpretation.

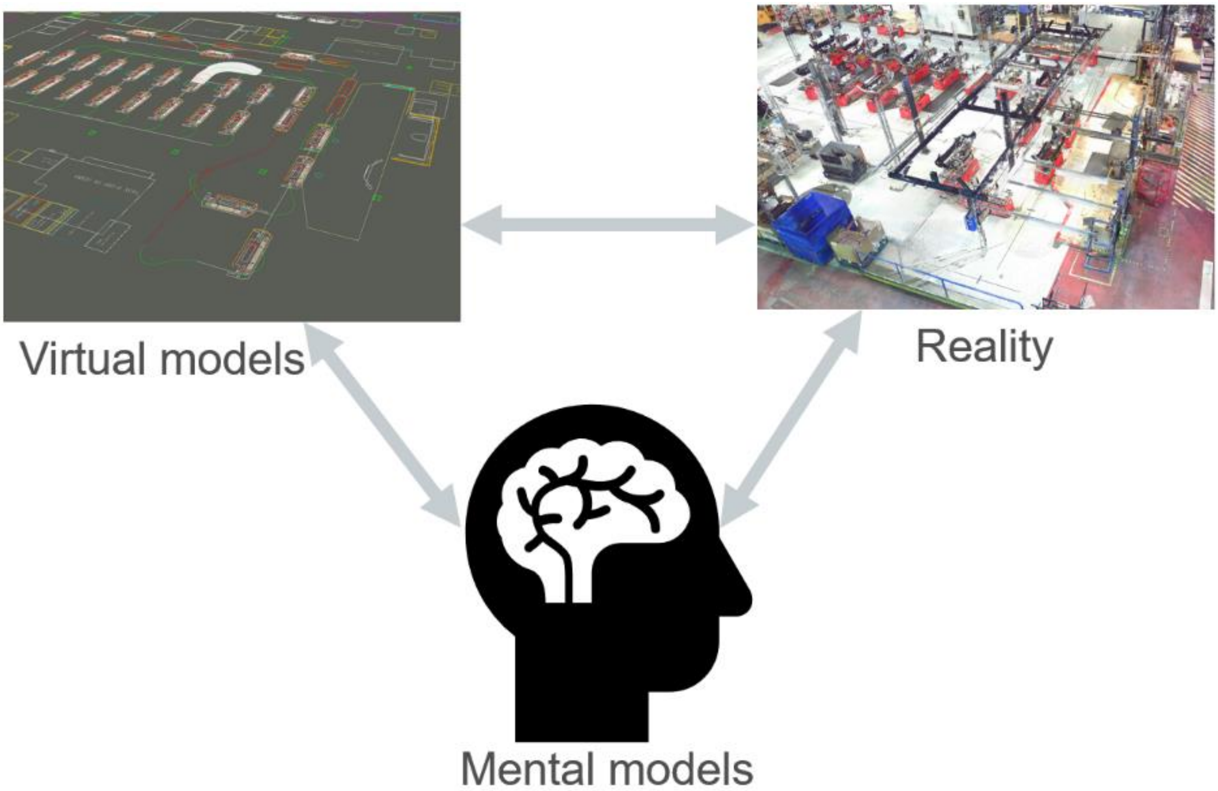


Figure 28. Relationship between mental models, virtual models and reality.

By using realistic virtual models for brownfield factory layout planning, industry can also practice more inclusive development. Involving more stakeholders, such as operators, maintenance, personnel, safety responsible and others, means that change resistance may be reduced and more thorough layout plans developed; ones that will more likely succeed in both installation and operation. Realistic virtual models also enable the use of virtual safety rounds, as highlighted in Paper VI. This is a specific step that layout changes need to pass prior to being put into use. If critical parts are missing, this may lead to costly delays in the ramp-up process. By using a realistic virtual environment, much of the related risk may be reduced.

7

Discussion

This chapter discusses the author's research journey and the results. It connects the research to aspects of sustainability, examines the academic and industrial contributions of the research and assesses its validity, covers future steps towards realisation and pinpoints obstacles to further implementation within industry.

The aim of this thesis was to ensure that the manufacturing industry can adopt realistic virtual models in its brownfield factory layout planning processes. This aim was addressed by three research questions. One covered the challenges industries face in supporting a problem-solving approach, another covered how 3D laser scanning and VR could be applied to address these challenges, and the third covered the effects of applying these technologies to create and use realistic virtual models in brownfield factory layout change processes.

The findings show that challenges arise mainly in data accuracy and richness, in grasping scale and perspective and in difficulties communicating ideas and gathering input in the planning phase. These challenges may be addressed by applying 3D laser scanning and VR, as shown in section 6.3. This leads to early identification of flaws and improvements and an overall improved brownfield factory change process.

7.1 MY RESEARCH JOURNEY

This research journey has not been a straightforward one, as foreseen in Williamson (2002). Indeed, when I started my PhD journey in September 2016 I did not expect to end up here. Initially, I was more focused on implementing 3D laser scanning in factory layout planning. The more I came to understand previous research in the area whilst running studies alongside industry, the better I understood the gap between academia and industry. While several impressive solutions had been developed as optimal solutions to the factory layout problem, few recent publications have focused on the design issue, which seemed more pertinent to the industrial setting. This led me to focus on the problem-solving approach; identifying and addressing challenges using the technologies to which I had access (in terms of equipment and skillset), namely 3D laser scanning and VR.

7.1.1 Research approach

I consider myself a pragmatic researcher, so I have tried to take the perspective of the industrial side of brownfield factory layout planning. This is the reason for the brownfield focus. It is the setting in which most current layout planning is conducted but also one in which I would expect most future layout planning to be conducted. As a pragmatist, focusing on what works in solving particular problems means that the chosen methods applied have varied slightly. Based on action research, which is meant to be a collaboration between diagnosing problems and developing solutions (Bryman & Bell, 2007) in a cyclic iterative fashion, I built my knowledge and understanding sequentially, as suggested by Oosthuizen (2002). I applied participant observation as, to my knowledge, it was the best way to introduce and guide industrial practitioners in using new tools, whilst attempting to keep a rather low research profile.

The full observer role was not deemed feasible to implement, as it would imply a high degree of autonomy on the part of participants using the solutions. But, on the other side of the spectrum, the full participant role would imply being part of the group without disclosing any research interest, which might have raised some ethical issues. Since I used the observer-as-participant and participant-as-observer roles instead, the results cannot be completely unbiased. To minimise bias, I and my fellow researchers involved in the studies gathered and analysed data and insights separately before discussing results and drawing conclusions.

Another key component of this research was semi-structured interviews, in which some of the interviewees interacted with similar prior research from the research group. In essence, some interviewees had seen point clouds in factory settings and experienced VR prior to the interviews. They may also have taken part in a similar study before and may have chosen to participate in research projects focusing on these elements. For that reason, this research does not identify any optimal way of working. Instead, the purpose was to use realistic virtual models to see whether and how 3D laser scanning and VR might be applied in addressing the identified challenges. There may be other ways to address these challenges, as this thesis does not provide an exhaustive evaluation of the potential solutions.

One challenge stemming from this approach involves difficulties specifying (and therefore also quantifying) the impact of using realistic virtual models in a brownfield factory layout change process. Was the risk identified as a direct effect, or would it have eventually been identified without using realistic virtual models? The challenges identified in this research are therefore more general. Fixing mistakes or finding issues is something that might have happened without using realistic virtual models. However, the benefits of using such models have been seen across all industrial studies. Without using realistic virtual models, would a completely different solution be developed and, if so, would that layout be better? A potential approach to quantifying and comparing layouts might be to use a defined method such as Systematic Layout Planning (Muther, 1973). However, that might be a different research topic entirely.

As a final reflection, the research in this thesis was conducted alongside Swedish companies and, with one exception, in Swedish factories. The culture and hierarchy of Swedish industry may lead to the identification of challenges and the application of 3D laser scanning and VR adapted to those. For example, the challenge of communication and gathering input may not be relevant in other cultures and/or hierarchies. Nevertheless, the two other main challenge areas would likely remain the same. Scale and perspective can be very hard to grasp in 2D (and in 3D without depth perception), and I see no local connection to the data challenges. I would still argue that realistic virtual models would give good benefits when applied in contexts other than Swedish industry, although some adaptations in, say workshop structure might be required.

7.1.1.1 Longitudinal studies in factory layout planning

Having read hundreds of published papers in the area of layout planning, I noticed that rarely, indeed almost never, do these papers go beyond the planning stage. Only one paper I found revisited the facility post-installation and after a period of operation to assess the outcome (Aghazadeh, Hafeznezami, Najjar, & Huq, 2011). It makes sense to focus on the planning phase, as that is where the main part of layout planning is conducted. However, it is important to not forget the other phases as well. A layout may be in the operational phase for decades, while the planning phase may last a year or two. From a research perspective, it can be very difficult to partake in the process of layout planning at all. Even when that opportunity is given, it can be very hard to follow up as the right time to go back may be years later. There are also challenges in terms of what to follow up and how. Does good layout planning equal a long-lasting layout? Does it imply happy operators? If the goals were met (productivity goals for example), does that mean that the layout planning part of the project was successful? Perhaps the goals were set too low, or maybe the layout was not especially great but the operations team worked around it and created a well-functioning unit anyway. These issues make it very difficult to attribute specific successes or failures to the layout planning process.

7.2 RESEARCH RESULTS

The results of the research in this thesis do not exist in a void; this is not a unique, never-before-examined area. The problem-solving approach applied in this thesis (identifying and solving issues alongside multiple companies) is unique. However, portions of the whole picture that has emerged may be found in previous publications. For example, the challenge regarding the accuracy of 2D data versus real-world data (Stoli & Rex, 2014), people perhaps struggling to understand and grasp 2D CAD layouts (Iqbal & Hashmi, 2001) and even the fact that incorrect information presented in VR may lead to problems (Smith & Heim, 1999). However, one might argue that incorrect information may lead to problems, no matter where and how it is presented (as seen in all studies involving data-related challenges).

An important feature of the realistic virtual model is that it allows almost anybody to assist in the factory layout planning development process, as visualisation is an important factor in enabling collaborative work (Pehlivanis, Papagianni, & Styliadis, 2004). Good visualisation can enable those with prior knowledge and experience to evaluate their expert areas (such as machines for machine operators, as anticipated in previous research (Dahl, Chattopadhyay, & Gorn, 2001)). On the one hand, this may enable fine-tuning of details and the identification of individual preferences but, on the other, it may also push the project's focus toward very narrow focus areas aligned with those of the experts. This might perhaps be mitigated by following, say, a workshop structure as presented in Lindskog, Vallhagen, et al. (2016), thus ensuring that the bigger picture is not being lost in all the details.

Skills and competences

As shown in Section 6.3, the skills and competences required to work with 3D laser scanning and VR in factory layout planning are currently quite specialised. Doing a good quality 3D laser scan of a facility takes some practice and the equipment is expensive compared to the cost of a factory scan. Processing point cloud data and building a realistic virtual model requires a good computer and, although no special skillset or expertise is required to learn these tasks, those carrying them out become vastly more efficient with experience. The somewhat ad-hoc method of getting all the assets to function well in Unity3D is a trial-and-error process which may be learned, while the C# coding required to develop realistic virtual model features is a specific programming skill. In addition to these more or less technical skills, there are the softer skills of hosting workshops and involving others, creating an environment in which feedback is appreciated. This skill may be a personality trait or something developed on a cultural level. Either way, it is important to make the most of the workshop sessions.

As 3D laser scanners become better and more widely used and the data output becomes usable in more software, the skillset requirement may change. VR is also becoming more integrated into modern engineering software and, in future, might be used as a standard tool. Software that can support and visualise point cloud data and 3D CAD models, whilst allowing a programmer to smoothly add meaningful interactions to the model (in, say, Unity3D) could make this process much easier. Combined with improved computing power, it may be possible to work on the layout in VR using the same dataset. In other words, no hoops to jump through; just changing the visualisation and input method.

Who might benefit from the findings?

The guidelines presented in Section 6.3 may be useful for any company, large or small and not just in the manufacturing industry but also in planning office spaces, or indeed anywhere that might benefit from qualitative input and inclusive development. It may be easily adapted by altering the level of involvement (how much the company does itself). The general idea of working with complete and accurate data and, in the planning process, specifically involving those most routinely affected by the changes are key points that might make this solution applicable across a broader spectrum than the focus of this thesis.

Innovation

OECD/Eurostat (2005) defined innovation as “the implementation of a new or significantly improved product (good or service), process, marketing method or organisational method inbusiness practices, workplace organisation or external relations”. An innovation does not have to be new and novel to the entire world; only to the context in which it is applied. Working in groups may have been an organisational innovation in one area but may have been used for many decades in others. However, making that radical, valuable change does make it an innovation. Innovations may differ in size and effect but are always noticeable. Linton (2009) presents different terms used in previous research to describe innovation. These include: “administrative”, “architectural”, “breakthrough”, “continuous”, “discontinuous”, “incremental”, “product”, “process”, “radical” and “technical”. The article also discusses fundamental and social innovations and how they need each other in order to become impactful. Boer and During (2001) state that, “technological innovation, i.e., the in-house development of new process technology, or the adoption and implementation of technology developed elsewhere, usually also requires organisational adaptation, but need not be linked to a new product or new market development”. Gartner IT Glossary (2021) defines digitalisation as “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”. Using these definitions of digitalisation and innovation, this thesis is aligned to provide the basis for innovation, as it focuses on finding valuable uses of digital technologies to provide valuable opportunities. It also leaves it up to the manufacturing industry to take the final step of implementation and offers a guide on how to do it.

Economic justification

Having worked extensively with the manufacturing industry during my PhD studies, I understand the need for economic justification if any changes are to truly be implemented. As previously discussed, it is difficult to pinpoint precisely what results from using realistic virtual models. However, on the cost side, things are much clearer. To digitalise a facility using 3D laser scanning costs around EUR 5-10k; less for smaller parts of facilities but more if the facility is very large or only available for scanning at awkward times. In addition to 3D laser scanning, there is post-processing, data preparation, model-building and various degrees of expert involvement. The cost of these is estimated to be roughly the same as the scans to produce what was seen in the industrial studies. Or at least, such is the case if done by a seasoned expert who knows the challenges and how to overcome them.

For a company that rarely makes layout changes, it may be most sensible to apply this process by buying in all the necessary support from consultants. For one that makes layout changes very often, there may be heavy reliance on bought expertise during the pilot project (to enable learning) but less so in subsequent ones. As described when discussing the skills and competences, some only require time and can be learned by doing. If these projects are frequent enough, companies may have one or more people responsible for supporting the organisation's need for realistic virtual models, provided those people are allowed to do it often enough to become highly skilled at it.

On the cost-saving side, there are immediate connections when it comes to using employees' creativity; in lean philosophy, often called "the eighth of the seven wastes". Employees involved in change projects may be less resistant to change and more content with their workplaces. Thus, they may perform better and remain at the workplace for longer periods. Discrete savings (in terms of costly mistakes avoided) involve: moving machines worth tens of thousands of Euros; production stoppages costing tens of thousands of Euros; production stoppages due to safety issues that could have been identified in the planning phases, costing tens of thousands of Euros; delays in maintenance due to poor accessibility that could have been identified in the planning phases, costing tens of thousands of Euros; installation delays due to equipment not being able to transport from point A to point B, costing thousands of Euros; and so on. This list could be lengthened with more examples, costing thousands or tens of thousands of Euros. And many of them could be avoided or prevented by applying realistic virtual models at a cost of less than one of the above mistakes. In essence, the benefits of working with detailed and accurate data include avoiding mistakes, avoiding control measurements, reducing the need for travel and not needing to interrupt production to gather data (all of which may be assigned numbers). Ultimately though, if the solution is superior in most ways, is a strict economic justification necessary?

7.3 ASPECTS OF SUSTAINABILITY

Sustainable development may be defined as per World Commission on Environment and Development (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 may be divided into three pillars although, for unknown reasons of unknown origin (Purvis, Mao, & Robinson, 2019), these pillars help in discussing sustainability. The three pillars of sustainability are: economic, environmental and social. The impact of this research's output on each pillar is as follows.

Economic sustainability. By doing things right in the planning process and making fewer mistakes due to using people's talents and knowledge (such as shop-floor operators who know the area better than anyone), the cost of making mistakes can be reduced. Moreover, having an accurate realistic model allows office personnel to carry out highly accurate work without interrupting or distracting those in the production area. In other words, there are fewer production disturbances.

Environmental sustainability. By having accurate, realistic models available, less travel is necessary. This is shown in Paper IV, in which engineers in Sweden could carry out work remotely instead of travelling to Brazil. The neutral, objective point cloud data also fosters the use of existing resources instead of making excessive changes. Being aware of existing assets makes them easier to redeploy.

Social sustainability. Realistic virtual models enable inclusive development which, in turn, allows more people to participate in the changes. As summarised in Section 6.4, the mental models may differ widely if a lot of interpretation is needed. Some people may be able to learn a lot from a 2D drawing, while others may struggle with connecting it to reality. By using realistic virtual models, nearly anybody may be involved in the change process and give valuable feedback, however it is important to consider the shop-floor operators whenever implementing new technologies (Li, Landström, Fast-Berglund, & Almström, 2019). Implementing wisely may potentially also lead to reduced change resistance.

7.4 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 continue to steer research toward identifying and alleviating challenges in brownfield factory layout planning, an area quite prominent in industry. The answers to the first research question offer a good starting point for such research. The second research question offers one potential solution but there are other ways to approach these challenges. This thesis has also identified a research gap by examining the field from a different standpoint. It has shown that much research remains to be done if the complete process is to be covered, 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, by helping industry to advance and helping academia to target real problems. The answer to the second research question presents a guide to help industry immediately find the benefits identified in the third research question.

7.5 RESEARCH QUALITY

Quality is an important criterion for any research. For the research in this thesis, the most important concept was 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 high, since it applies established research methods to industrial contexts. None of the findings (other than the discrepancy between academic focus and industrial practice) 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 and virtual reality.

The transferability of this research (how well the findings apply to other contexts) has been high. The research transferred the findings from one study to the next, transferring to different contexts and companies in various ways. 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 difficult to prove. Any repetition of the same research in the same context may yield slightly different results. This is because the research subjects, the people, will likely have been affected by the previously conducted research. Their understanding of challenges in their layout planning processes may well have been impacted by the industrial study of which they were part. Nevertheless, the research process has been well-documented so that a subsequent researcher can follow the trail from data to analysis, likely reaching similar conclusions.

Confirmability, or the rationale for decisions made during the conduct of research may be evaluated when considering whether the researcher's values have affected the study. For example, the 89 papers printed and reviewed in the literature study, plus notes, have been kept in folders at the university office. Interview notes, transcriptions, and other notes are similarly stored. Hence, it is possible to assess whether the researcher's values have had much impact on the interpretation of the data.

7.6 FUTURE STEPS TO REALISE

A few immediate steps may be realised in line with the work presented in this thesis. Companies need support when ordering 3D laser scans; a standard, easily understood specification or other simple method. Furthermore, too many skills and competences are needed when working with these things for an employee to simply start doing it. Thus, a software solution might advantageously be developed; one that simplifies the process and stops the burden from falling on just one expert. There may be solutions available via commercial software in the near future. However, it is uncertain whether these would satisfy everything that has been done with the models in this thesis, or whether they might be good enough as they are. One idea that could be highly useful in the future is a software solution that displays different types of information within the same model. This would allow logistics, safety, maintenance, operations and the like to see information relevant to them when examining the model.

Working with point cloud models also requires significant computer power, especially when visualising them at a sufficiently high framerate in immersive VR. This issue may be overcome in the future as computers keep improving but, in the short-term, only the very strongest laptop and desktop computers are sufficient to run these models. Insights from gaming developers on how to render only what is required in any given frame may be useful.

As brought up in several of the industrial studies, the ability to carry out installations based on realistic virtual models is something several companies would find beneficial. It would also eliminate the need to go back to 2D models. This is possible today but is a challenge that requires special knowledge. However, there has been progress in this field. As 3D laser scanning finds increasing use in industry, contractors are learning how to use it for installations and so the circle may eventually be complete.

Finally, a key element of future research may be how to evaluate layouts and develop key performance indices to support this. The question of what makes a good layout is highly subjective and may change over time as new priorities are identified. Space utilisation may eventually become volume utilisation and planning for unknown future demands can be hard. However, understanding what makes a good layout may be necessary to inspire change and could be a vital ingredient in spurring innovation.

8

Conclusions

Brownfield factory layout planning represents a significant proportion of industrial layout planning, as companies strive to make the most of what already exists for the sake of economic and environmental sustainability. This author's vision is of a future in which industry exploits existing facilities by using realistic virtual models to improve its brownfield production systems.

Several challenges have been identified in brownfield factory layout planning:

- poor quality in terms of both accuracy and richness of detailed data;
- difficulties grasping scale and perspective;
- difficulties communicating ideas and gathering input.

3D laser scanning is a well-known and tested technology, used in this research to provide neutral, realistic and accurate models. Alongside virtual reality, which provides immersion and scale, realistic virtual models have been created to provide benefits at all stages of factory layouts.

The installation phase has become more efficient by identifying improvements in the planning phase. Moreover, employee engagement has been improved and resistance to change reduced by involving more stakeholders in the planning process using a recognisable format (VR). In combination, these yield the improved brownfield factory change process described in this thesis.

The methods and technological solutions used in this thesis have been proven mature and ready for use in the manufacturing industry. The start-up costs are around EUR 10k, 10% or less of the total budget for individual layout change projects (these usually range from EUR 100k and much higher, including engineering hours, tools, machinery, installation and so on).

Using realistic virtual models quickly generates tangible benefits as having good visualisation and accurate data helps identify and solve many issues. For companies interested in using the benefits shown in this thesis, the recommended starting point would be to bring in assistance and then learn the process during their next brownfield factory layout change process.

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APPENDIX A

The results of applying the review guide to the 89 identified articles are presented in Table 14, with marks assigned for each column, based on the review guide. The first column is the paper ID and correlates to the reference in Table 15.

Table 14: Table of all reviewed literature and results of applying the review guide.

ID	Non-survey	Brownfield	Full facility	Real case	Expert involved	Implemented	Results assessed
1	✓	✓		✓		✓	✓
2							
3	✓	✓	✓				
4							
5	✓	✓		✓			
6	✓	✓	✓				
7							
8	✓	✓		✓	✓	✓	
9	✓	✓	✓				
10	✓	✓	✓	✓			
11	✓	✓	✓				
12	✓	✓					
13	✓	✓	✓				
14	✓	✓					
15	✓	✓		✓	✓		
16	✓	✓	✓				
17	✓	✓	✓	✓			
18							
19	✓	✓	✓	✓			
20	✓	✓		✓			
21	✓	✓					
22	✓	✓	✓				
23	✓	✓	✓				
24							
25	✓	✓	✓				
26	✓	✓		✓			
27	✓	✓	✓				
28	✓	✓					
29	✓	✓	✓				
30							
31	✓	✓	✓				
32	✓		✓	✓			
33							

ID	Non-survey	Brownfield	Full facility	Real case	Expert involved	Implemented	Results assessed
34	✓	✓					
35	✓		✓	✓			
36	✓	✓	✓	✓	✓		
37	✓	✓		✓	✓		
38							
39	✓	✓		✓			
40							
41	✓	✓		✓	✓		
42	✓	✓		✓	✓		
43	✓	✓	✓	✓			
44	✓	✓	✓				
45							
46							
47	✓	✓	✓				
48							
49	✓	✓	✓	✓			
50	✓	✓	✓				
51	✓	✓	✓	✓			
52	✓	✓	✓				
53	✓	✓					
54	✓	✓	✓				
55							
56	✓	✓	✓				
57	✓	✓	✓				
58	✓	✓	✓				
59	✓	✓	✓				
60	✓	✓	✓				
61	✓	✓	✓				
62	✓	✓	✓				
63	✓	✓	✓				
64	✓	✓		✓	✓		
65	✓	✓	✓		✓		
66	✓	✓	✓				
67	✓	✓	✓				
68	✓	✓	✓	✓			
69	✓	✓	✓				
70	✓	✓	✓	✓			
71							
72	✓	✓	✓	✓	✓		
73	✓	✓	✓		✓		
74	✓	✓	✓				
75	✓	✓	✓	✓			
76	✓	✓	✓				

ID	Non-survey	Brownfield	Full facility	Real case	Expert involved	Implemented	Results assessed
77	✓	✓	✓				
78	✓	✓	✓				
79	✓	✓					
80	✓	✓	✓				
81							
82	✓	✓		✓			
83	✓	✓	✓	✓	✓		
84	✓	✓	✓				
85	✓	✓					
86	✓	✓	✓	✓			
87							
88	✓	✓					
89	✓	✓	✓				

Table 15. References to the reviewed literature, corresponding to the ID from Table 14.

ID	Reference
1	Aghazadeh et al. (2011)
2	Ahmadi et al. (2017)
3	Kheirkhah Kheirkhah, Navidi, and Messi Bidgoli (2015)
4	Amri, Darmoul, Hajri-Gabouj, and Pierreval (2016)
5	Delgado Sobrino, Holubek, Košťál, and Ružarovský (2014)
6	Caputo, Pelagagge, Palumbo, and Salini (2015)
7	Arnolds and Nickel (2015)
8	Lin, Liu, Wang, and Liu (2015)
9	Ripon and Torresen (2014)
10	Ali Naqvi, Fahad, Atir, Zubair, and Shehzad (2016)
11	Pourvaziri and Pierreval (2017)
12	Phoon, Yap, Taha, and Pai (2017)
13	Pinto et al. (2016)
14	Chraibi, Kharraja, Osman, and Elbeqqali (2015)
15	Barrett (2008)
16	Pourhassan and Raissi (2017)
17	Faishal, Saptari, and Asih (2017)
18	Singh and Sharma (2006)
19	Schmidtke, Heiser, and Hinrichsen (2014)
20	Tsarouchi et al. (2017)
21	Pai, Yap, Md Dawal, Ramesh, and Phoon (2016)
22	Morinaga, Wakamatsu, Iwasaki, and Arai (2016)
23	Fowosere, Ismail, and Rashwan (2017)
24	Meller and Gau (1996)

ID	Reference
25	Amar, Abouabdellah, and Ouazzani (2018)
26	Garcia, Zúñiga, Bruch, Moris, and Syberfeldt (2018)
27	Zhao, Aranha, and Kanoh (2016)
28	Shi, Hou, and Zheng (2015)
29	Yiyong Xiao, Xie, Kulturel-Konak, and Konak (2017)
30	Smith and Heim (1999)
31	Wang (2011)
32	Liao, Cong, Liu, and Meng (2017)
33	Drira et al. (2007)
34	Liu, Hwang, Hsieh, Max Liang, and Chuang (2016)
35	Zha, Guo, Huang, Wang, and Huang (2017)
36	Maina, Muchiri, and Keraita (2018)
37	Lindskog, Berglund, Vallhagen, and Johansson (2016)
38	Hosseini-Nasab et al. (2018)
39	Hakim and Istiyanti (2015)
40	Zetu, Banerjee, and Schneider (1998)
41	Lindskog, Vallhagen, and Johansson (2017)
42	Lindskog, Berglund, Vallhagen, and Johansson (2013)
43	De Carlo, Arleo, Borgia, and Tucci (2013)
44	Vitayasak, Pongcharoen, and Hicks (2017)
45	Menck, Weidig, and Aurich (2013)
46	Weidig, Menck, Winkes, and Aurich (2014)
47	Saraswat, Venkatadri, and Castillo (2015)
48	Sharma and Singhal (2016)
49	Ighravwe and Oke (2015)
50	Kaveh, Dalfard, and Amiri (2014)
51	Han, Bae, and Jeong (2013)
52	Mohan and Pillai (2013)
53	Díaz-Ovalle, Vázquez-Román, Lira-Flores, and Mannan (2013)
54	Navidi, Bashiri, and Messi Bidgoli (2012)
55	Keller and Buscher (2015)
56	Dong, Wu, and Hou (2009)
57	Keshavarzmanesh, Wang, and Feng (2010)
58	Wang, Keshavarzmanesh, and Feng (2010)
59	Chen, Jiang, Wahab, and Long (2015)
60	Solimanpur and Kamran (2010)
61	Zuo, Murray, and Smith (2014)
62	Kia, Khaksar-Haghani, Javadian, and Tavakkoli-Moghaddam (2014)
63	Ripon, Khan, Glette, Hovin, and Torresen (2011)
64	Bénabès, Bennis, Poirson, and Ravaut (2010)
65	Garcia-Hernandez, Pierreval, Salas-Morera, and Arauzo-Azofra (2013)

ID	Reference
66	Leno, Sankar, Raj, and S.G (2012)
67	Neghabi and Ghassemi Tari (2015)
68	Hosseini, Mirzapour, and Wong (2013)
69	Madhusudanan Pillai, Hunagund, and Krishnan (2011)
70	Ulutas and Islier (2015)
71	Moslemipour, Lee, and Rilling (2012)
72	Hasan, Sarkis, and Shankar (2012)
73	García-Hernández, Palomo-Romero, Salas-Morera, Arauzo-Azofra, and Pierreval (2015)
74	Wiese and Kliewer (2010)
75	Azevedo, Crispim, and Sousa (2012)
76	Yujie Xiao, Seo, and Seo (2013)
77	Ariafar and Ismail (2009)
78	Chan and Malmborg (2011)
79	Arnolds and Nickel (2013)
80	Altuntas and Selim (2012)
81	Liggett (2000)
82	Kovačič, Rožej, and Brezočnik (2013)
83	Shahin and Poormostafa (2011)
84	Forghani, Arshadi Khamseh, and Mohammadi (2012)
85	Prasad, Rajyalakshmi, and Reddy (2014)
86	Yalaoui, Mahdi, Amodeo, and Yalaoui (2011)
87	Tao, Wang, Qiao, and Tang (2012)
88	Izui et al. (2013)
89	Ramtin, Abolhasanpour, H, Hemmati, and Jaafari (2010)