UNIVERSITÉ DU LUXEMBOURG

PhD-FSTM-2022-113
The Faculty of Science, Technology and Medicine

DISSERTATION

Presented on 06/09/2022 in Luxembourg

to obtain the degree of

DOCTEUR DE L'UNIVERSITÉ DU LUXEMBOURG

EN GÉNIE MÉCANIQUE

by

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Born on 29 August 1991 in place India

A HOLISTIC METHODOLOGY TO DEPLOY INDUSTRY 4.0 IN MANUFACTURING ENTERPRISES

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Doctoral Thesis

A Holistic Methodology to Deploy Industry 4.0 in Manufacturing Enterprises

Assessment, Observations, Experiments, & Applications

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A thesis submitted in fulfilment of the requirements for DOCTEUR DE L'UNIVERSITÉ DU LUXEMBOURG

in the

Faculty of Science, Technology and Medicine (FSTM)
Department of Engineering

September 7, 2022

Declaration of Authorship

I, Sri Sudha Vijay Keshav KOLLA, declare that this thesis titled, "A Holistic Methodology to Deploy Industry 4.0 in Manufacturing Enterprises
Assessment, Observations, Experiments, & Applications" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: Sri Sudha Vijay Keshav Kolla

Date: 07-09-2022

“*Thanks to my wonderful wife Salijona Dyrmishi, my mom Sridevi Kolla, and my sister Sudha Sree Kolla. Completion of this degree wouldn't have been possible without your love, support, and encouragement*”

- - *Sri Kolla*

UNIVERSITY OF LUXEMBOURG

Abstract

Faculty of Science, Technology and Medicine (FSTM)
Department of Engineering

A Holistic Methodology to Deploy Industry 4.0 in Manufacturing Enterprises
Assessment, Observations, Experiments, & Applications

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In the last decade, manufacturing industry has seen a shift in the way the products are produced due to the integration of digital technologies and existing manufacturing systems. This transformation is often referred to as **Industry 4.0** (I4.0), which guarantees to deliver cost efficiency, mass customisation, operational agility, traceability, and enable service orientation. To realize the potential of I4.0, integration of physical and digital elements using advanced technologies is a prerequisite. Large manufacturing companies have been embracing the I4.0 transformation swiftly. However, Small and Medium-sized Enterprises (SMEs) face challenges in terms of skills and capital requirements required for a smoother digital transformation.

The goal of this thesis is to understand the features of a typical manufacturing SME and map them with the existing (e.g. Lean) and I4.0 manufacturing systems. The mapping is then used to develop a Self-Assessment Tool (SAT) to measure the maturity of a manufacturing entity. The SAT developed in this research has a critical SME focus. However, the scope of the SAT is not limited to SMEs and can be used for large companies. The analysis of maturity of manufacturing companies revealed that the managerial dimensions of the companies are more mature than the technical dimensions. Therefore, this thesis attempts to fill the gap in technical dimensions especially Augmented Reality (AR) and Industrial Internet of Things (IIoT) through laboratory experiments and industrial validation. A holistic method is proposed to introduce I4.0 technologies in manufacturing enterprises based on maturity assessment, observations, technical road-map, and applications.

The method proposed in this research includes SAT, which measures the maturity of a manufacturing company in five categorical domains (**dimensions**): Strategy, Process and Value Stream, Organization, Methods and Tools, and Personnel. Furthermore, these dimensions are attributed to 36 modules, which help the manufacturing companies measure their maturity level in terms of lean and I4.0. The SAT is tested in 100 manufacturing enterprises in Grande Région consisting of pilot study a (n=20) and maturity assessment (n=63). The observations from the assessment are then used to set-up the technological road-map for the research. AR and IIoT are the two technologies that are associated with the least mature modules, which are explored in depth in this thesis. A holistic method is incomplete without industry validation. Therefore, the above-mentioned technologies are applied in two manufacturing companies for further validation of the laboratory results. These applications include: 1) application of AR for maintenance and quality inspection in a tire manufacturing industry; and 2) application of retrofitting technology for IIoT on a production machine in an SME.

With the validated assessment model and the industrial applications, this thesis overall presents a holistic approach to introduce I4.0 technologies in manufacturing

enterprises. This is accomplished through identifying the status of the company using maturity assessment and deriving the I4.0 road-map for high potential modules. The skill gap in the addressed technologies is compensated by designing and testing prototypes in the laboratory before applying them in the industry.

Keywords: Industry 4.0, Maturity Model, Augmented Reality, Industrial Internet of Things, Manufacturing Enterprises, Productivity, SMEs

0.1 Graphical abstract

A graphical abstract is shown in Figure 1 to quickly present the overview and salient features of the thesis.

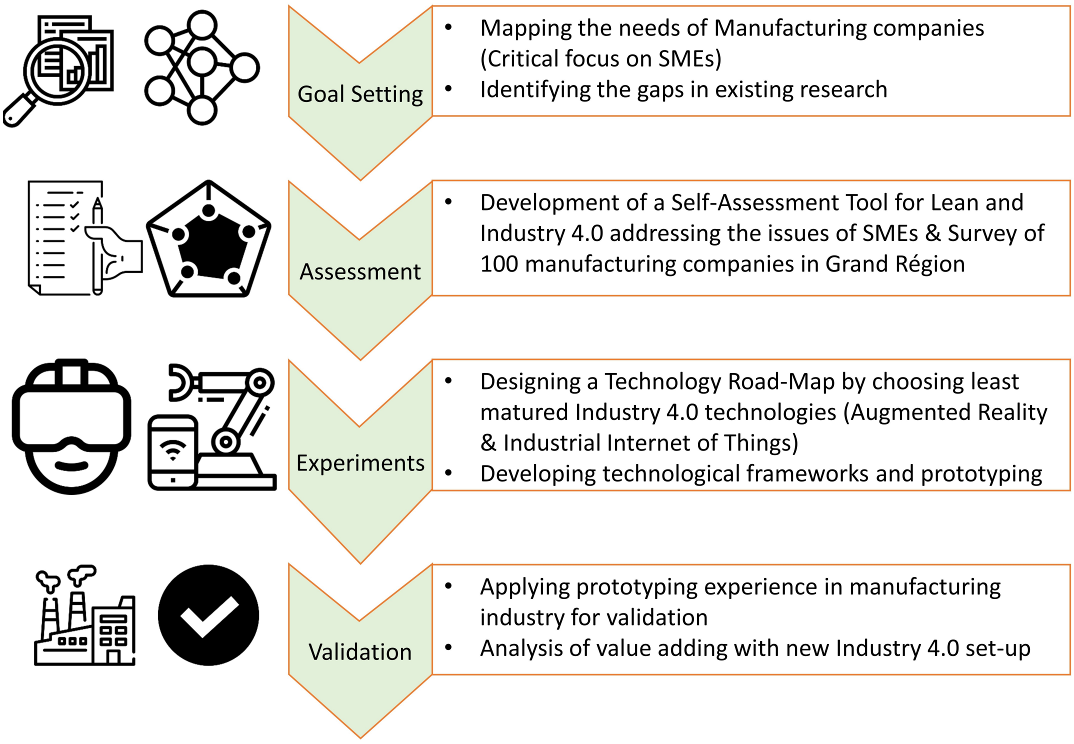

FIGURE 1: Graphical abstract

Acknowledgments

The PhD journey wouldn't have been possible without the support of many people.

Many thanks to my adviser, Prof. Peter Plapper, for all the support throughout my PhD years. Thanks for giving me the freedom to shape my PhD research project and allowing me to work stress-free.

I'd like to thank my colleagues and friends at the Department of Manufacturing Engineering for providing a friendly working environment and insightful lunch-hour discussions. Special thanks to Jeff Mangers, Alexej Simeth, Andre Sanchez, Diogo Machado, Thierry Decker, Lou Thoussaint, and Atal Kumar. Thanks to Heidi Backström, Bertrand Dessart, Berta Rato, and Rita Giannini for top-notch administrative support.

Thanks to the University of Luxembourg for providing a platform and infrastructure to conduct research.

Thanks to the consortium of the PRODPILOT project for external support and guidance. Special mentions to Prof. Thomas Korne and Fiona Loewenkamp for managing the project very effectively.

Thanks to all my friends, especially Olga Ogorodnyk, Kiran Kumar, Gopi Krishna Yadav, and Krishna Kanth, for always being there for me.

Thanks to my wife Salijona Dyrmishi, for her love and constant support and for keeping me sane over the past few years.

Thanks to my family, my mother Sreedevi Kolla, and my sister Sudha Sree Kolla for believing in me and supporting me to get all the way here. Thanks to my dad who is showering his blessings every day from beyond. I miss you dad

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List of Abbreviations

AM	Additive Manufacturing
AMT	Advanced Manufacturing Technologies
ANT	Analytical Network Process
CI	Continuous Improvements
CPFR	Collaborative Planning in the Supply Chain
CPMS	Cyber Physical Manufacturing Systems
CPS	Cyber Physical Systems
CT	Capturing Technology
EP	Error Prevention
FoV	Field of View
GPIO	General Purpose Input Output
HHD	Hand-Held Devices
HMD	Head-Mounted Devices
HMI	Human Machine Interface
I4.0	Industry 4.0
ICT	Information and Communication Technology
IT	Information Technology
KPI	Key Performance Indicators
LPS	Lean Production Systems
MCDM	Multi-Criteria Decision Making
MR	Mixed Reality
NFC	Near Field Communication
OEE	Overall Equipment Efficiency
PLC	Programmable Logic Controllers
POI	Point of Interest
PU	Processing Unit
SAT	Self-Assessment Tool
SLAM	Simultaneous Localization Mapping
SME	Small and Medium-sized Enterprises
SOP	Standard Operating Procedure
SPICE	Software Process Improvement and Capability determination
SUS	System Usability Score
TCT	Task Completion Time
TS	Tracking System
UI	User Interface
VR	Virtual Reality
VSM	Value Stream Mapping
VT	Visualisation Technology
XR	Extended Reality

Dedicated to my father ... Dad you are my superhero and you will always be. I'll tell you all about it when our paths cross again ...

Chapter 1

Introduction

1.1 Background

The term Industry 4.0 was first presented to the wider audience during the Hannover fair in 2011 (Kagermann, Lukas, and Wahlster, 2011) as a high-tech strategy for paradigm shift in the industry. This transformation is referred as the fourth industrial revolution enabled by new business models based on the integration of digital and physical entities. Among the key value drivers of I4.0 are cost efficiency, traceability, decentralization, customer focus, agility, real-time information, service orientation, and scalability (Wilson, 2021)(Sung, 2018). In manufacturing industry, productivity is a key indicator of industrial performance. With the advent of new digital technologies and their integration into the industrial shop-floor is expected to deliver superior production performance of goods and services. In recent times, most European manufacturing companies are characterized by Lean Production Systems (LPS) (Kolla, Minoufekr, and Plapper, 2019) and the adoption of new business paradigms would potentially affect the existing manufacturing systems. Therefore, it is essential to assess the existing manufacturing situation before adopting the new digital solutions. In this thesis a holistic approach is considered which includes the in-depth analysis of the status-quo of a manufacturing entity using an assessment tool followed by identifying the value drivers of the company. I4.0 technologies considered in this research are first explored through laboratory experiments before applying them in the industry for productivity improvement.

1.2 Industry 4.0

Digital refinement is the need of the hour in industry to transition from highly centralised manufacturing systems to customer-centered and in most cases, decentralized manufacturing systems. The first three industrial revolutions focused on mechanization, mass production, and automated production respectively to fulfil the market demands. However, in today's world mass customization and servitization demands are ascending. Moreover, the current manufacturing set-up is undergoing huge pressure to stay relevant in the ever-changing market demands. The fourth industrial revolution, dubbed I4.0, promises to deliver the new demands by integrating advancements in digital technologies with the existing manufacturing entities. There is no universally agreed definition for I4.0. However, the following definition is considered in this thesis as it presents the perspective of applied research.

> "The term Industry 4.0 stands for the fourth industrial revolution, which is defined as a new level of organization and control over the ***entire value chain of the life cycle of the products.*** It is geared towards increasingly individualized customer requirements (Neugebauer et al., 2016)"

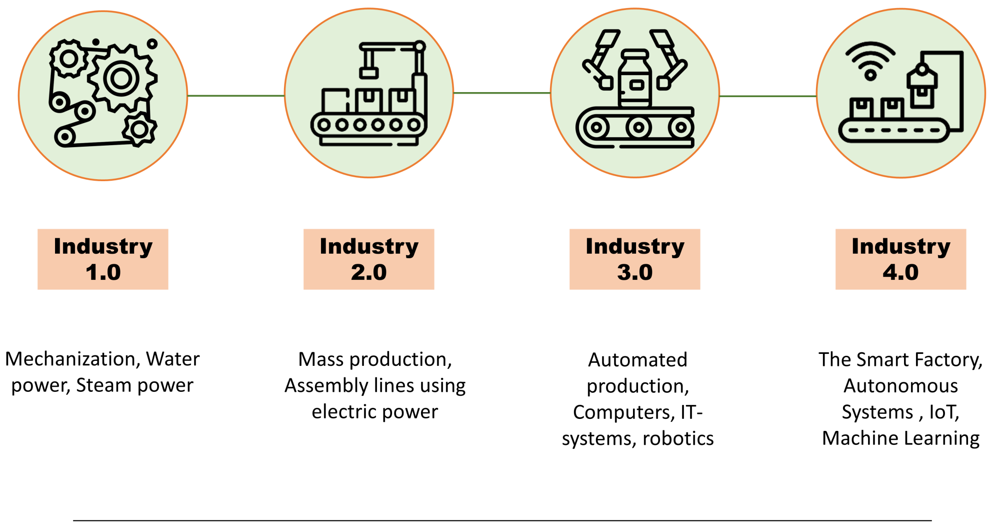

FIGURE 1.1: Industrial Revolutions

Figure 1.1 depicts the four industrial revolutions and their associated features. The first industrial revolution introduced the mechanical production facilities powered by water and steam power. The second industrial revolution was marked by increased market demands and the introduction of electrical power into industry. In industry 3.0, automation was the key feature enabled by the introduction of computers and robotic technology. I4.0 leverages the data from the connected industrial assets such as machinery. The emergence of smart factories is featured by intelligent machines, which are connected to digital systems through various communication protocols. In I4.0, the digital integration is not limited to the shop-floor but also across the complete value chain to streamline end-to-end business and engineering processes (Pérez-Lara et al., 2020). Current research suggest nine such technologies, referred to as the pillars of I4.0, for reconstructing the existing business models.

Pillars of Industry 4.0

The creation of integrated networks and real-time access to the information is enabled by the advancement of technologies in different fields. The essence of I4.0 is integrating these advancements in the Information Technology (IT) with manufacturing systems. To achieve this, the current literature (Rüßmann et al., 2015) (Vaidya, Ambad, and Bhosle, 2018) suggests nine enabling technologies, as shown in Figure 1.2. A brief summary of each technology is presented below.

Big Data and Analytics – The usage of large sets of data is a relatively new approach in manufacturing. The complex data collected from various sources such as machines, enterprise systems, and customer-management tools can aide in informed decision-making (Li, Chen, and Shang, 2021) concerning strategy, quality management (Stojanovic et al., 2016), and maintenance (Ji and Wang, 2017) (Seele, 2017) etc. Comprehensive analysis of data collected across the value chain helps in identifying the threats to manufacturing systems based on historical data patterns.

Augmented Reality – AR is a technology that enhances the human-machine interaction by overlaying the virtual information in the real world (Novak-Marcincin et al., 2013). Various applications of AR can be potentially employed in virtual

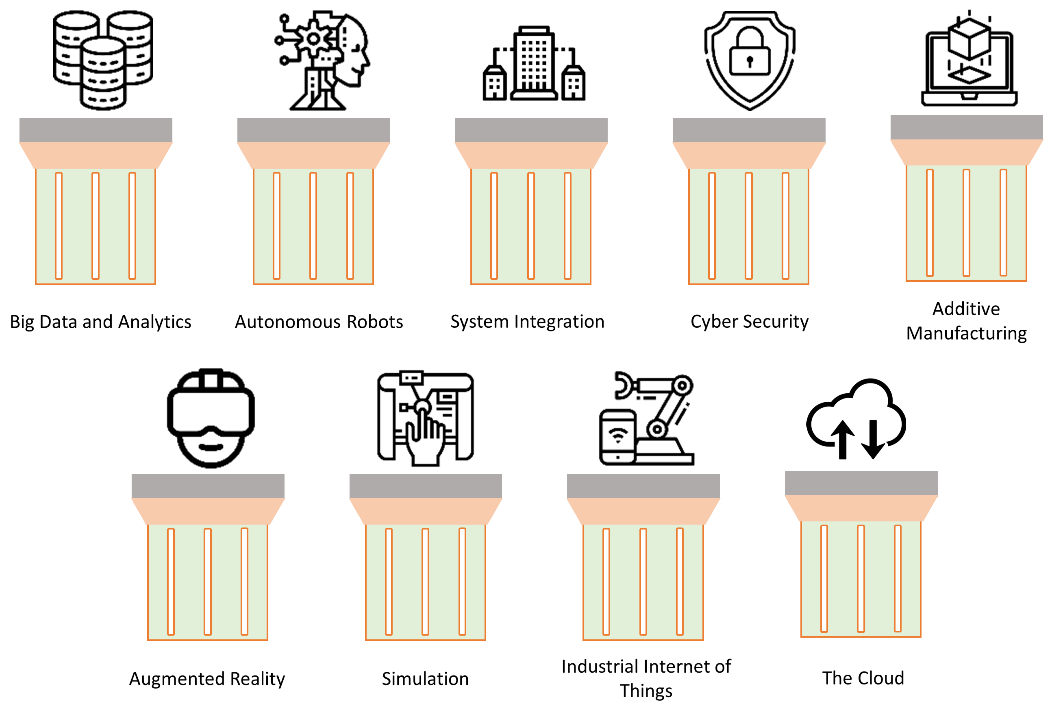

FIGURE 1.2: The Pillars of Industry 4.0

instructions for assembly (Danielsson et al., 2018)(Lampen et al., 2019), quality assurance (Frigo, Silva, and Barbosa, 2016), maintenance, training (Ferrati, Erkoyuncu, and Court, 2019), remote assistance (Masoni et al., 2017) and safety etc. AR in a shop-floor environment can be seen as a supportive tool for operators to minimize the error rates, increase reliability, and aid standardization.

Autonomous Robots – Robotic technology is not new to manufacturing. In the advent of the third industrial revolution manufacturers of different industries have adapted robots in their manufacturing environment for greater precision, increased repeatability, and to solve complex tasks. However, robots are evolving day by day for safe, autonomous, flexible, and cooperative tasks with a human by their side. It is also expected that robots will soon be able to interact with each other and work collaboratively. Robotic adaption in industries will increase with I4.0. However, this adaptation is not to replace the human workers but to aid them in production, logistics, and distribution activities (Goel and Gupta, 2020).

Simulation – Currently, simulations are extensively used in product design, material selection, and optimising the production processes (Weyer et al., 2016) (Uhlemann, Lehmann, and Steinhilper, 2017) etc. In I4.0, the real-time data can be incorporated from the physical world into a virtual model. This allows the engineers to test and optimise machine and product settings before they are applied in the physical world. Therefore, simulations reduce the machine downtime and increase the reliability, and thus, the quality (Azimpoor and Taghipour, 2021) of the products and processes.

System Integration – In today's manufacturing landscape, neither the IT systems across the value chain nor the internal business process is integrated. With I4.0, the functions in and off the enterprise can be more cohesive with universal integration of networks and data. A total system integration helps to achieve the agility and streamlining of end-to-end engineering and business processes (Erol et al., 2016).

Industrial Internet of Things – IIoT are the networked systems that integrates physical and digital worlds. This means more machines can be connected to the computing devices through standard communication protocols (Rahman and Rahmani, 2018). The data gathered from the machines through smart sensors can be analyzed in real-time for decision making, thus enabling intelligent, agile, and self-configurable systems.

Cyber Security – As I4.0 foresees increased connectivity through standard communication protocols, the need to protect the sensitive data from cyber threats is becoming increasingly important. Cyber Physical Systems (CPS) is rapidly developing in parallel with I4.0 that undertakes the secure integration between the physical (human & machine) world and cyber (computation, communication, & control) worlds (Bagheri et al., 2015).

The Cloud – With I4.0, organizations not only share an extensive amount of manufacturing data but also be able to use computing services across the value chain. The cloud-based IT solutions serve as a technical backbone for storage, sharing, and provide computing requirements (Landherr, Schneider, and Bauernhansl, 2016). The cloud enables data-driven production services to all the supply chain partners: suppliers, manufacturers, and customers.

Additive Manufacturing – Additive Manufacturing (AM) has been successfully employed in many manufacturing enterprises for prototyping and to produce independent components. In contrast, I4.0 enables AM to be widely applied for producing small batches of customized products (Vaidya, Ambad, and Bhosle, 2018).

For a successful digital transformation, it is not required to adapt all the above-mentioned technologies in a manufacturing environment. One must do analysis on the value generated before going for a full-scale adaption of a specific or combination of I4.0 technologies. At the European level, the European Commission is promoting the idea of "test before invest" (EuropeanCommission, 2022) for improving business processes, production processes, & services using I4.0 technologies. The goal of the thesis is to develop an assessment tool, which helps in identifying the productivity potentials of the company using lean & I4.0. Based on the assessment, a future road map can be derived using the templated solutions from the assessment tool. As per the "test before invest" philosophy, the technological solutions are first developed in the laboratory before enterprise adaptation.

The following section explains the motivation and aim of the thesis and then proceeds to describe the research questions and research objectives.

1.3 Motivation and aim

Almost a decade ago, in 2013, a working group was established with a joint co-operation between the German government, academics, and industry to set-up a strategic vision for Germany to strengthen its position as a manufacturing location, a supplier of manufacturing equipment, and a provider of IT business solutions. The report Kagermann et al., 2013 by the working group coined the word I4.0 and since then the idea of digital transformation or I4.0 has became increasingly popular. The application of new digital technologies can rapidly transform the current manufacturing practices to I4.0.

In 2015, European Parliamentary Research Service (Davies, 2015) acknowledged that Europe is at the beginning of a new industrial revolution enabled by the usage of ubiquitous sensors, intelligent robots & machines. The briefing document to the European Parliament focused on opportunities and challenges related to I4.0 that will shape the European manufacturing landscape. These advanced digital technologies can help manufacturing companies increase productivity. In Luxembourg, where the current research is performed, a thematic report (Rifkin, 2016) is published that summarises the key ideas, insights, and initiatives for third the industrial revolution. This interdisciplinary report highlights the measures need to be taken to improve manufacturing industry (& other sectors) from 2016 to 2050. One of the key strategic measures is to "develop technology platforms for co-located industry and university researchers working on common transversal issues". This key strategic measure underlines the importance of digital transformation for securing a sustainable manufacturing ecosystem in Luxembourg. The European Union's strategies for digital transformation and the national digital transformation policy of Luxembourg inspires the inception of the PhD project.

On the other hand, The existing methodologies in the literature, according to Mittal et al (Mittal et al., 2018), do not meet the needs of all manufacturing industries in terms of digital transformation. Existing methods aren't focused on SMEs, and they don't take into account existing production processes such as lean manufacturing systems. As a result, the current study focuses on developing a methodology that is crucial to SMEs. The methodology developed in this research considers both existing manufacturing systems and I4.0 systems. Wang et al (Wang, Törngren, and Onori, 2015) stated in another study that the majority of manufacturing companies will find themselves in uncharted area, especially SMEs while implementing the new digital technologies. The unknown zones in the digital transition, according to the author's experience include technological complexity, industry push, competitiveness, and the merging of physical and digital components. Therefore, the PhD research focuses on developing an end-to-end approach that includes both organizational and technical deployment aspects. Knowledge of new I4.0 technologies was limited at the start of the PhD project. There is a lack of research on the influence of I4.0 technologies on current manufacturing systems. Therefore, the author decided to survey these technologies using an assessment tool. The survey results were used to select two of the least mature technologies for further investigation in the thesis.

This PhD thesis was motivated by a lack of end-to-end (holistic) methodologies in manufacturing research, as well as European and Luxembourg state policies on digital transformation. Hence, the aim of this research is to offer a groundbreaking addition to research on digital transformation from both organizational and technological standpoint. This thesis presents a holistic methodology that includes assessment, observations, experiments, and applications to assist every manufacturing organization through successful I4.0 transformation.

Figure 1.3 depicts the elements of European and Luxembourg national digital transformation policies as well as research gaps that inspired the PhD project.

Motivation & Aim

To make a groundbreaking contribution to academic research in the area of digital transformation of all manufacturing businesses based on EU and Luxembourg national strategies. The thesis' goal is to provide an end-to-end holistic methodology that encompasses assessment, observations, experiments, and applications to aid in overcoming institutional and human-related problems in the digital transformation process.

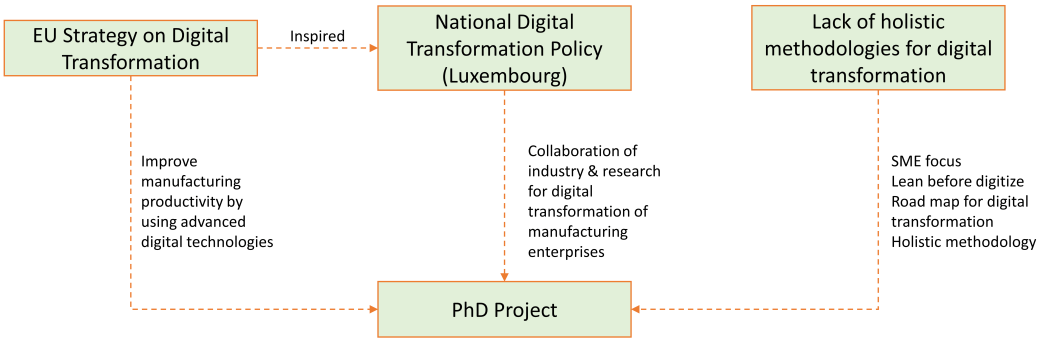

FIGURE 1.3: Motivation of the PhD project

1.4 Research objectives

Based on the definition of motivation and aim provided in the previous section, I have three objectives in this PhD study. These objectives are to fill research gaps in the current literature, determine the status of I4.0 maturity in the broader Luxembourg region, and ultimately identify the least mature I4.0 technologies and propose an end-to-end road map for adapting them.

Objective 1: To design and develop a hybrid Self-Assessment Tool (SAT) that encompasses lean & I4.0 elements with a critical focus on manufacturing SMEs.

Objective 2: To determine the status of lean and I4.0 maturity in manufacturing enterprises in the greater region.

Objective 3: To develop an end-to-end road-map for the I4.0 technologies selected in Objective 2.

Several supporting objectives were required to achieve research objectives, which could aid in the development and formulation of the PhD thesis' guiding research questions. These were the supporting objectives:

- Investigate existing maturity models, assessment tools, and quick checks of lean and I4.0 and define the research gaps
- Map the needs of manufacturing companies especially SMEs with lean and I4.0 tools
- Identify the companies to survey in Grande Région and collect quantitative and qualitative data
- Develop software frameworks for Augmented Reality technology for manufacturing as well as for the Industrial Internet of Things
- Collect empirical evidence using user study of developed AR technologies vs traditional paper-based instruction methods
- Identifying the industrial applications to validate the AR and IIoT prototypes

1.5 Research questions

To achieve the research objectives, it was critical to develop a comprehensive research question (RQ1) that could capture the underlying issues of research, governing policies, and industry requirements. As a result, the thesis's leading research question is defined as follows:

Leading Research Question (RQ1)

How to design and develop an end-to-end (holistic) method that meets the needs of all manufacturing companies as well as European governing policies for a smooth transition to Industry 4.0?

In addition to this leading research question, supplemental research questions (RQ2-RQ6) were necessary to examine each underlying issue independently. It was possible to answer the key research question sufficiently by adequately answering the supplementing research questions. The supplementing research questions are presented below:

Supplementing Research Questions

RQ2: What are the essential components of a manufacturing SME to assess its present status of lean and industry 4.0?

RQ3: In view of the emergence of various digital technologies, how should manufacturing companies approach the design and development of Augmented Reality applications?

RQ4: How can software frameworks and input modalities influence the choice of Augmented Reality technology for a particular manufacturing application?

RQ5: How does the introduction of Augmented Reality instruction systems in manufacturing affect lead time, precision, workload, and usability when compared to paper-based instruction systems?

RQ6: How should manufacturing companies approach the design, development, and deployment of Industrial Internet of Things in connection with Industry 4.0?

After analyzing the current literature (Chapter 2) on maturity models, assessment tools, and quick checks on lean and I4.0, it became clear that these models primarily target larger manufacturing companies, with little to no emphasis on SMEs. The goal of RQ2 is to learn about the characteristics of a manufacturing SME so that necessary components of a hybrid assessment tool with a focus on manufacturing SMEs may be derived. RQ2 is the driving force behind the assessment tool developed in this study. By Jan 2022, 100 manufacturing companies in Grande Région were surveyed using the assessment tool. RQ3, RQ4, and RQ5 investigate and provide an end-to-end work flow for Augmented Reality, one of the least mature and investigated I4.0 technologies in Grande Région. RQ6, on the other hand, aims to develop new knowledge for manufacturing companies in the area of the Industrial Internet of Things, which is another least mature and researched I4.0 topic. The relationship between the RQs and the academic publications offered in this thesis is depicted in Figure 1.4

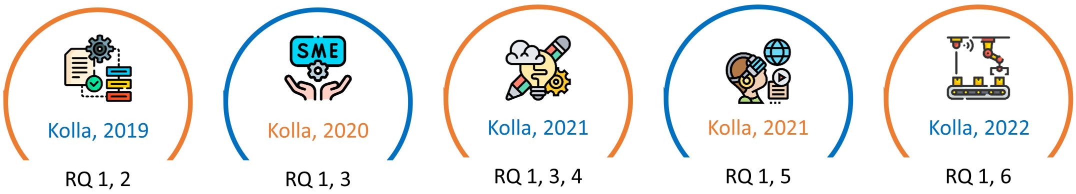

FIGURE 1.4: Research Questions and their connection with the academic publications presented in this thesis

1.6 Achieved results and contribution

Several scholarly articles based on the thesis have been published, featuring fresh findings and contributions to the current literature. Each publication focused on the major research issues in order to meet the research aim and objectives. The order of papers 2, 3, and 4 is extremely important because they build on each other. Papers 1 and 5 can be read independently, therefore the order is not crucial.

Paper 1: Deriving essential components of lean and industry 4.0 assessment model for manufacturing SMEs

Paper 1 serves as the foundation for the Self-Assessment Tool (SAT) developed later in the research (Chapter 2). The primary goal of this publication is to provide an overview of existing maturity and assessment models, as well as to map lean and I4.0 features to the characteristics of manufacturing SMEs. The findings of this study were later used to create a hybrid model that combines lean and I4.0 elements.

Achieved results

- Identified research gaps in the existing literature relating to maturity models, assessment tools, and lean and industry 4.0 quick checks.
- Summarised the typical characteristics of a manufacturing SME to facilitate the development of a new SAT.
- Identified the dimensions of a manufacturing company and mapped them with the SME characteristics. This mapping is then used to develop SAT.

Contribution

- Identifying and quantifying research gaps in current maturity models. The present literature lacks SME focus, and existing manufacturing methods such as Lean Production Systems (LPS) are excluded from maturity models.
- A list of lean and I4.0 components is identified which will be part of the different level descriptions in the new assessment tool.

- The features of a manufacturing SME are mapped against the lean and I4.0 components.

Paper 2: Augmented Reality in manual assembly processes

This paper serves as a foundation for the PhD project's AR research. A road-map for future research is generated from the SWOT analysis of AR in manufacturing. The article outlined a five-step process for developing a successful AR case study in manufacturing.

Achieved results

- Interactions among basic components of an AR system are outlined based on current research.
- Internal and external elements that influence AR research in manufacturing are derived using a SWOT analysis of AR systems.
- A five-step methodology for creating AR applications from the ground up is described.

Contribution

- The major contribution of this publication is the AR architecture for manufacturing to build applications on a Hand Held Device (HHD) such as mobile phone or tablet.

Paper 3: Comparing software frameworks of Augmented Reality solutions for manufacturing

Development of AR applications for manufacturing requires multi-disciplinary knowledge. The current AR literature is primarily concerned with engineering aspects such as design. However, the existing research lacks a software development perspective. The purpose of this article is to bring AR development knowledge from software development to manufacturing.

Achieved results

- Two separate AR technologies, Hand Held Device (HHD) and Head Mounted Device (HMD), were used to construct two different AR applications for assembly instructions.
- Interaction with AR systems is achieved through uni-modal as well as multi-modal input systems. The modalities such as touch, gesture, and speech are successfully tested.

Contribution

- A Software framework for both HHD and HMD is presented using C4 architecture notation.
- In terms of hardware, software, and supported capabilities, a comparison of two separate AR systems, HHD and HMD, is presented.

Paper 4: Comparing effectiveness of paper-based and Augmented Reality instructions for manual assembly and training tasks

AR systems have been seeing rapid adaptations especially in training tasks utilising the overlaying of virtual instructions in a real environment. However, there is a substantial gap in the literature when it comes to comparing AR technologies to legacy systems like paper instructions. The purpose of this study is to compare task completion time, the number of errors, workload index, and system usability between AR and traditional paper-based work instructions.

Achieved results

- HHDs are the quickest systems in terms of task completion time.
- When compared to paper-based instruction systems, participants made fewer errors when using AR systems (HHD & HMD).
- When compared to paper-based instruction systems, AR systems resulted in a lower overall workload for the participants.
- AR instruction systems outperformed paper-based methods in a system usability test.

Contribution

- This publication compared task completion time, number of errors, workload index, and system usability between AR and traditional paper-based work instructions with statistically significant results

Paper 5: Retrofitting of legacy machines in the context of the Industrial Internet of Things (IIoT)

During qualitative interviews with manufacturing firms, particularly SMEs, it became clear that the firms are willing to adapt data-driven decision-making systems. However, the majority of SMEs lack data readiness, which is a key roadblock to digital transformation. The RQ6 is addressed especially in this paper, with a focus on design and development for IIoT using retrofitting technology.

Achieved results

- A legacy machine (vertical drilling machine) was successfully retrofitted with depth and speed sensors. The data from the sensors is seamlessly connected to a cloud database using Ethernet communication protocol.
- The architecture for IIOT proposed in the research has been successfully validated in an SME in Luxembourg.

Contribution

- A general architecture for IIOT in the context of retrofitting any legacy machines is provided.

1.7 Outline of the thesis

The remainder of the thesis is structured as follows:

The creation of a Self-Assessment Tool (SAT) for manufacturing enterprises is discussed in Chapter 2, with a special emphasis on manufacturing SMEs. By addressing SME demands linked to lean and I4.0 features. The SAT created in this research aims to fill research gaps in the existing literature.

Section 2.1 - 2.3 summarizes the background, existing literature, and identifies research gaps. The methodology used to develop SAT is described in Section 2.4. Section 2.5 explains the design and development of the initial SAT. Section 2.6 deals with the pilot study and improvement potentials in the initial SAT. Section 2.7 of the chapter concludes with a description of the validated SAT.

Chapter 3 presents the quantitative assessment of manufacturing companies in the Grande Région. Section 3.1 covers the background of the assessment and the respondents of the Self-Assessment Tool. A correlation test, micro & macro analysis, and hypothesis testing are presented in section 3.2.

Chapter 4 describes the holistic methodology to deploy I4.0 technologies in the manufacturing enterprises. The 4 phase methodology is explained in detail in section 4.2. The methodology includes Maturity Assessment (section 4.2.1), Improvement Potentials (Section 4.2.2), Technical Road-map (Section 4.2.3), and Post Evaluation (Section 4.2.4).

Chapter 5 presents a case study in a Luxembourgish SME. The chapter deals with the Industrial Internet of Things (IIoT) and the steps needed for it's deployment in the manufacturing companies. Section 5.1 and 5.2 covers the introduction and the recent literature published in the databases. The technical part of the case study is described in section 5.3. The case study follows the methodological steps presented in Chapter 4.

Chapter 6 presents a case study of a large company from Luxembourg. The chapter presents the basic concepts of Augmented Reality related to manufacturing engineering such as fundamental components of AR, and input modalities. Following the methodological steps in Chapter 4, a case study is presented in sections 6.4, 6.5, and 6.6 of the chapter.

Chapter 7 presents the contribution of the PhD project to research as well as to practice. All the Research Questions (RQs) are answered in this chapter.

Finally, Chapter 8 concludes the PhD thesis and acknowledges the funding partners of the project.

Chapter 2

Development of Self-Assessment Tool (SAT) for Manufacturing Enterprises

2.1 Background

Productivity is significant for manufacturing companies as it is an important measure of the production performance of goods, processes, and services. It is widely known that at various phases of the industrial revolution, substantial improvements in productivity were obtained through scientific and technological innovations. Recent tools such as lean and I4.0 will have a positive impact on productivity in manufacturing companies irrespective of their size. Lean implementation is lagging among European SMEs (Kolla, Minoufekr, and Plapper, 2019), which is further delaying the adoption of I4.0. To help accelerate the digital transformation, it is necessary to assess the current status of manufacturing entities. The purpose of this chapter is to describe the design, development, and validation of a Self-Assessment Tool (SAT) for lean and I4.0 while addressing the research gaps in the existing literature.

It is possible to measure the current productivity levels by measuring the maturity of lean and I4.0 using maturity models, which are primarily based on the practical experience of employees working in a specific domain (Korne, Loewenkamp, and Luckscheiter, 2019). Maturity models are used to evaluate the maturity in terms of reactivity, capability, and the level of optimization of a specific domain or all the domains in an enterprise using a comprehensive set of criteria (De Bruin et al., 2005). A recent study (Terstegen et al., 2019) summarized 28 such maturity models that exclusively deal with the implementation of I4.0 in manufacturing companies. However, these models with one-dimensional focus on digitalisation, do not cover the complex needs of all the manufacturing companies. During the last few decades, organizations have evolved through a learning process and built standardized production systems such as Lean Production Systems (LPS) or any other best practices that are appropriate for their production. LPS was created with the primary purpose of lowering operating costs by eliminating any non-value adding entities (waste/-muda) from the company's value chain (Monden, 2011). Any digital adaption affects existing production systems such as LPS. In this regard, a hybrid model that considers both LPS and I4.0 for assessment is preferable to models that solely include one of the two (Kolla, Minoufekr, and Plapper, 2019).

This chapter describes the design, development, and validation of a hybrid maturity model that features LPS, strategy, and I4.0 for self-assessment in all the manufacturing companies. The tool efficiently assesses the current state of the business and recommends the next actions on the path to digital maturity, focussing on increasing productivity.

2.2 State of the art

This section examines existing maturity and assessment models obtained from research databases. In the existing literature, there were 42 such models found. After reading the abstracts, 20 models were identified as being relevant to this study. Below there is a critical assessment of these articles, as well as their strategic alignment. This overview of existing literature is divided into three categories. The first group of works focuses on LPS models, whereas the second group of works focuses on I4.0 models. The final category, which had a far lower number of search results, includes both lean and I4.0.

In the first category, two models resulted our search criteria. The research on LPS models dates back to 2002 when researchers from MIT first proposed the LESAT model (Nightingale and Mize, 2002). This is a top-down maturity model targeted at enterprise leadership teams to support both "as-is" analysis and "to-be" vision related to leanness of an enterprise. Each of the provided practices is assessed from maturity level one ("some awareness of the practice") to level five ("exceptional understanding of the practice and fully deployed across enterprise"). The assessment itself consists of five steps from introduction of the tool to setting-up an action plan with priorities for the enterprise.

In the second study, the authors of a more visual, data-driven operational lean maturity model (Maasouman and Demirli, 2015) were focused on mix of product and people aspects of the enterprise. The assessment is very detailed to the manufacturing cell level. This model is developed to measure the leanness of an enterprise in seven axes: people, facilities management, working conditions, production processes, quality, JIT, and leadership. During the assessment stage, four levels are identified: understanding, implementation, improvement, and sustainability. Furthermore, the assessment identifies lean indicators in each axis and they were assigned to a control item for better understanding. For the collection of data, a checklist is used instead of traditional approach of questionnaire or interviews. Using this data, the leanness of each indicator is calculated on a scale of zero to one. The sum of all indicators gives the final lean score of the manufacturing cell.

In both the lean assessment models, neither I4.0 features nor the characteristics of SMEs were included. Even though lean management is widely practised among the enterprises, there are only few models to assess the leanness of an enterprise. Therefore, there is still high need for models that assesses the leanness in an enterprise.

The second category of works is concentrated on I4.0 models. 17 out of 20 models belong to this category. Even though these models are similar there are some differences among them. These differences led to the categorization of I4.0 models in three sub-categories: *conventional models, holistic models, and technology-focused models*. In conventional models, the current status of I4.0 in an enterprise is assessed from a filled questionnaire or by interviews. The holistic models extend the scope a bit further and propose a road-map or action plan for digital transformation. Technology-focused models, on the other hand, focus on the technical components of I4.0 and their maturity in an organization.

The conventional sub-category included six models. On the contrary to the existing methods, the self-assessment tools to measure I4.0 readiness (Brozzi et al., 2018) explored the SME craftsmanship self-assessment with selective and specific features. The assessment determines four levels of predetermined profiles of craftsmanship namely the traditional craftsman, the digital newcomer, ambitious, and digital champion. The model didn't detail the next steps after the assessment. In another study (Dr. Lichtblau et al., 2015), the authors of the I4.0-readiness model developed a model composed of six dimensions: employees, strategy and organization, smart factory, smart operations, smart product, and data-driven services. Sixteen modules were associated with these dimensions, taking into account the difficult milestones that many businesses must still overcome on their way to I4.0 readiness. In addition, six stages of maturity are taken into account when determining I4.0 readiness. However, the model doesn't meet the needs of SMEs. Furthermore, the authors of the SMEs maturity model assessment of IR4.0 digital transformation (Hamidi et al., 2018) used the formally mentioned I4.0-Readiness-model with additional feature of weighing each dimension. The formula was determined in the survey by asking the companies to assess the relative importance of each dimension in the implementation of I4.0. The needs of SMEs are included in the model. However, the model is a simple extension to another existing model. The inherent limitations of the original model are still pertinent in the new extended model.

With the maturity and readiness model for I4.0 strategy (Akdil et al., 2018), the authors presented a strategic model based on a review of existing models. The new model contains three dimensions: smart products and services, smart business processes and strategy, and organization. The assessment is evaluated in four levels: absence, existence, survival and maturity. In a further investigation (Schumacher et al., 2016), the authors of the maturity model for assessing I4.0 readiness developed a rather comprehensive model assessing I4.0 readiness with the scope of extending dominating technology-focused maturity models by adding organizational aspects to it. Their model focuses on manufacturing enterprises and it has overall 62 aspects that are classified into nine dimensions: products, customers, operations, technology, strategy, leadership, governance, culture, and people. The model has been tested and validated in many enterprises, but it is not available as an open-source tool for companies to test their status of digitalisation. The final model in this sub-category is the smartness assessment framework for smart factories using Analytical Network Process (ANP) (Lee et al., 2017), which focuses on decreasing the bias of various actors' priorities. To achieve an unbiased measurement of maturity in five levels, the authors used the Multi-Criteria Decision Making (MCDM) and ANP methods for weighing the various assessment items. The five levels mentioned in this study are" maturity, checking, monitoring, control, optimization, and autonomy.

The *holistic model sub-category* includes five models. The researchers from Acatech developed a detailed I4.0 model (Schuh et al., 2017), which covers both the aspects of digitalisation and I4.0 in six development stages. Their methodology includes identifying the gaps between current and desired state by gap analysis and introducing missing capabilities to attain desired benefits. In the end, a digital road-map presents evolutionary steps towards the desired state. In another study, the authors of the I4.0 quick checkup (Mittal et al., 2020) developed a model to meet the requirements of SMEs. The model contains five dimensions: business management, development, manufacturing, supply chain, and services with 17 items all together. The analysis process contains various stages such as workshop, awareness, questionnaire, identification of opportunities, and road-map for improvements. In a separate investigation, the authors of the VDMA guideline I4.0 (Anderl et al., 2016) were focused on how to implement I4.0 business models especially in SMEs. The method includes five stages: preparation, analysis and creativity, evaluation, and implementation. The model considers the commitment of management, cross-disciplinary teams and tool box I4.0 as the essential tools for digital transformation.

The way to I4.0 road-map (Braun et al., 2018) is another publication where the authors considered that a company specific road-map is a must to realize the I4.0 potentials. On the other hand, the authors of the I4.0 road-map (Issa et al., 2018) developed an I4.0 road mapping process for digital transformation in manufacturing companies based on capability maturity. The idea behind this approach is that the technological adaptations and organizational change should go hand-in-hand. The balance between these two key aspects of a company is managed by business-IT-alignment and integration method.

In the third sub-category of *technology-focused models*, the focus is given on IT system landscape and deployment of advanced technologies. 6 such models were found in the literature. However, the models are very similar to each other. In SIMMI 4.0 (Leyh et al., 2016), the authors classified IT systems of a company in four dimensions: vertical integration, horizontal integration, digital product development, and cross-sectional technology criteria. The key aspects which must be conducted to achieve a certain level of maturity in each stage are briefly explained. In another study, the authors of the I4.0 MM (Gökalp, Şener, and Eren, 2017) used ISO/ IEC 15504 reference for maturity models and Software Process Improvement and Capability Determination (SPICE) approach for developing the maturity model in five dimensions: asset management, data governance, application management, process transformation and organizational alignment. The assessment of each aspect uses a six-level scale from incomplete to optimization. In another study, a hardware manufacturer presented a stage maturity model that encompasses both technological and organizational cultures. As a result, the maturity model is called a connected enterprise maturity model (Rong and Automation, 2014) and contains five levels for evaluating an organization's IT network. The stage of collaboration in the connected enterprise model is a critical last stage in the digital transformation, as it creates an environment that anticipates activities throughout the company and through the supply and demand chain.

The authors of the checklist digitization and I4.0 in practice (Weber et al.,

2018) focused on digitization measures to optimize processes using a checklist. The users are appointed to areas where action is needed. In another study, the authors of the categorical framework of manufacturing for I4.0 and beyond (Qin et al., 2016) concentrated on the achievement criteria for I4.0 by focusing on four major aspects such as factory, business, products, and customers. In their study, the existing manufacturing systems are compared to the manufacturing concepts and I4.0 concepts in order to derive the research gaps between current and future manufacturing systems. The framework considers automation and intelligence at three different capability levels, e.g. a shop floor with automation level 'c' and intelligence level 'k' is considered as "I4.0 ready". In a recent study (Rauch et al., 2020), the authors of the maturity level-based I4.0 assessment tool in SME identified a large set of I4.0 concepts and technologies that are used for assessing an enterprise in terms of organization, culture and technology. The assessment is done using a Likert-scale questionnaire with five maturity levels.

The third category of works focused on hybrid models, which contains both the elements of LPS and I4.0. Only one such model was found from the researchers of Fraunhofer Institute for Industrial Engineering. With a model named production assessment 4.0 (Pokorni et al., 2017), the authors were focused on existing manufacturing systems while presenting the practical answers to new business paradigms such as I4.0 with feasible and practical migration plans. The model consists of five strategic areas of manufacturing companies such as strategy, process and value stream, organization, methods and tools, and personnel with subgroups in each strategic area. These subgroups are evaluated from level one to level four in the first stage of assessment. The second stage includes a necessary differentiation of skill classification and derives a migration plan to I4.0. The model is complex and focused on large companies.

The next section summarizes the research gaps in the existing literature and describes the need for a new hybrid maturity model for all manufacturing enterprises.

2.3 Research Gaps

The first and most evident research gap in the existing literature is that it focuses primarily on either Lean or I4.0, except for Production Assessment 4.0 (Pokorni et al., 2017). This implies that more research is needed in the area of hybrid maturity models, particularly for SMEs. A hybrid model is more relevant in the current scenario because any new industrial revolution such as I4.0 will have effect on existing manufacturing systems such as LPS. Another research gap in the existing models is that the majority of them were designed to meet the needs of large companies. This leads to the false assumption that the companies already have basic resources of I4.0 which is not true for SMEs. Therefore, there is a need for a level description which highlights the unawareness as the lowest maturity level. Some models only focus on the technological aspects of I4.0 such as inter-connectivity, data management, and advanced machines etc. In contrast, holistic models such as the Acatech maturity index model (Schuh et al., 2017) explicitly recommends on a broader perspective in which technology, managerial and people aspects must be considered in the successful transition to higher maturity levels.

Some models, such as I4.0 quick checkup (Mittal et al., 2020) or the self-assessment tool to increase I4.0 readiness (Schumacher et al., 2016) do not emphasize either strategic or organizational aspects of the enterprises. However, strategic advice for leaders will also be crucial for lean and I4.0 implementations in SMEs and should be an important part of any maturity model concerning manufacturing entities. Not every model provides details on how to improve the maturity and thus the productivity of the company, e.g. the categorical framework of manufacturing and I4.0 (Qin et al., 2016). Some model descriptions such as production assessment 4.0 do not include case studies in practice and are rather theoretical. Another finding is that the models use different scale types. Likert scale measurements (e.g. from one to five) are sometimes utilized, which might be difficult to distinguish and lead to subjective assessment. Therefore, well-defined level descriptions are a better alternative to Likert scale type measurements in maturity models.

These significant research gaps are addressed in the maturity model developed in this research for assessing lean and I4.0. Users can self-assess their lean and I4.0 status using the maturity model developed as part of this research, which is known to as the Self-Assessment Tool (SAT). In summary, the hybrid SAT developed in this research addresses the following research gaps:

Research gaps addressed in this research

RG1: Most of the models consider either lean or I4.0. The SAT developed in this research is a comprehensive and hybrid tool integrating lean and I4.0 aspects in a single model.

RG2: None of the models consider different starting points for SMEs compared to larger companies. The SAT fulfils the needs of SMEs as it addresses different starting points for SMEs.

RG3: In current models there is a disconnect between different stages as they employ Likert scale without any level descriptions. The disconnect between current level and next steps for a successful transition is addressed by the SAT using level descriptions (Likert items rather than Likert scale)

Section 2.2 and Section 2.3 are summarized in Table 2.1, Table 2.2, and in Table 2.3

TABLE 2.1: Summary of State of the art and Research gaps - Part 1

Model	Structure & Design	Research Focus	Research Gaps
Lean enterprise Self-Assessment Tool (LESAT) (Nightingale and Mize, 2002)	3 dimensions including 54 modules	• Focused on enterprise leadership (top-down approach) • Demonstrate a step-by-step methodology to initiate lean transformation in enterprises	• Elements of I 4.0 are not considered • SME perspective of I4.0 is not addressed
Lean maturity level in manufacturing cells (Maasouman and Demirli, 2015)	7 axes including several indicators	• Leanness indicators are used to keep track of the implementation of lean manufacturing • An audit is proposed to measure the indicators	• No focus on I4.0 or digitalisation • SME perspective of either lean or I4.0 is not addressed
Self-assessment tools to measure I4.0 readiness (Brozzi et al., 2018)	3 dimensions including 23 items encompassing selective and specific features	• Focus on operations, digitalisation and ecosystem dimensions • Targeted the needs of SMEs • Provides current digital level as well as insights on future steps	• Elements of LPS are not considered • No focus on the strategic elements • The toolbox is primarily technical
I4.0 readiness model (Dr. Lichtblau et al., 2015)	6 dimensions including 16 modules	• Presents a detailed and strategic picture of I4.0 in mechanical engineering sector	• Elements of LPS are not considered • SME perspective is not considered • Limited application due to focus on mechanical engineering
SMEs assessment of I4.0 digital transformation (Hamidi et al., 2018)	6 dimensions including 16 modules (additional weighing factor)	• Extension of I4.0-Readiness • Understanding the readiness of SMEs towards I4.0 sector	• Elements of LPS are not considered • Limited application due to focus on mechanical engineering
Maturity and readiness model for I4.0 strategy (Akdil et al., 2018)	3 dimensions including 13 modules	• Company's business and strategy perspective on I4.0 Including applications for smart finance, smart marketing and human resources	• Elements of LPS are not considered • SME perspective is not considered
Maturity model for assessing I4.0 readiness (Schumacher et al., 2016)	9 dimensions including 62 modules	• Both technical and organizational aspects of I4.0 are considered	• Elements of LPS are not considered • SME perspective of I4.0 is not considered
Smartness assessment framework for smart factories using ANP (Lee et al., 2017)	3 categories of SMEs are identified	• Published works used as assessment criteria for SMEs in Korea • Uses ANP to weight different items	• Steps to implement lean and I4.0 are missing from the model • Strategic aspects of transition considered for some levels only

TABLE 2.2: Summary of State of the art and Research gaps - Part 2

Model	Structure & Design	Research Focus	Research Gaps
Acatech I4.0 maturity index (Schuh et al., 2017)	6 development stages including 4 structural areas	• Emphasizes the importance of before implementing I4.0 solutions • IT, cultural, and strategic elements are given equal importance	• Elements of LPS are not considered • SME perspective is not addressed
I4.0 quick check-up (Mittal et al., 2020)	5 dimensions including 17 modules	• Designed to suit the needs of SMEs • Critical focus on environmental, social, benefits of transforming to I4.0	• Elements of LPS are not considered • No focus on the firm's strategy • Key elements of I4.0 such as horizontal and vertical integration are not addressed
VDMA guideline I4.0 (Anderl et al., 2016)	2 categories including 6 modules in each	• Designed to suit the needs of SMEs • A "toolbox I4.0" is used for production and product assessment, each categorized in feasible development stages	• Elements of LPS are not considered • No focus on the strategic elements • The toolbox is primarily technical
Way to I4.0 road-map (Braun et al., 2018)	3 stages with 11 sub-stages	• Focused on strategic road-map for specific company requirements • Designed to suit the needs of SMEs	• Elements of LPS are not considered
I4.0 road-map (Issa et al., 2018)	6 step methodology towards I4.0 road-map	• Presents a theoretical framework for manufacturing companies • Logical sequence of road-map is presented with focus on task force setup, digitalisation assessment, focus definition, use case idea generation, use case impact estimation, use case selection	• Elements of LPS are not considered • SME perspective is not addressed • No details on how or which I4.0 tools shall be implemented
System Integration Maturity Model for I4.0 (SIMMI 4.0) (Leyh et al., 2016)	4 dimensions with descriptions of 5 stages each to enable self-assessment	• Exclusive focus on IT system landscape in the company Key activities for transitioning from one stage to another stage are briefly explained	• Elements of LPS are not considered • Focus is primarily on IT aspects of I4.0 • Managerial and people aspects are missing from the study
I4.0 Maturity Model (Gökalp, Şener, and Eren, 2017)	5 aspect dimensions at 6 levels	• Based on ISO/ IEC 15504 • Includes organizational considerations for IT such as data governance	• Elements of LPS are not considered • SME perspective of I4.0 is not considered • Steps to evaluate the maturity of I4.0 are not presented

TABLE 2.3: Summary of State of the art and Research gaps - Part 3

Model	Structure & Design	Research Focus	Research Gaps
Connected enterprise maturity model (Rong and Automation, 2014)	5 stage maturity model with several measures for improvement	• Includes measures for IT improvement • Integrates IT with operations technology for better performance • Holistic method with progressive states of maturity from assessment up to collaboration	• Elements of LPS are not considered • SME perspective is not addressed • Steps to evaluate the maturity of I4.0 are not published
Checklist digitization and I4.0 in practice (Weber et al., 2018)	Two step approach with assessment of 11 application fields	• Analysis of the "as-is" status including organizational elements • Users are appointed to areas where action is needed	• Elements of LPS are not considered • Assessment criteria and SME perspective of I4.0 are missing • High-level know-how is required to answer the checklist
Categorical framework of manufacturing for I4.0 and beyond (Qin et al., 2016)	Based on 4 major aspects of future manufacturing visions, leading to 9 potential gaps	• Focuses on comparing current manufacturing technologies and I4.0 concepts	• Elements of LPS are not considered • SME perspective is not addressed • No details for measures or strategy are provided
Maturity level-based assessment tool to enhance the implementation of I4.0 in SMEs (Rauch et al., 2020)	3 dimensions including 42 I4.0 concepts	• Focused on SME interests of I4.0 • Includes practical approaches for strategic aspects in major dimensions: operations, organization, socio-culture, and technology	• Elements of LPS are not considered
Production assessment 4.0 (Pokorni et al., 2017)	5 dimensions including 140 modules	• Focused on both LPS and I4.0 • Holistic model covering major aspects of an enterprise	• Complex model and primarily technical • Not tailored to the needs of SMEs

2.4 Methodology

A six-step methodology based on de Bruin, T. et al. (De Bruin et al., 2005) is applied to develop a comprehensive SAT for lean and I4.0. This framework provides a solid and practical foundation for developing a SAT. The methodology employs six phases as shown in Figure 2.1, with a particular emphasis on the domains of business process management and knowledge management. The framework supports the development of SAT that represent the existing "as-is" condition and suggest the "to-be" scenario, such as how to improve maturity to increase for e.g. productivity. Furthermore, the framework allows for the development of models that can utilize the collected data as a benchmark to compare company's' maturity levels across industry sectors and geographical regions. During the development of SAT, the six-phases are followed in a sequential order although progression through some phases may be iterative, e.g. test results may lead to re-adjustments in design.

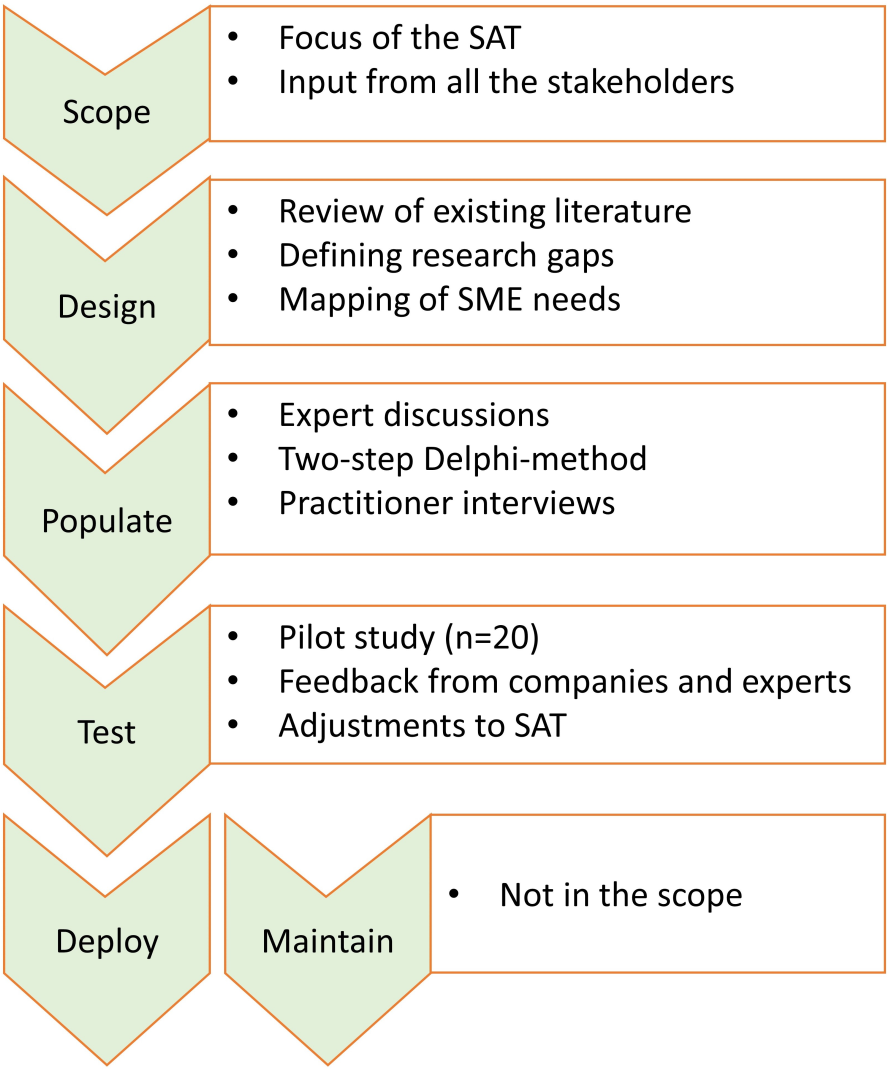

FIGURE 2.1: Maturity model development phases according to De Bruin et al., 2005

The first phase in the development of SAT is to define the **Scope**. The strategy used in the scoping phase is to establish the model's focus and identify the stakeholders who will help with its development. After defining the scope, the next step is to **Design** the initial SAT. In this phase, it is necessary to distinguish the proposed model from other existing models. To this end, de Bruin T. et al. recommend conducting domain-specific literature reviews and identify relevant gaps in current models (in Section 2.2 and Section 2.3). Incorporating institutional, governmental, and enterprise needs were the top priority during the design phase. The design phase concluded by defining the first set of dimensions and modules of the SAT.

In the **Populate** phase, a two-step Delphi method (Turoff and Linstone, 2002) is applied to rank and select the modules for SAT and also to agree on the level descriptions. The next logical step is to **Test** SAT for it's relevance and rigor. Validity and reliability of initial SAT modules were tested with surveys and personal interviews (n=20), noting relevance, applicability and issues with misunderstanding. Major and minor modifications were made to the modules of SAT based on the feedback received from the pilot test as well as from expert discussions. Pilot tests are conducted in manufacturing companies while the experts are based in universities and institutions of Grande Région. The last two phases **Deploy** and **Maintain** are not in the scope of this research.

2.5 Design and development of initial SAT

The first three phases (Scope, Design, and Populate) of de. Bruin methodology are detailed in this section.

2.5.1 Scope of SAT

The scope of the new tool (SAT) is productivity improvement in all manufacturing enterprises, with critical focus on SMEs. The scope is defined in a way to overcome the research gaps in the existing literature. For productivity improvement, methods and tools from lean and I4.0 are considered in the design of SAT. Based on De Bruin et al., 2005, during the scoping of SAT, two criteria are addressed with their respective needs/ characteristics. Table 2.4 presents the summary of the scope of SAT.

TABLE 2.4: Summary of the scope of SAT

Criterion	Needs/ Characteristics
Focus of the model	• Focus on all manufacturing enterprises (Domain-specific) • Include the needs of SMEs and critical focus on SME characteristics • Strategic importance - involve various experts from a multitude of domains for input in developing the SAT (I4.0, LPS, and strategy) • Develop a tool that SMEs can use and assess themselves without any intermediaries
Involvement of all the stakeholders	• Identification of academic, industrial, political, and strategic stakeholders • Involvement of experts from the following fields in the development of the initial SAT: manufacturing, logistics, strategy, corporate governance, people, information and communication technology (ICT), change management

Inputs from multiple domain experts and relevant stakeholders are important criteria according to the applied methodology. As a result, inputs are collected from the experts in academic, industrial, political, and strategic stakeholders. Academic experts interviewed in this research posses vast knowledge in the fields of manufacturing, logistics, strategy, corporate governance, change management, people, and Information and Communication Technology (ICT). Industrial, strategic, and political experts from Grande Région contributed their inputs to the SAT in various phases of the development.

To emphasize the suitability of the tool for own evaluation purposes without involvement of intermediaries, the tool developed in this research is referred to as the Self-Assessment Tool (SAT). After discussing with the academic experts and other stakeholders, the SAT is built on a presumption that LPS (or efficient processes) is a prerequisite for digital transition (I4.0). This avoids digital manifestation of inefficient processes. Specific needs and characteristics of SMEs are well addressed since SMEs have different starting points than the large companies (Mittal et al., 2018). The mapping of SME needs and characteristics are presented in subsection 2.5.2. The scope of the SAT is also to represent the holistic perspective which is missing from most of the state-of-the-art models. Using SAT developed in this research, all the manufacturing companies especially SMEs can determine their "as-is" status concerning lean and I4.0 without the involvement of external consultants. The SAT also provides templated solutions for maturity improvements using level descriptions instead of Likert-scale type measurements.

2.5.2 Design of initial SAT

In general, increased productivity gives businesses a competitive advantage. The SAT is designed to identify specific starting points for enhancing a company's productivity quickly and easily without the need for external support. The needs of SMEs, as well as the use of simple technical vocabulary, are carefully considered while designing the initial SAT. To prepare a solid foundation for level descriptions in SAT, SME needs and characteristics are mapped employing LPS and I4.0 components (shown in Table 2.5). What constitutes an SME has been debated in the literature for a long time and there is still not a universal definition of the term. Therefore, the European Commission definition stating that SMEs include between 10 and 250 employees is chosen European-Commission, 2022. Table 2.5 shows a characteristic mapping of SME with lean and I4.0 components (the table's contents are slightly modified from the original publication Kolla, Minoufekr, and Plapper, 2019). Based on the mapping presented below, the dimensions of the SAT are chosen. This reduces the immense number of instruments available in the state-of-the-art models. Typical deficiencies and necessities of SMEs such as knowledge gap in decision making can be eliminated by organizational solutions such as tracking of Key Performance Indicators (KPIs) or digital tools such as use of algorithms or data visualization etc.

TABLE 2.5: Mapping of SME characteristics with Lean and I4.0 components

Characteristics of SMEs	Dimension of the company	Lean components	Industry 4.0 components
Ability to produce customized products (Krämer, 2003)	• Methods and Tools • Strategy	• Reduction of change over times (SMED) • Continuous improvement (Kaizen) • Production leveling (Heijunka)	• Simulation • Smart facilities
Scouting for rapid innovations (Hossain and Kauranen, 2016)	• Strategy	• Technology and innovation management	• Technology and innovation management
Lack of up-to-date ICT infrastructure (Mittal et al., 2018)	• Methods and Tools • Design of the value stream	• Not applicable	• Vertical integration and setting up company-wide network (e.g. ERP, CPFR)
Lack of Advanced Manufacturing Technologies (AMT) (MEZGA´ R and KOVA´ CS, 1998)	• Methods and Tools • Design of the value stream	• Not applicable	• Machine to machine communication (e.g. IoT) • Human Machine Interface (e.g. AR)
Close relationship with customers (Schirrmann, 2006)	• Design of the value stream	• Value Stream Mapping (VSM)	• Horizontal integration
Lacks of awareness of standards and decentralization of processes (Brown, Van Der Wiele, and Loughton, 1998)	• Organization	• Horizontal and vertical integration of all the socio-technial systems in the company	• Not applicable
Excess storage (Kleindienst, Ramsauer, et al., 2016)	• Design of the value stream	• Material replenishment	• Digital tools to help material replenishment
Knowledge gap in strategic decision making (Schirrmann, 2006)	• Organization	• Key Performance Indicators (KPIs) • Strategic planning	• Data driven decision making
Lack of strong collaborative network (Singh et al., 2007)	• Design of the value stream	• Multiple suppliers	• Horizontal integration
Qualification of employees, lack of mentoring, targeted individual training and supervision (Kleindienst, Ramsauer, et al., 2016)	• People	• Training • Quality and Standardization	• Training in digital tools

Another factor to consider when creating a maturity model is how the maturity stages are communicated to the audience. The optimum number of maturity stages should allow for variability and respondent's ability to meaningfully distinguish among stages. The type of question determines whether there are an odd or even number of stages, with an odd number implying a central neutral point. An even number forces the respondent to make at least a weak commitment to one extreme or the other. In the literature, various types of scales have been presented, such as a Likert scale with varied degrees of agreement for a proposition (DeVellis and Thorpe, 2021). In designing the new SAT, four cumulative stages similar to Likert scale were chosen offering the respondents a degree of variability with low complexity and time requirements. Moreover, the each stage is supplemented with a level description to avoid subjectivity in the assessment. As shown in the Figure 2.2, the SAT structure includes two layers. Layer 1 covers the domain specific classification (hereinafter referred to as dimensions) while layer 2 incorporates the domain components (hereinafter referred to as modules). Modules are important and independent aspects of dimensions to assess the maturity.

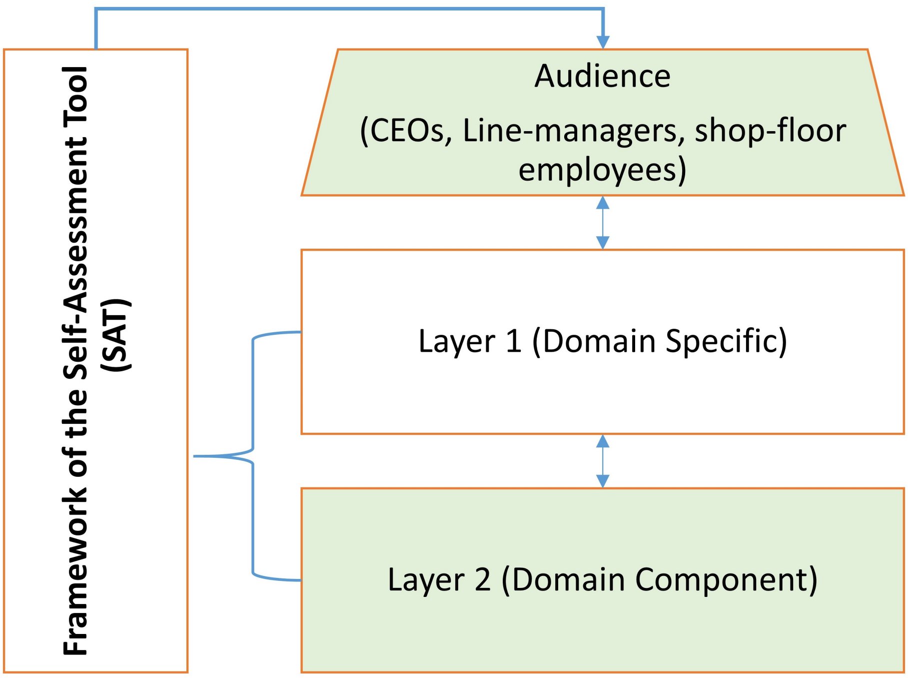

FIGURE 2.2: Framework of the Self-Assessment Tool

2.5.3 Population of initial SAT

After the scope and the design of the initial SAT are finalized, the content of the SAT is decided in a three-step process. In step 1, experts from different fields as mentioned in 2.5.1 are interviewed regarding applicable methods and tools for level descriptions. The lean and I4.0 components presented in Table 2.5 are the focus points of the semi-structured interviews with subject-matter experts. In step 2, qualitative interviews with managing directors and experts from manufacturing companies in Germany, Luxembourg, France and Belgium were conducted (n=29). The proportion of SMEs in the survey was 79%. The results of the interviews revealed that competitiveness and efficiency were primarily secured by measures in planning and control, optimization of processes and adaptation of the business strategy to customer needs. Only a small percentage of respondents mentioned measures in the areas of company culture and digitalisation. Some respondents stated that they have lean processes and working towards optimizing the processes using new digital tools. Nevertheless, more than a third of respondents stated the need for actions to optimize their processes. Within their own organizations, the general potential of digital technologies, sensors, and cloud computing was regarded to be more for the future. The interviews with the companies showed the necessity for SMEs to consider preceding maturity levels with fundamental organizational or process-related tools before advanced maturity levels with I4.0.

In step 3, the selection and ranking phase, a two step Delphi method (Turoff and Linstone, 2002) is used to prioritize the domain components (modules). The Delphi method assumes that expert group judgments are more valid than expert individual judgments. A survey was created with a first set of dimensions, modules and level descriptions that were result of the first three phases. This survey was sent to the experts (n=12) for assessing the importance of modules to be included in the SAT. In each round, the experts were asked to complete the survey using color scale, e.g. red, orange and yellow for very important, moderate importance and low importance, respectively. A balance in the number of questions of the SAT was considered to be important. A sufficient number is required to ensure complete measurement but too many questions may reduce reliability of data by resulting in a reduction in total survey responses or an increase in incomplete surveys. The two-step Delphi method allowed the author to prioritize and reduce the number of modules from 134 to 33 modules within layer 2. According to the de. Bruin methodology, the next phase in the development of SAT is to test the model with audience and collect feedback for continuous improvement of the model. The next section summarizes the testing phase of the initial SAT.

2.6 Pilot study and validated SAT

Initial SAT model with 5 dimensions and 33 modules with each module having 4 different level descriptions is used to survey 20 manufacturing companies from Grande Région. As Grande Région involves English, German, and French speaking enterprises, the initial SAT is translated to all three languages. Figure 2.3 shows the Characteristics of pilot test companies. The 20 manufacturing companies came from food industry, chemical industry, fabricated metal industry, electrical equipment, trailer production and furniture production. The respondents of the SAT are generally top executives of the company and/ or line-managers of production facility. Respondents had also the possibility to mark modules as not relevant if they think that the specific module isn't important for the productivity improvement of the company. Regional differences in understanding the initial SAT were discovered during testing in different parts of Greater Region mainly because of variety of educational and methodological backgrounds, as well as language-related interpretation problems. It was discovered, for example, that organizations in France and Belgium were

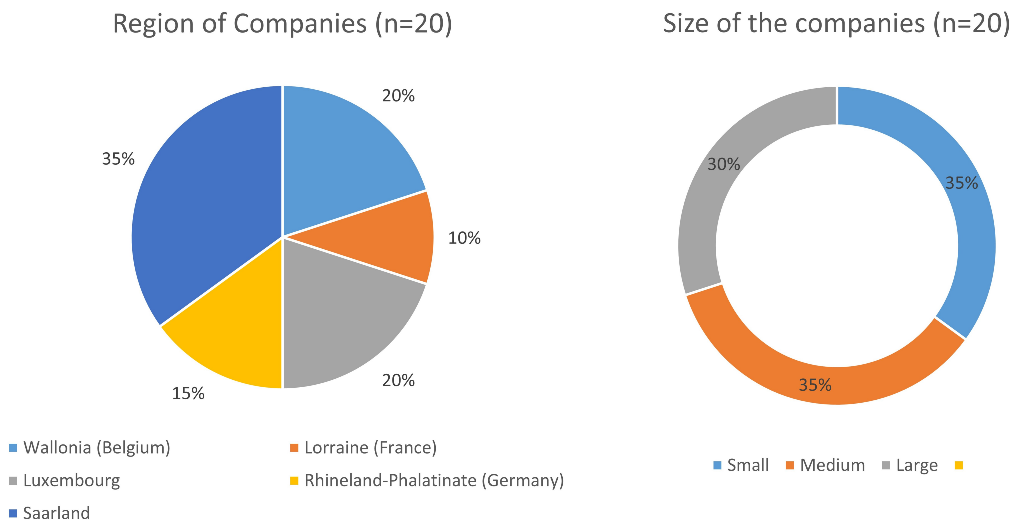

FIGURE 2.3: Characteristics of pilot test companies

unfamiliar with the REFA methodologies which were developed by Germany's oldest organization for work station design, company organization, and development. In order to confirm the SAT's applicability for various business sectors, other companies from the construction and logistics sectors were interviewed. Despite the fact that the modules relating to logistics attracted their attention, the majority of the logistics service providers surveyed saw the need for a different SAT developed solely for logistic companies.

Based on the feedback received from the pilot test companies, the improvements to the model are classified in to **major** and **minor** changes. Minor changes include the changes that improves the understanding of level descriptions. Moreover, any changes that could lead to a change in the user's assessment are classified as major changes. However, the majority of the changes made to the initial SAT are mainly simplification of the terminology and adding more examples of the methods and tools related to each module. Table 2.6 shows the overview of the major and minor modifications to initial SAT.

TABLE 2.6: Modifications to the Initial SAT

Type of modification	Quantity
Number of initial SAT questions changed in language	19
Number of initial SAT level descriptions changed in content	54
Number of initial SAT level descriptions changed for simplification	70
Number of completely deleted modules	1
Number of new modules	4
Number of modules shifted between dimensions	3

A model that is oversimplified don't adequately reflect the complexities of the domain and domain components. On the contrary, a model that appears too complicated may limit interest, create confusion, and increases the risk for incorrect application resulting in misleading outcomes. In this regard, the use of language containing technical terms or concepts was avoided to enable users with limited knowledge of both LPS as well as I4.0 to complete the assessment. One example for a minor change is the module about value stream mapping, in which the term *future state mapping* was taken out of the explanation and added as a possible example to describe a desired plan for production within maturity level 3. Another example in terms of oversimplified language such as *major focus on lean manufacturing* which was changed in to *mainly for efficient production, better material flow and elimination of waste, e.g. Lean Production.*

The major changes are based on the feedback from the companies from pilot studies. These changes include sectoral additions, cut-outs, transfers and content modifications of the modules. One example for a major change is the module Material replenishment, in which respondents had problems to distinguish between level two, three and four. Therefore, the content is changed to reflect the feedback. Advanced procurement strategies were initially in level 4 and it is moved to level 3 to have the stages more distinct. Examples were added to give correct interpretation of the level descriptions. Level four was purely dedicated to Collaborative Planning in the Supply Chain (CPFR) which is a new addition to level descriptions.

One module was deleted from initial SAT and exchanged with four new module topics that came up in company interviews. The module on the use of *cloud* applications was deleted because many respondents did not see direct relationship between productivity and cloud applications. Furthermore, the productivity effect of software applications, which may well be cloud-based, was already queried in several other assessment modules on IT-based control. The descriptions of the module *use of indicators* were perceived as too complex and overloaded. This led to questions and ambiguities among many respondents. Therefore, the actual module is divided in to two modules, one focusing on the existence of indicators and the other on their use and accuracy. Methods of environmental sustainability and reverse logistics were neither part of Lean nor of I4.0, but were mentioned in some discussions in the companies as a possibility for efficiency. A module on automation of processes for customer-oriented design and production planning had already been discussed among experts in the population phase but was incorporated afterwards, when the benefit for a manufacturing company became visible in the pilot test. A module on innovation culture in human resources was added to assess the companies lookout for new trends in the market.

Finally, the validated SAT is derived with 5 dimensions and 36 modules. A brief description of the SAT is presented in the next section.

2.7 Description of the Self-Assessment Tool

The self-assessment tool consists of five categorical domains (dimensions) in layer 1 and 36 domain components (modules) in layer 2. The SAT has been designed for self-assessment in manufacturing companies by company representatives (audience) without the need to involve intermediaries such as consultants or subject matter experts. To do so, structure, content and language of the SAT level descriptions were designed to meet the needs of all manufacturing companies using a structured approach. The structure and content were simplified but covered all aspects considered important to the production entity. Thematically, the tool encompasses 5 dimensions:

- Strategy
- Process and Value Stream
- Methods and Tools
- Organization
- Personnel

Furthermore, the dimensions are attributed with 36 modules (as shown in Figue 2.4). SAT covers various aspects of Lean Production Systems, I4.0, as well as organization and strategy that are related to manufacturing. The modules query about a specific aspect of the particular dimension. For example, the personnel dimension (layer 1) has training (layer 2) as one of the modules. In terms of productivity improvements, the SAT serves both to understand the 'as-is' status as well as the "to-be" status with potential opportunities to be derived as result of the assessment. Each of the modules is divided into four levels of maturity with decision enforcement but also well-defined and distinctive descriptions. Additionally to the four levels, a fifth option is available to choose that the particular module is not relevant. Appendix A provides the entirety of the SAT dimensions and modules.

The SAT is in the form of a questionnaire with a statement (Likert item) describing the application or effect of the method or a tool on the dimension or module. At level one, the company has no or limited awareness of the module. Level two generally includes aspects of lean management or organizational fundamentals. Level three has a focus on I4.0 fundamentals, lean management or good strategic practices. Level four is intended for the use of advanced I4.0 technology or sophisticated management techniques. This structure is applied to all the 36 modules to have consistency across the SAT. For example, the module Material Replenishment from the dimension Process and Value Stream is visualized in Figure 2.5. The module addresses the procurement strategies and subsequent methods applied by the company. In the companies at level one, procurement traditionally based on push-principle tend to have higher inventory levels and may frequently experience material out-of-stock situations. At level two, tools from lean management such as Kanban or one-piece flow can dramatically reduce inventory levels and waste. At level three, more sophisticated methods which require thematic expertise such as Vendor Managed Inventory etc. are included. Level four is the highest level in procurement process which requires collaboration in production planning and scheduling activities over a larger group of the supply chain to tackle inventory levels. This maturity stage generally requires connected IT systems across the supply chain.

The validated SAT is then used to assess manufacturing companies in the Grande Région with the support of PRODPILOT https://prodpilot.eu/fr consortium. The results and the outcomes of analysis of the survey data is presented in Chapter 3. This analysis serves as the foundation for the thesis's later chapters.

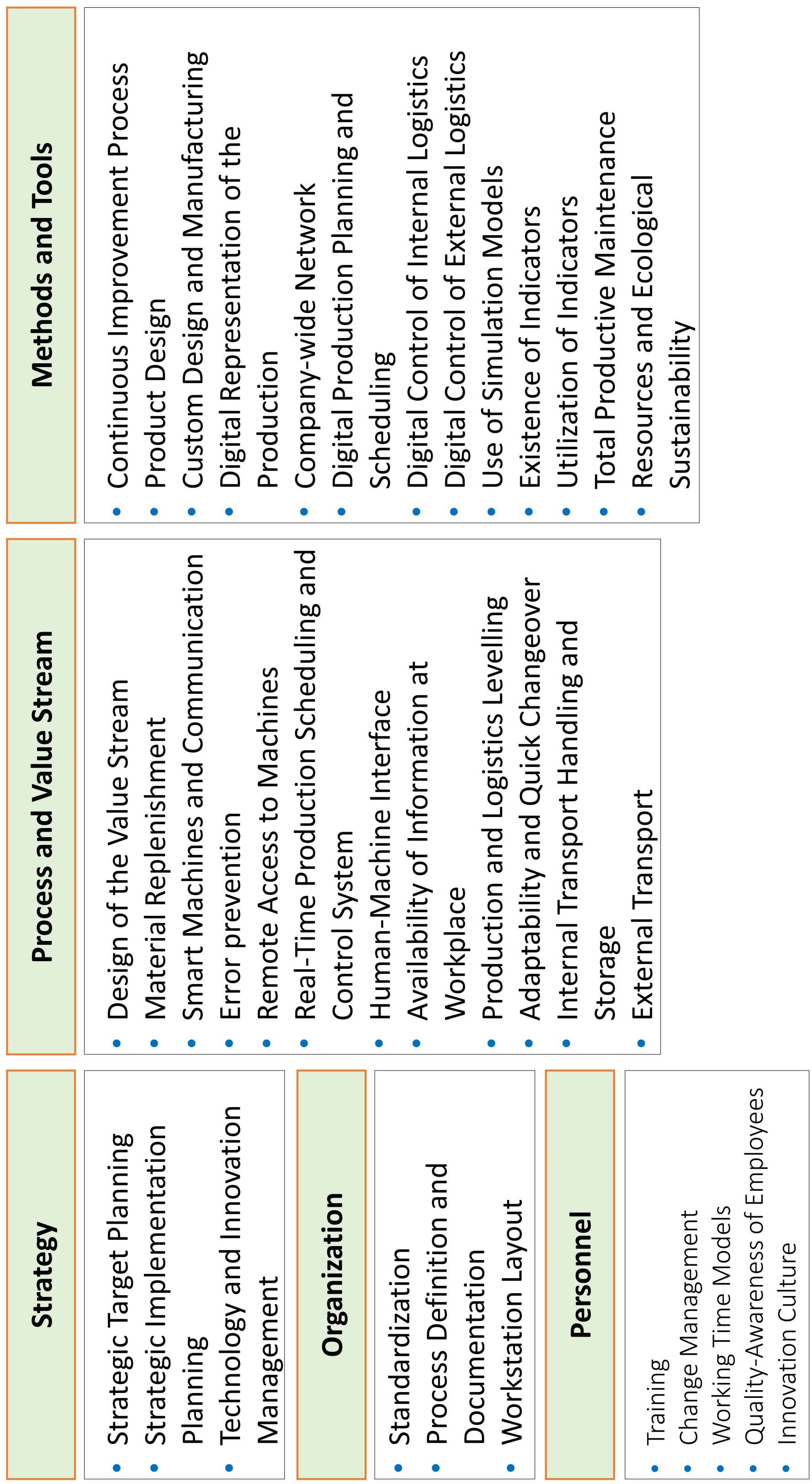

Figure 2.4: Dimensions and Modules of the SAT

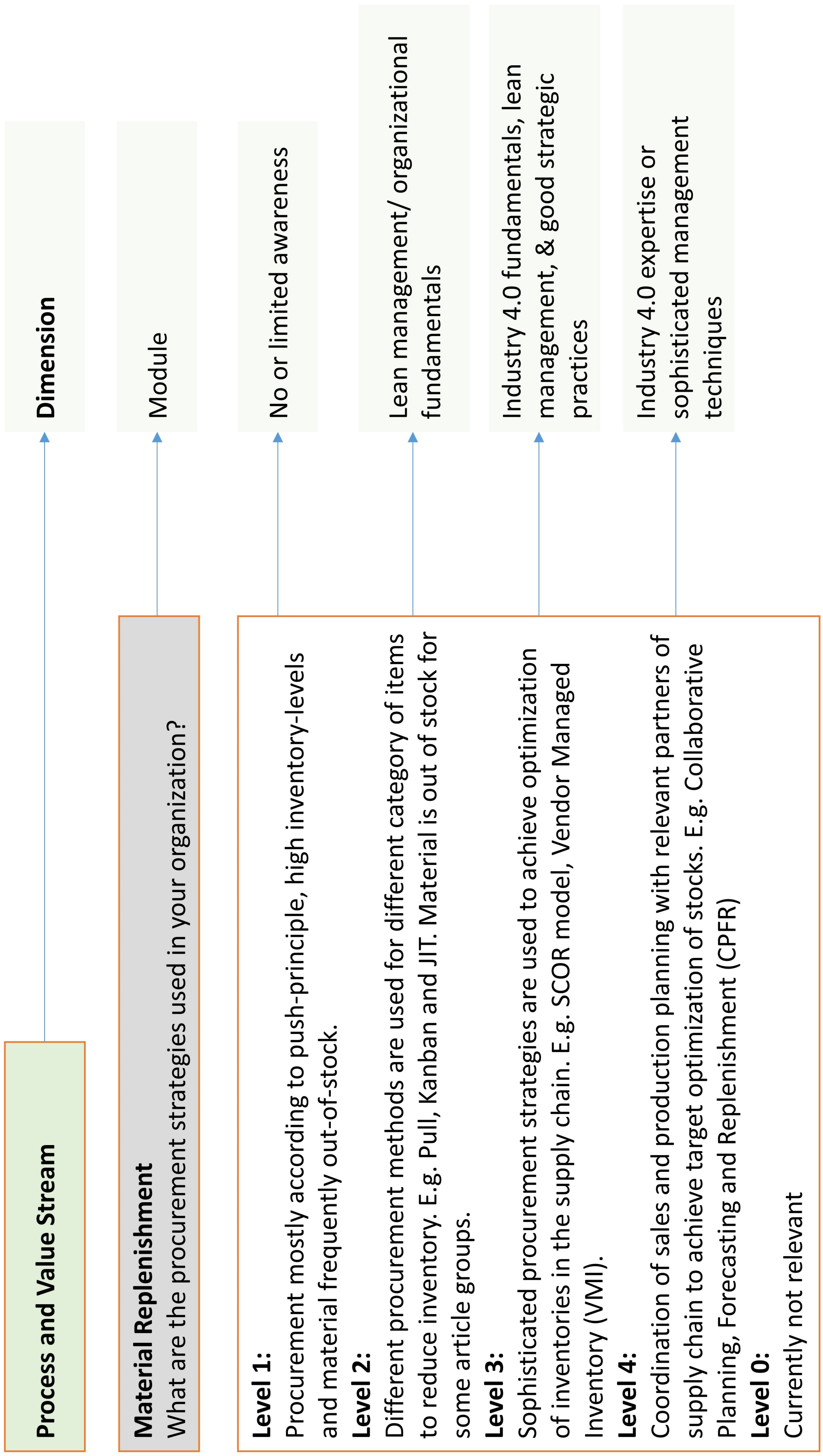

Figure 2.5: Example of the module: Material Replenishment

Chapter 3

Assessment of Manufacturing Companies in Grande Région

3.1 Background

The aim of the SAT is that the companies can self-assess the maturity of lean and I4.0 and set clear targets for transformation towards higher maturity levels. The assessment tool uses a holistic approach for production area covering the aspects of lean, vertical digitalization (internal hierarchy) and horizontal digitalization (horizontal partners along the value chain). The tool has a comprehensive structure where each module is explained in detail based on the feedback from the manufacturing companies in Greater Région (see section 2.6). The modules' level descriptions are based on the presumption that LPS or efficient manufacturing processes are a prerequisite for I4.0. Even though these levels are defined in the Likert item fashion, they are still quantifiable because there is a uniformity in the way each module is structured (see Figure 2.5). Based on the level descriptions provided in the SAT, the respondents of the questionnaire can clearly identify next maturity level and set their targets autonomously.

Respondents

The SAT is sent out to manufacturing companies in Grande Région in the form of a survey. Before September 2020, a total of 63 companies responded to the questionnaire out of which 19 were small-sized, 27 were medium-sized, and 17 were large-sized. In majority of the companies the respondents were CEOs, line-managers of the production facilities, and IT representatives. Some modules can only be answered by IT responsible of the company. Therefore, more than one respondent from the same company must be present for the assessment. Additionally we collected responses from operators on the shop-floor in some companies for better understanding of the company's processes.

3.2 Analysis of assessment data

The module construction matched the concept of a Likert item, in which respondents were asked to rate a statement (Brown, 2011). The data received from the respondents is ordinal as clear ordering of various level descriptions are presented in each module. The application of averages and statistical evaluation is justified for this analysis because the intervals between each level is spaced equally with a defined structure (Figure 2.5). The analysis on the data collected is carried out in two layers: macro and micro layers. Macro analysis covers the dimension level analysis while the micro analysis focuses on the modules. Moreover, a correlation test is conducted to identify the redundancies among the modules before performing the macro and micro analysis.

3.2.1 Correlation test

Analysis of the collected data started with a correlation test to identify association between the modules of SAT. As explained in section 2.5.3, two-step Delhi method was used to reduce the number of modules from SAT. However, it is important to find out the redundancies in the model before analysing the data.

Kendall's Tau (WarwickUniversity, 2010) correlation test is used to evaluate the relationship between modules. This test measures the ordinal association between two measured quantities, hence appropriate for the ordinal data. The correlation coefficients can take values between -1 and +1. A correlation coefficient closer to +1 indicates a positive relationship and a correlation coefficient closer to -1 indicate a negative relationship. A value of 0 indicates that the two variables are not correlated to each-other (Frost, 2018).

The heat-map in Figure 3.1 shows the correlation matrix obtained after applying Kendall's Tau correlation test to every module pair. None of the modules have strong positive relationship between each other. However, the following pairs Strategic Target Planning (STP) and Strategic Implementation Planning (SIP), Error Prevention (EP) and Resource and Ecological Sustainability (RES), Simulation (SM) and Material Replenishment (MR) showed a positive relationship with correlation coefficient values between 0.6 and 0.63.

Based on the correlation with Kendall's Tau method on the survey data it is proved that there is no strong relationship among modules and hence there are no significant redundancies.

3.2.2 Macro analysis

Macro analysis is done at the dimension level (layer 1) to understand the maturity of the companies in each dimension. In Macro analysis, the dimensions are divided in to two categories. Dimensions such as Strategy, Organization, and Personnel are classified as managerial dimensions. The other two dimensions namely Process and Value Stream, Methods and Tools belong to technical dimensions. First the average maturity level of each dimension is calculated. The results are shown in Figure 3.2. Process and Value Stream has an average score of 2.05 while Methods and Tools averaged at 2.30. Furthermore, none of the dimensions averaged higher than 2.63, indicating that the Greater Region's companies are still in the early stages of digital transformation. As this analysis

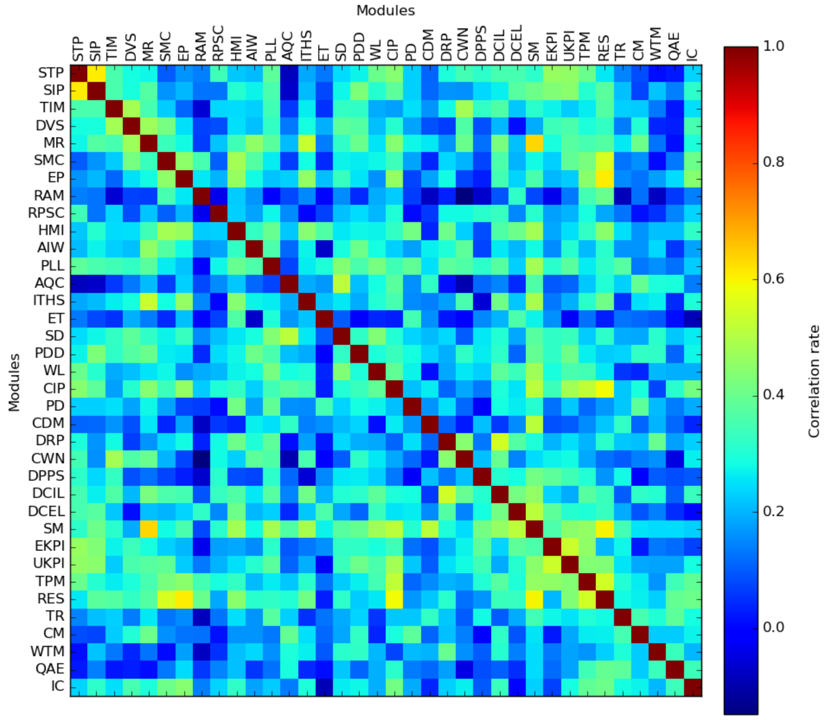

FIGURE 3.1: Kendall Tau Correlation Score among the modules of SAT

is performed on a sample of data there needs to be a further hypothesis test to confirm its statistical significance (in Section 3.2.3).

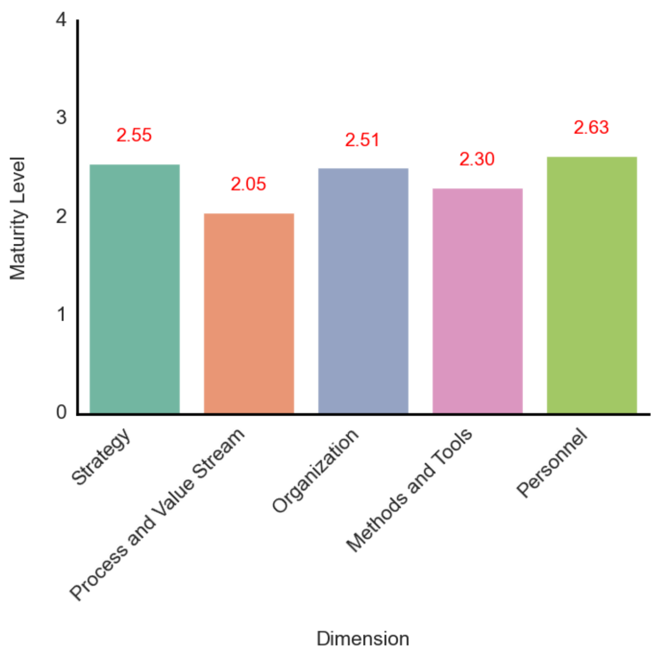

FIGURE 3.2: Average enterprise maturity level for each dimension of the SAT

A more detailed visualization is given in Figure 3.3 which represent maturity levels distribution through box-plots. In Strategy, Organization, and Personnel dimensions 75% of the values lies below level 3. While for the technical dimensions, 75% of values lies below level 2.5.

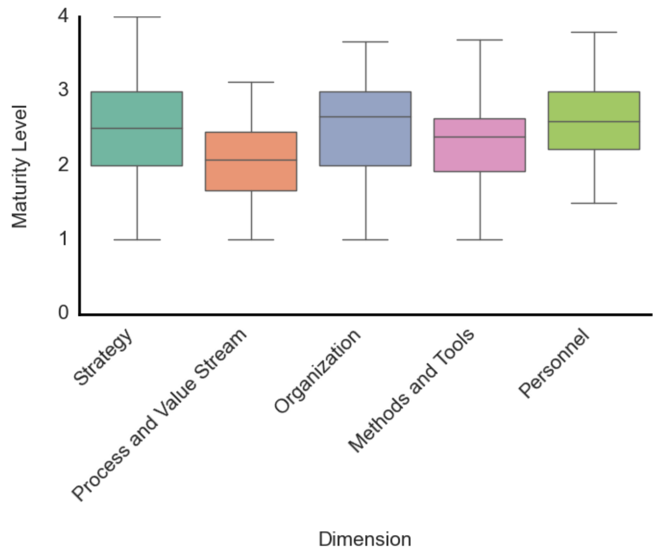

FIGURE 3.3: Distribution of enterprise maturity levels for each dimension of the SAT

The results of macro levels showed that the technical dimensions (Process and Value Stream, Methods and Tools) are less matured in enterprises of Greater Region compared to managerial dimensions (Strategy, Organization, Personnel).

Even though average values provide valuable insights, a statistical significance is only achieved through hypothesis testing. The next section presents the hypothesis testing on the sample data received from manufacturing companies in Grande Région.

3.2.3 Hypothesis testing

The responses to the questionnaire's (Likert item type) were averaged across each module to create an average score for each company's dimension. This results in Likert-type data and allows hypothesis testing analysis. Initially the normality of the data is verified using Shapiro Wilk test in order to decide whether to use parametric or non-parametric tests. According to the results, the sampled data from each dimension follows the Gaussian distribution. Therefore, use of parametric tests such as a t-test is justified. As mentioned earlier, Process and Value Stream is the least matured dimension from macro analysis. In order to test this observation for statistical significance, a t-test with a level of significance $\alpha = 0.05$ is conducted. The results of the parametric test are shown below.

- H_0: μ Process & Value Stream $\geq \mu$ Strategy
  H_1: μ Process & Value Stream $< \mu$ Strategy
  Result: t-test = 4.76 & p=5.16 e^{-06}

- H_0: μ Process & Value Stream $\geq \mu$ Organization
  H_1: μ Process & Value Stream $< \mu$ Organization
  Result: t-test = 4.75 & p=5.5 e^{-06}

- H_0: μ Process & Value Stream $\geq \mu$ Methods & Tools
  H_1: μ Process & Value Stream $< \mu$ Methods & Tools
  Result: t-test = 3.02 & p=0.003

- H_0: μ Process & Value Stream $\geq \mu$ Personnel
  H_1: μ Process & Value Stream $< \mu$ Personnel
  *Result: t-test = 6.68 & p=7.10*e^{-10}

The null hypothesis H_0 is rejected when p/2 < 0.05 and t-test >0. For all cases above, the null hypothesis was rejected based on the t-test results. Therefore the dimension Process and Value Stream is significantly less matured than the other dimensions.

Another dimension with an average maturity value less than 2.5 is Methods and Tools. The hypothesis given below are to check if this result is statistically significant compared to other dimensions. It is already proved that Process and value Stream is less matured than the Methods and Tools therefore the comparison is not shown again.

- H_0: μ Methods & Tools $\geq \mu$ Strategy
  H_1: μ Methods & Tools $< \mu$ Strategy
  Result: t-test = 2.18 & p=0.031

- H_0: μ Methods & Tools $\geq \mu$ Organization
  H_1: μ Methods & Tools $< \mu$ Organization
  Result: t-test = 1.87 & p=0.063

- H_0: μ Methods & Tools $\geq \mu$ Personnel
  H_1: μ Methods & Tools $< \mu$ Personnel
  Result: t-test = 3.54 & p=0.0005

For all cases above based on the result of the t-test the null hypothesis was rejected, therefore the Methods and Tools is significantly less matured than the Strategy, Organization, and Personnel dimensions.

3.2.4 Micro analysis

Micro analysis is done at the module level (layer 2). Research on least matured modules add more value to the needs of enterprises in Grande Région. Therefore, a study on the least matured modules is carried out in this section to select the potential research areas. Additionally, an analysis of the relationship between the company size and the levels of maturity is presented.

The least matured modules and their data are shown in Figure 3.4. Internal Transport Handling and Storage (ITHS) is the least matured module with an average maturity score of 1.49/4 followed by Error prevention (EP, 1.69/4), Digital Control of External Logistics (DCEL, 1.79/4), Human Machine Interface (HMI, 1.8/4), and External Transport (ET, 1.82/4). Out of these five modules, ITHS, DCEL, and ET have logistics focus and hence they are not explored further in this research. EP and HMI fall under manufacturing domain. On one hand, research on EP has the potential to explore the needs of manufacturing companies in relation to data-readiness for digital transformation. On the other hand, technologies such as Augmented Reality has the capability to improve the HMI by efficient information exchange and real-time assistance. Therefore, the further research in this thesis is carried out on EP (Chapter 5) and HMI (Chapter 6).

In the EP module, the majority of the companies (50 out of 63) are at Level 1 or 2. During the assessment with company representatives, it is understood that the companies in the greater region use legacy equipment in their daily operations. These legacy machines do not produce data for real-time monitoring. Therefore, the companies employ manual monitoring and diagnosis in case of defects and break-downs. This indicates that companies are not data-ready to do predictive maintenance for preventing errors and downtime. None of the companies are at level 4 in the EP module. This level requires machines to produce and understand the data for real-time monitoring, statistical forecasting of critical production conditions, and be able to perform real-time autonomous actions in case of defects and break-downs.

Similarly for the HMI module, the majority of the companies (51 out of 63) are at Level 1 and Level 2. These levels consists of displaying machine information locally or on the central screens. The higher maturity levels requires continuous usage of mobile and portable devices and usage of Augmented Reality systems for efficient information exchange. As the AR in manufacturing is one of the least researched ares, there are ample opportunities for research in terms of improving HMI using AR.

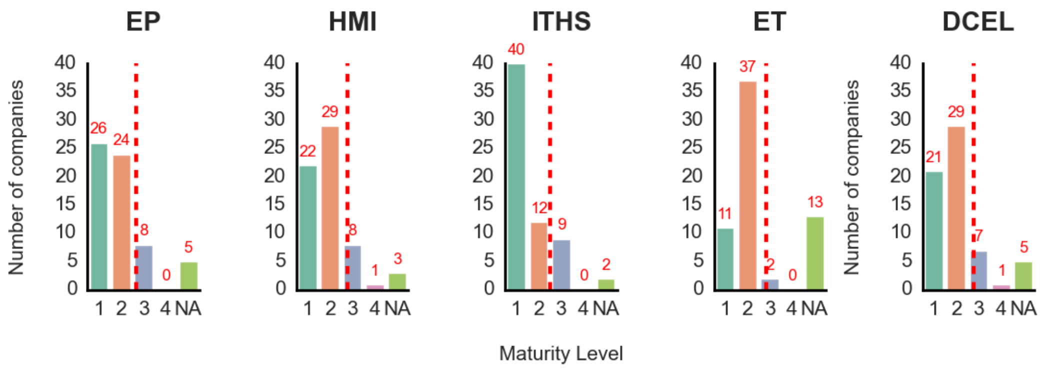

FIGURE 3.4: Five least matured modules in average out of thirty-six modules. Vertical red line indicates the average maturity level score for the module.

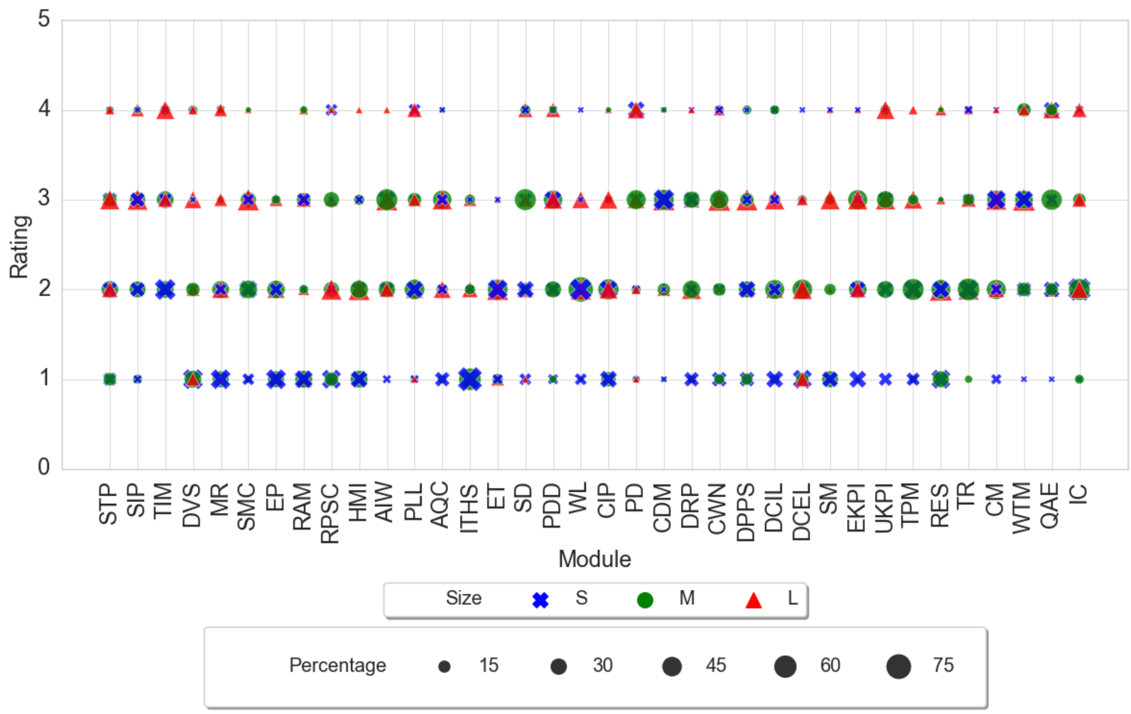

FIGURE 3.5: Distributions of company size across maturity levels of different modules.

After the analysis of the least mature modules, an analysis on the effect of company size on the maturity levels is presented. An overview of small, medium, and large companies and their responses to the self-assessment tool is presented in Figure 3.5. The population of small companies is seen mostly in Level 1 and Level 2. Moreover, in small companies, modules like Product Design (PD) and Quality Awareness of Employees (QAE) are spaced in level 3 and level 4 because of their inherent characteristics of producing customized products for their customers (Kolla, Minoufekr, and Plapper, 2019). The responses of medium companies are mostly spread in Level 2 and and Level 3. However, for the modules Internal Transport Handling Systems (ITHS), Simulation (SM), and Resource Ecological Sustainability (RES), the medium companies are still in the unaware or limited knowledge level. For large companies, responses are not concentrated in one or two levels. They are seen in high percentages in Level 3 and with lower percentages in Level 2 and Level 4. Nevertheless, looking at the sample data, some large companies in Greater Region started transformation towards digitalization in many modules. However, EP and HMI still are the lowest mature modules in the manufacturing domain irrespective of the company size.

The next chapter presents a holistic methodology to deploy lean and I4.0 technologies in manufacturing companies. This methodology is further used in subsequent chapters to design case studies in AR and IIoT. These two tools correspond to the least matured modules that are analysed in this chapter. The tools are first prototyped in the laboratory before deploying in the partnering companies.

Chapter 4

The Methodology

This chapter explains how manufacturing companies can transform their current manufacturing processes to higher maturity levels with regards to lean and I4.0, using a holistic methodology. The term holistic is used to indicate that the actions taken toward digital transformation are interconnected, and that all of the components must be considered together. The term also indicates that the methodology considers both human as well as technical aspects of digital transformation and provides an end-to-end solution for manufacturing enterprises.

4.1 Introduction

The digital transformation of manufacturing industry is following two major trends. The first trend is driven by the increasing market demands and gaining a competitive advantage over the competitors. This could be considered as "Industry 4.0 push". On the other hand, companies are creating different applications based on a clear objective to improve a specific process or a machine using lean or I4.0 technologies. This can be argued as "Need-based pull". The methodology presented in this research is majorly aimed at need-based improvement opportunities because such transformations have clear and measurable targets. The lean or digital transformations emerging from a need has the following characteristics: an existing problem, clearly defined objectives, a technical road-map, and a post-evolution.

4.2 Methodology

The methodology developed in this research consists of four phases: Maturity Assessment, Improvement Potentials, Technical Road-map, and Post Evaluation. The four phases are illustrated in Figure 4.1.

4.2.1 Maturity assessment

The fist phase in the digital transformation journey is the maturity assessment of the current manufacturing processes. This phase is important to find out the as-is status of the company using the Self-Assessment Tool presented in Chapter 2. In this phase, different participants from various departments in the company are selected to answer the questionnaire. Inputs from different people gives a comprehensive picture on the maturity of the company. Individuals from top management, line managers, and shop-floor should answer the

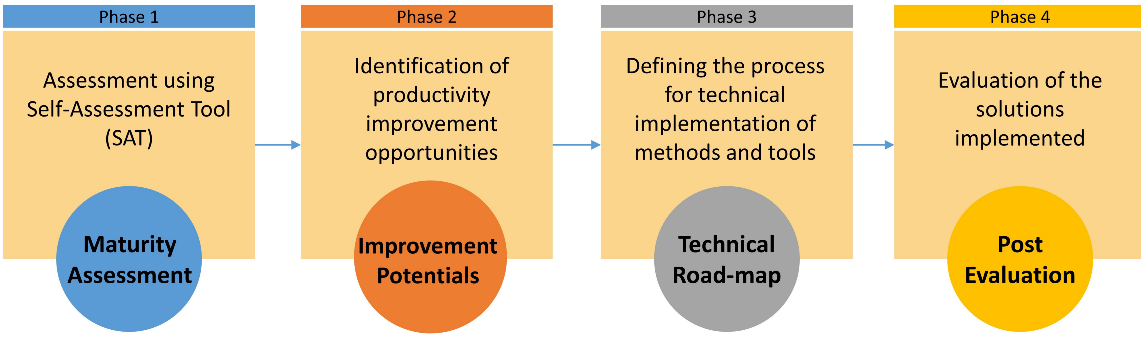

FIGURE 4.1: The 4 phases of the holistic methodology

questionnaire either individually or together. This allows for a wide range of viewpoints, from the shop-floor workers to the top management. The output of the maturity assessment should be visualized in order to present the results to management. The assessor should comment on the responses to the modules to get a deeper understand of the enterprise wherever necessary. An optional last stage is to have a semi-structured interview covering the aspects of organizational structure, productivity, costs, results, production processes, challenges, change management, and innovation in the company to gain a deeper insight into the enterprise. Figure 4.2 depicts the stages of maturity assessment.

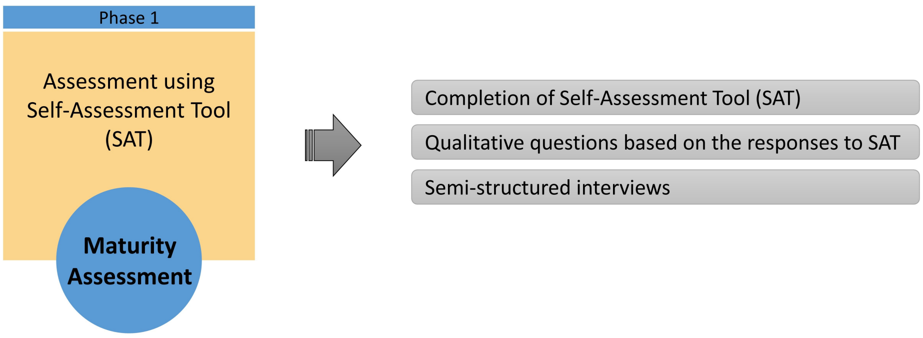

FIGURE 4.2: Phase 1: Maturity Assessment

4.2.2 Improvement potentials

From the maturity assessment, the modules that are rated level one or level two are the most interesting since they have the highest potential for improvement. Level three can be included in especially well-positioned enterprises where only a few modules are evaluated as level one or two. In SMEs, the appropriate transformation strategy includes a tailored technology implementation along with incremental modifications using lean methods. In addition to the maturity assessment, the viewpoint of the top management and workers must be considered to understand the company priority areas, expectations etc. This is necessary in order to have a complete view of the problem and increased acceptance of the subsequent implementation. In order to add more value to the improvement potentials identified in the maturity assessment, an external analysis of the manufacturing processes is highly recommended. Especially in SMEs, the value chain is very short so it's easy to track the processes and get a holistic view of the functionality and bottle-neck processes of the company. The external analysis of the process typically include a tour to the shop-floor along with plant manager or any line manager who understands the complete manufacturing process. The insights gained from the external analysis are crucial in decided the most value-adding improvement potential for further implementation. At the end of the phase 2, define an action plan to implement solutions for identified areas. A solution could be the adaption of I4.0 technology for a specific problem or using lean tools to improve the existing processes etc. Figure 4.3 depicts the stages of phase 2 of the methodology.

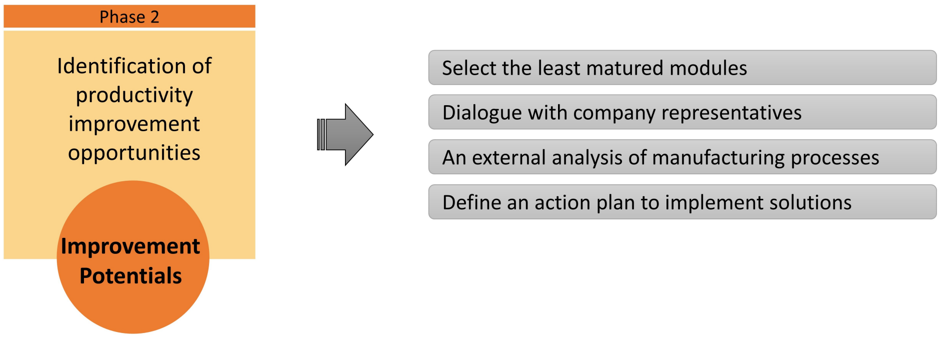

FIGURE 4.3: Phase 2: Improvement Potentials

4.2.3 Technical road-map

The road-map phase consists of three sub-phases: Preparation, Experiments, and Application. The central component of the preparation phase is to highlight the importance of having a change management methodology that is appropriate for the enterprise. This can be developed together with the company based on the insights gained from the previous phases. During the preparation phase, a method or a tool or a technology is selected to improve the identified potentials in phase 2. An implementation team can be deployed to plan and manage the technical implementation. The planning procedure should include all personnel in the affected area. The worker's involvement has the added benefit of familiarizing them with the unfamiliar settings and technology, which helps them to accept the changes relatively easily. Because their expertise is unique, workers should be able to freely express their concerns and recommendations for improvements, as well as actively participate in the process redesign.

The chosen technique, tool, or technology will be tested in a lab or pilot environment during the experimentation phase. For instance, if phase 2 led to the adoption of new technology to improve the processes, a suitable pilot test guarantees the technology's proper operation and identifies areas for improvement. It is recommend that the pilot test is already carried out by employees who will use the technology after the full deployment. The next step is to identify the challenges faced in the pilot environment and collect feedback from company and the employees. In the spirit of Continuous Improvements (CI) or Kaizen, the feedback is helpful for analyzing the difficulties encountered and making

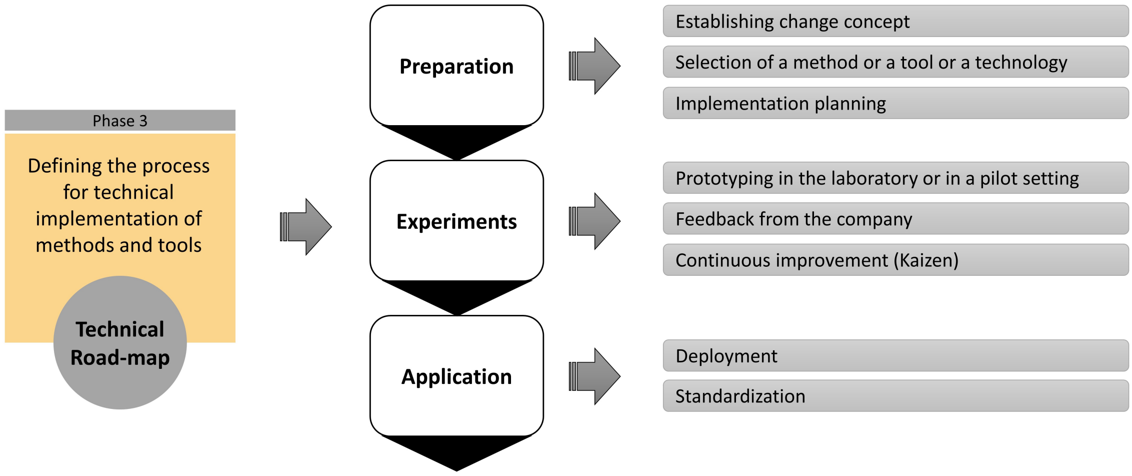

FIGURE 4.4: Phase 3: Technical Road-map

further improvements. This is an iterative process until an optimal solution is devised and tested. The experiments phase is completed by defining and documenting the best practices. Figure 4.4 depicts the stages of phase 3 of the methodology.

The piloted or laboratory tested concept is expanded over the selected process in the application phase. It is important to note that the application phase is the most time consuming phase as it often requires the restructuring the existing layout and training the employees. Therefore, planning of application phase for rolling out the new technology is a prerequisite in order not to overwhelm the operators. All the employees effected by the new technology are communicated with necessary documentation of the process and new work steps. For the purpose of making sure that all the employees understand the new work steps, a workshop or internal training can be organized to reduce ambiguities.

4.2.4 Post evaluation

Change is often faced with resistance and it is not long before the employees go back to old work steps. This can happen mainly because of two reasons; not enough training on the new technologies and the new solution is not adding as much value as expected. Therefore, a frequent inspection of implemented solutions must be carried out. For a broader perspective, an assessment of the implemented solutions in the context of sustainability can be executed to measure the performance in economic, ecological, and societal perspectives. During the post-evaluation phase, the assessment using SAT can be repeated to see the difference between 1st and 2nd self-assessments. Figure 4.5 depicts the stages of phase 4 of the methodology. During the post-evaluation phase, care must be given to assess the following three aspects:

- Usage: Whether the technology is being used in accordance with the initial purpose?
- Satisfaction: Satisfaction with the project results, technical quality, and usability.

- Effectiveness: Whether the technology is benefiting the users directly?

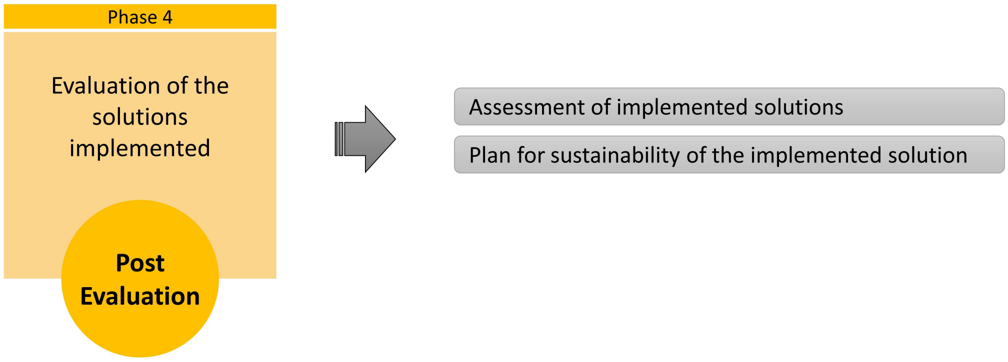

FIGURE 4.5: Phase 4: Post Evaluation

The methodology developed in this research is further applied to industrial environment to validate it's suitability to deploy I4.0 in manufacturing enterprises. Chapter 5 and Chapter 6 presents 2 case studies in the two least matured modules of SAT (section 3.2.4) based the methodology presented in this chapter.

Chapter 5

Industrial Internet of Things (IIoT)

This chapter presents the overview of IIoT which is one of the least matured I4.0 technology in manufacturing enterprises. The chapter also includes a case study that implements IIoT in an industrial environment using the methodology described in Chapter 4.

5.1 Introduction

Industrial Internet of Things (IIoT) combines different disciplines such as sensor technology, retrofitting technology, and data analytics to have better control over the manufacturing processes. Adopting IIoT in the current manufacturing environment can benefit companies with increased production efficiency, reduction in down time, and increased profits (Burresi et al., 2020). However, there are inherent difficulties with IIoT adoption for the industries, particularly for SMEs. The majority of SMEs still use legacy equipment, which are incapable of data exchange. This raises the first problem that SMEs are not data-ready to benefit from IIoT. Additionally, SMEs don't comprehend the advantages and difficulties associated with IIoT. Another barrier to deploying IIoT is SMEs' lack of knowledge of new manufacturing technologies and employee skills (Kolla, Minoufekr, and Plapper, 2019).

The primary goal of IIoT, as previously noted, is to have more control over what happens in the plant. This is accomplished by collecting data or information and making it accessible in a helpful manner to anyone who requires it, whether it be a shop-floor worker or the top management of the organization. These details could include the rate at which a machine is operating, the quantity of a specific part in stock, the number of sick employees, and most importantly, the current status of the production machinery. This is already possible in some ways. However, IIoT implementation would make it more uniform, easier to do, and take it further than the simple data gathering. Most factories are built over the years, and additions to them are made over time, which means that the companies can have machines, sensors, Programmable Logic Controllers (PLCs), and other devices that have different ages, interfaces, and are from different manufacturers in the same factory. This combined with the fact that manufacturers have their proprietary software, interfaces, etc. makes it extremely difficult to unify data and information.

Furthermore, another hurdle in the digital transformation of an SME is the lack of investment needed to replace legacy machines with advanced machinery.

Moreover, it is unclear either from research or real-world examples which path to take for a plant to be IIoT ready. The current research presents retrofitting as a starting point for SMEs with legacy machines towards the digital transformation journey. Retrofitting deals with the idea of upgrading the existing legacy machines without compromising their functionality in preparation for IIoT. As per Lins et al. (Lins and Oliveira, 2020), retrofitting is directly linked to the longer life of the old machines (sustainability), productivity, and increasing the technology level (to I4.0). Moreover, the concept of "smart" retrofitting is gaining popularity as well, where virtual counterparts such as smart glasses are added to physical items to gain control of the manufacturing process (Al-Maeeni et al., 2020).

The case study presented in the section 5.3 is carried out in an SME located in Luxembourg. Therefore, a retrofitting approach that suits the needs of an SME are researched further.

5.2 State of the art

A successful implementation of IIoT requires the integration of production processes with digital technologies to enable extended benefits such as predictive maintenance, and real-time monitoring of production processes etc. The existing literature presents the retrofitting of machines in two different categories (Zambetti et al., 2020): "industry 4.0 push" and "need-based pull." In the first category, the research aims to develop and retrofit all the equipment to provide connectivity and data collection capability for legacy machines, which is a prerequisite for transition to I 4.0. The second category focuses on specific equipment and improving its efficiency, productivity, predictive maintenance capability, etc. Nevertheless, the basic needs across both categories stay the same: external sensors, data connectivity, databases to store the data, data processing, data analytics for predictive maintenance, and security. The authors in (Wöstmann et al., 2019) employed retrofitting and demonstrated the development of a predictive maintenance model from the data collected using low-cost embedded systems and sensor technology. The case study was focused on a robotic cell for the detection of abnormalities and forthcoming failures. The researchers in (Di Carlo et al., 2021) highlighted the importance of retrofitting and its role in predictive maintenance in a process industry. They performed retrofitting in a two-phase process plant and developed a framework to guide the transition process from a classical process plant to an Industry 4.0 ready process plant. They showed that the retrofitted system allowed efficient maintenance and operator safety management using the proposed anomaly detection and simulation platform.

Jeschke et al. (Jeschke et al., 2017) talks about the start of IIoT and defines some of the focus points of it which could be adapted in the context of retrofitting. Preuveneers and Ilie-Zudor (Preuveneers and Ilie-Zudor, 2017) goes into details about the state of development of different subjects that are included under the IIoT umbrella. However, the research is still at a superficial level of details.

In current literature, there are two publications focused on the security aspects of IIoT in manufacturing domain. These papers are relevant for retrofitting scenario as in SMEs, retrofitting can be seen as the first step towards IIoT. In the first paper (Sadeghi and Yuen, 2015), they look at the whole I4.0 and identify potential risk factors. They do not detail any specific security problem but show where in each part of the development of I4.0 there could be problems. The second one is (Tedeschi et al., 2017) and they focus on the development of an architecture that enables secure communication between sensors and the rest of the communication system of a company.

Most of the publications in the recent literature don't present the details on how they did the retrofit (a general technical architecture) and what software and hardware tools are used. Some publications lack the cloud connectivity while almost all of them don't pay attention to security issues concerning the retrofitting. Therefore, the case study presented in the next section addressed the research gaps and presented practical solution for retrofitting in the context of IIoT.

5.3 Case study

This section is dedicated to the practical application of the methodology (Chapter 4) in laboratory and industrial environments.

5.3.1 Company overview

The Luxembourgish company GCL Technologies is a subsidiary of the Guala Closures Group. The entity in Luxembourg is an SME that scouts, pilots, and validates the state of the art technologies and transfer them to the partner factories around the globe. GCL Technologies is specialized in NFC technology development, 3D printing, and cutting. Based on the demand, they manufacture closures for beverage bottles labelled with an NFC tag. The company has less than 15 employees in Luxembourg. However, their innovative applications using modern technologies puts them in the front runners and early I4.0 adaptors.

5.3.2 Maturity assessment

In the first phase, a maturity assessment of existing processes is conducted using the Self Assessment Tool (SAT) developed in Chapter 2. The SAT is answered by an executive officer who is aware of the manufacturing processes in the company as well as works closely with the top management for strategic decisions. During the data gathering using SAT, each module is read out loud to the respondent with some practical examples from industry to avoid misinterpretations. Out of 36 modules, 5 modules were answered as not relevant for the company. The result of five dimension assessment at GCL technologies is shown in Figure 5.1. Strategy and Personnel dimensions are more mature in the GCL Technologies than the average of Greater Region. However, the company positions itself slightly below the Greater Region in other dimensions. The dimensions with the least maturity are Process and Value Stream, Methods and Tools as both of them are rated below level 2 in the self assessment. The outcomes of all the five dimensions based on SAT and semi-structured interviews with the company representative are discussed below.

Note: Appendix A gives the full form of acronyms shown in the Figure 5.2, 5.3, 5.4, 5.5, & 5.6.

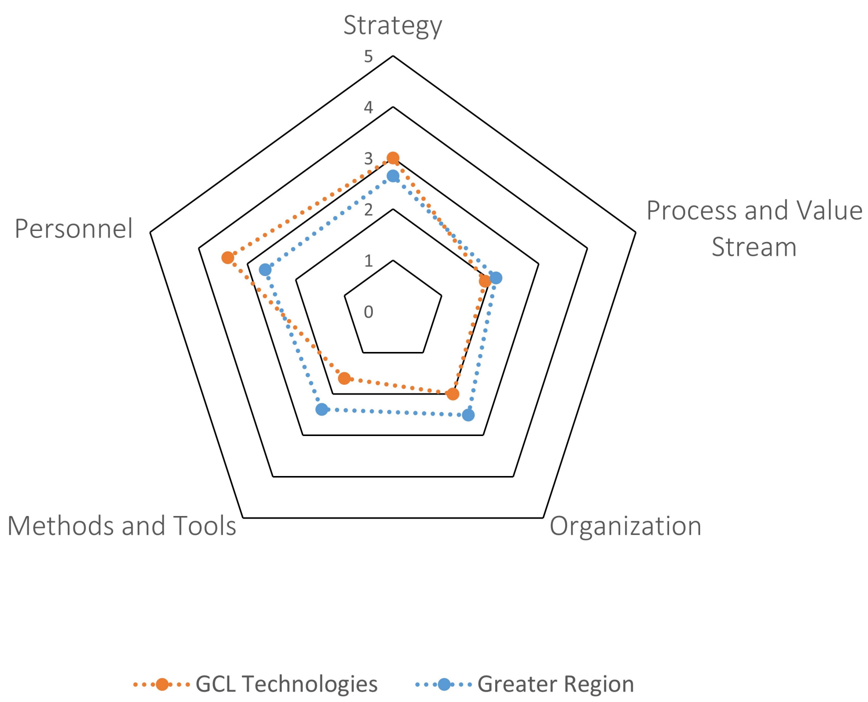

FIGURE 5.1: Overall assessment at GCL Technologies

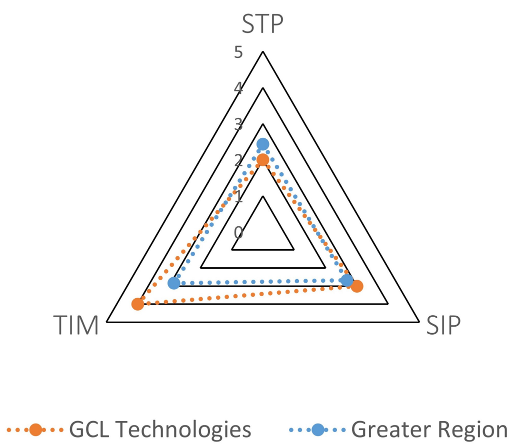

FIGURE 5.2: Assessment of Strategy

In the assessment of Strategy dimension, it is evident that the company is slightly ahead of it's counterparts in Greater Region. The company has measurable targets for short-term and it's own action plan to implement them. As mentioned before, the company also has formal processes to scout for the innovations and integrate new trends in manufacturing into their strategic action plan. Therefore, the improvements to strategy dimension are regarded out of scope for this research.

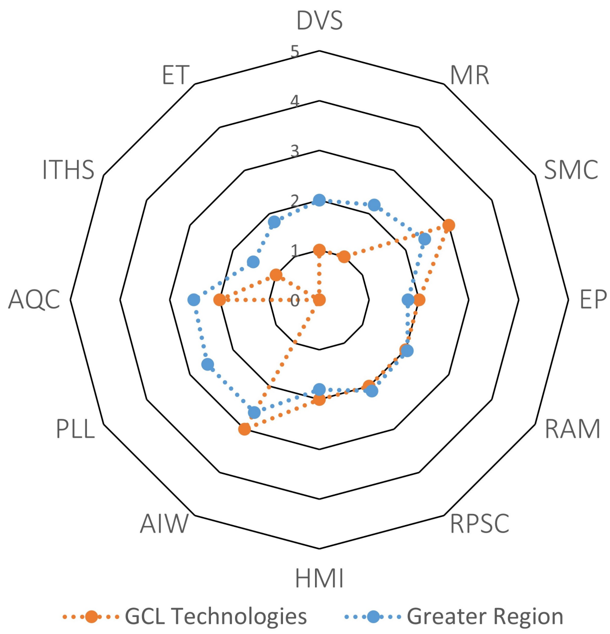

FIGURE 5.3: Assessment of Process and Value Stream

Process and Value Stream is one of the least mature dimension in GCL technologies. The company has no systematic analysis of activities in production and supply chain as the innovation centre only manufacturers based on demand and not a mass producing entity. However, the production machines in the company provide digital information of machine status with the support of a manual intervention. In terms of error prevention, the company monitors critical production parameters using PLCs installed in the production machinery. Currently, they are manually diagnosing and removing the defects as they arise. During the semi-structured interview, the company representative expressed his interest in improving the error prevention module for real-time monitoring without a manual intervention. The company also have a systematic process to reduce the changeover times using parallelization of activities.

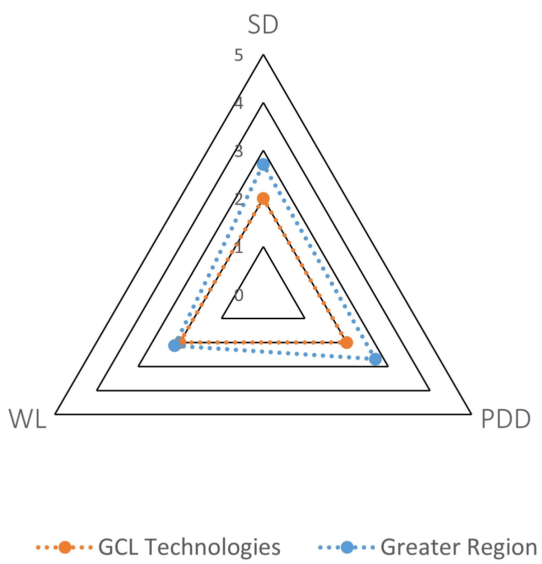

FIGURE 5.4: Assessment of Organization

In the assessment of Organization dimension, it is revealed that the company is positioned slightly below of it's counterparts in Greater Region. The company uses simple techniques such as 5S for a clean and orderly work place environment. The processes are documented but the information is not directly available at the workplace. However, the company has already initiated steps to digitize work instructions at the production machinery. The standardisation of activities are done at the workstation level because the production is discrete rather than a continuous process.

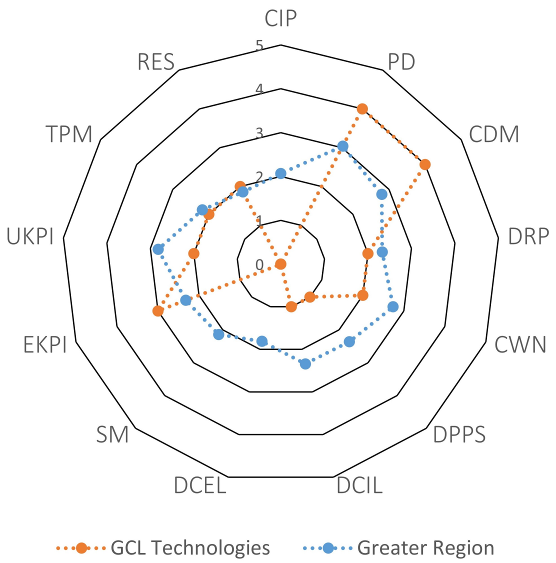

Figure 5.5: Assessment of Methods and Tools

Methods and Tools is the least mature dimension at GCL technologies. The production control is managed by excel spreadsheets which is considered as a least matured level according to SAT. Moreover, the company employs early preventive maintenance for maintaining the production machines. This is because the data generated by the machines are not further used for real-time to monitor or predictive maintenance. During the semi-structured interviews, the company representative quoted that it is of the strategic importance to the company to change the situation of machine breakdowns by employing solutions from new digital technologies.

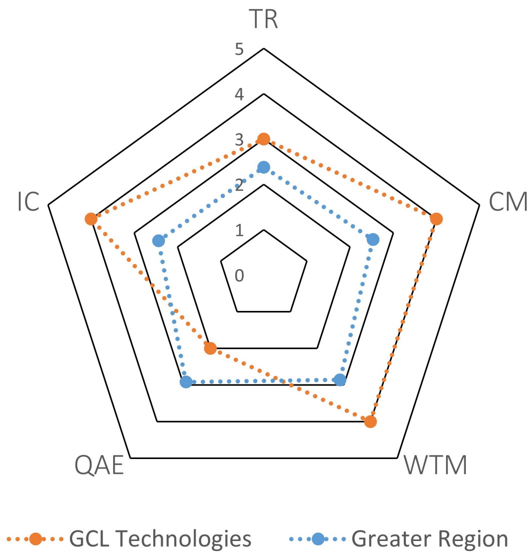

Figure 5.6: Assessment of Personnel

In the assessment of Personnel dimension, it is evident that the company is slightly ahead of it's counterparts in Greater Region. The company has a individual staff development policy and most of the employees are involved in the change management aspects related to design, process improvements etc. However, improvement opportunities in the personnel dimension is out of scope for this research.

5.3.3 Improvement potentials

The value-adding improvement opportunities lies in the modules that are of lower maturity levels such as level 1 and level 2. According to SAT, there are five modules that are at level 1 and fourteen modules are at level 2. Dialogue with head of production as well as operators on the shop-floor revealed that machine break-downs is an ongoing issue on the shop-floor and this is caused because of unknown reasons. Further analysis of internal process revealed that the data from the machines is not saved outside of the machines and is incomplete. Therefore, they can't use the data in monitoring and control of the machines. The module Error Prevention (EP) of SAT deals with defects and breakdowns of the machine. As a result, the module EP is selected as a highest value-adding module for the company and this is aligned with the expectations of the company. Table 6.2 shows the outcomes of maturity assessment, dialogue with internals, and external analysis of the processes.

5.3.4 Technical road-map

Preparation

Retrofitting the production machinery especially the labelling machine which has frequent breakdown is selected for the case study. By adding additional sensors as a part of retrofitting, the machine parameters can be monitored in real-time, which could improve Overall Equipment Effectiveness (OEE) of the machine. The company's network should then be made accessible to this data so that it may be processed and analyzed. The analysis of the data is useful in making decisions related to predictive maintenance of the machine.

Experiments

The experiments stage started with prototyping retrofitting technology for a legacy machine in the laboratory of University of Luxembourg. As a guideline, a technical architecture for retrofitting in the context of IIoT is developed. The architecture provides a broad perspective of IIoT that can be utilized while retrofitting any legacy machine. There are several steps involved in integrating legacy equipment (physical layer) with reporting and analytical systems (cyber layer). To successfully retrofit, collect data, and build databases for legacy machines, these tasks must be carried out in a sequential order. In order for a company to properly enter the I4.0 space, the databases must be connected to monitoring and analytical tools. Each stage of the integration process requires the use of particular hardware and software.

Maturity Assessment Results		
Dimensions	**Level 1 evaluated modules**	**Level 2 evaluated modules**
Strategy		Strategic Target Planning
Process and Value Stream	Design of the Value Stream Material Replenishment Internal Transport Handling and Storage	Error Prevention Remote Access to Machines Real-Time Production Scheduling and Control System Human-Machine Interface Adaptability and Quick Changeover
Organization		Standardization Process Definition and Documentation Workstation Layout
Methods and Tools	Digital Production Planning and Scheduling Digital Control of Internal Logistics	Digital Representation of the Production Company-Wide Network Utilization of Indicators Total Productive Maintenance Resources and Ecological Sustainability
Personnel		Quality Awareness of Employees
Results from Dialogues with Internals		
Issue	**Consequence**	
Machine Breakdowns	High cycle time Reduction in productivity Deviations from target throughput	
Material out of stock	Delays in production Lost revenue Losing customers	
Process Analysis Results		
Human errors while operating the machines		
Functioning issues with the production machinery		

Table 5.1: Summary of outcomes of Phase 1 & Phase 2

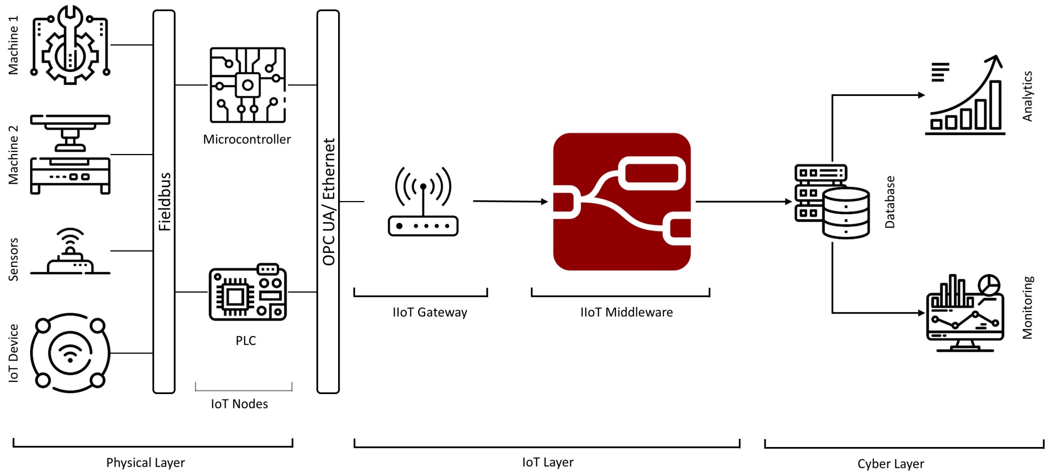

FIGURE 5.7: General architecture of IIoT in the context of retrofitting

The first step in the integration process is to upgrade the infrastructure of the legacy machines by retrofitting. At the beginning of retrofitting, the only infrastructure available is the machine itself. I4.0, however, requires that the machine is connected to the digital environment. Therefore, installing intelligent sensors, actuators, and IoT devices to the machine can create a foundation for integrating the real and digital worlds. Additionally, data extraction from machines is not guaranteed by upgrading the machines. Therefore, controllers such as micro-controllers, PLCs, or computers are introduced in this step, and they are referred to as IoT nodes. IoT nodes ensure that data is extracted from the sensors and connect the machine to the internet to facilitate the subsequent steps.

The second phase involves introducing a middle layer called IIoT gateway, which is further coupled to IIoT middle-ware, in order to provide a secure gateway between the physical and cyber layers. A standardized communication protocol is necessary for this. With the help of this protocol, data is sent between the machine and IIoT middle-ware accurately and quickly. The acquired data is finally kept in databases and transferred to a local edge computing device or a web-based software for analytical purposes. Figure 5.7 shows the general architecture of retrofitting a legacy machine to introduce it to the I4.0 environment.

To validate the general architecture presented in Figure 5.7, a column-drilling machine from the shop-floor is selected for retrofitting (Figure ??). This drilling machine has no sensors or any information-gathering capabilities. These machines are a classic example of legacy machines seen in SMEs and an ideal legacy machine to retrofit. The machine can offer a wide range of variables to measure. However, a decision was made to collect the critical variables such as drill speed and drill depth. A speed sensor in the form of a hall sensor that sits inside the top cover of the machine is added. For the functioning of the hall sensor, a small magnet is fixed to one of the disks that spins the drill. To measure the depth of the drill, an infrared distance sensor is retrofitted and placed on the stationary part of the column. In order to extract the data

FIGURE 5.8: Legacy machine (Contimac TB20)

from the machines, Raspberry Pi is chosen as a controller, and the sensors are connected to it with cables. The inclusion of a Raspberry Pi ensures extraction of the data and connects the machine to the internet via Ethernet protocol using LAN technology. Internet connectivity is the most critical feature for collecting and forwarding the data from machines to other software tools in the subsequent steps. Retrofitting of legacy machines is complex for many reasons, one of which deals with the type of output from the sensors. In this case study, the hall sensor provides digital output directly connected to the General Purpose Input Output (GPIO) of the Raspberry Pi. However, the infrared sensor gives an analog output; due to this, an analog to digital converter was added to the Raspberry Pi in the form of a Pi Hat and then connected to GPIO. This completes the hardware setup for retrofitting.

The gateway between the physical and cyber layer is achieved by installing an IIoT middle-ware software called Node-Red on the Raspberry Pi. Node-Red is a browser-based editor that has the benefit of being open-source and well documented, having a library of freely accessible nodes needed for the use of databases, and the reading of sensor data from multiple sources. Node-Red serves as an easy-to-use programming software that can combine various software and hardware interfaces, being it simple voltage readings or complex communication protocols used in industry. With an already existing node to access the GPIO Pins of the Raspberry Pi, one can quickly get the status of the pins on which the Hall sensor was connected. For the distance sensor, the manufacturer developed nodes for the use of Node-Red; this makes it easy to handle the signal that comes from the A/D converter connected to the pins of the Raspberry Pi. Both signals needed to be modified so that the needed information can be correctly displayed. The speed sensor, which simply switches from 1 to 0 each time the magnet passes in front of it, was connected in Node-Red to a node that calculates the frequency of a signal when it changes from 1 to 0. Then the frequency is multiplied by 60 to get the drill speed in RPM. The infrared sensor outputs a voltage from 0V to 3V and ranges from 10cm to

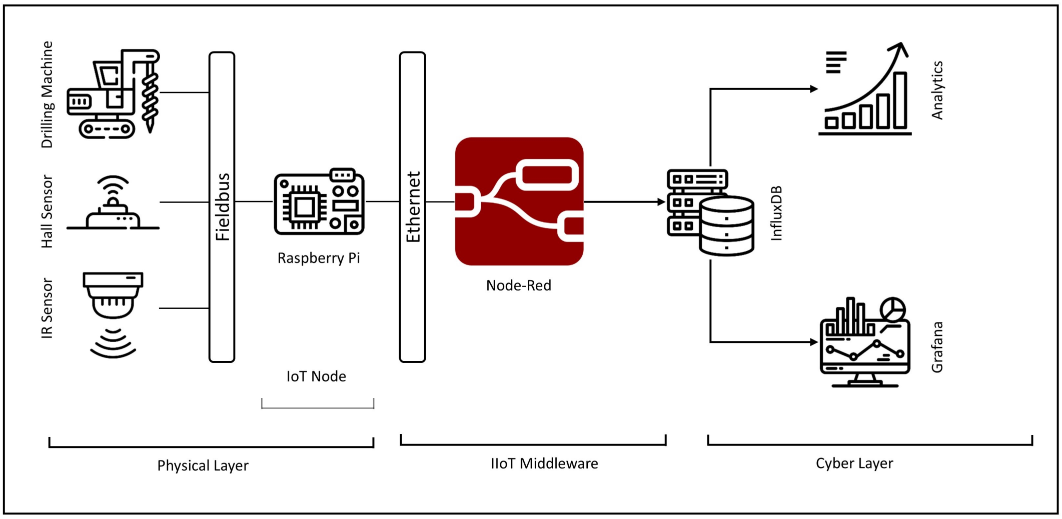

FIGURE 5.9: Adapted architecture of IIoT for laboratory implementation

80cm. To convert this voltage into understandable distance units, the output voltage for distances ranging from 10cm to 80cm was manually measured and curve fitted using MATLAB©. The output of a MATLAB curve fitting is a 3^{rd}-degree differential equation that can be easily programmed in Node-Red to get the distance in metric units.

To process the data received in Node-Red, two software tools are required. One is to store the data, and another one to do real-time reporting and analytics. We can use different software based on the amount of data collected and the needs of the company. However, in this research, InfluxDB is the choice of database because the software provides an in-built node in Node-Red, which reduces extensive interface development. In InfluxDB, the values are saved with a timestamp and the name given to those in Node-Red, such as speed, depth, and so on. For real-time reporting and analysis of the data, another software tool Grafana was used. Grafana is a powerful tool for creating live dashboards of the data directly fed from InfluxDB. These live dashboards can be adjusted to the specific requirements of the company making Grafana an ideal option for monitoring the real-time status of the machine. The laboratory implementation of the retrofitting technology based on the general architecture is shown in Figure 5.9 and the retrofitted column drilling machine is shown in Fig. 5.10.

The learning from the laboratory pilot is then applied in the industry scenario at GCL technologies which is explained in the next section.

Application

The labelling machine at GCL technologies applies Near Field Communication (NFC) tags to the plastic coins (which then will be used on the top of closure of beverage bottles) and writes information on the tags. The first step in the process is the positioning the coins in the right orientation to be picked up by pick and place process afterwards. A camera is placed before the coins placed in to the conveyor to control the orientation of the coins. The conveyor moves

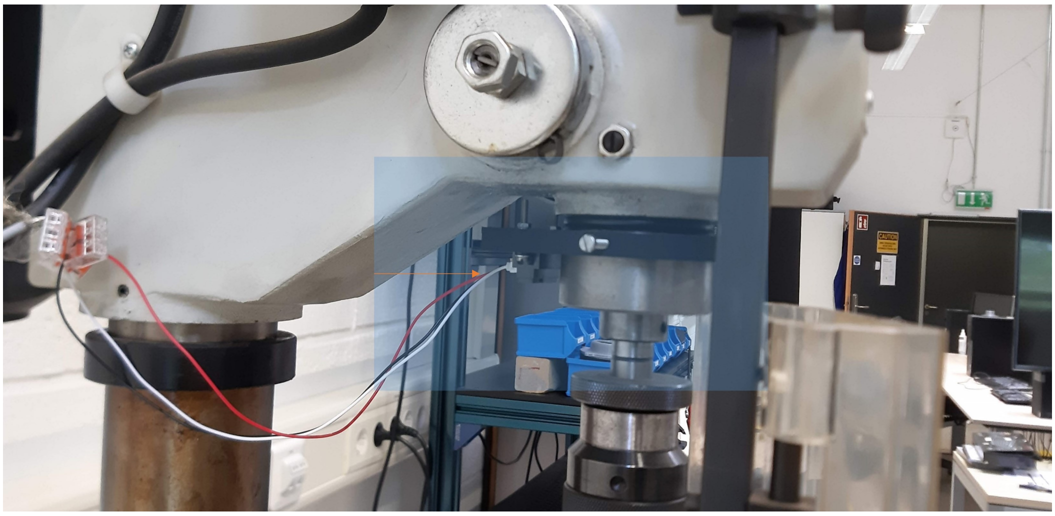

FIGURE 5.10: Drilling machine with retrofitted IR sensors

forward to take the coins to a pick and place system. The coins are picked by creating vacuum on the surface of the coins by a venturi system. The last step of the process consists of labelling of the NFC tags and writing information on to them. A holder takes the coins to the labelling station where a labelling machine run by a motorized roll is used to apply the tags. The liner containing the tags is controlled by a positioning sensor to apply the labels in the middle of the closures. The applicator of the tags uses a similar venturi system to strip and apply the tags. The centering of the tags is then validated by a camera. If the camera confirms that tags positioning is within tolerance, then the coin is taken to next station for writing the information on to it. Otherwise, the coin is sent to the scrap pile. There are two major issues with the labelling machine: it is frequently breaking down and generating a lot scrap.

The analysis of the processes revealed that real tension and manual positioning of the labeling on to the coins caused the issues mentioned above. The high reel tension is because of the blockage of the blade due to accumulation of the glue on the machine components. The positioning of the tags needs to be centred on the coin with high precision. However, there is no way to know how big the manual movements are made. This positioning, which may be done in both X and Y directions, requires frequent redoing. Additionally, it is quite challenging to determine whether the label is being placed appropriately from where the operator moves the machine.

Based on the above issues, the following variables of the machine are selected as critical variables to measure so as to monitor the machine status: Reel tension, coin diameter, X-Y coordinates of the labelling blade, and centering of the tags. The first two variables are mapped with the frequent breakdown of the machines and the last two are related to the scrap created in the process. The mounting parts for the sensors to measure the above variables are designed and 3D printed inside the company. The 3D printer available in house has bought the flexibility to design custom pieces which would be difficult or expensive to create otherwise.

The next step is to adapt the general architecture from Figure 5.7 to the labelling machine on which the retrofit is being done. The adapted technical

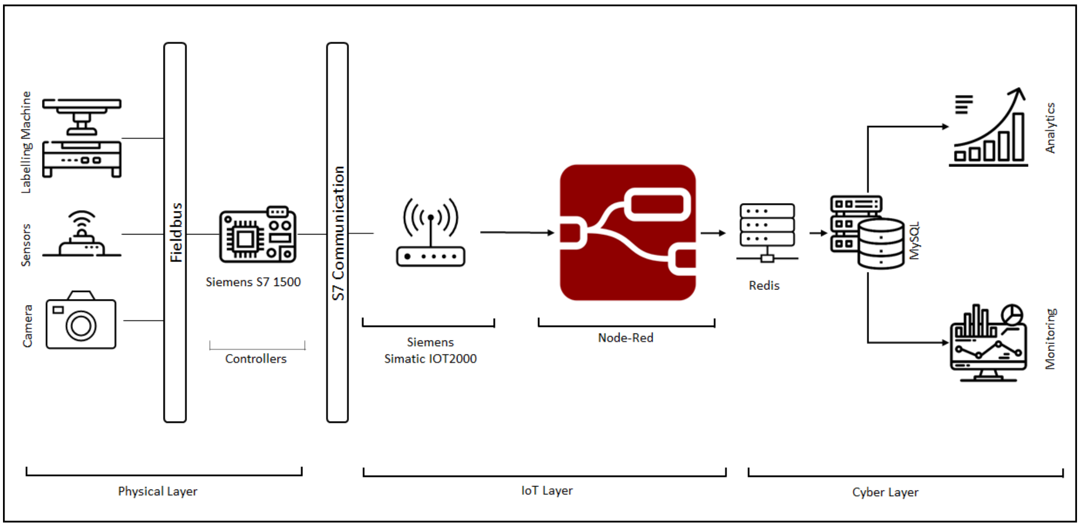

FIGURE 5.11: Adapted technical architecture for Retrofitting the labelling machine

architecture is shown in Figure 5.11.

FIGURE 5.12: The labelling machine chosen for retrofitting

The labelling machine that is chosen for the retrofitting in the context of IIoT is from Etipack which can be seen from Figure 5.12. All the sensors are mounted on the labelling machine without compromising it's functionality. As mentioned earlier, the machine already using a PLC from Siemens and there is an industrial PC attached to the machine. To be able to communicate with the PLC, an IoT gateway in the form for Simatic IOT2000 is installed. This device can connect to 2 different networks at the same time. However, it will only permit communication between itself and the networks. When using IoT devices that are directly connected to machines, adding an IoT gateway is an extremely crucial element. The company network, which is connected to the internet and has more users, needs to be separated from the industrial network, via which the machines are connected, for security reasons. The cameras used in the processes are from Cognex specifically In-Sight 2000 vision sensor.

Two out of three variables (Coil diameter and Reel tension) to measure can be measured using distance sensors. Ultrasonic sensors are chosen for two reasons. They have higher precision as well as they don't wear out because they do not touch anything. The other reason is that the placement of the sensors on the machine. The ultrasonic sensors can be mounted on the machine in a convenient way. However, to measure reel tension, there are no sensors available on the market and this sensor must be touching the liner to measure the tension. A 3D printed spring is designed for this purpose which fits the limited space available on the machine and the roll can easily be mounted on it. To measure and control the centering of the tags on coin, a software adjustment is made on already existing camera. The mounting parts and machine retrofitting sensors are shown in the Appendix B.

As per the laboratory pilot, Node-Red software is used to collect the data directly from PLC using Siemens S7 communication protocol and from the retrofitted sensors. The data is fed to Redis (local database) before uploading it to cloud. Redis is light and very fast database and this helps when more sensors are added to the machines in the company and more data is to be gathered. The Redis then push the data to MySQL database. The data pipeline to gather data, to save it to Redis, and then push to MySQL can be seen in the Figure 5.13

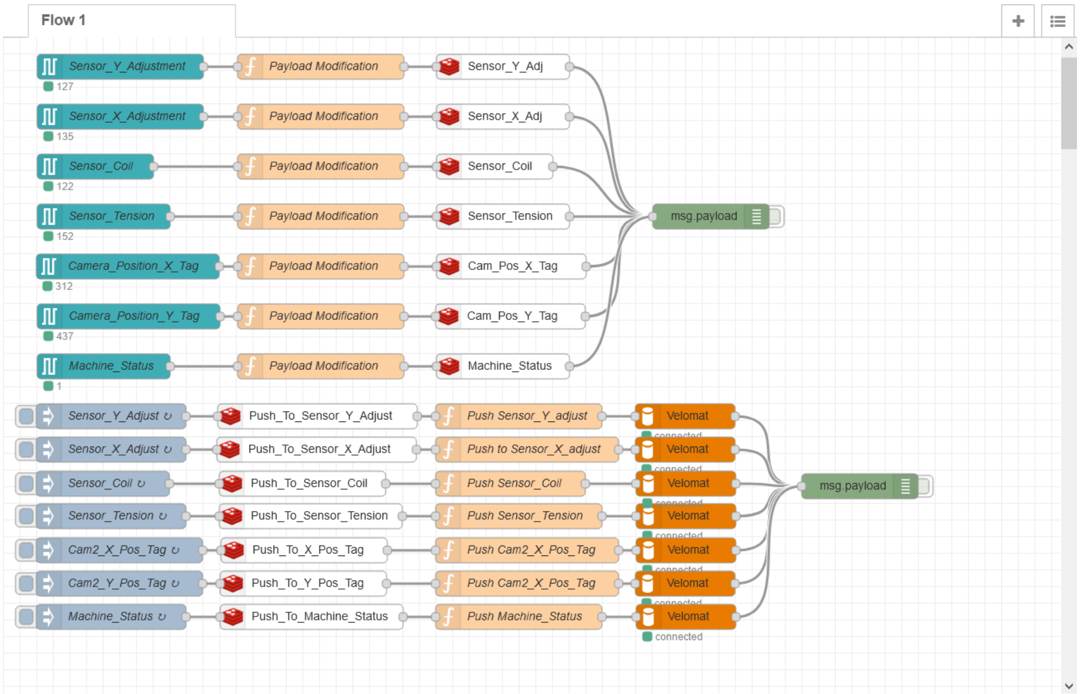

FIGURE 5.13: Data pipe-line from sensors to MySQL built in Node-Red

The next section presents the results of the case study and challenges faced while retrofitting the labelling machine at GCL Technologies.

5.3.5 Post evaluation

In this phase the implemented solutions were assessed in terms of usability, satisfaction of the company, and effectiveness of the solutions implemented. The sensors are mounted on the machine with the help of mounting points. The sensors were at a reading distance to maintain the high precision that is required for the purpose. Basically, the operators don't have to interact with the sensors so usability is not an issue in this case study. The retrofitted system didn't change the functionality of the machine except it is upgraded to data sharing capability. During the test run, a batch of 5000 coins were ran through the process. We encountered a challenge with the IoT device as it required static IP address for the operation. However, this problem is solved rather quickly with the help of internal IT engineers. The test gave the expected results as the data from the sensors are saved to Redis before pushed on to MySQL. The modifications done on to the camera program was also successful. The camera program successfully logged the XY co-ordinates of the every coin labelled in the test run. The communication between the IoT device and the PLC worked as planned and it was possible to send the information from PLC to the database (MySQL).

The interview with the company representative and production operator after the test run revealed that this case study is of strategic importance as they move forward to I4.0 deployment in other parts of the company. This case study enables the company to take first steps in real-time monitoring and predictive maintenance using the data gathered in MySQL database from the retrofitted sensors. The analysis of which will enable a better understanding of potential modifications that could be made to the process to make it more effective in the future. This will increase the machine's OEE and ensure less waste in terms of time, motion, or defective products in the production. The module Error Prevention (EP) of SAT is now between level 3 and level 4 after the implementation of the case study in the company. To reach to level 4, the company should start with analysis of the gathered data and find the possible correlation of the observed variables and the failure modes of the process. This is the starting step for predictive maintenance of the machines in the company. It was suggested to the company that more production machinery could be retrofitted with the help of IoT architecture presented in the case study to have a network of machines connected to a database for a complete implementation of I4.0 in the company.

The next chapter presents the case study in a tire manufacturing company in Luxembourg in another least mature module of the Self-Assessment Tool (SAT) - Human-Machine Interface (HMI). To improve the maturity of HMI module, a case study using Augmented Reality (AR) technology is implemented.

Chapter 6

Augmented Reality (AR) in Manufacturing

6.1 Introduction

The least researched aspect of I4.0 in the manufacturing sector is Augmented Reality (AR). In SAT, the module Human Machine Interface (HMI) defines AR as the highest maturity level as AR has the potential to enable efficient information exchange between employees and machines. However, the adoption of AR in manufacturing enterprises is hindered by a lack of research as well as lack of design expertise in AR applications. The aim of the fourth industrial revolution is not to create factories without human, but to improve the human and machine collaborations combining the advantages of accuracy and efficiency of intelligent machines with human flexibility (Masood and Egger, 2020). On the other hand, growing number of product variants has increased the demands on shop-floor activities (Kolla et al., 2020) such as assembly, quality inspection etc. One way of looking at the problem is to improve the existing HIMs to not only interact with machines but also assist operators in completing shop-floor tasks. The implementation of Extended Reality (XR) technologies in the industry provides workers with visual and interactive information that can improve completion time and error rate of human tasks (Fast-Berglund, Gong, and Li, 2018; Doolani et al., 2020).

In both the academic and industry sectors, it is still difficult to distinguish between concepts like Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR). The terms listed above fall under the Extended Reality (XR) continuum with varying degrees of awareness of reality. Figure 6.1 illustrates the XR spectrum which encompasses technologies that goes from AR, through MR all the way to VR (Çöltekin et al., 2020). The key variable that differentiates these technologies is the awareness of the reality when exposed to the specific system.

VR is the term for the virtual end of the spectrum, which completely immerses the user by only using digital components and isolating users from the real environment (Mujber, Szecsi, and Hashmi, 2004). The user is completely surrounded by virtual objects and is not aware of reality when they are in a VR environment. On the other extremity, the real world, which consists of only physical objects without any virtual objects to enhance the operator's perception.

There is a real ambiguity in the current literature when distinguishing AR from MR because both AR and MR makes use of virtual objects overlaid into the real environment. However, for the purpose of this research, a vaguely

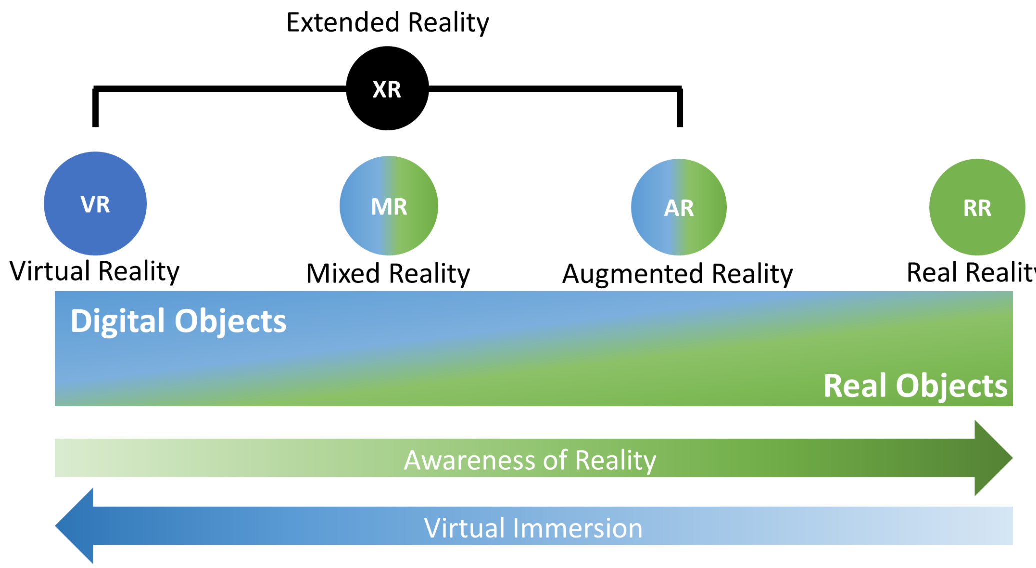

FIGURE 6.1: Extended Reality Spectrum

defined difference between AR and MR from Milgram and Kishino's research is adapted and modified (Milgram and Kishino, 1994). According to Milgram and Kishno's research, MR is an umbrella term for technologies such as AR and Augmented Virtuality (AV). However, in this research it is considered to bring MR to the same hierarchy as AR and VR and clubs them to an umbrella term XR. As we understand, the main difference between AR and MR is how the digital and real objects interact with each other. AR simply overlays the digital object on top of the real background, without any interactions between them. However, MR on the other hand generates interactions such as occlusion and collision through spatial mapping and physics simulation, which provides further immersion for the user.

A detailed research on state-of-the-art, prototyping, and testing in the laboratory are essential before implementation in the industry. The next section presents the existing literature for AR in manufacturing, comparison of AR systems for work instructions with paper-based systems.

6.2 Augmented Reality - A glimpse

The basic components of an AR system consists of a Capturing Technology (CT), such as a camera or a sensor to capture the real-world environment. A Visualization Technology (VT), to project virtual models on the real images captured by the camera. Generally used VTs are, Hand-Held Devices (HHDs) such as tablets and smart phones, Head-Mounted Devices (HMDs) such as smart glasses, and spatial displays such as projectors. A Processing Unit (PU), to analyze the input data and output virtual information (visual rendering). A Tracking System (TS), such as a marker (for example a QR code). The main function of TS is to trigger the display of virtual information and establish the orientation of virtual data with respect to the physical world. A User Interface

(UI), such as a touch display of a tablet, for an operator to interact with digital world (Fraga-Lamas et al., 2018)(Lee et al., 2017)(Wang, Ong, and Nee, 2016). Figure 6.2 presents the components required for an AR system. Usually in the industry, AR systems with markers are used as they significantly reduce the computing power when compared to marker-less technologies such as target capturing etc. Furthermore, HMDs are a more suitable option in the industry as they give a hands-free experience when compared to HHDs.

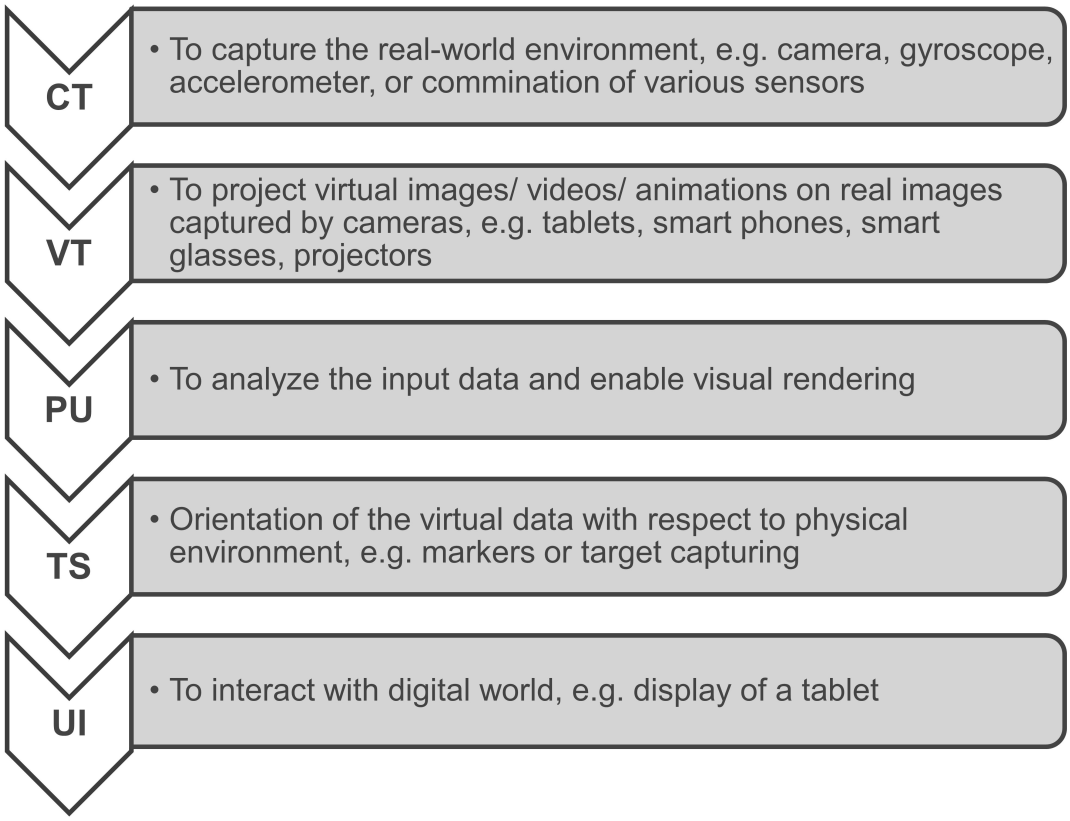

FIGURE 6.2: Basic components of an AR System

Benefits and limitations of AR systems

In general, for an assembly application HMDs are preferred as it provides operator with hands-free experience and improves operator's perception of the real world, as the view through an HMD is almost intact with the real world. On the other hand, nowadays most people are familiar with HHDs (ex. tablet or a smart phone). Using an HHD reduces the amount of training and allows an operator to directly work with the system with no or less training. Economically and ergonomically, HHDs are better alternatives to HMDs. In spatial displays, operator's hands are free and he/ she does not need to carry anything. In terms of TS, AR systems with markers are less computationally intensive, robust and accurate. Marker-less systems do not need physical markers that has to be placed and maintained in an industrial setting. AR applications are not computing-intensive, both mid-end and high-end devices can be used. Portability is another advantage as AR hardware and AR applications are easily transported from one location to another.

The limitations of AR systems are associated with the maturity of the available technology. HMDs are still uncomfortable to wear, have limited field of view (FOV), and at times display distorted 3D objects. Limited FOV can cause work place accidents and affects the safety of the operators (Palmarini et al., 2018) and limited resolution can cause sickness of operators when exposed for long periods of time. The heavy weight associated with existing HMDs is not an ideal option for the operator. On the other hand, HHDs do not provide a hands-free experience which is crucial in the industrial setting. Moreover, HHDs need a physical support to hold them in place and ends up hindering their portability. One more disadvantage of an HHD system is the limited dimension of its display unit (UI) which limits the information that is overlaid on it. AR systems that use markers require physical markers that need to be placed at the right place on the workbench and maintained periodically. On the contrary, AR systems without markers need more computational power for the object tracking in real time. Other aspects such as processing power, battery consumption, limited memory, and connectivity issues are still being researched.

Interaction modalities in AR systems

Interaction modality is a way of sensing such as touch (haptical), voice (acoustical or auditive), or vision (optical) etc. In AR interaction modalities help users to interact with AR interfaces (Esteves et al., 2017). Currently, there are three ways to interact with AR systems: touch, touch-less and wearables. These interaction modalities are divided in to input modalities and output modalities. Input modalities are for the user to give instructions to AR system and output modalities are for user to receive the feedback from AR systems. The modalities are shown in Figure 6.3.

Touch modality isn't new in the manufacturing industry. Most of the existing operator panels on the machine systems have touch modality enabled either with buttons or with touch screen displays. Especially in logistics sector, hand controllers are very widely used to scan the items. Even the modern Augmented Reality glasses such as Hololens® comes with a hand controller that can replace default gesture interaction. Joysticks are popular with gaming industry and not very commonly used in manufacturing companies. With the development of AR technology, especially with HMDs, the new type of deictic gestures to interact with AR devices is possible (Williams et al., 2019). These gestures are mostly given mid-air with operator's hands (Mistry and Maes, 2009). For example, raising an index finger in the FOV of a smart glass can indicate that the operator is ready for a selection and pinching the index finger with the thumb can follow the selection of a particular target. The physical gesturing is limited by FOV of the device, depth sensing capability of the device and fatigue of raising hand is often under quoted. The control and selection by physical deictic gestures also includes movement of head for a prolonged period of time, which limits the intuitiveness.

Voice, a natural interaction modality has been the most widely used in our daily communication yet industrial environment especially on shop floors, this modality is intercepted by machine noises. Enabled by speech recognition

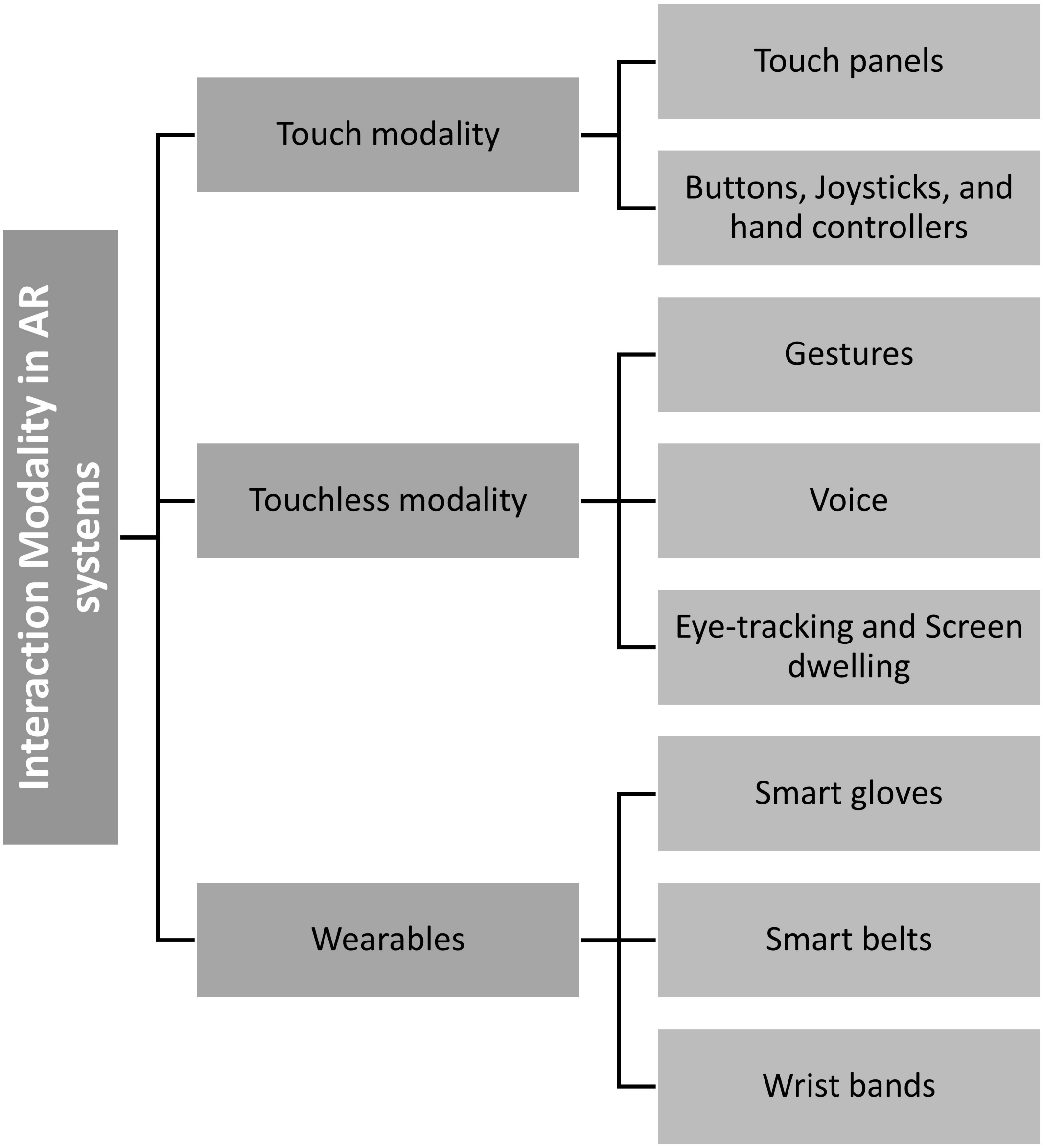

FIGURE 6.3: Modalities in Augmented Reality based on (Qian et al., 2020)(Liu et al., 2019)(Williams et al., 2019)(Mistry and Maes, 2009)(Nizam et al., 2018)(Chen et al., 2017)(Hsieh et al., 2016)(Dobbelstein, Hock, and Rukzio, 2015)(Hu et al., 2020)

techniques, the voice interaction modality allows the user to interact with the systems using voice commands (Nizam et al., 2018). The combination of more than one modality to interact with the AR systems is referred to as multimodal interaction technique (Nizam et al., 2018) (Chen et al., 2017). The multimodal interaction technique is efficient and enhances HMI in AR system. Eye tracking (Liu et al., 2019) is a recent development in AR that is derived by complex algorithms that estimates the movement of cornea and pupil of the eye in the space. In a HMD powered by eye tracking interaction modality, cameras that operate at high frame rate capture the images of the eyes. Screen dwelling (Qian et al., 2020), as the name suggests, the interaction with a system is possible by gazing at the target for a specified amount of time. Gyroscope and motion sensors of the system facilitate the dwelling interaction. Of course, dwelling is not possible without combining it with another modality such as head, hand or eye tracking. The most common use of screen dwelling is observed when a user tries to scan the QR code using a smart phone. However, screen dwelling in HMD environment costs excess time for each selection and therefore increased lead-time. On the contrary, it provides seamless hands-free interaction with the AR environment with a moderate-latency.

Even though wearables found their way in fitness industry and health tech, they aren't matured to be used along with AR devices in an industrial environment. However, research on wearables such as smart gloves (Hsieh et al., 2016), belts (Dobbelstein, Hock, and Rukzio, 2015), and wristbands (Hu et al., 2020) for better enhanced interactions with smart devices. Different sensors can be mounted on a smart glove for capturing interaction scenarios such as text entry, scrolling, choose and select. However, a smart glove with many sensors can limit the operator's interaction with physical parts. In (Dobbelstein, Hock, and Rukzio, 2015), the researchers developed a novel unobtrusive on body input device for smart devices by placing currently familiar interaction in the society, touch. By embedding the touch functionality in the wearable belt, the input space is larger when taken into account the whole surface area of the wearable. On the other hand, wristbands (Hu et al., 2020) provide hands free operation on physical parts but can't include many sensors to offer more interaction possibilities. However, wristbands can be very helpful in continuously reconstructing hand poses to help AR experiences. Normally, wristbands are mounted with thermal cameras tracking the position of hand joints and send to a deep model for the prediction process to estimate all hand joint positions.

In this research, both touch and touch-less modalities are experimented in laboratory followed by implementation of an AR application using multimodal interaction modality in the industrial setting. The next section presents relevant literature from the scientific databases. However, this is not a critical review on the existing literature.

6.2.1 Relevant literature

AR adoption in manufacturing is seen a great interest recently. AR applications can be found in assembly instructions, quality inspection, maintenance, training, and safety. However, the basic infrastructure needed for the development of an AR application is relatively same across the application domains. Researchers from University of West Bohemia (Hořejší, 2015) used AR to train students on how to assemble an industrial gully trap. Twenty students with no previous experience of assembling a gully trap, tried assembling it using paper instructions. For the first assembly, the participants took 5 to 7 minutes to assemble a gully trap and almost 12 attempts to learn how to assemble it without instructions. The researchers commented that most of the time was spent on looking for parts in the boxes. To tackle the problem above, the researchers developed an AR solution designed in Unifeye Design software. Another set of 20 participants with no experience in assembling a gully trap tried the new AR assembly instructions. In the first attempt, most of the participants could assemble it in 2 minutes, which is less than the average time from the participants with the paper instructions. It took almost 10 attempts for the participants to assemble the gully trap without instructions. Overall, the learning process with

AR assembly instructions is more efficient than using the paper instructions. The learning time could be shortened significantly for a product with complicated assembly processes.

In another reseach (Danielsson et al., 2017), a demonstrator was developed where an operator can collaborate with a Universal Robot® (UR3) to assemble and disassemble a simplified car model using AR assembly guidance system. The AR interface in the first iteration is created in gaming engine Unity-3D® with the help of Vuforia AR-system®. Then, in the second iteration Vuroria AR-system is replaced by ARToolKit®, as it supports windows platform. ARToolKit also support multi-marker functionality, therefore, in their research a greater number of markers are used to allow test operators and robot to move freely in-between the camera and markers. The test results show more than significant errors/ deviations by test operators. For a test group, where all the participants have committed errors, mistakes were made in 52% of all the attempts. The major reasons for significant error rate are that the interactivity of interface is unclear for the test operators since the interface has mainly test instructions with certain graphical marks but neither animations nor 3D views are provided. On the other hand, the camera was at a fixed angle; therefore, it was difficult to access the environment around the assembly operation. The problems with the interface design are tackled in the doctoral thesis using frames and cues explained in the next section.

Software frameworks are important to standardize designing AR applications for manufacturing. Designing an AR solution in a HHD (e.g. tablet or mobile phone) requires a different set of software and hardware elements compared to designing an AR solution in a HMD (e.g. HoloLens). In the existing literature there is only one publication (Masood and Egger, 2020) dealing with the AR software framework for HoloLens using a lean graphical representation technique called C4 framework, which is popular in software development. The framework presents the interactions between the software components. The framework is also appropriate for SMEs because the majority of the development tools are open source and do not require any further expenses beyond hardware. The framework does not, however, encompass elements of the hardware systems for mobile devices and instead primarily focuses on HoloLens/Smart Glass. In this doctoral research, we addressed software frameworks for both HMDs and HHDs.

The empirical evidence with user studies to measure the effectiveness of AR instructions compared with the paper instructions are explored in the last part of the literature survey. The authors in (Blattgerste et al., 2017) compared standard paper-based instructions with AR assistance utilizing a smart phone (HHD), HoloLens (HMD), and Epson (HMD). Participants completed the assignment more quickly when given paper-based instructions, but they made fewer mistakes when using HoloLens. Paper-based instructions also had a reduced perceived cognitive load. However, both the HoloLens and the smartphone have the same cognitive load. Handling the smart phone is one issue faced by the researchers while the other challenge is the instructions were interfering with the assembly task as they were displayed in the middle of Field of View (FoV). In this doctoral research, both the issues were tackled successfully, which were explained in the next section. In a similar research (), the authors built in-situ projection AR system and compared it against HMD, HHD, and paper instructions. In addition, the authors assert that the created AR systems can significantly cut down on the time and money needed for new employee training. In their empirical study, they found that on an average, the participants were quicker to finish the task in-situ projection AR system followed by paper instructions, tablet, and HMD.

In the next section, basic software, hardware requirements for an AR system are explained followed by software frameworks for both HHD and HMD. The laboratory implementation of AR systems and their comparison with paper instructions are presented at the end of the section.

6.3 Augmented Reality experiments in the laboratory

To design and develop an AR application both software and hardware elements are required. The function of each of these elements must be understood before adopting them for the development.

Function of software elements

C#: Programming language used to create all the actions and interactions performed within the application.

Vuforia®: A software platform used for the development of AR. It provides the capability of recognizing and tracking planar images, which enables the insertion of virtual 3D models into a real environment viewed through a camera in a desired orientation. The tracking allows the object's perspective to be always aligned with the viewer's perspective, making it appear to be a part of the real environment.

Autodesk Inventor®: Computer-aided design software used for the creation of the 3D models used in this research.

Unity®: A game engine, which creates applications with real-time rendering and interactive 3D environment. The whole application is developed and built with Unity, it creates the interface, animations and runs all the interactions within the software.

Android Application: Captures the input signals, processes the images and renders the 3D elements in the real environment to generate the augmented reality experience.

Function of hardware elements

Android device: Equipment responsible for running the application and allowing it to be interacted by the user through its input/output interface.

Camera: Responsible for capturing the real environment where the virtual elements are going to be projected.

Touchscreen: Acts as the input interface between user and application, as well as visual output medium.

Data storage: Recording media where the application is installed and ran.

Assembly parts: Physical parts that are hand manipulated by the user for assembly operations

Markers: Visual cues that trigger the displaying of the virtual elements on top of the real environment, which also allows its repositioning and orientation through tracking.

Figure 6.4 shows the software and hardware elements required to build an AR system.

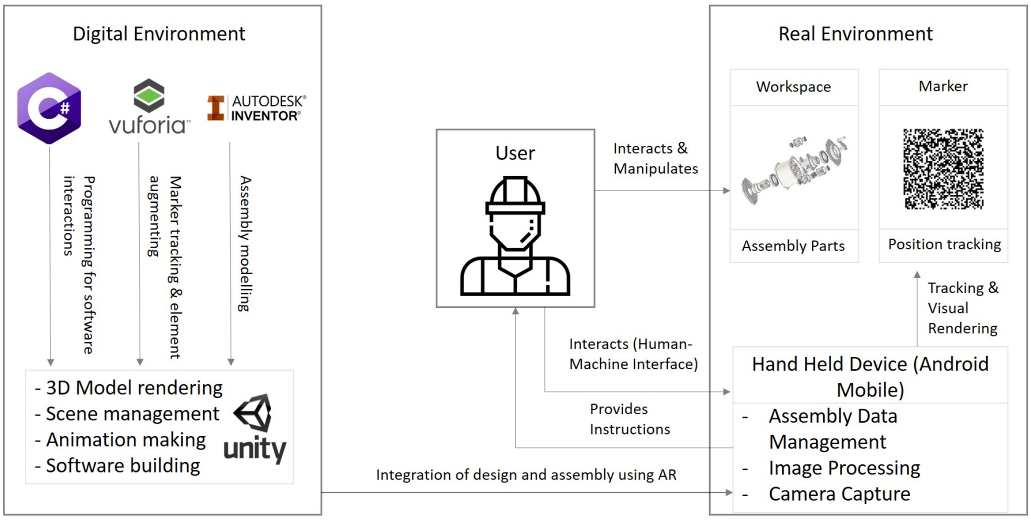

FIGURE 6.4: Hardware and Software elements in an AR system

6.3.1 Software frameworks for development of AR applications

In software development developers use frameworks to model an abstraction-first approach. As manufacturing domain is adapting software to assist their daily operations, it is important to understand and adapt the workflow from software developers. Therefore, before building the AR applications in the laboratory, two software frameworks are developed to visualize the development process of AR applications. Figure 6.5 & Figure 6.6 shows the software frameworks for a HHD (mobile device) and a HMD (HoloLens) respectively. C4 model is used to represent these two software frameworks and the interaction between different levels.

A big picture of an operator interacting with the Android application is presented in the level 1. In level 1, the operators (actors) and the android application (software system) are the critical focus points. In the level 2, all the executable units are presented in a container diagram. In the Figure 6.5, we have 3 containers: lean touch (Wilkes, n.d.) to provide touch modality, unity® scene provides development platform, and Vuforia (*Vuforia Engine 9.6* n.d.) for

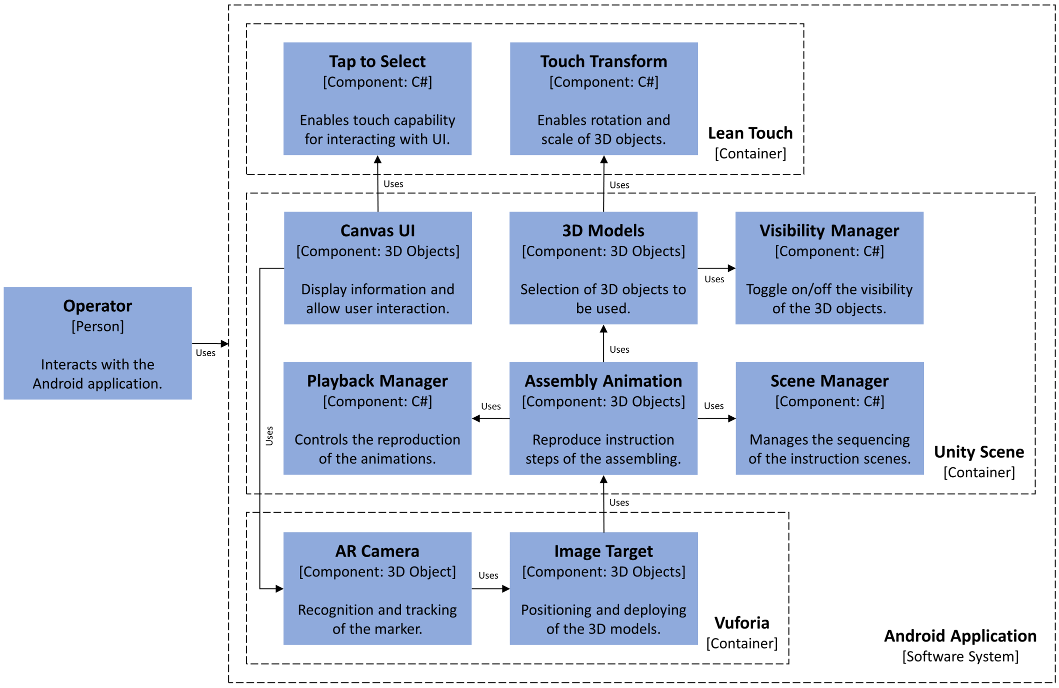

FIGURE 6.5: Software framework for HHD e.g. android device

recognizing and tracking images. The last level in the C4 framework is level 3, component diagram. The developer can enlarge and separate each container into the main components of the application (or normally executable functions). The interactions between the components are demonstrated at this level. Each component interacts with one or more other components and performs a specific function in the application.

A similar framework for a HMD is presented in Figure 6.6. It has only two containers: MixedReality ToolKit and Unity. The usage of spatial mapping from HoloLens eliminated the use Vuforia in the application development. Spatial mapping is based on Simultaneous Localization Mapping (SLAM) (Durrant-Whyte and Bailey, 2006) algorithm that recreates a 3D mesh representation of the surrounding environment from the depth data. Thus, by using spatial mapping, the virtual instructions can be populated and tracked exactly on top of the actual workstation, eliminating the use of markers.

6.3.2 Applications

Two different applications are developed on the basis of software frameworks presented in the previous section. These two applications aid the operator by giving instructions to assemble a planetary gear-box (shown in Figure 6.7). All the parts of the gear-box are 3D printed and standard components such as bearings, retainer rings are purchased off the shelf.

Application on Hand-Held Device:

An Android device (Samsung Galaxy S7) is chosen as a HHD in which the developed application is installed. For each step in the process, the virtual

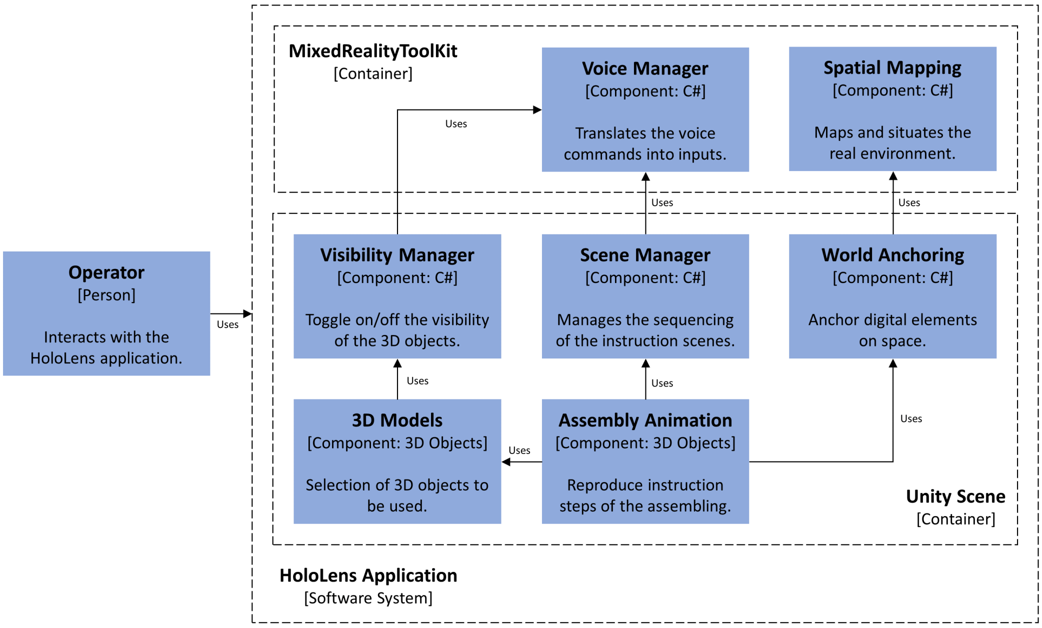

FIGURE 6.6: Software framework for HMD e.g. HoloLens

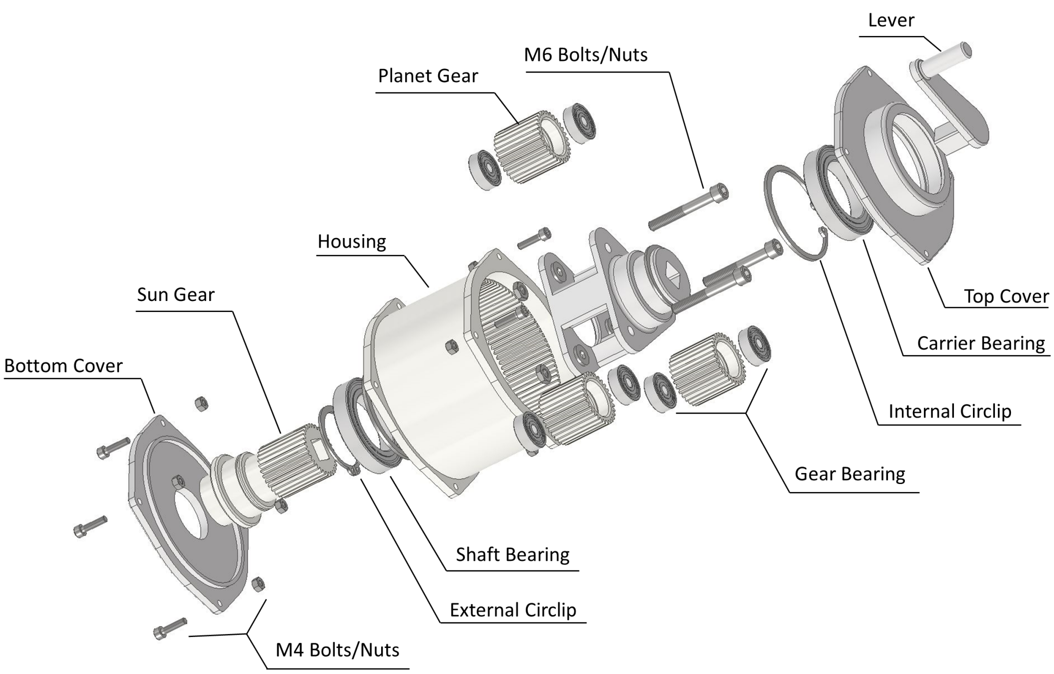

FIGURE 6.7: Exploded view of Planetary gear-box

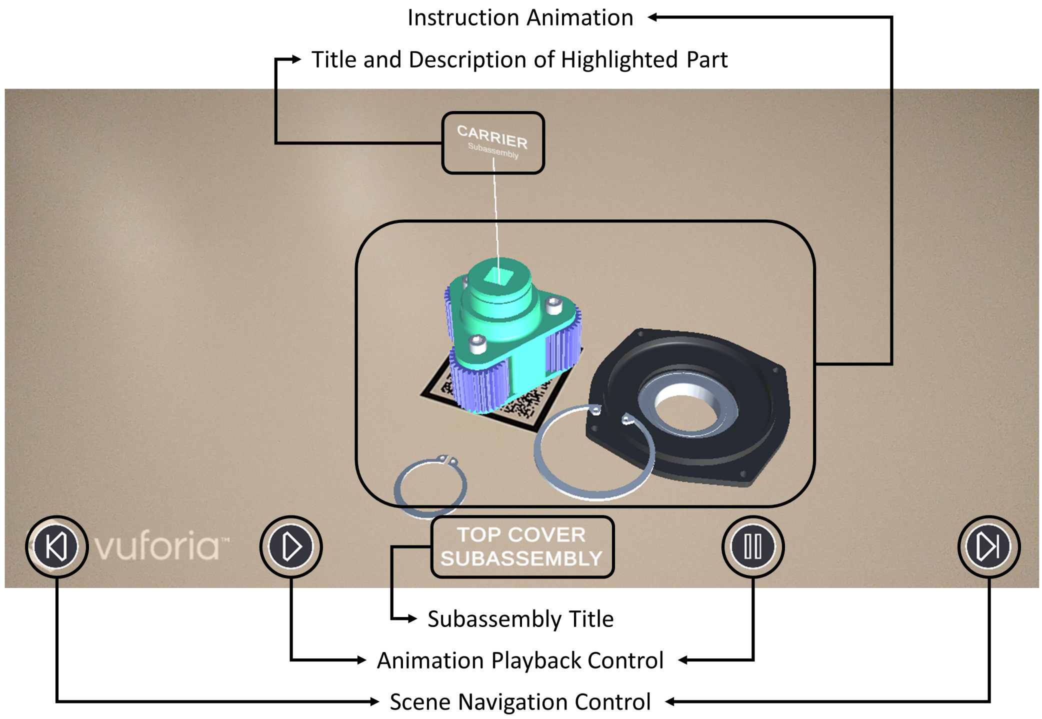

FIGURE 6.8: User interface in Android application

instructions are displayed on the QR code in the real environment. The user assembling the gear-box interacts with the application using touch modality. The user interface of the developed application is shown in the Figure 6.8. The animations can be replayed, paused, and can be scaled using the buttons on the user interface. The QR codes used for orientation of the instructions are optimized using Vuforia. The disadvantage of the HHD is that the field of view for the operator is limited as the android device is fixed to a fixture above the QR code.

Application on Head-Mounted Device:

Microsoft HoloLens 1 is chosen as a HMD. On the contrary to the Android application, the usage of markers is eliminated by employing the spatial mapping tool supported by HoloLens. The virtual instructions are displayed in real environment without limiting the operators real-world perception. Using the HoloLens, the field of view is improved substantially and enabled multiple new features in the application such as visual cues and pointers. The user interface of the developed application is shown in the Figure 6.9. The user interacts with the application using speech modality and gestures. To navigate to further steps or previous steps of assembly process, the user uses voice commands such next and previous respectively.

6.3.3 Comparison of AR and paper-based instruction systems

In this section, the HHD and HMD AR virtual instruction systems are compared with traditional paper-based instructions. Three distinct instruction systems

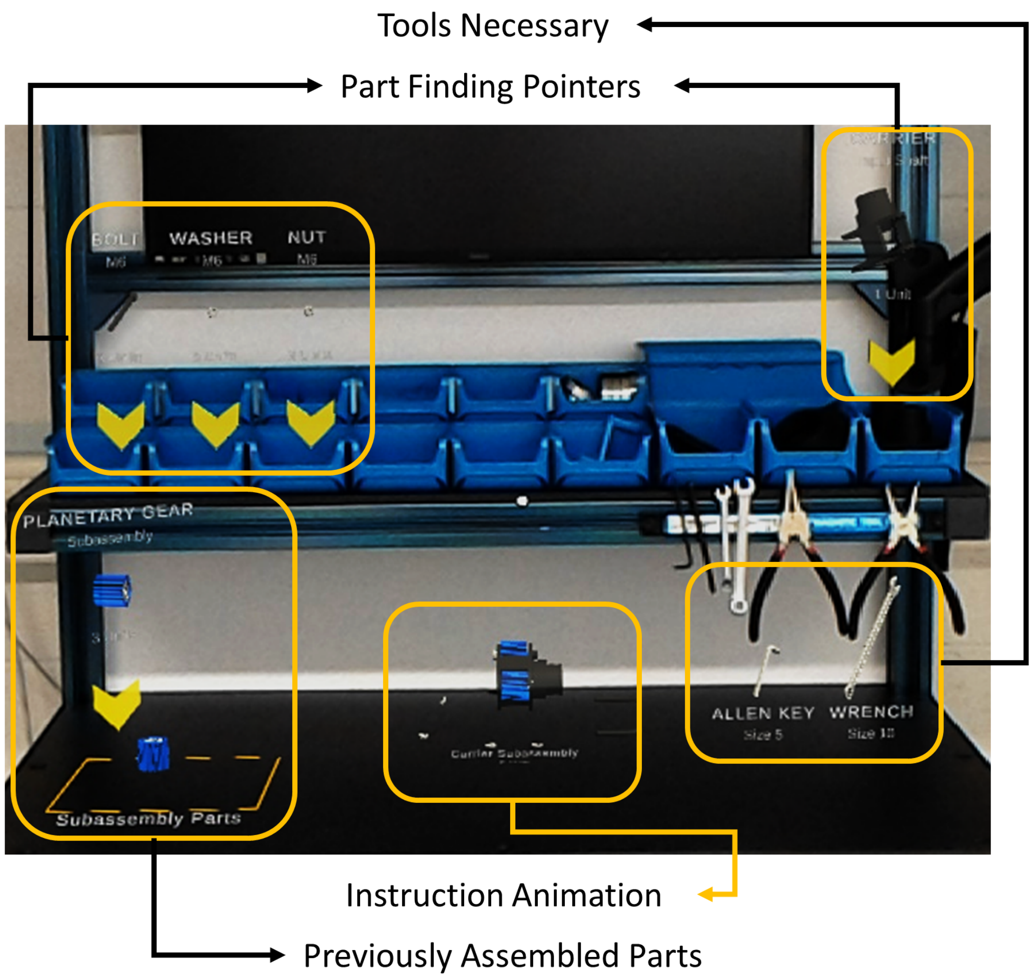

FIGURE 6.9: User interface in HoloLens

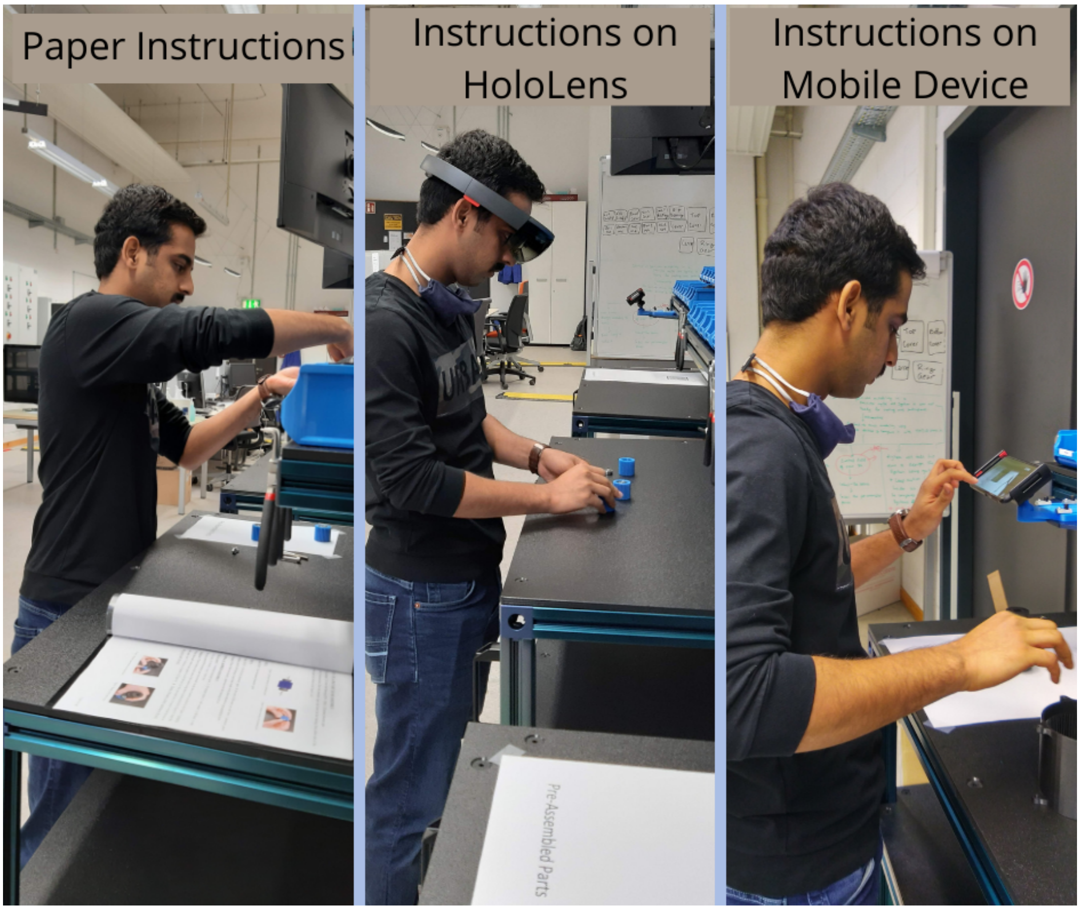

FIGURE 6.10: Workbenches in the assembly area

were used in the experiments to lead the participant, simulating a real shop-floor setting. A traditional paper-based instruction system, a HoloLens AR system, and a mobile device AR system are independent variables. The dependent variables such Task Completion Time (TCT), number of errors (n), workload index (p), and system usability (k) are measured and statistically compared. Eighteen participants were invited to the user study in order to balance out the biases, such as learning effects brought on by the order in which participants used the various systems . Each participant followed each set of instructions to accomplish the planetary gearbox assembly task. The first participant started with the paper instructions, second participant with the HoloLens, and the third participant with the android device. The fourth participant will start with the paper instruction and so on.

The assembly environment for the experiment is shown in the Figure 6.10. At the beginning of the user test, all the participants were given training on how to use each instruction system. After familiarizing themselves with all the systems, they were asked to finish the task as quick as possible and not to make any errors.

When the participants finish the assembly at one station, they were asked to fill the NASA-TLX questionnaire which will be further used for workload (p) measurement. The NASA-TLX questionnaire contains six subjective sub-scales: mental demand, physical demand, temporal demand, performance, effort, and frustration. The scales are defined from 5 (very low) to 100 (very high) with the increment of 5. At the end of all the stations, the users were asked to complete System Usability Scale (SUS) questionnaire to compare their usability experience with all the three systems. NASA-TLX and SUS questionnaire are shown in the Appendix C. While the participants were assembling the gear-box at each station, the facilitator counted the number of errors (n). On an average, it took 1.5 hours for each participant to finish the experiment. The results of the experiments are shown in the Table 6.1. Results show that the mobile device with AR instructions is the fastest method with shorter TCT followed by HoloLens AR instruction systems. The paper instruction systems are fell short by 2 minutes compared to AR instruction systems. In terms of number of errors, the participants made fewer errors using HoloLens followed by mobile device and paper instructions. The workload using AR instructions is considerably short compared to paper instructions. Finally, the AR instruction systems scores higher in the system usability score compared to paper instructions.

The learning's from these experiments are further used in the industry for deploying AR in manufacturing. The next section presents a Augmented Reality case study using methodology presented in Chapter 4.

TABLE 6.1: The mean and standard deviation for the dependent variables

Instruction System	**Task Completion Time (TCT in sec)**		**Number of Errors (n)**		**NASA-TLX Workload Index (p)**		**System Usability Score (k)**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Paper	1003	344	1.39	1.33	34.31	1.2	44.31	16.06
HoloLens	912	243	0.611	0.77	29.1	10.69	76.25	76.25
Android device	883	240	0.66	1.029	28.07	12.69	73.75	14.28

6.4 Case study

6.4.1 Company overview

The Goodyear Tire & Rubber Company is an American multinational tire manufacturing company situated in 2 places in Luxembourg. This particular case study took place in the new factory (Mercury plant) in Dudelange. The plant includes highly automated and interconnected workstations (Industry 4.0), using additive manufacturing technologies to efficiently produce premium tires in small quantities and on demand for customers in the replacement tire market. The plant has a strategic importance to advance their connected business models from production to consumers.

6.4.2 Maturity assessment

In the first phase, the SAT is answered by a senior engineer in the plant. The result of five dimension assessment at Goodyear is shown in Figure 6.11. Strategy, process and value stream, and organization dimensions are more matured in Goodyear than the average of Greater Region. However, the company positions itself slightly below the greater region average in the methods and tools, and personnel dimensions.

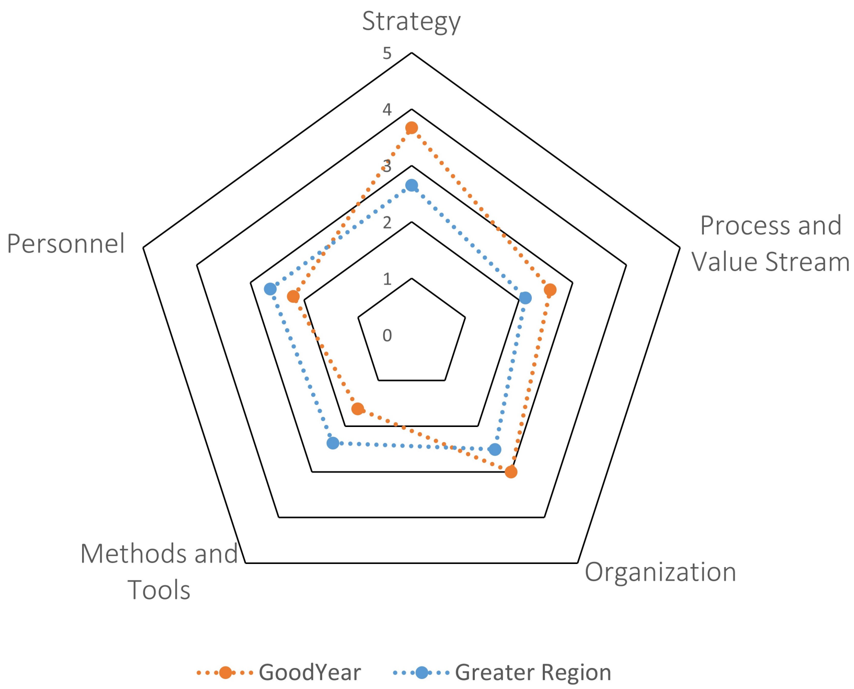

FIGURE 6.11: Overall assessment at Goodyear

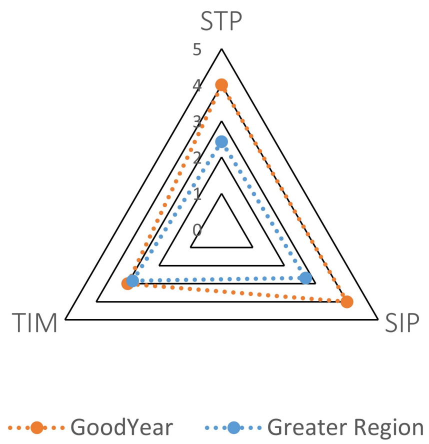

FIGURE 6.12: Assessment of Strategy

In the assessment of Strategy dimension, it is evident that the company is ahead of it's counterparts in Greater Region. The company has long term goals for I4.0 and adopting new technologies in production. The company also has a strategic action plan to achieve the digitalization goals in the production. Therefore, the improvements to strategy dimension are regarded out of scope for this research.

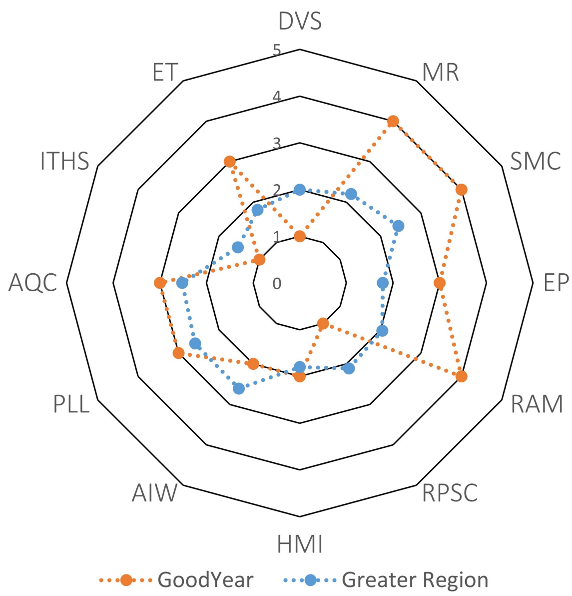

FIGURE 6.13: Assessment of Process and Value Stream

Goodyear is ahead of companies in Greater Region in the dimension of Process and Value Stream. Three modules Design of Value Stream, Real-Time Production Scheduling and Control System, and Internal Transport Handling and Storage are marked level 1. The company is recently established and the focus to improve these modules are already started. Currently the information between machines and humans is limited to central screens and computers. External analysis of the processes revealed that the standard operating procedures for some key machines is not documented and only few employees know how to work with specific machines.

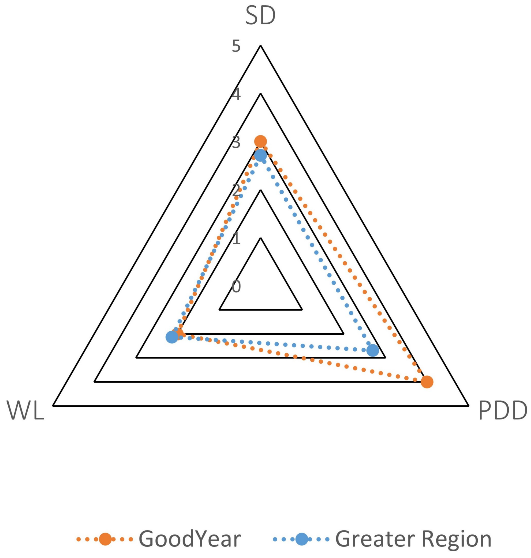

FIGURE 6.14: Assessment of Organization

In the assessment of organization dimension, it is revealed that the company is positioned above it's counterparts in Greater Region. The company has standardised processes that are regularly monitored by the line-managers. In terms of documentation, most employees feel responsible for updating the documentation of processes and process objectives. The company also uses simple techniques such as 5S to maintain a clean and orderly workplace.

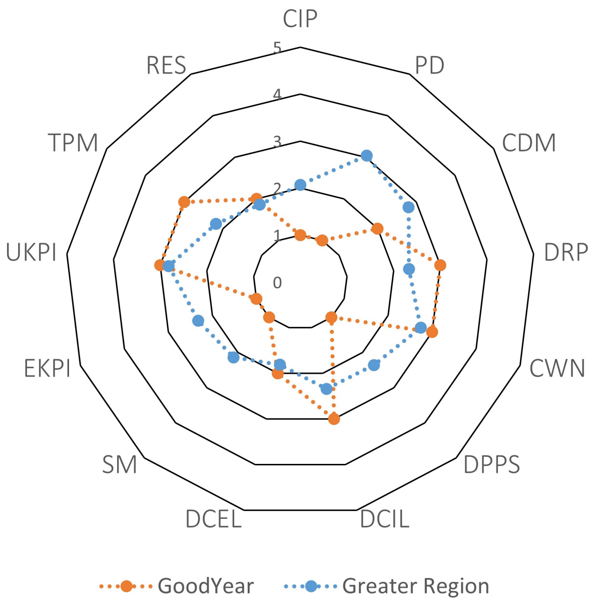

FIGURE 6.15: Assessment of Methods and Tools

Methods and Tools is the least matured dimension in Goodyear. Currently, the company is employing unstructured problem solving with recurring issues and mostly responding to the issues as they arise. The individual customer requirements are considered to a small extent but it require high manual efforts in design and manufacturing. The company is still employing Excel spread sheets for production planning and scheduling, which is labor intensive and time consuming. However, the company wide networks ensure the production status is digitally available for staff as well as to the customers. Moreover, the KPIs do not exist in all areas of the company but regular meetings on KPIs is conducted for systematic decision making.

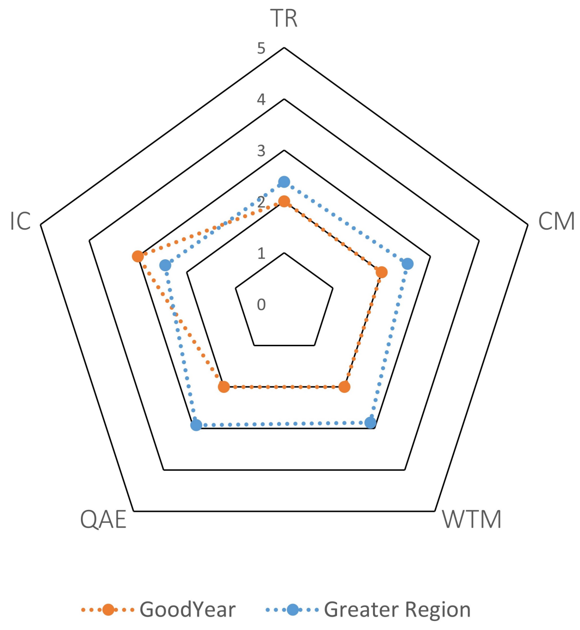

Figure 6.16: Assessment of Personnel

The personnel dimension is the second least matured dimension at Goodyear and it falls significantly below the greater region average. Employees are offered participation in the training activities. However, these are determined by supervisors or by the regulations. With regards to change concepts, employees accept the changes but minor interest towards the change. Employees work with rigid time schedules with some flexibility. With regards to standards, Goodyear is compliant with safety, security, and quality management standards.

6.4.3 Improvement potentials

According to SAT, there are 8 modules at level 1 and 10 modules at level 2. Dialogue with senior engineer and the operators on the shop-floor revealed that some of the production machinery used for quality assurance of the cured tires do not have documented Standard Operating Procedures (SOP). Only few experienced operators know how to use the machines and the training of the new operators is delayed because of non-availability of the senior operators. Further analysis of the other areas of production facility disclosed that the set-up times of few important machines are taking more than 8 hours and the instructions to set-up are on paper and can easily be misunderstood. As result of these discussions, the module HMI is selected as the highest value adding module for the company and this is aligned with the expectations of the company. Table 6.2 summarises the results of phase 1 and phase 2.

Table 6.2: Summary of outcomes of Phase 1 & Phase 2

Maturity Assessment Results		
Dimensions	**Level 1 evaluated modules**	**Level 2 evaluated modules**
Strategy		
Process and Value Stream	Design of the Value Stream Real-Time Production Scheduling and Control System Internal Transport Handling and Storage	Human-Machine Interface Availability of Information at Workplace
Organization		Workstation Layout
Methods and Tools	Continuous Improvement Processes Product Design Digital Production Planning and Scheduling Use of Simulation Models Existence of Indicators	Custom Design and Manufacturing Digital Control of External Logistics Resources and Ecological Sustainability
Personnel		Training Change Management Working Time Models Quality Awareness of Employees
Results from Dialogues with Internals		
Issue	**Consequence**	
Missing Standard Operating Procedures	Reduced machine safety Reduced product quality Unexpected idle times	
Process Analysis Results		
Human errors while set-up, maintaining the machines Missing information at the workstation		

6.5 Technical road-map

6.5.1 Preparation

The preparation phase started with the understanding of the tire making process. Completion of a tire manufacturing requires 11 different components, 3 different fabric reinforcements, 2 steel reinforcements and several different raw materials. There are two major stages in the manufacturing of the tire. In the first stage the green tire is manufactured which will then sent for curing in the second stage. The first stage is manual process involving 14 steps with two different drum test stands. Operators employ visual quality inspection before sending it to the second stage. The second stage is completely automated.

The Augmented Reality (AR) technology is chosen for the improvement of the 1st stage of the process. The machines under focus are drum test stand & creel machine. On the contrary to the open source software used in the laboratory experiments (Section 6.3.2), a proprietary software package "Reflekt" is used for the application development purposes. This is because of two reasons, the software package support multiple devices, different modalities, and supports visual guidance in two modes: Point of Interest (POI), and Step-by-step instructions.

Three areas are chosen for AR application development to improve the Human-Machine Interfaces in the company. For pilot test, virtual instructions for a cured tire for inspecting its quality are developed using HoloLens 2 and iPad. For application in the company, drum test stand and creel machine are chosen. For the drum test, the sequence of SOPs are virtually overlayed on top of machine. For creel machine, the step-by-step set-up procedure is digitalized using AR technology.

6.5.2 Experiments

For pilot test, quality inspection for the cured tire is chosen because of two reasons. The cured tire is portable and it is easy to draw 3D CAD for a tire rather than for a shop-floor production machinery. Moreover, there is a request from the senior quality technician to digitalize the standard quality inspection procedure for cured tire to train new recruits. Marker-less tracking and combination of gesture & speech modality are used in the development of the application. The application is designed in two devices: HoloLens 2 (HMD) and iPad (HHD). Figure 6.17 shows the object tracking for cured tire followed by visual clues in step-by-step inspection process in Figure 6.18.

The training time used to take between 1.5 to 2 days with senior technician explaining all the steps and supervising the new recruits in their trails. After the digital instructions using AR are introduced, the training time for two new recruits is reduced to 1.5 hours. The only training the senior technician needs to give is how to work with AR applications in iPad and in HoloLens.

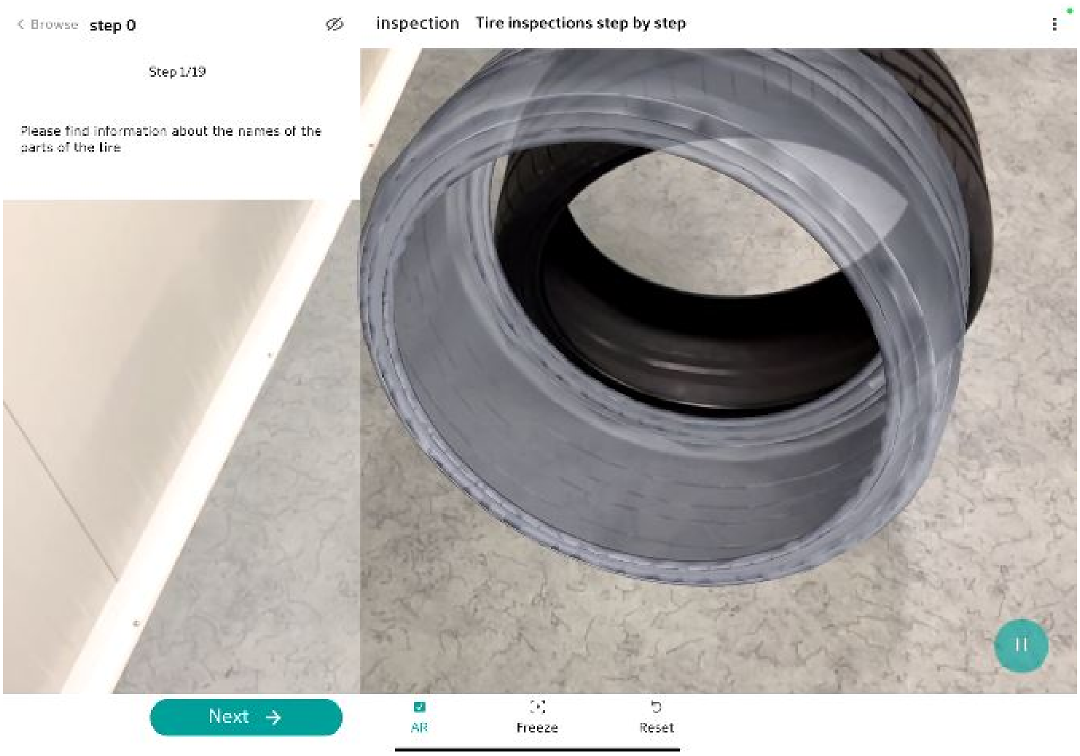

FIGURE 6.17: Object tracking for a cured tire inspection

FIGURE 6.18: Visual clues for the step-by-step inspection process

6.5.3 Application

During the first stage of tire manufacturing process, layers of rubber need to be blown to form a drum. The drum needs to be tested for it's centering using drum test machine. The operating steps of the machine are not documented. Therefore, it was necessary to document the procedure of operating the machine before digitalizing it. When the machine is operative, the operating steps were taken on paper, which were then used to develop AR aiding systems using HoloLens 2 and iPad.

Two kinds of applications were developed. The first one is point of interest, where the operators were able to see the detailed information of the parts for the first time. This benefits the operator with much needed knowledge of the machine parts for maintenance purposes. Figure 6.19 depicts the POI representation of a air service unit in the drum test machine.

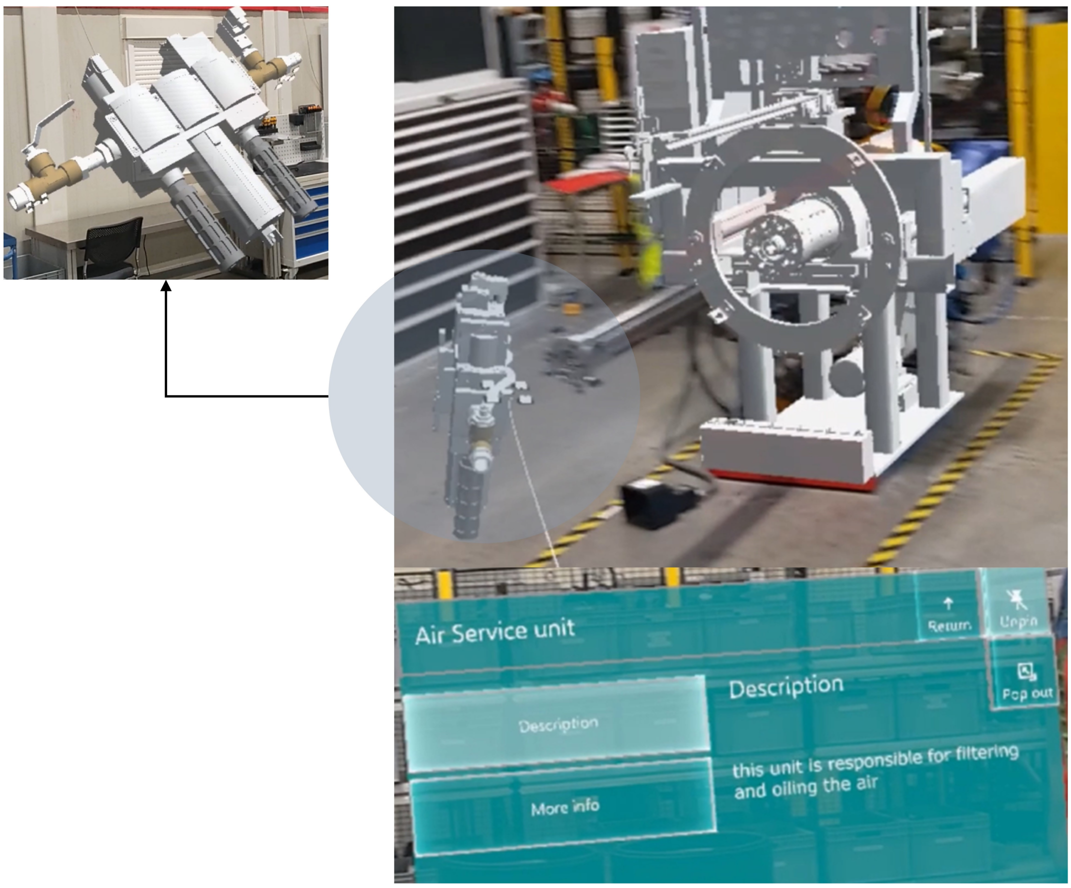

FIGURE 6.19: Point of Interest (POI) representation of air service unit

The second application on the drum test machine is step-by-step AR aided operation procedure. The machine requires 18 steps to complete the drum test and it must be followed sequentially. With the help of AR instruction system, the operators were much quicker in conducting the drum test without making errors. Figure 6.20 depicts the step 9 of drum test.

In the application phase, the operators requested for digitalizing the instructions for set-up and loading of creel machine. There are four creel machines in

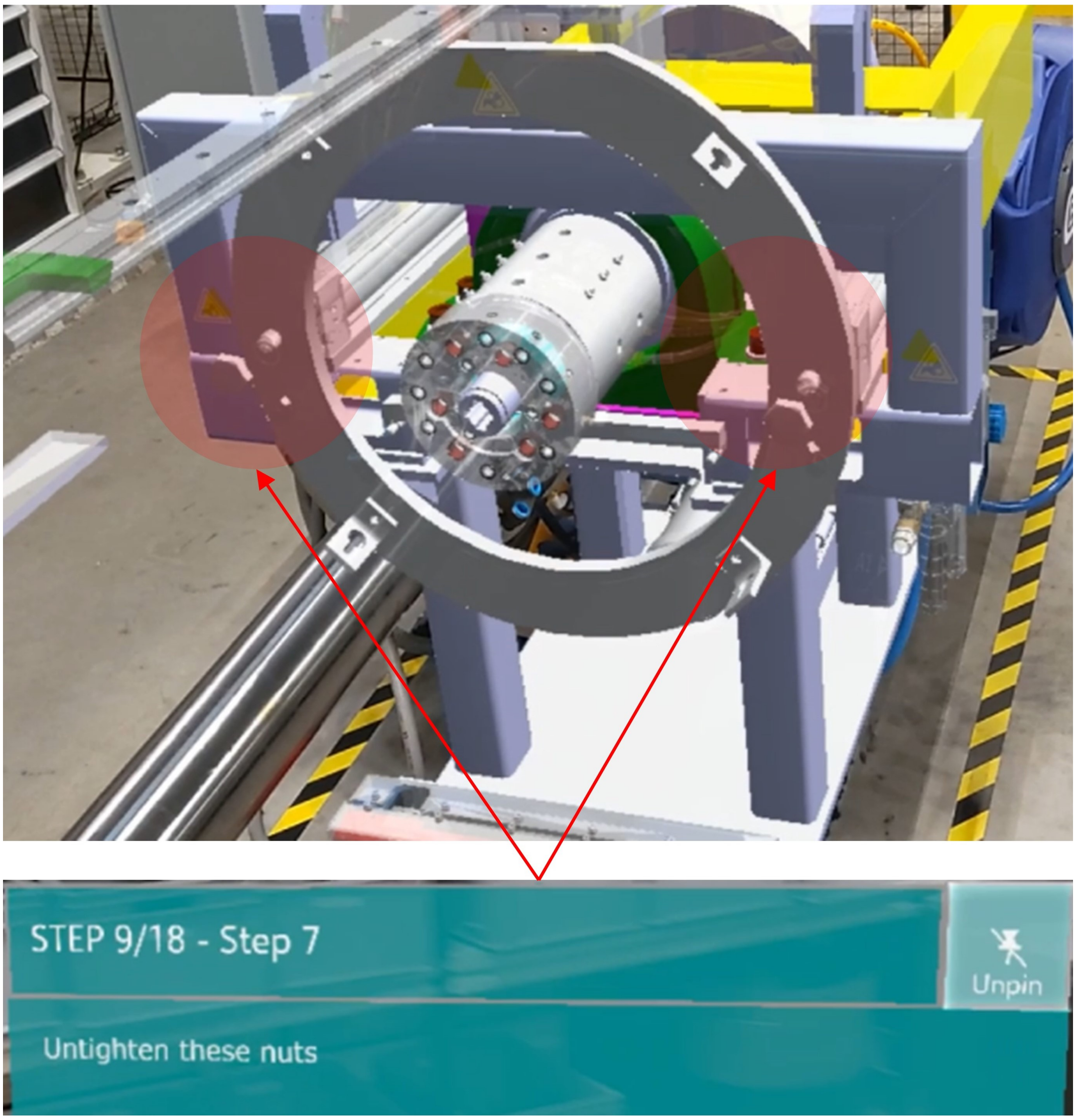

FIGURE 6.20: Step-by-step representation of working with Drum Test Machine

the company and it takes approximately 8 hours to load the creel machine for a fully experienced technician. Therefore, the objective of deploying AR instruction is to reduce the lead-time of loading the creel machine. As the project demands larger field of view, only HoloLens 2 with the combination of speech and gesture modality is used for the development. Using the AR instruction systems, each creel machine can be loaded in 6 hours which is 2 hours per day saving per machine. Figure 6.21 shows one of the overlayed instruction while loading the creel machine.

6.6 Post evaluation

In terms of usability of implemented solutions, the operators needed training before using AR instruction systems for both HoloLens 2 and iPad. It was easier to train the operators on iPad as they are used to the mobile interfaces in their

FIGURE 6.21: AR instruction for loading the Creel machine

daily life. However, the challenging task is to train the operators to use HoloLens 2. Working with HoloLens 2 is tiresome especially when interacting with it using gestures. Multimodal input system is used for designing the applications in HoloLens 2 to reduce the tardiness working with the it.

The training times were considerably reduced using AR instruction systems. For the cured tire inspection system, the training time is reduced from 1.5 to 2 days to 1.5 hours. Digitalizing the drum test machine helped operators to understand the machine parts better than before, which further speeds up the maintenance process of the machine. Significant time reductions were also seen in the creel machine as loading time is reduced by 2 hours per machine using AR instructions.

Chapter 7

Discussion

Even though the concept of Industry 4.0 was introduced in 2011 (Kagermann, Lukas, and Wahlster, 2011), it appears that most industrial enterprises are still in a transitional stage and have not yet realized the full potential of I4.0. This is further evident from an empirical study presented in Chapter 3 that most of the SMEs are below level 3, which suggests a transitional phase from traditional manufacturing systems to I4.0. Transition to I4.0 is a difficult process without methodological guidance, which is highlighted in chapter 4. By using the methodology presented in chapter 4, six case studies are conducted in the Greater Region of which two case studies relate to the transition towards I4.0. Chapter 5 and chapter 6 explored the workflow of introducing I4.0 technologies in two companies in Luxembourg. The summary of 4 other case studies in given in the Appendix D.

In the following sections, the research implications and contributions are discussed, as well as detailed responses to the main and supplementing research questions are provided.

7.0.1 Contribution to Research and Practice

This PhD thesis contributes to both research as well as practice in several ways. Chapter 2 presented the critical research review on the existing maturity models for lean and I4.0 and identified the research gaps. The research gaps are addressed by developing a new Self-Assessment Tool (SAT) involving both lean and I4.0 features. The SAT also has a major focus on manufacturing SMEs. In practice, the new SAT can be used as a strategic tool for Greater Region to analyse the status of manufacturing enterprises and support them to transition towards digitalization. A total of 100 companies are assessed using SAT developed as a part of this research. The assessment data provides a benchmark about the status of the companies in Greater Region and in practice each company can compare themselves with their counterparts in the region. The assessment data is also useful for making strategic decisions for governmental institutions with regards to establishing digital policies etc.

It is very clear from the assessment presented in Chapter 3 that the companies in Greater Region are behind in the technical dimensions such as Process and Value Stream, and Methods and Tools. This is because of lack of understanding and prerequisites for digital transition. To address this issue, an end-to-end methodology is developed in Chapter 4. The methodology covers the aspects from assessment to deployment of applications in any manufacturing enterprise. The methodology contributes a step-by-step process towards lean or I4.0 with manageable amount of resources. However, collaboration between companies and research units can accelerate the digital transition journey. Based on the experience from 6 case studies in Luxembourg, the companies find it difficult to identify I4.0 applications, which will have positive impact in the company. The methodology eases this issue by having four phases that develop from the results of the previous phases. Involving operators and higher management during various phases of the methodology, the real pressing issues can be tackled. The cases studies have seen a greater adaptation even after the project is finished because of the involvement of different actors in different phases of the case study.

Chapter 5 & Chapter 6 presented detailed requirements of Industrial Internet of Things (IIoT) and Augmented Reality (AR). Chapter 5 contributed to the existing literature especially in terms of a general architecture for IIoT in the context of retrofitting the legacy machines. This architecture is attractive to SMEs as the capital needed for retrofitting is minimal compared to purchasing new machinery for digital transition. For research, the laboratory validation of the general architecture of IIoT opens up ample amount of new opportunities in learning factories, and project based learning. The architecture is further validated in an industrial environment contributing to real world positive implications.

Chapter 6 significantly contributed to both research as well as industry concerning the adaptation of AR in manufacturing domain. AR architecture for manufacturing to build applications on a HHD (e.g. mobile phone) is presented with open source software. This significantly reduces the cost for developing AR applications especially in SMEs. AR software frameworks are the least researched area in manufacturing domain. To fill this gap, software frameworks for both HHD and HMD are presented using C4 notation. Two applications are developed in laboratory using a mobile device and a HoloLens 1 to validate the software frameworks. Another research gap in the existing literature is that the comparison of AR instruction systems with paper-based instruction systems. This gap is successfully filled by providing empirical evidence of benefits of using AR instruction systems over paper-based instructions. AR systems significantly reduce lead time, and number of errors. Moreover, human aspects such as cognitive work load and usability are vastly enhanced using AR instruction systems. The learning' from the laboratory experiments are applied in a Luxembourg company to improve the manufacturing processes such as quality inspection, maintenance, and machine set-up using AR.

7.0.2 Responses to supplementing Research Questions (RQ2-RQ6)

It is important to answer the five supplementing research questions (RQ2-RQ6) to sufficiently address the leading research question (RQ1) of this thesis. This section responds to RQ2-RQ6 and provide sufficient insights to answer RQ1.

Research Question 2 (RQ2)

What are the essential components of a manufacturing SME to assess its present status of lean and industry 4.0?

TABLE 7.1: Essential components of Lean and Industry 4.0 maturity model

Dimension	Lean Components	Industry 4.0 Components
Products	Reduction of change over time (SMED) Production levelling (Heijunka)	Simulation models Smart facilities
Strategy	Continuous improvements (kaizen)	Scout for new technologies
Technology	-	Vertical integration Machine to machine communication Human Machine Interfaces (HMI)
Customers	Value Stream Mapping (VSM)	Horizontal integration of supply chain
Operations	Key Performance Indicators (KPIs)	Data analytics Vertical integration
Leadership	-	Data driven decision making
Suppliers	Multiple suppliers	Horizontal integration of supply chain
Employees	Training on lean tools Quality awareness	Training on digital tools
Culture	Innovation culture	Change management

Chapter 2 and (Kolla, Minoufekr, and Plapper, 2019) provide a comprehensive response to RQ2. For a manufacturing enterprise, especially for an SME, the following dimensions are very crucial in measuring their lean and I4.0 status: Products, Strategy, Technology, Customers, Operations, Leadership, Suppliers, Employees, and Culture. These meta level dimensions provide a good starting point to design a hybrid maturity model addressing both lean and I4.0 elements. Table 7.1 shows the essential components of a maturity model to assess the status of lean and I4.0 with their respective dimension. These components are used in the development of SAT presented in chapter 2.

Research Question 3 (RQ3)

In view of the emergence of various digital technologies, how should manufacturing companies approach the design and development of Augmented Reality applications?

With the emergence of I4.0, there are many technologies available for improving specific area in a manufacturing enterprise. Augmented Reality (AR) can significantly improve the Human-Machine Interfaces in a company. However, for SMEs, the starting points for design and development of AR adaptation is still fuzzy. RQ3 is answered in detail in Chapter 6 and (Kolla et al., 2020). In the design and development of an AR application, the starting point is to understand the basic components required for application design. The five basic components that are essential for AR application development are: Capturing Technology, Visualization Technology, Processing Unit, Tracking System, and User Interface. The selection of device depends on the type of application. For simple assembly instructions a Hand-Held Device such as mobile phone or iPad are sufficient. However, for a complex task or when the operators needs a hands-free experience, it is recommended to use a Head Mounted Device such as HoloLens. The final step is to understand the software and hardware requirements for the AR application. The most useful hardware elements are markers, the machine parts, and the AR device. The most useful software elements are

C# for interaction design, Unity for development environment, Vuforia for enable QR tracking, Autodesk inventor for 3D design, and addons as required.

Research Question 4 (RQ4)

How can software frameworks and input modalities influence the choice of Augmented Reality technology for a particular manufacturing application?

Design of the software framework and selection of input & output modalities influence the AR application being developed. Software frameworks guide the whole software development process and describes the software system at different levels of detail. The framework presented in this research has three levels: software system, container diagrams, and components. A software system presents the overarching idea of an operator interacting with an AR system. This could be taken as a objective of the application. The container diagrams are the executable software or the platforms where the AR is being developed. The choice of containers influence the cost, design workflow, modes of tracking, input and output modalities. To keep costs minimum, this research only used open source software that are free for academic use. However, this comes with different challenges as some containers don't interact with others and need a specific API development or additional addons to establish the integration. Proprietary software avoid these difficulties but involves capital investment. In the level 3, the component diagram, where the functionality of each container is encapsulated. Therefore, the choice of software framework influence the development of AR applications in each stage of the development process. This research presented two software frameworks for HHD and HMD and validated both in laboratory as well as in an industrial environment (Kolla, Sanchez, and Plapper, 2021b)

The choice of modality (the way to interact and perceive information from an AR system) influences the performance and the usability. In this research, touch, gesture, speech, and multi-modal interactions are employed. Touch modality is intuitive yet in a real industrial environment it is not practical. For example, operator might not be able to interact with AR system wearing gloves. The noisy industrial shop-floor doesn't support speech modality. Gesture could be cumbersome if employed for a longer time. Therefore, the choice of interacting with AR system depends on the application. For training, the combination of speech and gesture presented in this research resulted in superior performance and usability.

Research Question 5 (RQ5)

How does the introduction of Augmented Reality instruction systems in manufacturing effect lead time, precision, workload, and usability when compared to paper-based instruction systems?

As a part of the PhD project, AR instruction systems are compared with paper-based instruction systems to provide empirical evidence on lead time, precision, workload, and usability. The outcomes of the research are published in (Kolla, Sanchez, and Plapper, 2021a). The results showed that the lead time using mobile device AR instructions are faster compared to HoloLens and paper-based instruction systems. However, Wilcoxon non-parametric test revealed that there is no statistically significant difference among three proposed systems. Precision wise, operators were more successful using HoloLens with minimum number of errors compared with mobile device and paper instructions. The Wilcoxon non-parametric test revealed a statistically significant difference between paper and HoloLens AR instructions. The participants experienced less workload using AR instruction systems compared with paper instructions. With regards to usability, AR instructions systems scored higher usability score than the paper-based instructions.

Research Question 6 (RQ6)

How should manufacturing companies approach the design, development, and deployment of Industrial Internet of Things in connection with Industry 4.0 transition ?

The manufacturing companies in the transition phase aren't data ready to use technologies like Industrial Internet of Things (IIoT). Therefore, in this research a generic architecture for retrofitting the legacy machines in the context of IIoT is presented with a laboratory case study and an industrial validation. Before deploying IIoT for a specific machine or group of machines, the knowledge of sensors, retrofitting technology, understanding of ICT concepts such as communication protocols, databases, and analytics is a prerequisite. One must design an architecture to guide the design and development process. The architecture normally consists of 3 layers: Physical layer, IoT layer, and cyber layer. One such architecture is presented in (Kolla et al., 2022) and be used by anyone who wants to retrofit legacy machines. For industrial use cases, it is important to consider the security aspects of data gathering or else the system is vulnerable to external attacks. An IIoT gateway is proposed in the general architecture of this research to tackle security issues that may arise with the deployment of IIoT. For industrial validation, a local database is employed to reduce the latency in data gathering. Using a local database is optional, however, highly recommend if one wish to do a real-time monitoring.

7.0.3 Response to Leading Research Question (RQ1)

Leading Research Question (RQ1)

How to design and develop an end-to-end (holistic) method that meets the needs of all manufacturing companies as well as European governing policies for a smooth transition to Industry 4.0?

A holistic method should provide an end-to-end solution for any enterprises from the assessment of status-quo until the deployment of I4.0. The methodology presented in this research (Chapter 4) has four phases: Maturity assessment, improvement potentials, technical road-map, and post-evaluation. Each stage of the methodology has sub-phases that were carefully designed to follow a logical order to conduct a case study. The methodology supports the deployment of I4.0 in manufacturing enterprises using one or combination of the 9 pillars presented in Chapter 1. The methodology encompasses both human aspects as well as the technical aspects. The smooth transition to I4.0 requires acceptance by the operators and end users of the new technology. Therefore, all the stakeholders who are effected by the implementation of the change concept are involved in all phases of the methodology. Experience from the case studies show that the acceptance of the technology implementation were well accepted by employees as they were involved since the beginning of Phase 1 of the methodology.

The leading research question (RQ1) is answered by adequately answering the supplementing research questions. RQ2 answers the organizational and human aspects of the manufacturing companies and derives the essential lean and I4.0 elements for Self-Assessment Tool (SAT). RQ3-RQ6 addresses the technical aspects related to 2 major I4.0 technologies Augmented Reality (AR) and Industrial Internet of Things (IIoT). The methodology is also suitable for lean implementation in manufacturing enterprises. In the framework of PRODPILOT project, this holistic methodology is used to implement lean methods and tools in 4 enterprises in Luxembourg (Appendix D). Following European digital transformation policies, "test before invest" concept has been employed throughout the case studies. Moreover, prototyping in laboratory followed by a pilot on shop-floor provide sufficient knowledge for a full deployment in the companies.

Chapter 8

Conclusion

Many manufacturing companies in the Greater Region of Luxembourg are in a transition phase towards Industry 4.0. The validated 4-phase methodology presented in the thesis provides steps for successful digital transition. The methodology developed in this research is holistic because of the end-to-end support it provides from status quo assessment to the deployment of new technologies in the company. Assessment of 100 manufacturing companies in the Greater Region revealed that small companies are positioned in level 1 or 2 and medium companies are positioned in level 2 or 3. Therefore, the companies need more support from research units, institutions, and government entities. Experience from 6 case studies in Luxembourg provides a significant conclusion that the collaboration between research units and companies accelerates the digital transition journey.

The technical objectives of the project are based on the analysis of responses to the Self-Assessment Tool. The survey revealed that aspects such as Error Prevention (EP) and Human-Machine Interfaces (HMI) are the two least matured modules in the Greater Region. Therefore, two technologies from I4.0 (IIoT and AR) are chosen to improve the maturity of EP and HMI. Following "test before invest" philosophy, both the technologies were developed from scratch in the laboratory environment before deploying them in the industry environment.

The general architecture of IIoT in the context of retrofitting is a new scientific contribution. Using this architecture any engineer can retrofit legacy machines in their shop-floor/ company. The architecture is tested and validated in both laboratory environment as well as in an industrial environment. The thesis also contributes significantly in the AR domain. The software frameworks for AR for manufacturing in both HHD and HMD are presented using open source software. SMEs can reproduce the workflow just by following the frameworks. However, skills in programming and 3D design are prerequisites before entering the AR domain. The thesis also provides statistically significant results of comparing AR instruction systems with paper-based instructions. AR showed superior performance in the user tests when compared to paper-based systems.

In a nutshell, the PhD thesis delivers a methodology, a Self-Assessment Tool, and two case studies to validate the methodology.

8.1 Acknowledgment

The PhD project is a part of PRODPILOT project, which is supported by INTERREG V program. The program aims at intensifying cross-border cooperation. This goal is to be achieved by means of local and regional projects between partners from the various areas in the Greater Region of Luxembourg. Find more details about the project PRODPILOT at https://prodpilot.eu/de. Thanks to GCL Technologies and Goodyear for providing support and access to your facilities for technical validation of the thesis.

Appendix A

Interreg
EUROPEAN UNION
Grande Région | Großregion
PRODPILOT
Fonds européen de développement régional | Europäischer Fonds für regionale Entwicklung

Study to determine the productivity level of companies

Notes on the study:

- Only one answer per question is possible; if necessary, answers should refer to the most important company or production area.
- All data are anonymized for analysis

1. Please select the business sector of your industry

   ____

   Note: You will find a list of business sectors in the last page

2. Please select the region of your industry

3. Please select the size of your company

   a. Small (< 50 employees)
   b. Medium (< 250 employees)
   c. Large (> 250 employees)

4. What is the annual turnover of your company?

   a. < € 50 Million
   b. € 50 Million - € 100 Million
   c. € 100 Million - € 500 Million
   d. > € 500 Million

5. What position do you occupy in the respective industry?

   a. Technician/ Worker (Specialized)
   b. Engineer/ Business Expert
   c. Executive Officer
   d. Senior Management

Category 1: Strategy

Strategic Target Planning

Does your organization have an existing long-term plan (≥ 3 years) with a focus on production?

1. No precise or just short-term targets
2. Short-term (1 to 3 years) measurable targets exist
3. Long-term goals exist, mainly for efficient production, better material flow, and elimination of waste. E.g. Lean Production
4. Long-term goals exist, mainly for digitization and adoption of new technologies in production. E.g. Industry 4.0
5. Currently not relevant

Strategic Implementation Planning

Does your organization have an existing long-term plan (≥ 3 years) for production improvement or logistics?

1. Only uncoordinated isolated actions, management has different views on priorities
2. Company has individual transformation plan with short and long-term projects
3. The company has its own strategic action plan, mainly for efficient production, better material flow or elimination of waste, E.g. Lean Production, which is supported at all hierarchical levels
4. The company has its own strategic action plan, mainly for digitization and new technologies in production, E.g. industry 4.0, which is supported at all hierarchical levels
5. Currently not relevant

Technology and Innovation Management

To what extent is your organization scouting for innovations for production and logistics?

1. New technological developments and innovations are not monitored
2. New technological developments and innovations are monitored occasionally and informally
3. Innovations and relevant technological developments are monitored and integrated in an uncoordinated way into the strategic action plan
4. There are a formal processes or organization to monitor and integrate innovations relevant to production and technology development into strategic action plan
5. Currently not relevant

Category 2: Process and Value Stream

Design of the Value Stream

Are non-value added activities in production and supply chain systematically analyzed and eliminated?

1. No systematic analysis
2. Tools for Value Stream Analysis are used to visualize value and waste in the business, E.g. Value Stream Mapping (VSM)
3. In order to continuously improve internal processes and organization, a desired end state for production is derived from value creation analysis. E.g. Future State Mapping
4. The complete value chain is continuously optimized according to a desired end state
5. Currently not relevant

Material Replenishment

What are the procurement strategies used in your organization?

1. Procurement mostly according to push-principle, high inventory-levels and material frequently out-of-stock
2. Different procurement methods are used for different category of items to reduce inventory. E.g. Pull, Kanban and JIT. Material is out of stock for some article groups
3. Sophisticated procurement strategies are used to achieve optimization of inventories in the supply chain. E.g. SCOR model, Vendor Managed Inventory (VMI)
4. Coordination of sales and production planning with relevant partners of supply chain to achieve target optimization of stocks. E.g. Collaborative Planning, Forecasting and Replenishment (CPFR)
5. Currently not relevant

Smart Machines and Communication

How your production machinery communicate and use information?

1. Machines do not generate information
2. Machines can receive information (e.g. programs) but only have simple displays without sending information to a central system. E.g.: lamp signal in case of a failure
3. Machines receive and provide digital information on progress of work and downtime but usually require manual intervention
4. Machines respond autonomously and flexible in case of changes, E.g. Automatic adaptation of the machine assignment based on the changes to the production plan
5. Currently not relevant

Operational Data Monitoring

How are defects and breakdowns of machines in production avoided and removed?

1. Manual monitoring and diagnosis of defects and break-downs in production based on worker's experience
2. Partly automated monitoring of critical production conditions, mainly manual diagnosis and removal of defects and break-downs
3. Automated monitoring and communication of critical production conditions in real-time with automatic diagnosis to eliminate errors and malfunctions
4. Automated monitoring and statistical forecasting of critical production conditions in real-time and autonomous actions
5. Currently not relevant

Remote Access to Machines

To what extent production machinery can be controlled remotely?

1. Control of machines only locally
2. It is possible to retrofit the existing machinery with remote control and monitoring
3. Control and Monitoring of machines is possible remotely with a time-delay. E.g. diagnosis of the machine by manufacturer after a failure
4. Control and Monitoring of machinery is possible remotely in real-time. E.g. control or maintenance of machine from another production site
5. Currently not relevant

Real-Time Production Scheduling and Control System

To what extent information regarding planning, monitoring and production control are available?

1. The information is managed in simple tables (E.g. Excel) or in many unconnected IT solutions. E.g. different IT solutions for quality management, personnel management, machine data acquisition and production planning and control
2. The replacement of different IT solutions by a central and networked computer system in production is underway. E.g. Manufacturing Execution System (MES)
3. For efficient production monitoring, there is a central system that collects all relevant information and make it available in real time. E.g. quality defects, availability of personnel, condition of machinery, etc.
4. A central system exist in production planning and control that is also used to optimize products and processes in non-production areas. E.g. purchases, sales (sales planning), human resources, development, etc.
5. Currently not relevant

Human-Machine Interface

How are the interfaces between employees and machines designed in your company?

1. No or only local machine displays for information
2. Information is displayed on central screens or computers
3. Continuous usage of mobile and portable display devices. E.g. Tablets
4. Efficient information exchange and assistance with augmented or virtual reality, E.g. by smart glasses
5. Currently not relevant

Availability of Information at Workplace

To what extent is workplace-information available regarding tasks, orders and safety?

1. No or incomplete description of tasks, orders and safety instructions at workplace
2. Important information is available in paper form at the workstation. Information from adjacent services only available upon request. E.g. quality issues, customer specific requirements, change of supplier
3. Order-specific information at the workplace is standardized and visualized; all necessary information provided to perform work
4. The information is fully digital and built into the computer system and adapts to the capabilities of the employee at the workstation. E.g. Support system for experienced / new staff, translation of information
5. Currently not relevant

Production and Logistics Levelling

Does your company strategically plan production processes and production orders in case of demand fluctuations?

1. No strategy between orders and production planning leading to frequent supply shortages
2. Strategies exist in some parts of the business to balance variations in demand and production resources. E.g. Daily capacities are available in production line
3. Strategies exist across the business to balance variations in demand and production resources
4. Integration of relevant supply chain partners in the strategy to smoothen demand and production resources
5. Currently not relevant

Adaptability and Quick Changeover

How flexible is the changeover of machines in case of product change?

1. Changeover of machines is avoided if possible because it takes long-time and/ or machines are not flexible
2. Systematic actions are taken to reduce machine changeover time or/ and to improve machine flexibility. E.g. Parallelization of activities during the machine change over, incorporating SMED methods
3. Quick changeover of machines and systems has been implemented
4. Machines perform changeover autonomously; changeover time no longer relevant for production scheduling
5. Currently not relevant

Internal Transport Handling and Storage

How do you manage internal material transport in your organization?

1. Simple manual warehouse activities. E.g. transportation using forklifts
2. Use of different logistic strategies according to the groups of articles. E.g. train concepts, supermarket, milk-run
3. Internal material flow and warehouse processes are partly automated, E.g. Autonomous Guided Vehicles (AGV), Automatic Small Parts Storage
4. Completely autonomous material flow with AGV and automated handling
5. Currently not relevant

External Transport

How do you manage external material transport in your organization?

1. Different departments/ divisions do not coordinate their external transports
2. Centralized planning and management of transport
3. Transport management based on digital monitoring of container positions and infrastructure
4. Use of autonomous driving trucks and platooning concepts
5. Currently not relevant

Category 3: Organization

Standardization

How processes are standardized and monitored in your organization?

1. Activities are not standardized and control of deviations is not possible
2. Processes are mostly standardized and monitored by employees themselves or at downstream workstation level
3. Processes are standardized and monitored regularly by line managers at different levels
4. Standards are continuously improved in a transparent way, deviations are controlled and effectively eliminated with combined effort of line managers and employees
5. Currently not relevant

Process Definition and Documentation

To what extent processes are defined and documented in your organization?

1. Process descriptions and goals are unknown to the employees or are not understood
2. The processes and process objectives are documented (E.g. As a hard copy) and communicated to the employees. The information is not directly available at the workplace
3. Comprehensive documentation of processes and process objectives are available at the workplace and process objectives reflect current problems and challenges of the process
4. Most of the employees feel responsible to create and update documentation of processes and process objectives to achieve desired process goals
5. Currently not relevant

Workstation Layout

To what extent do you use methods for efficient, safe and ergonomic workstation layout?

1. No structured workstation designs
2. Use of simple techniques for a clean and orderly work place environment. E.g. 5S
3. Methodology is applied throughout production to design activities and workstations, e.g. Analysis tools for ergonomics, REFA tool kit, Methods-Time Method (MTM)
4. A software for autonomous design of activities and workstations is used
5. Currently not relevant

Category 4: Methods and Tools

Continuous Improvement Processes

How effective are your problem-solving methodologies for continuous improvements?

1. Unstructured problem solving, recurring issues and "firefighting"
2. Usage of simple tools for structured problem solving and error prevention. E.g. Poke Yoke, PDCA, Kaizen
3. Usage of advanced methods to solve complex problems in all services. E.g. Six Sigma, 8D etc.
4. Analyze problems using advanced software to connect large amounts of data and solve them autonomously. E.g. Big data, machine learning etc.
5. Currently not relevant

Product Design

To what extent production and Logistics departments are contacted in the design decisions for new products?

1. Decisions regarding design of new products are made exclusively in the development department
2. Influence of production or logistics department on product design is limited
3. The essential stages of product design are discussed with production and logistics
4. Product design decisions proactively involve production and logistics as well as key suppliers and key customers
5. Currently not relevant

Custom Design and Manufacturing

To what extent the individual wishes of customers are taken into account in the design and manufacturing of the products?

1. Only standard products are offered and manufactured. E.g. Make-to-stock
2. Individual design at the customer's request is possible to a small extent but involves a high manual effort in design and manufacturing. Ex: Make-to-order or Assemble-to-order
3. The company has its own processes or organization for custom design and fabrication by the staff. E.g. Engineer-to-order
4. Using standalone software, individual product design and manufacturing plans are automatically created. E.g. rule-based design software with knowledge of specialized departments
5. Currently not relevant

Digital Representation of the Production

To what extent the status of machines, material flows and production orders are transparent in the production?

1. Production information is only available upon request and production data is not evaluated
2. Transparency in production is at it's infancy by recording the positions of production orders (E.g. by scanning barcodes) and by using panels to visualize the status of production (E.g. Andon)
3. The production status is, with restrictions and deadlines, available as digital information to staff and certain suppliers or customers. E.g. for queries regarding the status of orders, stocks or a delivery date
4. Information on the current status of production is made available to staff and some suppliers or customers as a digital image of the plant, so that deviations and problems can be quickly identified and effectively avoided.
5. Currently not relevant

Company-Wide Network

How production department communicates with other departments and sites?

1. Tedious exchange of information, mainly by e-mail or telephone, so that the changes in production can only be made with considerable delay. E.g. customer changes are not included in the production schedule until the next day
2. Departments or sites exchange information in standardized data formats to effectively control production. E.g. electronic document retrieval, electronic exchange of stock lists
3. Essential information for production control is stored in software systems and made available throughout the enterprise, but is only updated at a particular time. E.g. ERP system SAP R/3
4. A fully interconnected IT solution between the departments and/ or factories that enables the efficient exchange of real-time information to control and improve production processes. Ex: ERP system SAP S/4 HANA
5. Currently not relevant

Digital Production Planning and Scheduling

Which IT systems do you use for production planning and management in your organization?

1. IT tools nearly doesn't exist except the usage of Excel spreadsheets. High communication effort is required. Capacity utilization and time are mainly estimated or approximately calculated
2. Central system for planning and scheduling of the production according to defined criteria (E.g. FIFO) and past data; need for communication with other departments to coordinate changes
3. Production planning and scheduling with specific software based on past data, expected resources, constraints and lead-times; system triggers manual modifications in real-time
4. Dynamic and autonomous production planning and scheduling based on real-time data, sophisticated forecasting and capacity analysis, and the system communicates changes if human support is required
5. Currently not relevant

Digital Control of Internal Logistics

To what extent IT systems are used to support internal logistic processes?

1. No IT systems are in place to control the internal logistics processes (e.g. use of excel tables). Intensive internal communication efforts are required to control in-house logistics
2. Partial use of IT systems for efficient communication, warehouse management and control of internal logistics processes. E.g. Inventory management systems, ERP
3. The use of IT systems are seen in parts of production and warehouses by use of systems for the automatic identification of materials, goods or containers (E.g. RFID, Barcode, Narrow band IoT)
4. Consistent use of IT systems for warehouse management and efficient control of internal logistics processes with the use of automatic identification systems (E.g. RFID, Barcode, Narrow band IoT)
5. Currently not relevant

Digital Control of External Logistics

To what extent IT systems are used to support external logistic processes?

1. No IT systems are in place to control the external logistics processes (e.g. use of excel tables). Intensive communication efforts with partners are required to control external logistics processes
2. Partial use of IT systems for efficient communication and control of supply chain. Eg: Transport Management Software (TMS), ERP
3. The company's IT systems are fully connected to external suppliers and customers via electronic interfaces/ internet and making efficient and effective communication throughout the supply chain
4. Advanced software are used to anticipate stocks, deliverability, and transportation time throughout the supply chain. Eg: Predictive logistics software etc.
5. Currently not relevant

Use of Simulation Models

To which extent simulation models are used for better understanding and control of complex processes or systems?

1. Employees do not recognize the value of simulation models
2. Potential of simulation models are recognized in company
3. Competency for simulation are available and simulations done from time to time
4. Competency for simulation are available and systematically used to optimize production and logistics processes if economically reasonable
5. Currently not relevant

Existence of Indicators

Do you have an up to date and logically structured Key Performance Indicators (KPI) system exist in your company?

1. KPIs don't exist for all areas in the company or don't fully reflect the current issues and opportunities in the company. E.g. Existence of financial indicators but production indicators don't exist. There is no recent update for the indicators
2. Indicators exist mainly for the hierarchy, they are standardized at the company level. These indicators are updated regularly and adequately represent current challenges of the company
3. There is an up-to-date and logically structured indicator system at all levels of the enterprise, including operational departments
4. There is logically structured system of indicators throughout the company as well as relevant partners of the supply chain with the possibility to track in real-time
5. Currently not relevant

Utilization of Indicators

To what extent do you utilize KPIs for decision making in your company?

1. KPIs are not systematically used to derive measures, make decisions and control effectiveness
2. KPIs are not regularly discussed for measures and decision-making but only for critical cases
3. Regular meetings on KPIs are conducted (Eg: monthly) to systematically derive the measures and decision making
4. Systematic and regular use of KPIs at all levels of hierarchy, including in operational areas (E.g. shop-floor management, gemba-kaizen)
5. Currently not relevant

Total Productive Maintenance

To what extent are maintenance methods are used to improve the performance, availability and cost-effectiveness of equipment?

1. Issues with machine cleanliness and downtimes are not recorded. Maintenance mainly in case of breakdown
2. Early preventive maintenance, downtimes are systematically recorded and machines are kept clean
3. The staff are trained in Total Productive Maintenance (TPM) methods, and use performance indicators to improve equipment performance. E.g. OEE measurements
4. Advanced technologies and software are used for predictive analysis of the machine status to reduce equipment downtime (E.g. Predictive maintenance)
5. Currently not relevant

Resources and Ecological Sustainability

How does your company reduce emissions and use of resources?

1. The company doesn't take systematic approach to reducing energy inputs, resources and harmful environmental emissions
2. The company has a systematic approach to control and reduce inputs, resources and emissions (e.g. energy, gas, water etc.). E.g. Environmental certifications, ISO 14001 etc.
3. The company implements holistic concepts for resource optimization. E.g. Life Cycle Assessment of Products, Circular Economy etc.
4. Sensors are consistently used to visualize consumption and trend development of supplies, critical resources and emissions in real time with the objective of optimizing the consumption and emissions
5. Currently not relevant

Category 5: Personnel

Training

Does your organization offer regular trainings and do the staff recognize the importance of training?

1. Trainings are not offered. Employees and supervisors have no interest or do not recognize the benefits of training
2. Trainings are offered but the participation of the staff in the training is determined by the superiors or by the regulations
3. Existence of an individual staff development policy and motivation to follow with the help of incentives
4. Existence of an individual staff development policy with a focus on efficient production, digitization and use of new technologies
5. Currently not relevant

Change Management

To which extent are employees committed to change of processes in your organization?

1. Changes are only implemented under pressure from management
2. Employees accept changes but have only minor interest and passion towards changes
3. The majority of employees accept change and are interested in efficient production processes, digitization and the use of new technologies
4. The majority of employees make suggestions for improving the efficient design of production processes, digitization and the use of new technologies
5. Currently not relevant

Working Time Models

How flexible are the working time models in your operational areas?

1. Rigid working time models without opportunity to adapt. E.g. fluctuation in demand
2. Mainly rigid working time models with some flexibility. E.g. group holidays etc.
3. Working time models are generally flexible and allows reaction on market changes. E.g. Through the rapid employment of temporary work, flexible hours
4. Flexible working time models are regularly adapted to respond quickly to changes in the market. E.g. work schedules and variable staff assignments etc.
5. Currently not relevant

Quality Awareness of Employees

How do employees see their influence and their responsibility for quality?

1. Employees think that their way of working has no impact on quality
2. Employees are aware of their impact on the quality but are not accountable for it at all levels of hierarchy. E.g. compliance with standards, quality management according to ISO 9001
3. Employees at all levels of hierarchy are aware of their impact on quality and act according to their responsibilities
4. Employees at all levels of hierarchy are aware of their influence on quality and initiate activities to improve quality on their own
5. Currently not relevant

Innovation Culture

To what extent does your corporate culture promote innovation and creativity?

1. Management doesn't encourage employees to share their innovative ideas
2. Each employee is implicitly invited to share his or her innovative ideas
3. The management explicitly encourages staff to share their innovative ideas by setting up concrete mechanisms (e.g. innovation competitions, specific training, etc.) to stimulate creativity and innovation.
4. Management actively involves staff in implementing innovations
5. Currently not relevant

List of business sectors (according to the NACE Rev. 2)

10	Manufacture of food products
11	Manufacture of beverages
12	Manufacture of tobacco products
13	Manufacture of textiles
14	Manufacture of wearing apparel
15	Manufacture of leather and related products
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
17	Manufacture of paper and paper products
18	Printing and reproduction of recorded media
19	Manufacture of coke and refined petroleum products
20	Manufacture of chemicals and chemical products
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
22	Manufacture of rubber and plastic products
23	Manufacture of other non-metallic mineral products
24	Manufacture of basic metals
25	Manufacture of fabricated metal products, except machinery and equipment
26	Manufacture of computer, electronic and optical products
27	Manufacture of electrical equipment
28	Manufacture of machineryand equipment n.e.c.
29	Manufacture of motor vehicles, trailers and semi-trailers
30	Manufacture of other transport equipment (e.g. ships, railway locomotives, air and spacecraft)
31	Manufacture of furniture
32	Other manufacturing (e.g. jewellery, musical instruments, sports goods, games and toys, medical instruments and supplies)
33	Repair and installation of machinery and equipment

Appendix B

Figure B.1: Retrofitted tension measuring spring with a distance sensor

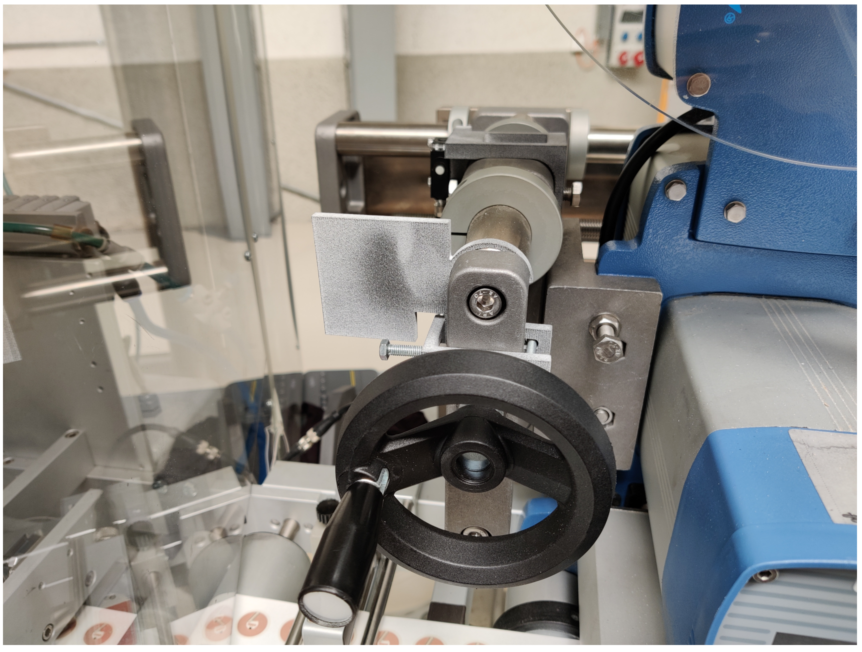

Figure B.2: Retrofitted X-Adjustment sensor on the machine

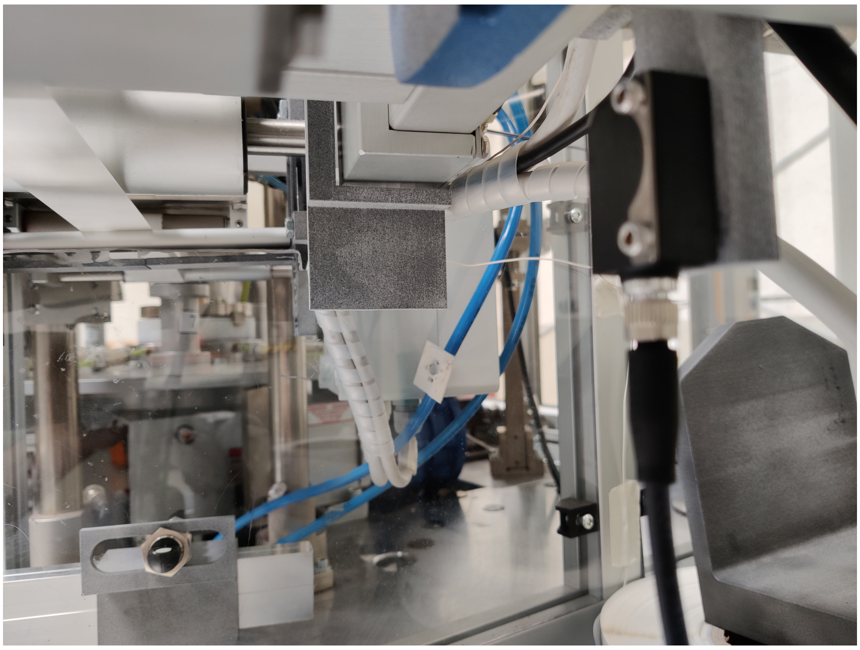

Figure B.3: Retrofitted Y-Adjustment sensor on the machine

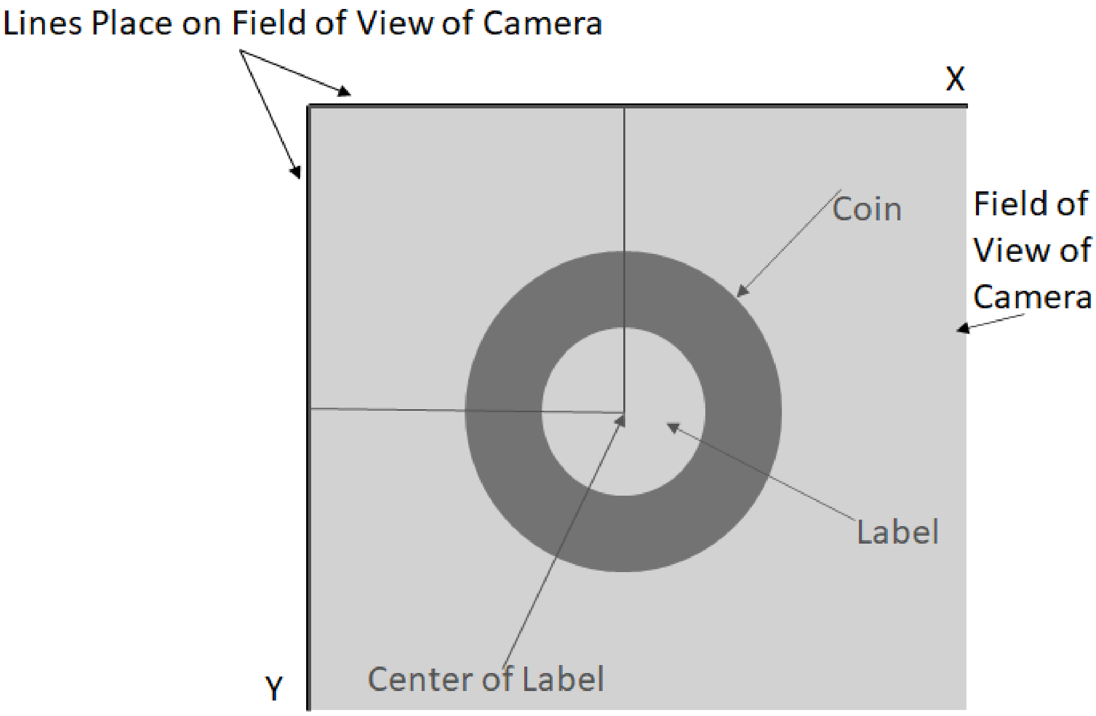

Figure B.4: Change of camera set-up for measuring the centering of tags on the coins

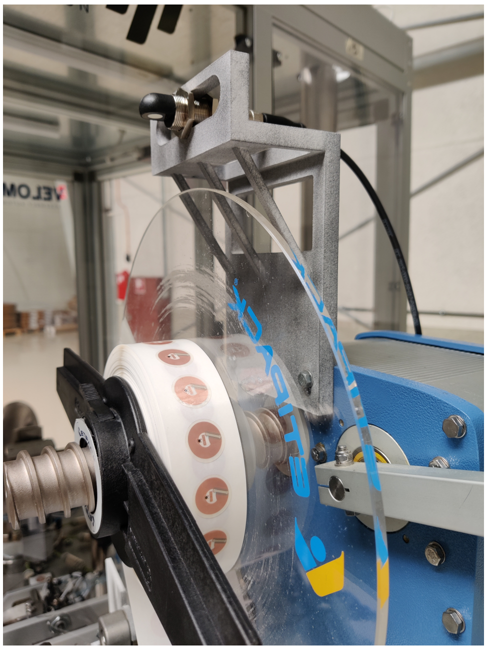

Figure B.5: Retrofitted ultrasonic sensor to measure coil diameter

Figure B.6: Front view of the labelling machine

FIGURE B.7: Retrofitted vision sensor to measure the centering of the tags on the coins

Appendix C

NASA – TLX

Experiment ID:

Participant ID:

Choose your experience in the Task: ☐ 0-1 year ☐2-4 years ☐5-7 years

Metal Demand: How mentally demanding was the task?

[Very Low] 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 [Very High]

Physical Demand: How physically demanding was the task?

[Very Low] 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 [Very High]

Temporal Demand: How hurried or rushed was the pace of the task?

[Very Low] 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 [Very High]

Performance: How successful were you in accomplishing what you were asked to do?

[Perfect] 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 [Failure]

Effort: How hard did you have to work to accomplish your level of performance?

[Very Low] 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 [Very High]

Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?

[Very Low] 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 [Very High]

Out of the following pairs of two workload measures, which one contributed more to the task?

Physical Demand ☐ Frustration Level ☐	Performance ☐ Frustration Level ☐	Temporal Demand ☐ Effort ☐	Performance ☐ Effort ☐	Effort ☐ Frustration Level ☐
Mental Demand ☐ Frustration Level ☐	Physical Demand ☐ Effort ☐	Physical Demand ☐ Temporal Demand ☐	Mental Demand ☐ Effort ☐	Mental Demand ☐ Temporal Demand ☐
Mental Demand ☐ Performance ☐	Temporal Demand ☐ Frustration Level ☐	Temporal Demand ☐ Performance ☐	Physical Demand ☐ Performance ☐	Mental Demand ☐ Physical Demand ☐

Mental Demand: Physical Demand: Temporal Demand: Performance:

Effort: Frustration:

PARTICIPANT NAME: ______________________ DATE: ______________

System Usability Scale

For each of the following statements, please mark one box that best describes your reactions to Paper Instructions today.

		Strongly disagree				Strongly agree
1.	I think that I would like to use Paper Instructions frequently.	1	2	3	4	5
2.	I found Paper Instructions unnecessarily complex.	1	2	3	4	5
3.	I thought Paper Instructions was easy to use.	1	2	3	4	5
4.	I think that I would need the support of a technical person to be able to use Paper Instructions.	1	2	3	4	5
5.	I found the various functions in Paper Instructions were well integrated.	1	2	3	4	5
6.	I thought there was too much inconsistency in Paper Instructions.	1	2	3	4	5
7.	I would imagine that most people would learn to use Paper Instructions very quickly.	1	2	3	4	5
8.	I found Paper Instructions very cumbersome (awkward) to use.	1	2	3	4	5
9.	I felt very confident using Paper Instructions.	1	2	3	4	5
10.	I needed to learn a lot of things before I could get going with Paper Instructions.	1	2	3	4	5

Comments (optional):

PARTICIPANT NAME: DATE:

System Usability Scale

For each of the following statements, please mark one box that best describes your reactions to Mobile Device today.

		Strongly disagree				Strongly agree
1.	I think that I would like to use Mobile Device frequently.	1	2	3	4	5
2.	I found Mobile Device unnecessarily complex.	1	2	3	4	5
3.	I thought Mobile Device was easy to use.	1	2	3	4	5
4.	I think that I would need the support of a technical person to be able to use Mobile Device.	1	2	3	4	5
5.	I found the various functions in Mobile Device were well integrated.	1	2	3	4	5
6.	I thought there was too much inconsistency in Mobile Device.	1	2	3	4	5
7.	I would imagine that most people would learn to use Mobile Device very quickly.	1	2	3	4	5
8.	I found Mobile Device very cumbersome (awkward) to use.	1	2	3	4	5
9.	I felt very confident using Mobile Device.	1	2	3	4	5
10.	I needed to learn a lot of things before I could get going with Mobile Device.	1	2	3	4	5

Comments (optional):

PARTICIPANT NAME: DATE:

System Usability Scale

For each of the following statements, please mark one box that best describes your reactions to HoloLens today.

		Strongly disagree				Strongly agree
1.	I think that I would like to use HoloLens frequently.	1	2	3	4	5
2.	I found HoloLens unnecessarily complex.	1	2	3	4	5
3.	I thought HoloLens was easy to use.	1	2	3	4	5
4.	I think that I would need the support of a technical person to be able to use HoloLens.	1	2	3	4	5
5.	I found the various functions in HoloLens were well integrated.	1	2	3	4	5
6.	I thought there was too much inconsistency in HoloLens.	1	2	3	4	5
7.	I would imagine that most people would learn to use HoloLens very quickly.	1	2	3	4	5
8.	I found HoloLens very cumbersome (awkward) to use.	1	2	3	4	5
9.	I felt very confident using HoloLens.	1	2	3	4	5
10.	I needed to learn a lot of things before I could get going with HoloLens.	1	2	3	4	5

Comments (optional):

Appendix D

Short version of the case study at Electricité Wagener et fils

Brief description of the company: Electricité Wagener et fils is engaged in distribution, installation and repair of electrical equipment. Their area of operation is limited to Greater Region.

Location: Kehlen, Luxembourg

Employees: 47 permanently employed & 3 to 4 independent craftsmen

Turnover: < 50 Mio €

Modules of the maturity assessment: Digital Control of Internal Logistics, Process Definition and Documentation

Background: At Wagener et Fils the quality of the service is defined by the accessibility of goods. However, their warehouse management has some bottlenecks, which reduce the efficiency and effectiveness of the department. The implementation of advanced technology is expected to significantly improve warehouse control and the associated process flows. Nevertheless, putting such a system into use requires extensive planning and change management. The goal of this case study was the structured implementation of a 1D barcode system and the definition of best practice, in order to offer optimized work instructions to the employees and enable continuous improvement.

Activities: First weekly meeting have been set up, to control the status of the project and discuss upcoming issues. Additionally, to the 1D barcode system lean adaptations have been selected for process optimization, building a complete change management concept represented in figure 1.

Figure 1: Change Management Concept

New means of transportation have been made available to the warehouse-keeper to enable a faster and more ergonomic way of working. Additionally, a kitting system has been introduced to simplify the collection, exchange and charging of goods. Furthermore, this system allows better control and overview over projects as visualized in the figures below.

Figure 2: Project shelves with kitting system

Figure 3: Project shelves with kitting system

The process description and standardization ensure consistent execution of the tasks in the way of best practice and enables continuous improvement. Lastly the reorganization of the warehouse is intended to reduce the waste of transport and movement.

The implementation plan, designed for the successful incorporation of the change management concept comprises a prototyping phase, testing the effects of the changes. Subsequent adjustments in the process design have been realized and problems have been solved. The resulting best practice have been deployed, documented and communicated. Additionally, a post evaluation has been conducted to rate the success of the project and define lesson learned. Finally, a plan for sustainability of the project has been set up to ensure employees fulfill the tasks according to the defined best practice.

The implementation of the change management concept was linked to the redesign of the warehouse processes. The transformation of a process is illustrated in figure 4 using the example of the project preparation operation. Before realization of the change management concept the warehouse-keeper had to collect the articles in the warehouse with his bare hands during the first phase. Thereupon he packed them in cardboard boxes from old deliveries and transported the boxes to the pickup area during a second phase. In the office the last phase took place, all article numbers of the collected articles had to be entered manually and posted on the project. The combination of the change management aspects enabled a complete redesign of the process, now consisting of one preparation phase and a second phase containing the collection and identification of goods at once with the help of the scanner, a kitting system and a new warehouse trolley.

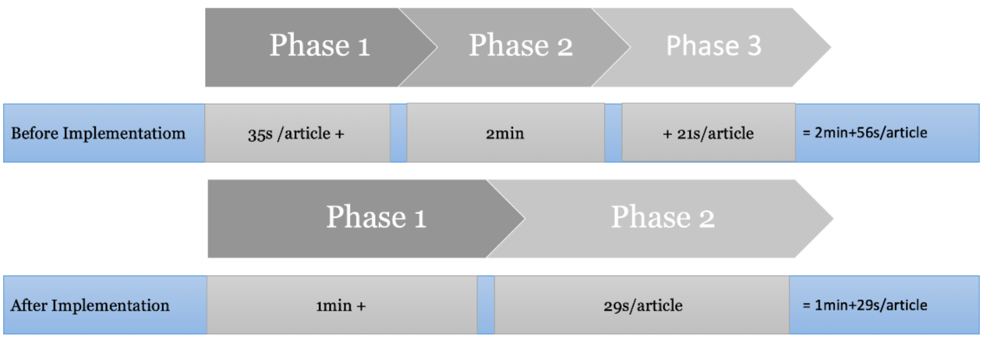

Figure 4: Project preparation phases before and after implementation of the change management concept

Results: Through the structured and detailed implementation of a change management concept considerable improvements have been observed during this project.

- Cycle time reduction
- Creation of an ergonomic work environment
- Accessibility to real time data
- Reduced internal transport and movement of employee
- Minimized paperwork
- Reduced manual work

The measurements allowed a quantitative evaluation of the project results. Below the time consumption of the project preparation in function of the number of articles is depicted.

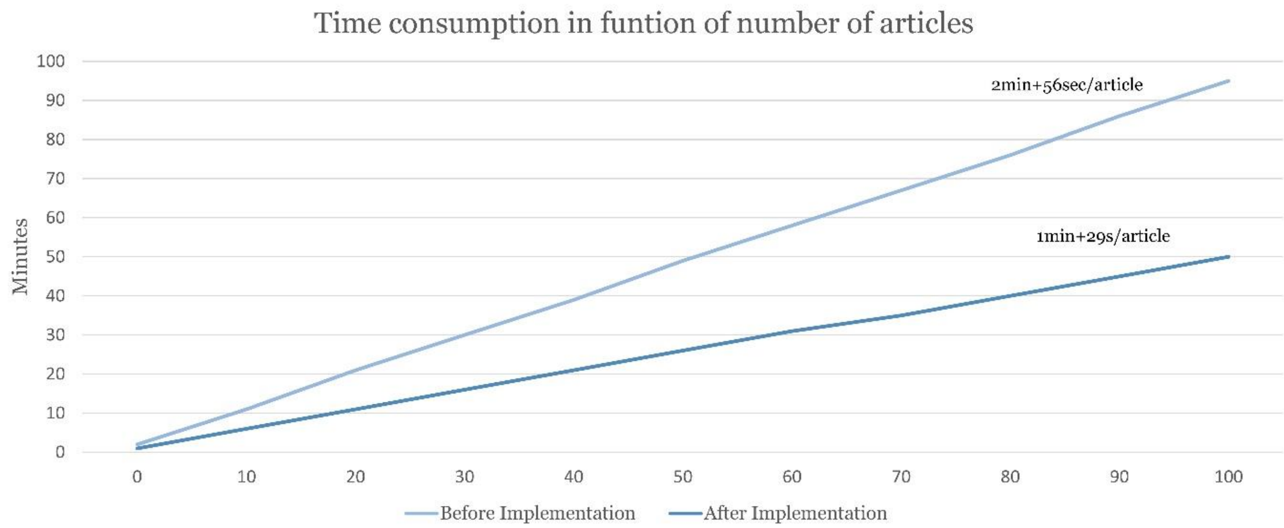

Figure 5: Time consumption for project preparation before and after implementation of the change management concept

It is clearly visible that the time savings get significant the more articles are prepared. In any case a time reduction of 47%-49% can be observed. For the warehouse replenishment operation, the time reduction is located 0% and 50% dependent on the number of articles. Additionally, the waste of movement has been reduced by 58%.

In terms of company culture, the employees' critical thinking has been strengthened, enabling them to actively contribute to continuous improvement and creating a participative work environment.

Success factor: This case study has demonstrated that large increases in productivity are feasible across a wide range of sectors by implementing a specifically selected technology, which directly addresses the company's weaknesses.

Short version of the case study at Astron biz

Brief description of the company: Astron biz offers steel building solutions to their customers throughout Europe.

Location: Diekirch, Luxembourg

Employees: 690 employees

Turnover: 90 Mio € (2020)

Modules of the maturity assessment: Design of the Value Stream, Real time Production Scheduling and Control System, Digital production Planning and Scheduling

Background: Astron is a structural steel manufacturing industry mostly dealing with custom fabricated components where the raw material is cut to its required length, punched with holes, bent to its shape, and assembled to create various products. Astron manages a highly varied profiles with low volume productions. Also due to its variable volumes and non-predictable properties, the major difficulties would be the Production Scheduling or internally referred as the capacity planning. The use of standard tool is not accurate enough to handle the delivery deadlines, available resources, material shortages and this leads to many problems. It is observed that the major time of operations is Necessary Non-Value Adding Time (NNVAT) at Astron and it can be optimized by implementing the custom-made Production Planning and Scheduling tools.

Activities: To optimize the Production Planning and Scheduling at Astron a set of lean methods and tools have been applied. First each process step is observed, and time required for each activity is clocked. All work steps fulfilled by the operator are measured recorded and segregated based on the activities whether it is Value Adding (VAT), Non-Value Adding (NVAT) or Necessary Non-Value Adding (NNVAT) to the customer. The same measurements have been performed for the helper and machine. The results are depicted in figure 1-3 below.

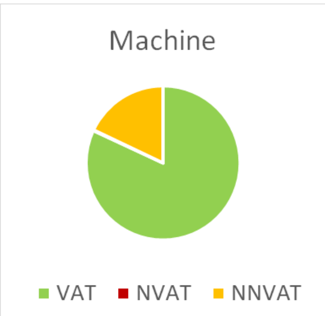

Figure 1: Machine expenditure of time

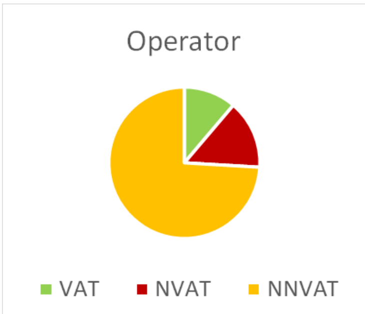

Figure 2: Operator expenditure of time

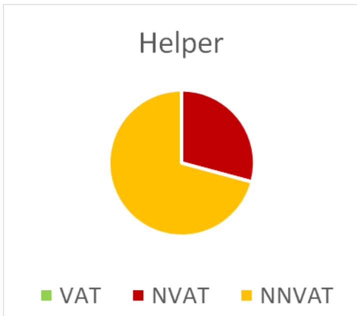

Figure 3: Helper expenditure of time

Thereupon a Value Stream Map of current State is drawn, to understand the total process and idle times of the secondary framing production line. In collaboration with the top management opportunities for Continuous Improvement (CI) have been identified and a selection has been made for this project. A custom-made tool is to be developed to provide the planning and scheduling of the existing production process. Various tools are studied and finalized the optimum solution, which is to modify the existing scheduling tool at primary framing and adapt it with the secondary framing parameters and requirements. This tool should provide information on the order of jobs to be produced and the time required to produce each job.

The scheduling tool also provides information on the sequence of production, which is based on the Shipping dates of the orders as the priority of jobs is their shipping date as per the company. Additional to this, the operators are provided with a table to have an overview over the sequence and remaining meters/pieces of the jobs.

Results: Optimized scheduling and planning has been reached by implementing the custom-made Production Planning and Scheduling tool. By the help of this tool, an average of 364 hours per a year is saved, which leads to 45 working days. Scheduling also reduces the risk of errors and improves the Overall Efficiencies of the Equipment (OEE). The existing and proposed capacity planning tools are depicted in figure 1 and 2 below.

Capacity Planning

Area 3

- done
- error
- in production
- not used

Prod.Week: 2144

Job	Builder	Prod.wk	LPZ (m)	LP (m)	LPZ_LP (m)			BEND (kg)			Finish	Ship.wk	Priority
+ 190013 B1	MABILUX S.A.	2144.2	- - -	- - -	5	99.5%	958	0	100%	2651	GAL	2146.3	10
+ 190258 B2	STAVMAT EPITOANYAG KERESKEDELMI Zrt	2144.2	- - -	- - -	5.5	99.7%	2037.9	0	100%	2399.9	GAL	2146.5	14
+ 190577 B1	TRADECO	2144.2	- - -	- - -	1	100%	2640.2	0	100%	2358.3	GAL	2146.5	17
+ 188559 B1	WILHELM BOUHS HOCH-, TIEF-	2144.2	- - -	- - -	128.8	88.4%	979.6	0	100%	2834.1	GAL	2150.5	20
+ 189361 K1	WILHELM BOUHS HOCH-, TIEF-	2144.2	- - -	- - -	89.1	0%	0	-	-	-	GAL	2150.5	22

TOTALS by ship week [Remaining values]

Ship.wk	LPZ (m)	LP (m)	LPZ_LP (m)	BEND (kg)
2146	-	-	11.5	0
2150	-	-	217.9	0

Figure 1: Existing in-house Capacity Planning tool for Secondary Framing

Job	Builder	Prod. wk	LPZ_LP Punch Plate (m)			LPZ_LP Roll (m)			PF (p)			BOSCHERT (p)			CERINI (p)			BEND (p)			WELD (p)			Total Job Weight (t)		CLPN (p)			Finish	Ship.wk	Priority
			rem	sch	hrs	rem	sch	hrs	rem	sch	hrs	rem	sch	hrs	rem	sch	hrs	rem	sch	hrs	rem	sch	hrs	rem	sch	rem	sch	hrs			
TOTALS by category [Remaining values]																															

	LPZ_LP Punch Plate (m)	LPZ_LP Roll (m)	PF (p)	BOSCHERT (p)	CERINI (p)	BEND (p)	CLPN (p)
SSB							

rem:	Remaining meters/pieces
sch:	Scheduled meters/pieces
hrs:	Hours required for production

TOTALS by ship week [Remaining values]

Ship.wk	LPZ_LP Punch Plate (m)	LPZ_LP Roll (m)	PF (p)	BOSCHERT (p)	CERINI (p)	BEND (p)	CLPN (p)
2147							
2148							

Figure 2: Proposed Capacity Planning tool for Secondary Framing

Success factor: This case study has demonstrated that decisive savings of time can be reached by detailed capacity planning, leading to higher OEE and a more efficient and effective working flow.

Short version of the case study at Fanuc Europe Corporation

Brief description of the company: Fanuc is a global manufacturer of smart manufacturing and intelligent automation systems. Fanuc provides solutions to every phase of the production processes such as front-line operations, processing, picking, handling, and end of line operations. For this purpose, Fanuc manufacturing industrial robots, collaborative robots etc. Fanuc is deeply committed to pushing back the boundaries of automation and helping its customers to optimize their production processes.

Location: Echternach, Luxembourg

Employees: 250 employees

Turnover: -

Modules of the maturity assessment: Design of Value Stream, Custom Design and Manufacturing

Background: Any sales team has the challenge to discover and attract potential customers from different industries and regions, at the same time, they need to identify and explore the needs of current accounts, ensuring customer retention and managing the relationships. The sales force has a critical impact on customer relationships. A new sales process is proposed, which includes sub-processes for sales, customer engagement and thus an appropriate defined customer value proposition. A sales process tool architecture diagram should be included in the proposal, which depicts the entire process from the first point of contact until quoting. The tool or application enabling this feature has to be designed to improve the whole process.

Activities: To begin this exploration, business process management (BPM) is used to analyze the current quoting procedure at FANUC. Next, data analysis is used to determine what improvements may be made to provide customers with more value at a lower cost and strengthen linkages to selling activities. Internal sales data collected during the last two years in the associated departments has been used for the setup of two case studies. In a first case study a general overview and quotations analysis of CRX (type of collaborative robot) is conducted. The second case study analyzes the quotes of the robotics division (RO). To find issues and gaps the current is divided into micro-processes by BPM. As part of the investigation, the conversion rate from RFQs (requests for quotes) to actual sales has been calculated. Additionally, the software processing process friction has been examined to determine which stage in the quoting process is most time consuming and the reasons behind this. A time study has been conducted by dry running randomly picked quotes from the last year and extracting the time used to generate quotes, in order to define the areas or processes that should be addressed. During the analysis it has been found that some options are free of charge, adding those options to the standard set of configuration leads to considerable time savings. It has been observed that at FANUC, different variations in the duration of the warranty are applied. By assuming that the standard warranty is 24 months, 35% of all RO Navigator Quotes last year deviated from the standard policy as depicted in figure 1. Therefore, based on the analysis, it is suggested to add 24 months standard warranty to all Bill of Materials (BOMs), and the customer is able to extend the warranty period by paying additional cost.

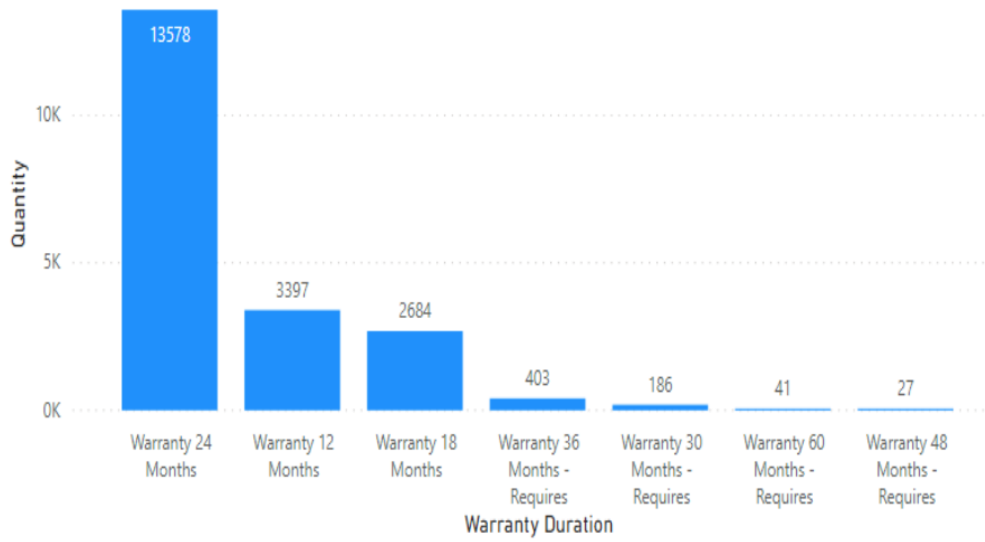

Figure 1: Warranties quoted last year

Based on the analysis and findings, the quotes generated last year were less complex, as 64 % of all RO quotes contains 1-10 lines. 80% of these quotes can be covered by the top 20% options opted to generate these quotes. A simple web-based configurator where the customer or salesperson can configure the robot from limited number of options simplifies the process and reduce the time investment. The proposed tool architecture is represented below.

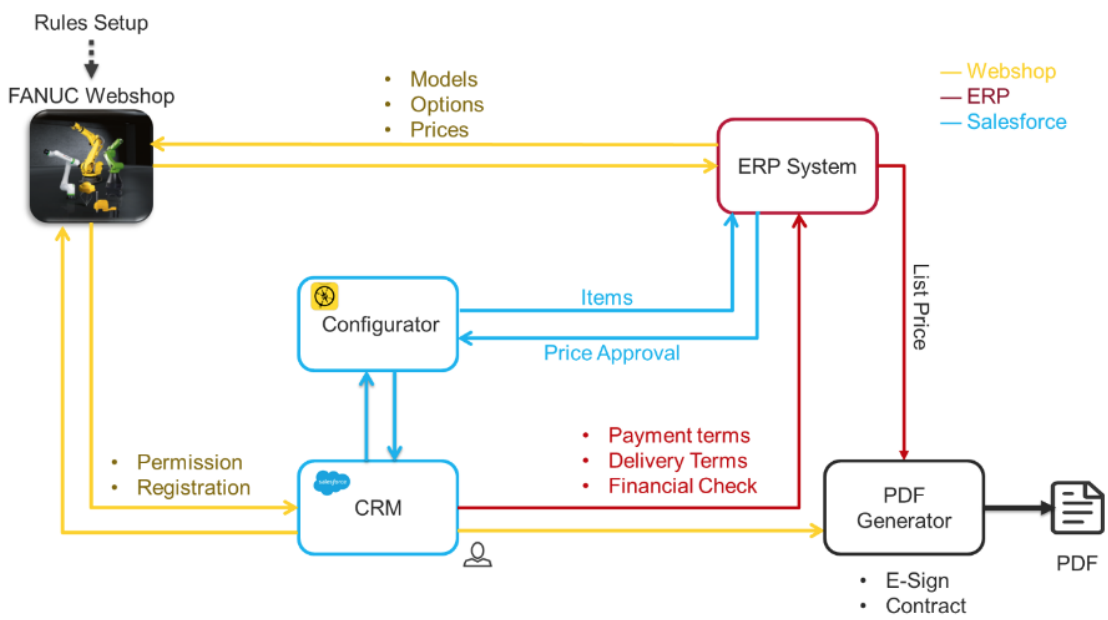

Figure 2: Tool Architecture

The new sales process tool will require a set of features to enable the functions mentioned above in the new Configure-Price-Quote (CPQ) process. The main difference between the proposed process and the current process is giving customers or salespeople less complex configuring methods to choose the product they want based on the application and the features they want.

Results: The quotation process has enhanced in multiple ways by targeted improvement approaches.

- Cycle time reduction
- Enhanced control and regulation
- Increased quality and quantity of outgoing quotes
- Greater hit rate and closed deals are expected

For example, if it takes 5 seconds to add one of options to a quote, last year sales team spent approximately six and a half hours adding those option. Furthermore, the standard warranty will save the salesperson's time, the company can save approximately 8 hours per year.

Success factor: This case study has revealed waste in seemingly efficient processes. Through targeted analysis and improvements, the processes have been redesigned and an advanced procedure has been created.

Short version of the case study at Rotarex

Brief description of the company: Rotarex is an international company specialized in manufacturing of gas control products and systems. The company is founded in 1922 with its headquarter in Luxembourg. The enterprise has developed into a major manufacturer of equipment and entire systems, including cylinder valves, pressure regulators, and other components, that provide improved gas safety, control, and productivity for all gas applications.

Location: Lintgen, Luxembourg

Employees: 1600+ employees

Turnover: > € 100 Millions

Modules of the maturity assessment: Design of the Value Stream, Adaptability and Quick Changeover

Background: The company Rotarex offers a high number of different product variants. Consequently, they need a very flexible production line, that can rapidly and smoothly meet changing demands. Unfortunately, this was not the case, the multiple die changes per shift took a lot of time and resulted in considerable idle time on the machine, thus reducing the machine Overall Equipment Effectiveness (OEE). Lean production methods and tools have been chosen to reach the goal of increased productivity and reduce the overall waste arising in the associated processes.

Activities: Lean tools and methods like Single Minute Exchange of Dies (SMED), 5S, 5Why's and PDCA have been applied to identify waste and realize continuous improvement. The application of SMED on two CNC workstations took place in different steps. First of all, the activities of a changeover process have to be defined and categorized. It is important to specify if an activity is internal or external, value adding (V.A) or non-value adding (N.V.A) or necessary non-value adding (N.N.V.A). The results of the classification are presented in figure 1.

S/N	Major Activities	V.A / N.N.V.A	External / Internal	Time (DMG Mori)	Time (Riello)
1.	Preparation of tools	N.N.V.A	External	20:03	39:03
2.	Change of tool	N.N.V.A	Internal	11:44	08:24
3.	Program settings	N.N.V.A	Internal	15:28	09:05
4.	Machining	V.A	Internal	21:51	19:20
5.	Inspection	N.N.V.A	Internal	20:18	19:37
6.	Profile Inspection	N.N.V.A	External	02:09	N/A
7.	Filling DMS	N.N.V.A	External	07:22	N/A

Figure 1: Major activities in the changeover process

In order to reduce the internal activities to a minimum, they are converted to external if possible. To ensure that everyone follows the designed workflow, the 5S checklist and preparation activities task sheet have been merged and has to be signed before the machine stops. The task sheet is represented in figure 2.

Preparation Task Sheet / 5S Checklist					
Date:		Job Commande:		Regleur:	
B.U:		Machine:		Production Order:	

S/N	No. of activities			Check/No.
1	Job / Commande and drawing sheet on the board			
2	No. of cutting / drilling tools to be changed			
3	Tool lists of previous and next work-order			
4	Cutting /Drilling tools Calibrated			
	Things to be arranged at the machine	**Emplacement**	**Location**	**Check/No.**
1	Raw Parts near the machine arranged	Machine		
2	Empty trolley for the machined parts	Machine		
	Outils de serrage:			
A	Allen Key	Tool board	TB-A1	
B	Wrench tools	Tool board	TB-A2	
C	Screw drivers	Tool board	TB-A3	
D	Torx Screwdrivers	Tool board	TB-A4	
E	Grinding wheel	Tool board	TB-B1	
3	Outils d'inspection	Table		
4	Keyboard	Tool board	TB-B3	
5	Boite de realise / rebut	Tool board	TB-B2	
6	Lamp	Table	T-A2	
7	Drawings	Tool board	TB-B4	
8	Tools list	Machine		
9	Work order commande	Machine		
10	Broom stick	Table		
11	Dustpan	Table		
12	Vernier calliper			
Signed by:				

Figure 2: Preparation Task sheet/ 5S checklist

Thereupon the possibility for streamlining of activities with the help of two setters had to be verified. To test the well-functioning of the new process design, the approach is tested in pilot environment. This allowed adaptations and improvements before deployment across the whole company. To enable continuous control a Management Daily Improvement (MDI) sheet has been introduced. This allows monitoring of the trend of changeover times with respect to the number of tools being changed. Of course, a specific training for the affected workers had been set up to ensure application of best practice.

Results: The change over time is reduced by 54% and 52% for the two CNC machines respectively by redesign of the internal and external activities. Simultaneously, the 5S method improved the working culture in a way that the workers adapted their habits to the new process flow and actively experience the added value of the changes.

Success factor: The lean tool SMED allows to reduce the downtime of any machine and increasing the production capacity of a plant with just a minimal investment.

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