An Axiomatic Universe for Industry 4

by

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Declaration of authenticity and author's rights

Signed: Hanna Lilja Jonasdottir
Date: Monday 25th January, 2021

Tileinkað ömmu í Hóló.

“It will be fine.”
Hanna Lilja Jónasdóttir, 2020

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Abstract

Since its emergence in 2011, Industry 4.0 aims to maximise productivity and efficiency in manufacturing and has gained momentum, both in academy as well as in industry. Many frameworks and international initiatives have been proposed for the implementation of Industry 4. However, research shows that industry is facing difficulties with implementing this concept and a formal definition of Industry 4 has not yet been agreed upon. To address these issues, this Thesis proposes a formal logic framework for the implementation of Industry 4 as formal logic enables rigours construction and explanation of a concept. Moreover, formal logic allows for automation of the framework.

The framework is based on a thorough literature review and its analysis where the key characteristics of Industry 4 are identified. The framework uses an axiomatic approach to formalise Industry 4. An expert system for practical applications of the framework is presented. The expert system enables an automatic inference of the rules and is used for part of the evaluation of the framework.

The soundness, completeness, utility and applicability of the framework are evaluated by an academic expert and through two case studies. The outcome of the evaluation was used to refine the framework. The evaluation revealed that the framework features the key characteristics of Industry 4 in a manufacturing setting and can successfully be applied to manufacturing organisations as well as devices. The findings of the evaluation support the research question, that is whether Industry 4 can be described with formal logic to identify the key components that should be considered before Industry 4 is implemented.

The framework for this Thesis will guide industry with the implementation of Industry 4. Future work includes, for example, incorporating more elements of Industry 4 that were not within the scope of the Thesis and further developing the application software.

Published work

Conference proceedings

Jónasdóttir, H., Dhanani, K., McRae, K. and Mehnen, J. (2018) Upgrading legacy equipment to industry 4.0 through a cyber-physical interface. In: Advances in Production Management Systems 2018, 26.-30. July 2018, Seoul National University.

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Abbreviations

Abbreviation	**Meaning**
AI	Artificial Intelligence
AR	Augmented Reality
BCG	Boston Consulting Group
BI	Business Intelligence
CM	Cloud Manufacturing
CPS	Cyber-physical system
CPLS	Cyber-physical logistic system
CPPS	Cyber-physical production system
HTO	Human, technology, organisation
IIoT	Industrial Internet of Things
IoT	Internet of Things
I4	Industry 4.0
MES	Manufacturing execution system
M2M	Machine-to-machine
PwC	Price Waterhouse Cooper
RE	Requirements engineering
SCADA	Supervisory Control and Data Acquisition
SME	Small and medium-sized enterprises
VR	Virtual reality

Glossary

Business: An organisation or a company which exchanges services or goods for some form of money.
Centralised: A location that is fixed to one place is said to be *centralised*. An example of a centralised location is e.g. a hard drive or a library.
Industry: A group of businesses that make and sell similar products.

Chapter 1

Introduction

The fourth industrial revolution commonly referred to as Industry 4, is taking place. Industry 4 is based on systems which connect the physical world to the virtual world and can resolve various manufacturing problems[1]. Industry 4 is a German governmental initiative from 2011 that aims to strengthen the German manufacturing industry[2]. However, other countries have followed such as China with Made in China 2025[3] and the USA with the Advanced Manufacturing Initiative[4]. Many companies have also started their Industry 4 journey. Companies such as Daimler[5] and Rexroth[6] have already started implementing Industry 4, which has resulted in greater efficiency and cost reduction.

Industry 4 is driven by application-pull and technology-push. On the application side there is a need for economic, social and political changes. These changes are for example resource efficiency and short development periods. On the technology side, there is a push towards increasing digitalisation and further automation[7]. The overall goal of Industry 4 is to maximise efficiency and productivity in a manufacturing environment[2]. It has led to increased profitability and better working conditions for employees[8].

To successfully implement Industry 4, the cooperation between multiple disciplines is required, both from academia as well as industry as Thoben et al.[9] noted. It is not enough to only apply the systems of combined technologies to the process but it requires a shift in paradigm, both in how the company is structured as well as how the technologies are used. The companies need therefore to adopt a new philosophy before attempting to move towards Industry 4[10].

Many frameworks have been proposed in various areas of Industry 4. Lee et al.[11] proposed a five-layer framework for implementing cyber-physical systems and Chien et al.[12] suggested a framework to bridge the gap between Industry 3 and Industry 4. Researchers have also developed frameworks which approach Industry 4 from a higher level such as the metamodel for Industry 4 transformation[13].

As Thoben et al.[9] noted, there are research issues associated with Industry 4. One of the issues they identified was the lack of reference models. However, to describe a complex system, a reference model is required[9]. Furthermore, Castelo-Branco et al.[14] assessed the readiness for Industry 4 from the standpoint of the EU. They discovered that a shared understanding of Industry 4 has not yet been, leading to difficulties in assessing the level of adoption of Industry 4[14].

Recent surveys on Industry 4 in industry indicate that companies are struggling with adopting Industry 4. In 2018 Deloitte[15] surveyed 1500 executives in 19 countries, focusing on how ready the leaders of their organisations were to implement Industry 4. Only 14% of them claimed they were confident their businesses were ready to manage the changes that come with implementing Industry 4. Boston Consulting Group (BCG) found in 2017 that even though 79% of companies had made progress, only 9% of companies had made significant progress towards Industry 4 in the last year in the UK, compared to 14% in Germany and 13% in China[16]. That is in line with the results of the analysis of KPMG who identified that most companies had not implemented Industry 4 technologies to their full potentials[17]. Finally, adapting Industry 4 in companies with legacy equipment is a major challenge[10].

Industry 4 offers great potential for industry, however, industry is struggling with the implementation of Industry 4 due to lack of understanding and formal structure. Moreover, a formal definition of Industry 4 within academia has not been agreed upon. A formal, analytical framework is therefore needed to guide industry to understand and implement Industry 4. Such a framework that is built on the characteristics of Industry 4 can help to explain and develop new Industry 4 solutions which is beneficial both to industry as well as academia. It would enable industry to identify the key factors required for a successful implementation of Industry 4 and it could guide academic research by identifying the key characteristics as well as to further develop models. Moreover, a formal logical framework on Industry 4 can be transferred into software, enabling easier access and adaptability to the framework and therefore Industry 4. Expert systems have been widely used both in academia as well as industry to solve various problems[18]. Furthermore, the emerging technologies extend the potentials such systems may have. This PhD research identified the characteristics and building blocks of Industry 4 and developed a formal logical framework for the formal design and validation of Industry 4, with a particular focus on manufacturing.

1.1 Scope of work

Industry 4 focuses on ways to improve manufacturing through emerging technologies[9]. However, just as its predecessors, it does not only affect the manufacturing industry. Other industries such as the service industry and banking benefit from Industry 4 as it offers the potentials to enhance customer experience. Furthermore, society can benefit from Industry 4 which is reflected in the Japanese initiative, Society 5.0[19]. There are therefore many elements, such as technologies, society and organisations, that are required to be addressed to realise Industry 4.

This Thesis presents a framework for Industry 4 that focuses on Industry 4 in a manufacturing setting. Key characteristics of Industry 4 were identified from the analysis of literature and case studies on implementations of Industry 4. The evaluation of the framework focuses on the application of the framework in manufacturing environments.

Discussing all aspects of Industry 4 is beyond the scope of the Thesis. This Thesis focuses on aspects related to the implementation of Industry 4 in a manufacturing setting, e.g. technology, equipment, workers and organisation of the factory. The business aspect of Industry 4 is touched on (see Subsection 3.2.1 and Section 3.7), however, it is not within the main scope of this Thesis. The entirety of societal or human aspect of Industry 4 are likewise not within scope but is part of the practical considerations as workers are an important element of the Industry 4 revolution. Details on social and human aspects within Industry 4 have been discussed by e.g. Benešová and Tupa[20], Roblek et al.[21] and Frey and Osborne[22].

1.2 Research question and objectives

The work presented in this Thesis was driven by a lack of common understanding of Industry 4. Moreover, industry is facing difficulties implementing Industry 4 despite existing frameworks for Industry 4. This PhD research addressed the research question whether Industry 4 can be described with mathematical reasoning. To answer this question, the following objectives were identified:

1. Identify key characteristics of Industry 4 in industry and academia:
   (a) Establish the current state of knowledge in Industry 4 in terms of an academic knowledge readiness levels.
   (b) Establish the current state of implementation of Industry 4 in various industries in terms of industrial readiness levels.
   (c) Establish the current state of Industry 4 theories and frameworks.
2. Establish a method to formally describe Industry 4 with mathematical reasoning:
   (a) Analyse established methods for the formalisation of an engineering phenomenon.
   (b) Establish the dependencies between those characteristics to form the basis of the framework.
3. Establish a practical basis to evaluate the Industry 4 framework:
   (a) Establish whether the framework can be modelled to allow for automatic inference of the framework.
   (b) Conduct an expert evaluation to validate the framework.
   (c) Apply the framework in a representative industrial setting to validate existing and future solutions with respect to the Industry 4 level.
   (d) Make improvements to the framework based on the findings of the evaluation.
4. Analyse the work to determine, advantages, limitations and potential future work.

1.3 Thesis structure

Figure 1.1 shows an overview of the structure of the Thesis and its relation to the research questions. Chapter 2 presents the research approach used for this work, addressing the research methods and theoretical positioning. It furthermore outlines the methodology applied in this Thesis and its structure.

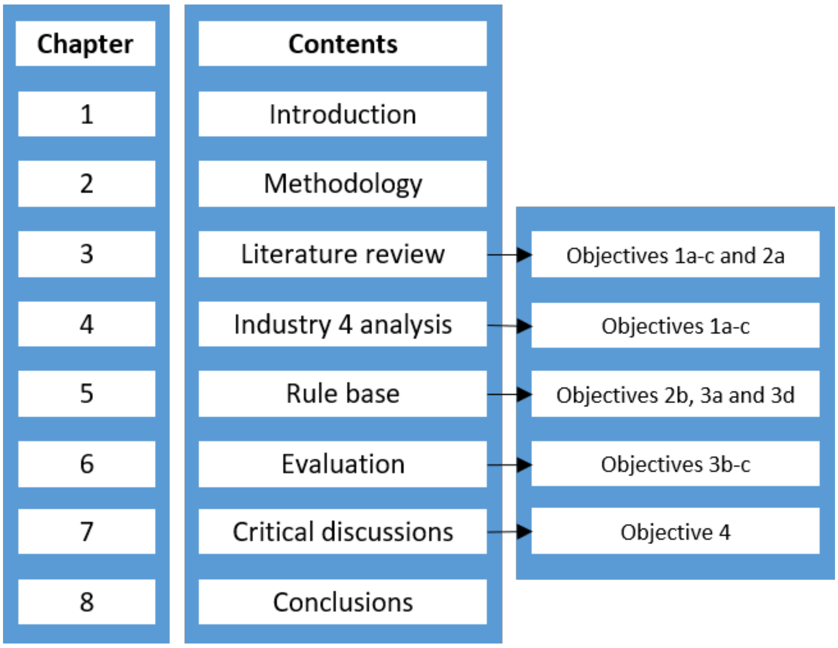

Figure 1.1: Outline of the Thesis

Chapter 3 presents the literature review, reviewing existing research on Industry 4 (Objective 1a), focusing on factories with manufacturing equipment. Different initiatives are compared to each other and the challenges and opportunities that come with Industry 4 are discussed. A selection of case studies of implementation of Industry 4 are presented (Objective 1b) as well as a review of existing frameworks for the implementation of various aspects of Industry 4 (Objective 1c). The chapter, moreover, explores methods for the formalisation of engineering phenomena (Objective 2a).

Chapter 4 addresses the second objective of this Thesis and presents an analysis of the literature presented in Chapter 3. Key characteristics and significant themes of Industry 4 are identified (Objectives 1a-1c) which can be mapped directly on to the framework.

Chapter 5 presents the framework of Industry 4 which uses a formal logical approach to describe the links between the elements of Industry 4 (Objective 2b). Axioms and theorems are the basis of the framework which is based on the analysis presented in Chapter 4. First, the rule base is introduced and the rationale given for every item in the rule base. The rationale acts as a bridge between the analysis of the literature and the rule base itself by discussing in detail every rule. The rule base itself is then presented which is composed of axioms, theorems, proofs and definitions. The proofs are based on the relations to the theorems within the rule base. The version of the rule base presented in this Thesis is the final version which is based on the findings of the evaluation (Objective 3d). Moreover, the chapter describes the expert system developed to apply the rule base in a programming environment (Objective 3a).

Chapter 6 contains the evaluation of the rule base which is presented in Chapter 5. The chapter presents the evaluation of the rule base, the results and evaluation (Objectives 3b-c). The rule base was evaluated by a leading academic expert, one paper-based case study and one case study in a manufacturing company in the UK. The expert system developed in Chapter 5 was used for evaluating the case studies.

Chapter 7 presents the findings of the research. It also presents discussions of the research presented in this Thesis and highlights the advantages and disadvantages.

Chapter 8 provides a conclusion of the research, limitations and benefits of the work as well as future work (Objective 4).

Chapter 2

Research approach

2.1 Introduction

Research can be defined as "a process that is undertaken in a systematic way with a clear purpose, to find things out" [23]. Kumar [24] moreover stated that for a process to meet the requirements of being research, it must be controlled, systematic, rigorous, critical, verifiable and valid and empirical. Research methodology can be defined as how the research should be approached based on philosophical and theoretical assumptions and their implications on the research [23].

The research presented in this Thesis aimed to address whether Industry 4 can be modelled with mathematical reasoning to aid companies to navigate the Industry 4 universe. Despite various frameworks, industry is still facing difficulties with the implementation of Industry 4. Furthermore, due to its complex nature, Industry 4 might benefit from using a rigorous approach for its implementation. An axiomatic approach was, therefore, identified to be a potential suitable method due to its characteristics. Axiomatic methodologies can act as a guide to action, are consistent and rigorous [25].

This chapter outlines and reasons the research methodology that was adopted for this research. Section 2.2 provides an overview of the elements that make up a research approach and their relationships, Section 2.4 outlines the adopted research approach and finally, Section 2.5 gives a summary of the chapter.

2.2 Research methodology

Research methodology can be defined as how research should be approached and encompasses the philosophical and theoretical assumptions that create the foundation of the research and how they affect the choice of methods [23]. As Reich [26] noted, a methodology is used synonymously with methods by some researchers. However, as he further noted, that definition lacks the fundamental meaning of the term which is "the theory of methods" [26]. Reich [26] therefore described research methodology as: "a collection of methods for doing research and their interpretations" [26]. A research methodology can consequently be characterised by the selected techniques and methods and how they are employed in the research.

Figure 2.1 portrays the elements of a research methodology based on the description of methodology as outlined above. A brief description of the elements is given below the figure.

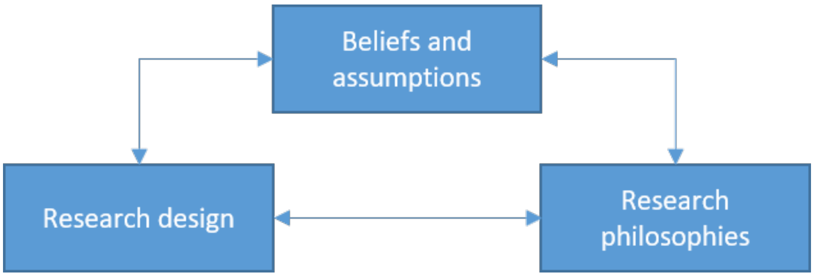

Figure 2.1: Research methodology elements (adopted from Saunders [23])

In this Thesis, *assumptions* refer to ontological, axiological, epistemological and methodological assumptions that differentiate different research philosophies. These assumptions are defined below.

Research philosophies is an overarching term used for the collection of research assumptions employed for the research. According Saunders [23], research philosophy "refers to a system of beliefs and assumptions about the development of knowledge" [23]. In research, multiple assumptions are made at every stage [27]. These assumptions can be classified as ontological, epistemological, axiological and methodological assumptions.

- *Ontology* describes the assumptions made on the nature of reality. It determines how the research field is looked at and consequently affects the choice of area of research [23].

- *Epistemology* focuses on assumptions on knowledge, how knowledge is communicated and what types of knowledge is considered acceptable, legitimate and valid.[23]
- *Axiology* explores the researcher's position regarding values and ethics[23].
- *Methodology* can be defined as: "the methods for creating knowledge about the world and the interpretation of this knowledge in light of the ontological and epistemological positions"[26].

Reich[26] refers to ontology, epistemology and methodology as *worldview* and Saunders[23] furthermore adds the fourth perspective, axiology, to the term. For this Thesis, the term worldview will be used to discuss all four perspectives that have been described in this section. These assumptions affect the understanding of the research as well as the methods chosen and the understanding of the findings[28].

Several worldviews exist in science, however, they can be grouped into two main categories of worldviews, that is scientism and practicism[23,26]. Scientism includes worldviews such as positivism and realism and is more predominant in the field of engineering. Practicism is more exerted in action research and human-centred engineering and encompasses worldviews such as interpretivism and pragmatism[26].

Methods can be defined as "techniques and procedures used to obtain and analyse research data"[23]. The selection of research methods is dependent on the philosophical assumptions made for the research[29]. An overview of the methods used in this research is given in Subsection 2.4.2.

Research design focuses on answering research questions, fulfilling the objectives of the research and provides a framework for the collection and analysis of data. It furthermore gives a rationale for the selected methods for the research[23]. The research design is outlined in Subsection 2.4.3.

2.3 Characteristics of an axiomatic system

Axiomatic systems are typically characterised by three properties, that is consistency, independence and completeness. An axiomatic system is said to be *consistent* if the statements within the system do not contradict each other. A system is said to be *independent* if the axioms cannot be derived from other axioms in the system. Finally, *completeness* describes the adequacy of a system, that is, for a system to be complete, if and only if every theorem in the system can be proven within it[30]. An axiomatic system is said to be valid if it is both sound and complete (refer to Subsection 2.4.3 for further details on soundness and completeness).

As the mathematician Gödel proofed, there are limitations to formal axiomatic systems. He put forward and proofed two incompleteness theorems. The first one states that a mathematical theory that uses an axiomatic approach cannot proof all truths in the system. The second theorem states that the consistency of such a system cannot be proved within the system itself[31]. For further discussions on axiomatic systems, refer to Chapter 3.

2.4 Adopted research approach

Having explored key factors of an axiomatic system, the approach adopted for the purpose of this research is discussed in this section. Subsection 2.4.1 explains the theoretical positioning adopted for this research, Subsection 2.4.2 outlines the methodology and Subsection 2.4.3 discusses the overall design of the research.

2.4.1 Theoretical positioning

This research addresses whether Industry 4 can be described with formal logic. The research is initiated by a research problem and a research question. The research requires investigation of both the technical systems needed to realise Industry 4 as well as the definition and implication of adopting Industry 4. The interpretation of the Industry 4 concept may vary between different people which results in a broad range of different definitions and meanings. The Industry 4 technologies are one of the enablers to realise Industry 4 and are developed by humans to meet the requirements of industry. The investigation of the implementation of Industry 4 may, therefore, be perceived to encompass both social actors and natural entities and their interrelation.

Based on what has been stated above, the most suitable philosophy for this research is argued to be pragmatism. Pragmatism emerged in the early 20th century in the USA and aims to combine subjectivism and objectivism[23]. The worldview of pragmatism is linked with practicism[26]. Pragmatism focuses on whether a proposition is useful and capable of being affective rather than whether it follows a particular ontology[32]. As Pitt[33] noted, one of the key features of pragmatism is the quest for understanding the world through looking at it from the big picture. The big picture provides an understanding of how the world works in the future [33].

The ontological approach is objective as well as subjective which is beneficial for the investigation of Industry 4. Pragmatism assumes that reality is complex and accepts that multiple realities may exist, it acknowledges that research is value-driven and the research is driven by the researcher's own doubts and believes. It furthermore acknowledges the use of qualitative as well as quantitative and multiple methods. That is beneficial for this research due to the complex and multi-disciplinary nature of Industry 4. Finally, pragmatism focuses on pragmatic problem solving which is highly suitable for this research as it aims to address issues associated with Industry 4. To summarise, the worldview of pragmatism adopted in this research is as follows:

- **Ontology:** complex and results from ideas. Multiple realities may exist and reality is a combination of experience, processes and practices and cannot be seen from a single point of view [23].
- **Epistemology:** knowledge is subjective to numerous interpretations as it is gained through experiences and sensing. To understand phenomena, they should be investigated at various levels [23].
- **Axiology:** research is value-driven and the research is driven by the researcher's opinions and doubts [23].
- **Methodology:** The focus of the research is on practical results and outcomes. Various approaches are, therefore, acceptable, such as multi-method approaches and quantitative and qualitative research. The research starts with a research problem and a research question [23].

2.4.2 Research methods

The research presented in this Thesis develops a formal theory for the implementation of Industry 4 in manufacturing with the objectives of understanding what Industry 4 encompasses to and gain a better understanding of the nature of the phenomenon. An investigation of a phenomenon that aims to lead to a better understanding of it, can be classified as an *exploratory study* [23]. A qualitative approach for data gathering and analysis is often utilised for explanatory studies as the aim is to gain an understanding of the phenomenon. *Explanatory studies* on the other hand seek to determine causal correlations between variables [23]. As opposed to exploratory studies, explanatory studies can use either quantitative or qualitative approaches. Research that uses more than one type of method is referred to as *combined studies*[23]. The research conducted for this Thesis can, therefore, be classified as a combined study based on what has been stated previously. As discussed above, this research adopts the theoretical positioning of pragmatism. Pragmatism can adopt qualitative and/or quantitative research methods[34]. As one of the objectives of this research is to determine the key characteristics of Industry 4 and establish their interconnection, quantitative and qualitative methods will be employed. Figure 2.2 shows an overview of the research methods adopted for this research.

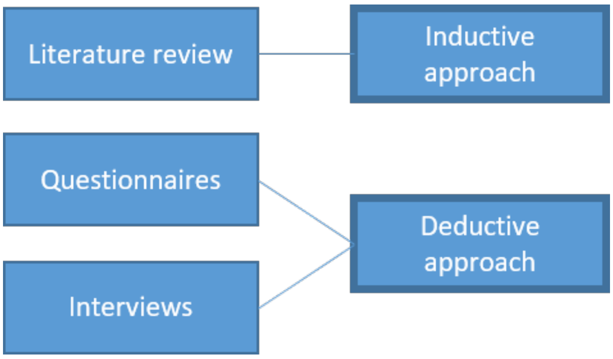

Figure 2.2: Research methods

Data collection

Three data collection methods were adopted to answer the research question. The practicality of those methods such as time and availability was taken into consideration when those methods were chosen. These three methods are outlined below.

- *Literature review* provides the foundation of the research[23]. A literature review was therefore conducted to identify the current state of research on Industry 4. The knowledge derived from that initial study was used to identify the knowledge and redefine the research focus. Furthermore, the literature review acted as a basis for the analysis of Industry 4 which is part of Objectives 1a-1c of this research and is presented in Chapter 4. Consequently, the literature review is the foundation for the development of the rule base (Objective 2b, presented in Chapter 5).
- *Interviews* that are initiated by the researcher can be used as a source of data to support the research aim[35]. Interviews were employed for two stages of this research, that is to support the foundation of the research

question and to evaluate the rule base (Objective 3). Structured interviews were conducted to gather information on the current state of Industry 4 in industry. For the evaluation, the interviews were semi-structured, that is, the questionnaire provided structured questions, while participants were encouraged to verbally discuss their responses.

- *Questionnaires* are a method to collect data which includes a set of predetermined questions answered by a group of people[36]. It is considered an efficient way of collecting direct responses from participants[37]. It was therefore deployed for the evaluation of the rule base (Objective 3), both for the expert review as well as the case studies although the questionnaires were different for those two groups. The questionnaire for the expert consisted of open questions which allowed the expert to express himself whereas the one for the case studies was a yes/no questionnaire with the option of leaving a short comment for every question.

Data interpretation

For data interpretation, two approaches can be applied, that is an inductive and a deductive approach. An inductive approach entails the development of a theory which results from the analysis of empirical data[23]. A deductive approach focuses on testing hypothesis that are derived from pre-existing theories[23].

For the development of the rule base for Industry 4, an inductive approach was adopted. During that phase of the research, the connection between the elements identified in the analysis of the literature review was established. A deductive approach was employed for the evaluation of the rule base. A mixed method approach is possible according to Guba and Lincoln[38].

2.4.3 Research design

The research philosophy and methodology that were outlined in previous subsections form the basis for the research design presented in Figure 2.3. The research design represents the overall structure of the research.

As Figure 2.3 shows, the research process is divided into eight phases. The literature review, literature analysis, development of the theory and theory evaluation each have their sub-methodologies. Each phase of the structure is detailed below.

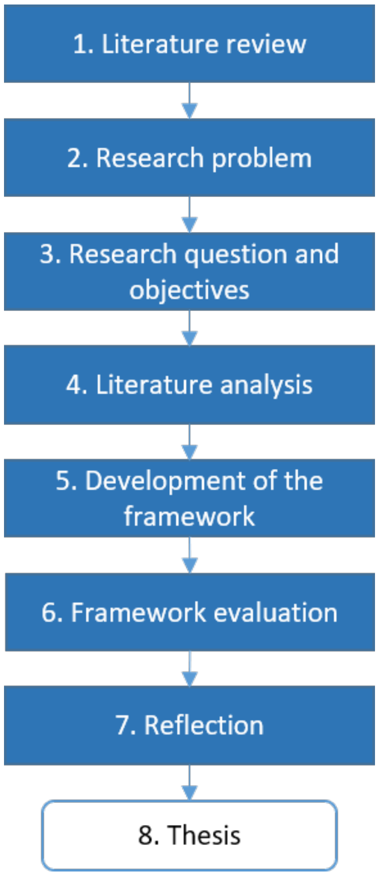

Figure 2.3: Research design

1. Literature review

A thorough literature review was conducted on Industry 4 by reviewing academic papers, industrial reports and case studies from industry (Chapter 3). The aim of the literature review was twofold, the identification of a research problem and the collection of data for the research. A literature review was selected as the main method of data collection as the first objective of the research is to identify the key characteristics and current state of the art within both academia as well as industry. The literature review provides the basis for the literature analysis (Chapter 4).

Methodology

The literature review conducted in this research without any formal methodology and is often referred to as a *traditional literature review*[39]. A traditional literature review has the advantage over a systematic review that it can result in a broader range of literature as it allows for more flexibility. However, as Jesson et al.[39] noted, a literature review conducted without a formal methodology can result in finding numerous of articles that may not be relevant to the research topic. The following steps were, therefore, employed for the literature review in this Thesis to reduce that risk.

The initial literature review focused on Industry 4 in manufacturing. The following search terms were used to establish a general basis for the literature review: “Industry 4”, “Industrie 4”, “smart factory” and “smart manufacturing”. The scholarly database Scopus was used to search for literature due to its wide scope. Furthermore, as Industry 4 is currently taking place in industry, industrial reports and case studies were included in the literature search. Google was used to find those reports and the search terms: “Industry 4 report” and “Industry 4 case studies” were used.

The papers found in the first step were evaluated based on the title and the abstract to identify the frame of reference to Industry 4. Papers that focused on Industry 4 within a manufacturing setting were included, others were excluded.

The third step involved categorising the articles and reports based on their relevance to Industry 4. After the categories had been established, the search terms were revisited to strengthen each category.

2. Identification of research problem

The findings from the literature review were used to identify the research problem (Chapter 1).

3. Definition of research question and objectives

The research question and objectives were defined based on the research problem (Chapter 1).

4. Literature analysis

The literature reviewed in Phase 1 was analysed to find common themes within Industry 4 and identify the key characteristics of Industry 4 (Chapter 4). The analysis of the literature is separated from the literature review as the objective of the analysis is to gain a deeper understanding of Industry 4 and identify the key characteristics of Industry 4. The results of the analysis layout is the foundation of the theory presented in Chapter 5.

To ensure a structured approach was followed for the analysis of the literature review, the method outlined in Figure 2.4 was followed.

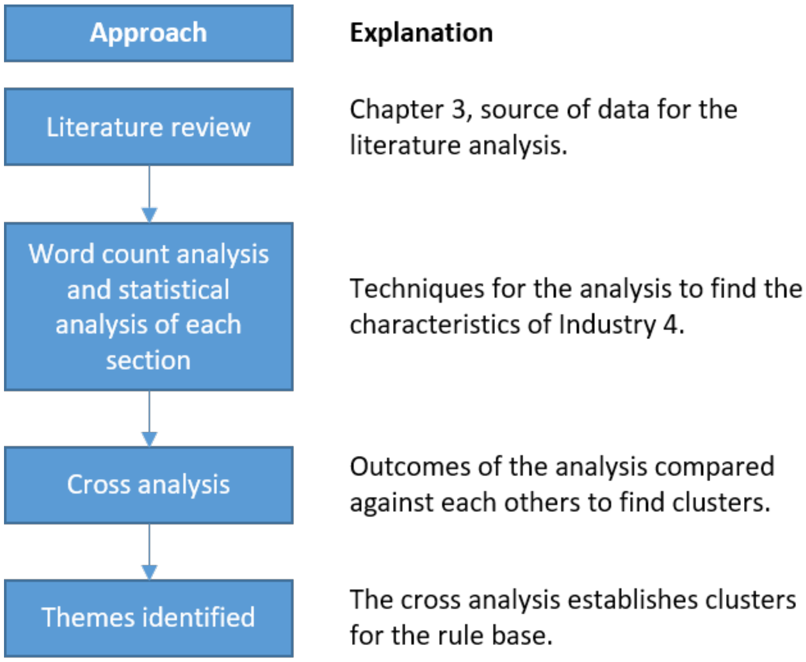

Figure 2.4: Approach for the analysis of the Industry 4 literature

The analysis used the literature review (Chapter 3) as a data source. The analysis of the literature review is twofold, first, a word frequency analysis of the academic papers using a qualitative data analysis platform was performed, presented in Section 4.2.1, followed by, second, a qualitative analysis of each section of the literature review (Sections 4.2.2-4.2.6).

The analysis of data is among the most critical steps in a qualitative research process[40]. Zipf[41] discovered relationship between the frequency of words and their frequency rank. The law named after him states that the frequency of a word is inversely proportionate to the rank of the word[41]. The reason why word frequency behaves in that way is still a mystery[42]. Piantadosi[42] proposed that research is needed on which words are required at every point in a conversation to unravel why this relationship exists.

Several tools can be used for analysing word frequencies as Leech and Onwuegbuzie[40] noted, such as classical content analysis, word count and keywords-in-context. For this analysis, word count was used as the assumption of word count is that words that appear more often are more significant and important than the ones that appear less frequently [43]. The motivation for counting words or themes is at least threefold as Nishishiba et al. [44] noted. These reasons are as follows: pattern recognition, hypothesis verification and analytic integrity.

The main weaknesses of using word count are that the words are decontextualised which may lead to the loss of understanding of the words. It can also be misleading as there is not a direct correlation between the importance of words and the frequency which they appear in text [40].

Wordcount analysis is best performed by specialised software that automatically identifies the most frequently used words. Many platforms offer text analysis such as Atlas [45] and NVivo [46]. Atlas is a qualitative analysis platform which can be used to analyse a wide range of document formats and visualise the results [47]. NVivo can be used for analysing data and enhancing the rigour of the analysis [48]. As Welsh [48] noted, the software has its limitations such as the validity of themes that emerge during the analysis. NVivo was the platform of choice as it offered word count analysis and its limitations do not affect the purpose of this research. It was furthermore recommended by the University of Strathclyde as a useful qualitative analysis platform [49].

NVivo is a qualitative data analysis platform that is commonly used in qualitative research. The platform can be used to analyse word frequency and discover relationships between words and phrases. All academic papers reviewed in Chapter 3 were analysed using this platform to find the most frequently used words in the papers. The analysis identified the main common characteristics of Industry 4 analytically. NVivo offers the user to adjust the level of abstraction of the word frequency analysis, that is:

- exact matches (e.g. "manufacturing")
- stemmed words (e.g. "manufacture")
- synonyms (e.g. "producing")
- specialisation (e.g. "forging")
- generalisation (e.g. "making")

All the options were explored and the stemmed word option was chosen after an initial review of the results of the five different analysis as stemmed words offered the appropriate level of abstraction without sacrificing any accuracy. When the papers were analysed using the abstraction level synonyms, the software grouped the word "fingers" with the word "digital" and "cycling" with the acronym “CPS” which distorts the results of the analysis. The abstraction level of stemmed words was therefore chosen. That abstraction level normalises words, that is the search is not case sensitive.

The analysis of each section leads to the identification of the key characteristics of each section. Every section in the literature review (Sections 3.2-3.7), apart from the section on formal logic (Section 3.8) was reviewed individually (Section 4.2). The section on formal logic was excluded from the analysis as the aim of the analysis was to identify key characteristics of Industry 4 and the logic section is therefore irrelevant for this analysis. Statistical analysis was then performed to identify the characteristics of Industry 4 within the literature.

A cross-analysis was then performed to identify common themes in the analysis (Section 4.3). These themes form the basis of the clustering of the rule base presented in Chapter 5.

5. Theory building

Based on the findings of the analysis, a formal logical rule base was developed for the implementation of Industry 4 in manufacturing (Chapter 5). A formal logical approach was selected as it is a structured approach and a key feature of pragmatism is problem solving and create practical solutions for future practices.

The theory provides a formal description of Industry 4. The theory can be described as a toolbox for Industry 4 and is dynamic, that is it can be expanded based on the scope. The theory of the theory was transferred to a software platform to apply it to real-world examples.

Methodology

The development of the theory uses an iterative approach as shown in Fig. 2.5. The selection of methods and sources was based on the research question and objectives of this research. Data was collected using the selected sources and methods. The data was then analysed as detailed above. The development of the theory was based on data analysis. Finally, the developed theory was reviewed and the outcome used to revise the process.

The first three phases of the methodology have been detailed previously in this Chapter but the theory development and reflection are explained below.

- Theory development: The outcome of the literature analysis was used to identify the key characteristics of Industry 4. The knowledge built from both the literature review and its analysis was then applied to identify the links between the characteristics.

- Reflection: Each version of the theory was reviewed by the researcher and an academic expert in Industry 4. The outcome of the reflection was used to improve the theory. The theory that was developed for the purpose of this research went through nine iteration cycles of theory development and reflection.

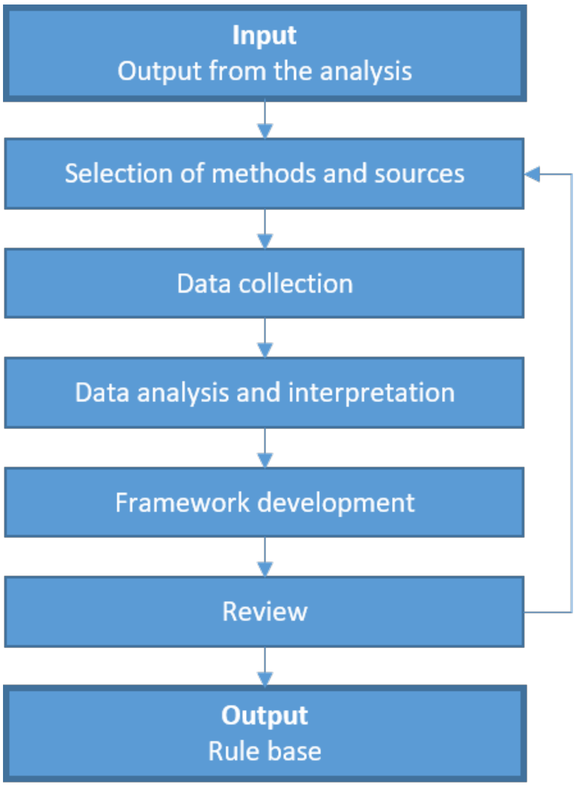

Figure 2.5: Overall development approach

6. Theory evaluation

The rule base was evaluated to identify whether it addresses the issues noted in the literature review (Chapter 3). The evaluation was based on four characteristics, namely soundness, completeness, applicability and utility which will be described in the methodology section below.

Methodology

The final evaluation of the rule base was done in two parts to ensure the evaluation encompassed the four characteristics. Firstly, the rule base was evaluated by an academic field expert and secondly, two case studies were conducted. The outcome of the case studies was run through the software platform (Chapter 6).

To establish whether Industry 4 can be described with mathematical reasoning, the rule base was evaluated based on four characteristics. These characteristics are as follows: soundness, completeness, applicability and utility.

- *Soundness.* If every formula in a logical system can be proven to be true within the defined system, the system is said to be sound. To meet that criterion, the proof needs to fulfil two conditions, that is the proof must be logically correct and the propositions must be true[50]. Soundness is commonly used for the evaluation of a logical system and as the rule base is such a system, its soundness needs to be evaluated. To evaluate whether the rule base is sound, it was evaluated by a field expert.
- *Completeness.* Logical systems are commonly evaluated based on two characteristics, namely soundness (as above) and completeness. As opposed to soundness, completeness describes the adequacy of a system, that is, for a system to be complete, if and only if every theorem in the system can be proven within it[30]. With formal logic systems, completeness of the system is proven through formal proofs. However, as the prime focus of this research is on Industry 4 rather than formal logic, the completeness was evaluated by a field expert, as well as by performing two case studies. That approach was also chosen as the abstract level of the proofs in the latter half of the rule base lend themselves to be evaluated by an expert.
- *Utility.* When building a model, it is important to consider its usage[51]. Pidd[51] furthermore suggests that: "careful consideration of how a model may be used is clearly an important part of any modelling project"[51]. The term *utility* can be defined as usefulness[52]. In this Thesis, *utility* is used to describe the usefulness of the rule base. It was observed from the literature review, that companies are struggling with implementing Industry 4. To address that issue, the utility of the rule base was evaluated. To evaluate its utility, two case studies were performed.
- *Applicability.* The applicability of a model can be defined as: "the extent to which it has been applied to design of different artefacts or different types of design processes (i.e. architectural, engineering, or software)"[53]. This Thesis focuses on Industry 4 within the manufacturing industry.

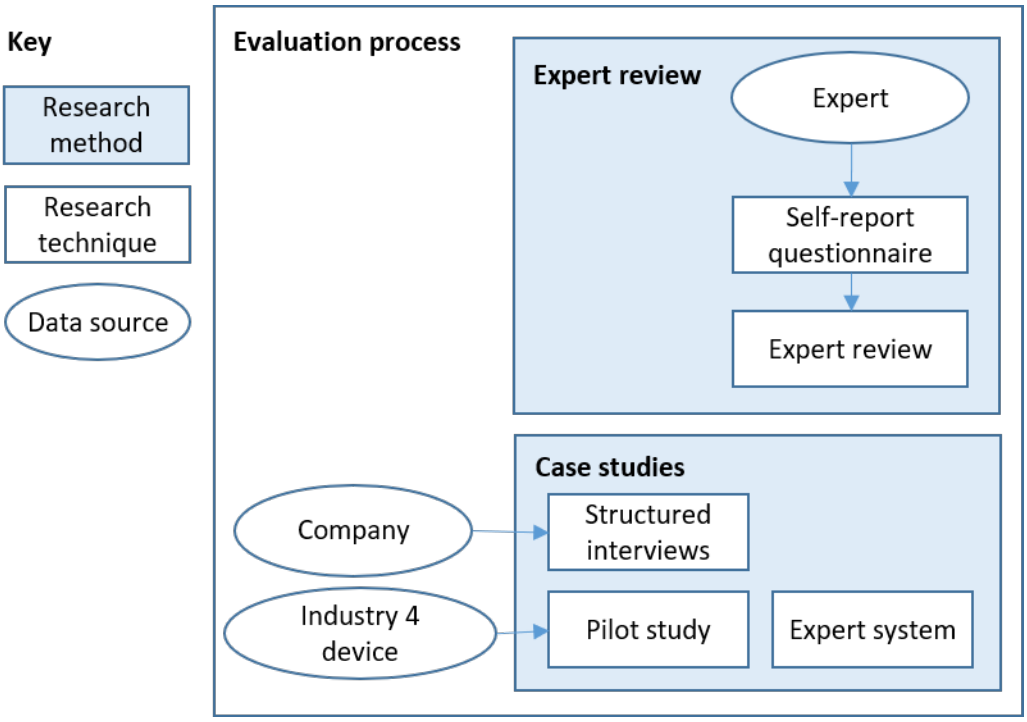

Figure 2.6: Overall evaluation approach

For the evaluation of the rule base (outlined in Fig. 2.6), the rule base was reviewed by a expert in the field as well as 2 case studies were performed. The expert is an academic and also holds strong industrial links. The expert review validated the rule base, that is validate that Industry 4 can be described in a formal logical way. The case studies were performed with a paper-based case study and in a company in the UK. The paper-based case study was performed on an Industry 4 device. The second case study was done at a company is a manufacturing company in the UK and does not have experience with Industry 4. The purpose of the case studies was to evaluate the utility and applicability of the rule base.

7. Reflection

The evaluation of the rule base was reflected upon (Chapter 7) and the general conclusion of the rule base and its evaluation were drawn based on the criteria of the evaluation. Limitations and opportunities of the rule base as well as the potential for future work were furthermore explored (Chapter 8).

8. Thesis

The final phase of this research is to consolidate the research to a Thesis.

2.5 Summary

This chapter outlines the methodology adopted for this research. Section 2.2 introduces the main concepts of research methodology used in this Thesis.

On the basis of what was discussed in Section 2.3, the adopted research approach was presented in Section 2.4. Pragmatism was argued to be the most appropriate research philosophy for this research (Subsection 2.4.1) as it is objective which is beneficial for the investigation of the technical aspect of Industry 4. It allows both qualitative and quantitative data methods as well as multi-methods. Furthermore, pragmatists assume reality is complex and acknowledge that the researcher is biased. As the research presented in this Thesis addresses issues related to Industry 4, it needs to consider both the technical aspect of Industry 4 as well as the softer aspect of it. Subsection 2.4.2 outlines the methods employed for this research and finally, Subsection 2.4.3 gives an overview of the entire research process and furthermore details the methodologies for the literature review, literature analysis, theory development and theory evaluation, respectively.

A literature review which is the foundation of this research is presented in the next chapter, Chapter 3.

Chapter 3

Literature review

3.1 Introduction

The first industrial revolution began in Britain in the late 18th century with the introduction of steam power in industry. This revolution was followed by the second industrial revolution in the late 19th when advancements, such as the build of rail roads and production of iron and steel at a large scale, were made that enabled mass production. The third industrial revolution did not start until the middle of the 20th century with the introduction of computers [54]. The fourth industrial revolution, or Industry 4, as it is often referred to, was first presented in 2011 in Hanover when the German government put forward a plan to strengthen its manufacturing industry. This was the first time an industrial revolution was identified before it started. It is, therefore, a developing term as it was identified in its infancy. Ever since it was identified in 2011, Industry 4 has become an important subject matter, both in academia as well as in industry.

Industry 4 is a growing field also in academia, which is reflected by the increasing number of related published papers. For example, the keyword "Industry 4" in the field of engineering returns just over 50 results from 2015 in Scopus and over 800 from the year of 2019 (Fig. 3.1) [55]. However, a consensus of the definition of Industry 4 has still to be reached yet (Bauer et al. 2014 as cited in Hermann et al. [56]).

This chapter presents a comprehensive literature review on Industry 4 which includes various characteristics, governmental initiatives and the technology enablers. Case studies on the implementation of Industry 4 in industries are presented and an overview of logics and their application is given. This chapter provides the basis for Chapter 4 where the literature from this chapter is analysed.

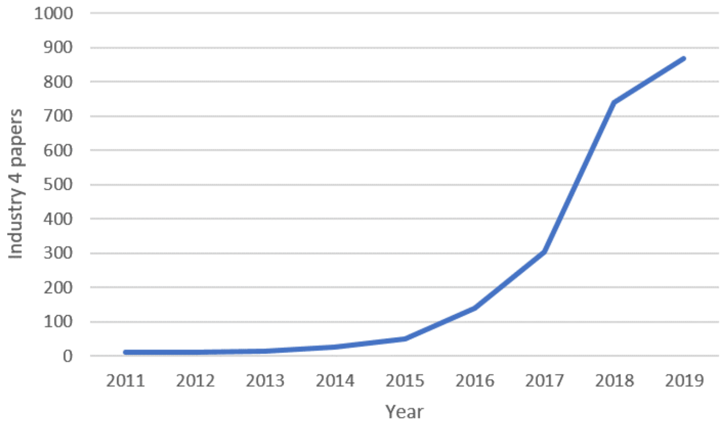

Figure 3.1: Journal papers on Industry 4 published between 2011-2019 (from Scopus)

The literature review, therefore, presents a structured compilation of facts on Industry 4 which are analysed in the next chapter. The literature and the analysis lay the foundation for the development of the axiomatic universe for Industry 4 which is introduced in Chapter 5.

For clarity, common Industry 4 terms will be capitalised, such as Cloud manufacturing and Big data. A list of abbreviations can be found on Page xi and a list of definitions of common terms can be found in the Glossary, Page xii.

Section 3.2 reviews the different definitions of Industry 4 and the various manufacturing concepts that are related with the Industry 4 paradigm. Section 3.3 presents emerging technologies and their relevance to Industry 4. Section 3.4 presents an overview of various international initiatives related to Industry 4. Section 3.5 presents existing frameworks for the implementation of different discrete aspects of Industry 4, such as CPPS and Big data (refer to Section 3.3) as well as the human and business aspect. Case studies on the implementation of Industry 4 in several industrial sectors are presented in Section 3.6 to explore the drivers for implementing Industry 4 in various industries, how industry has implemented Industry 4 and the benefits and difficulties that were associated with the implementation of Industry 4. Section 3.7 gives an overview of some of the opportunities and challenges associated with Industry 4 and associated technologies. Section 3.8 offers an overview of logics and axiomatic approach as this research answers the research question whether Industry 4 can be described with mathematical reasoning. Finally, Section 3.9 provides a summary of the literature review presented in this chapter.

3.2 Industry 4 and related terms

Many definitions for Industry 4 characteristics have been proposed since it was introduced in 2011. Furthermore, various manufacturing initiatives share similarities with Industry 4 such as Cloud manufacturing and Smart manufacturing. This section aims to give a high-levelled approach to an overview of Industry 4 and related terms and to explore the difference between these terms.

The section is organised as follows. Subsection 3.2.1 explores different characterisations of Industry 4. Subsection 3.2.2 introduces the term Smart factory. Subsections 3.2.3 gives an overview of Cloud manufacturing and Subsection 3.2.4 introduces Smart manufacturing. Finally, Subsection 3.2.5 presents a summary of the section.

3.2.1 Industry 4 characteristics

Kagermann et al.[2] defined Industry 4 initially for the German government as a new way of organising the value chain across the products' life cycle. To realise Industry 4, Germany put forward a strategic plan which includes the implementation of the so-called 3-way integration. The three-way integration consists of horizontal, vertical and end-to-end integration. Horizontal integration involves the integration of the value chain and vertical integration within a company. Finally, end-to-end integration refers to integration within the entire life cycle of a product[2]. Even though Industry 4 was initially an initiative from the German government, it has been re-defined later by various scholars.

According to Lasi et al.[7], Industry 4 can be defined by changes in applications and technology. On the application side, Lasi et al.[7] observed that enterprises need to shorten their "time-to-market" as customers are increasingly influencing the products they buy. Enterprises, therefore, move towards more customisation or even to batch size one. To cope with those requirements, processes need to become more flexible and decentralisation is necessary for faster decision making[7]. Maier[57] defined Industry 4, or industrial digitalisation as they refer to it, as the integration of digital technologies in manufacturing companies and their value chains. These technologies enable the connection between the digital and physical worlds and can increase productivity and enhance performance[57].

The RAMI 4.0 model was developed by ZVEI[58] in 2015 to combine the main elements of Industry 4 and allow for further Industry 4 development. The model has three axes, that is the hierarchy levels axis, the life cycle and value stream axis and the layers which represent the horizontal, end-to-end and vertical integration, respectively[58]. Hermann et al.[56] defined Industry 4 as a term used to collectively describe the emerging technologies and organisation of the value chain. Kagermann et al.[2] and Ahuett-Garza and Kurfess[59] state that the overall goal of Industry 4 is to maximise productivity and efficiency of manufacturing processes. Zheng et al.[60] stated that the ultimate goal of Industry 4 is industrial applications that can be used for various flexible solutions in e.g. manufacturing, logistics transportation and service.

To reach these goals, fundamental concepts of Industry 4 have been identified. Lasi et al.[7] listed their fundamental concepts of Industry 4, namely: Smart factory, CPS (see Section 3.3), self-organisation, new systems in logistics and development of products, adaptation to human needs and corporate social responsibility.

Roblek et al.[21] introduced his fundamental concepts of Industry 4. These concepts are Smart factory, new systems for the development of services and products, self-organisation, smart product, new systems in logistics, CPS, smart city and digital sustainability.

Liu and Xu[1] identified three principals of Industry 4 which can be categorised as CPS platform, horizontal value network and vertical integration and networked production system.

Finally, Akdil et al.[61] proposed that real-time data management, interoperability, decentralisation, virtualisation, agility, integrated business processes and service orientation are principles of Industry 4.

3.2.2 Smart factories

The Smart factory, along with Smart manufacturing (see Subsection 3.2.4), is one of the two main research themes in Industry 4. The focus of Smart factories is mainly twofold, i.e. the implementation of Smart manufacturing systems and connected manufacturing facilities[62].

MacDougall[63] defines the Smart factory concept of Industry 4 as the connection between the physical and the virtual worlds, enabled by cyber-physical systems. Cyber-physical systems that use data to control physical and digital systems[64] (for further details, see Subsection 3.3.2). Smart factories have a high level of automation which allows for customisation and optimisation of the production. Compared to traditional manufacturing, Smart factories offer cost advantage and optimisation of resources[63].

As Radziwon et al.[65] noted, the word smart is used excessively both in academia as well as in industry and there is no consensus on the definition of the term, especially in the context of a Smart factory. Therefore, Radziwon et al.[65] conducted a literature review on Smart factories and defined Smart factories as follows: "A Smart factory is a manufacturing solution that provides such flexible and adaptive production processes that will solve problems arising from a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity"[65].

Shrouf et al.[66] identified potential characteristics of Industry 4 with respect to Smart factories. Among the characteristics they identified were mass customisation, flexibility, new planning methods, remote monitoring and proactive maintenance and increased automation. Lee et al.[11] described the attributes of an Industry 4 factory as a factory that is self-aware, that can self-predict, self-compare, self-configure, self-maintain and self-organise.

Although the focus of Smart factories is primarily on the technological aspect[9], it is equally important to include the human aspect[67]. Herrmann[67] noted that people will continue to be the focal point, however, their roles in the factory will change substantially.

3.2.3 Cloud manufacturing

Smart factories are primarily locally distributed whereas Cloud manufacturing can be described as being globally distributed. Cloud manufacturing (CM) first emerged in 2010 when Bohu et al.[68] defined on a private website the term Cloud manufacturing as Smart manufacturing that is service orientated, knowledge-based, has low energy consumption and high efficiency. Since 2010, Cloud manufacturing has gained momentum with scholars and industry alike. However, a common definition of the term has not yet been reached although researchers have a mature view of the opportunities and benefits that Cloud manufacturing could offer[69]. Even though an international standard has not yet been defined, many of the definitions of Cloud manufacturing are based on manufacturing-services and resource-sharing concepts. Xu[70] defined Cloud manufacturing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction"[70]. Zhang et al.[71] defined Cloud computing as a manufacturing concept which uses information and manufacturing technologies to revolutionise standardised manufacturing into manufacturing services. Wu et al.[72] defined Cloud manufacturing as a manufacturing model with an emphasis on customers and shared access to manufacturing resources to optimise efficiency and enable flexible production whereas, Wang et al.[73] stated that Cloud manufacturing could be described as on-demand manufacturing services facilitated by integrated cyber-physical system to optimise manufacturing resources. Adamson et al.[69] furthermore noted that Cloud manufacturing will make manufacturing resources globally available through what they referred to as "pay-as-you-go".

According to Wu et al.[74], the key characteristics of CM are customer centricity, reconfigurable and dynamic processes, flexibility, demand-driven and shared responsibility. Fisher et al.[75] analysed current literature on Cloud manufacturing and identified the key characteristics of Cloud manufacturing. According to Fisher et al.[75], the key features are: flexibility and scalability, multi-tenancy, intelligent decision-making tools, smart on-demand manufacturing and manufacturing as service. They also noted the three roles of Cloud manufacturing: consumer, provider and operator.

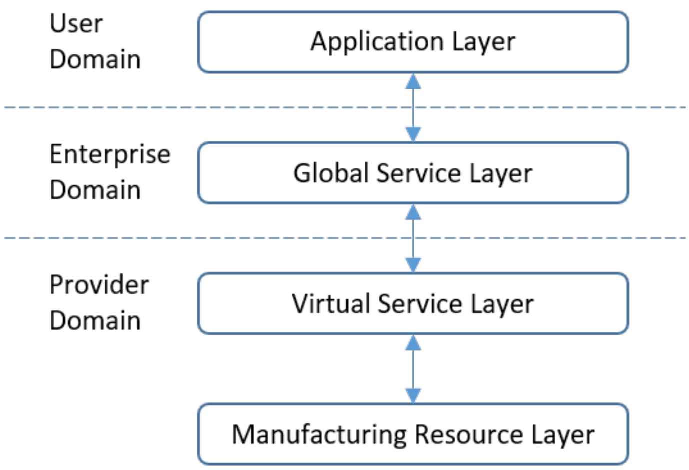

Figure 3.2: Proposed structure of Cloud manufacturing (adapted from Xu[70])

Xu[70] developed a platform which shows the principles of Cloud manufacturing which are split into three domains, namely provider, platform and consumer domain as seen in Fig. 3.2 whereas Adamson et al.[69] argued cloud manufacturing is composed of many layers. These layers can be summarised as resource layer, perception layer, virtualisation layer, cloud service layer, application layer and interface layer. Furthermore, there are supporting layers that cover security, knowledge and communication[69]. The definitions are based on the functional role of the users which may evolve over time[76]. As noted by Liu and Xu[1], the implementation of Cloud manufacturing requires many technologies such as IoT, Cloud computing, virtualisation and advanced manufacturing models and technologies (these technologies along with other emerging technologies will be discussed in Section 3.3).

To summarise, Cloud manufacturing can be seen as a manufacturing paradigm that enables global distribution of manufacturing resources. In next section, the manufacturing paradigm Smart manufacturing is explored.

3.2.4 Smart manufacturing

Smart manufacturing is a manufacturing paradigm which aims to optimise production by taking the full benefits of emerging manufacturing and information technologies (Kusiak 1990 as cited in Zhong et al.[77]). There are various definitions of Smart manufacturing such as Choi et al.[78] and Lu et al.[79],however, they all emphasise the importance of data and data analytics to improve manufacturing processes throughout the life cycle.

Mittal et al.[80] identified the characteristics of Smart manufacturing through a literature review. They found that Smart manufacturing has five key characteristics: context awareness, modularity, heterogeneity, compositionality and interoperability. They furthermore identified enabling technologies for Smart manufacturing which are e.g. data analytics, IoT, CPS, cloud manufacturing, cyber security and intelligent control.

Kusiak[81] defined Smart manufacturing systems as collaborative manufacturing systems that are fully integrated and react in real-time to the changing requirements and customer needs. He furthermore identified six pillars of Smart manufacturing, namely: data, predictive engineering, sustainability, materials, manufacturing technology and resources and resource sharing and networking.

Smart manufacturing, or Intelligent manufacturing, is the second research theme for the realisation of the German Industry 4.0. It focuses on emerging technologies such as additive manufacturing and human-computer interaction and aims to create a well-connected, flexible industrial chain[62].

3.2.5 Section summary

Three manufacturing paradigms related to Industry 4 were explored in this section, that is cloud manufacturing, Smart manufacturing and Smart factories. Each paradigm can be seen to focus on different aspects of Industry 4 where a Smart factory focuses on a local smart organisation of a factory whereas Smart manufacturing focuses on the processes. Finally, Cloud manufacturing aims to share resources across distributed Smart factories.

As Zhong et al.[77] noted, Smart manufacturing and Cloud manufacturing are both important concepts with regards to Industry 4. They have some commonalities such as smart decision making, however, their aims are different, i.e. Smart manufacturing focuses on optimising production by implementing emerging technologies while Cloud manufacturing aims to configure and model services in a network of Cloud manufacturing processes[77].

Industry 4 is based on cyber-physical manufacturing systems that can solve various problems whereas Cloud manufacturing is a model that concentrates on manufacturer-specific issues. Industry 4 moreover requires a 3-way integration while Cloud manufacturing focuses on integration related to service which refers to the horizontal integration in the Industry 4 concept as the horizontal integration relates to sharing resources across the entire value chain[1]. Liu and Xu[1] furthermore conclude that the scope of Industry 4 is broader than the one of Cloud manufacturing with regards to the issues the systems resolve and the integrity of the systems.

3.3 Enabling Industry 4 technologies

Industry 4 utilises a wide range of emerging technologies to collect, analyse and communicate data to improve processes and generate value as PricewaterhouseCoopers (PwC)[82] noted. Industry 4 technologies will furthermore enable more competitive and efficient industrial ecosystems[83]. Various technologies have been proposed as the key technology trends within Industry 4. As this research presents a framework which is based on formal logic for the implementation of Industry 4 in manufacturing environments, a review of required technologies is needed to identify the key technology trends of Industry 4 (refer to Chapter 4 for the analysis of technology trends).

This section presents different academic, industrial and governmental views of enabling technologies of Industry 4 (Subsection 3.3.1) and gives an overview of those technologies and their relevance to Industry 4 (Subsection 3.3.2). A brief summary of the section is provided in Subsection 3.3.3.

3.3.1 Proposed enabling technologies for Industry 4

Many papers reviewed in Section 3.2, noted the link between Industry 4 and technologies. Several papers, both academic and industrial, have proposed various key technologies to achieve Industry 4. This subsection explores the various opinions of technologies required to realise Industry 4. The technologies proposed in the sections below are not considered critical requirements to Industry 4 as the selection of technologies depends on the requirements of the company implementing them. As Industry 4 requires a collaborative effort between academia and industry, the papers were divided into three groups that is academic papers, industrial reports and international initiatives to explore any differences that might be between those groups.

Academic papers

Various technologies have been proposed for the realisation of Industry 4. Below are the multiple technologies that have been recommended as the key enabling technologies for Industry 4.

- Additive manufacturing
- Analytics
- Artificial intelligence
- Augmented reality
- Automation
- Big data
- Cloud computing
- CPPS
- Cyber security
- Intelligent robotics
- Intelligent systems
- IoT
- Mobile internet
- RFID

Zhou et al.[62] suggested that the technologies required for Industry 4 were: Cyber-physical production systems, Mobile internet and Internet of Things, Cloud computing, Big data and Advanced analytics. Wang et al.[8] proposed information technologies such as Big data, IoT and Cloud computing in addition to AI technologies for the implementation of Industry 4. Posada et al.[84] stated that the key technologies for Industry 4 are IoT, visual computing[1], industrial automation, intelligent robotics, cyber security, industrial Big data and semantic technologies[2]. Roblek et al.[21] claimed that Industry 4 is based on Big data, Cloud computing and Mobile computing[3]. Nikolic et al.[87] explored predictive manufacturing systems in Industry 4 and proposed the key technologies for those systems, namely: Big data and statistics, data mining and intelligent systems.

Frank et al.[88] divided Industry 4 technologies into two layers, namely front-end technologies and base technologies. The front-end technologies consist of Smart manufacturing, Smart supply chain, Smart working and Smart product. The base technologies feed into the first layer by providing connectivity and intelligence. They propose that the base technologies for the implementation of Industry 4 are cloud, IoT, Big data and data analytics. They moreover proposed and proved a hypothesis which states that companies which are advanced with regards to Industry 4 have a stronger existence of these base technologies[88].

Tao and Zhang[89] categorised the key technologies required for implementing a Digital-twin shop floor into five groups; namely interconnection and interaction in the physical world, modelling, operation and verification of the virtual world, construction and management of the Digital-twin data from the shop floor, operation and evolution of the digital-twin shop floor and Smart manufacturing based on the digital-twin data.

Akdil et al.[61] proposed that Industry 4 required 11 different technologies: adaptive robotics, simulation, data analytics and AI, communication and networking, cloud, cyber security, AM, sensors, virtualisation technologies, RFIDs and mobile technologies.

Choi et al.[78] classified technologies required for the realisation of a virtual factory into seven categories. Those categories range from module design technologies needed to produce the data for the plant, virtual reality and

[1] "Visual computing can be defined as the entire field of acquiring, analyzing, and synthesizing visual data by means of computers that provide relevant-to-the-field tools"[84]

[2] Semantic technologies is a group of technologies used to gain further insight into data. Artificial intelligence is an example of a semantic technology[85]

[3] Mobile computing is the usage of mobile devices for storing and processing data[86]

technologies used for system integration such as cloud and virtualisation technologies.

Industrial papers

As Industry 4 is both an academic topic as well as industrial, many organisations have put forward their proposals on the required technologies for Industry 4. Below are the technologies various industrial organisations have proposed as the enabling technologies for Industry 4.

- Additive manufacturing
- Analytics
- Artificial intelligence
- Augmented reality
- Automation
- Big data
- Cloud computing
- CPPS
- Cyber security
- Digital twin
- Integration
- Intelligent robotics
- IoT
- Simulation

Maier[57] identified the technical enablers for Industry 4 as follows: advanced robots (e.g. cyber-physical systems and collaborative robots), additive manufacturing, augmented reality, simulation, horizontal and vertical integration, industrial internet, cloud, cyber security and Big data and analytics. Boston Consulting Group (BCG) identified eight technologies as critical drivers to Industry 4: advanced robotics, industrial internet, simulation, cloud and cyber security, additive manufacturing, augmented reality, horizontal/vertical integration and Big data and analysis[90]. Berger[91] stated that the main technologies for Industry 4 are Big data, Cloud computing, additive manufacturing, CPS and smart sensors.

Gartner[92] identified the top 10 technology trends for 2019. The trends are categorised into three groups: intelligence, digital and mesh. Autonomous things, augmented analytics and AI-driven development make up the technologies in the intelligent group whereas the digital category deals with the integration of the digital and physical world including Digital twins, immersive technologies[4] and empowered edge[5]. The category "mesh" includes blockchain and smart spaces[6]. Finally, digital ethics and privacy and quantum computing[7] go across all three groups[92].

International views

Industry 4 has also sparked interest globally for many of the advanced manufacturing countries. As the needs of these countries are different, various technologies have been identified to support the agendas. Big data and Cloud computing are technologies that have been proposed by governments as the technologies that enable Industry 4 as shown below:

- Additive manufacturing
- Analytics
- Artificial intelligence
- Big data
- Cloud computing
- CPPS
- Hologram
- IoT
- Sensor
- Smart energy

Germany identified CPS, Big data, IoT, Cloud computing and sensor as the key technologies needed for upgrading their industry. The U.S. focuses on those technologies as well and furthermore adds additive manufacturing and smart energy and South Korea furthermore adds the hologram technology[94]. Singapore noted three technology enablers for Industry 4, that are automation, connectivity and intelligence[95].

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[4] Immersive technologies are platforms such as augmented reality and virtual reality that allow people to interact with the digital world[92]

[5] Empowered edge refers to the use of computing for endpoint devices employed by either people or the world around us[92]

[6] Physical or digital spaces that allow people to interact with technology-enabled systems can be defined as smart spaces[92]

[7] Classical computers use bits that have two states, on or off which are expressed as 1 and 0. Quantum computers on the other hand use quantum bits that do not have a defined state, before their state is measured, their state can be defined as a "mixed superposition"[93]

3.3.2 Technologies and their relevance to Industry 4

This section discusses the main technologies associated with Industry 4 as identified in previous subsection and explores their relevance to Industry 4. The purpose of this subsection is to provide an overview of these technologies with the aim of identifying how their characteristics with regards to Industry 4 (see Chapter 4 for the analysis). Technologies such as AI, Big data and Cloud computing are explored in this section.

The field of artificial intelligence was initiated in 1956[96], however, it is nevertheless an important part of Industry 4 as stated in the following section. As Wang et al.[8] stated, AI is one of the key enablers that make artefacts smart, that is, give them autonomy and sociality by allowing them to learn from experiences[77]. AI has also been identified as a key technology by e.g. Zheng et al.[60] and Akdil et al.[61].

Data can be defined as information organised in a formal way that allows for interpretation, communication or processing[97]. Big data is used for datasets that cannot be processed by using traditional data process methods due to their complexity and size[94]. Industrial Big data can be explained by the four V's, that is volume, variety, veracity and velocity[98] as presented in Fig. 3.3.

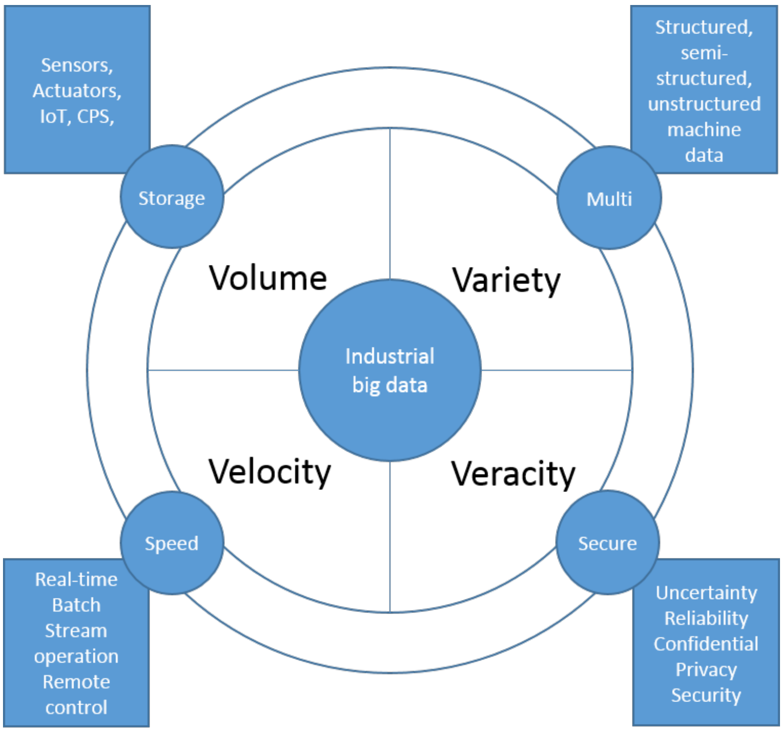

Figure 3.3: Industrial Big data (adjusted from Khan et al.[98])

Industry 4 does not only gather large volumes of data, it also processes and analyses the data. Big data analysis is important for the realisation of Smart manufacturing as they require effective visualisation, analysis and sharing of data gathered from various processes[94].

To meet the requirements that are associated with Industry 4, real-time data collection is required for most companies in the manufacturing industry[60]. Data from multiple sources is also required. To acquire a comprehensive and up-to-date portrayal of the manufacturing system, data needs to be collected from various sources on the factory floor such as movements of labour[99].

Manufacturing companies are already collecting data, however, the conventional technology does not have the capabilities to manage extensive databases. With Big data technology, data from multiple sources can be gathered, stored, analysed and used to improve processes[62].

Cloud computing enables on-demand access to decentralised computing resources to store and process data through the Internet[100]. Cloud computing furthermore covers both its services as well as the software and hardware that provide those services. These services are referred to as Software as a Service (SaaS). Terms such as Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) have also been used to describe the products offered[101]. Wu et al.[102] even included Hardware as a Service (HaaS).

Cloud computing and Big data are closely related as Big data relies on Cloud computing, however, they differ in two main aspects. First of all, big data is used in the decision-making process in an organisation while Cloud computing changes the architecture of the IT systems. Secondly, the two technologies are aimed at different users. As Big data is used to influence decision making, it is aimed at the business part of the organisation while Cloud computing targets the technology aspect of the organisation[103].

Industry 4 requires technology that enables data collection. Internet of Things (IoT) is a network that collects a large volume of data from various sources[103]. IoT aims to connect the physical world to the virtual world and enables communication between things[104]. The architecture of IoT is presented in Fig. 3.4. It is a network of sensors, software, network connectivity and physical objects and exchanges or collects data[105].

There are four main elements of the IoT architecture, according to Xu et al.[106], that is sensing, networking, service and interface which lay a foundation for the three-way integration needed for Industry 4[8]. Botta et al.[107] also noted

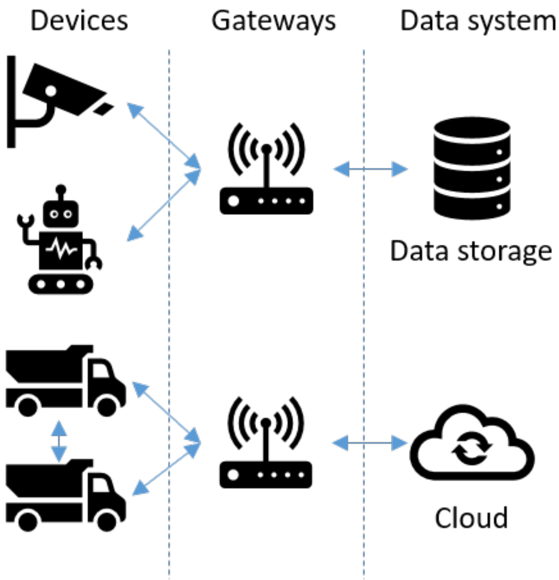

Figure 3.4: IoT architecture

the key elements of IoT. RFID plays an important role in IoT as this technology enables automatic identification of the components they are fixed to. Wireless sensor networks are another key element of IoT. If incorporated with RFID systems, they can enable better tracking of items[107]. Finally, addressing, that is the ability to identify items individually, and middleware which acts as a bridge between the application layer and the things are also important components of the IoT[107].

The IoT network collects a large volume of data from various sources which makes the Big data collected by IoT different from typical Big data. The key characteristics of IoT Big data are e.g. unstructured data, high redundancy and noise[103].

The term Industrial Internet of Things (IIoT) is a sub-paradigm of IoT, focusing on IoT in an industrial setting, where the “things” are e.g. tools and manufacturing equipment[106]. IIoT realises CPS and CM by collecting data and enabling data analytics, making it one of the critical technologies for the realisation of Smart manufacturing[94].

There are numerous definitions of CPSs as Penas et al.[108] noted. Cyber-physical systems can be defined as physical and digital systems which gather and process real-time data to control system[64]. MacDougall[63] stated that Smart factories are realised by the deployment of CPS. The 5C architecture provides a guideline for designing and implementing CPS systems for manufacturing environments[11]. The architecture consists of 5 layers, outlined in Fig. 3.5.

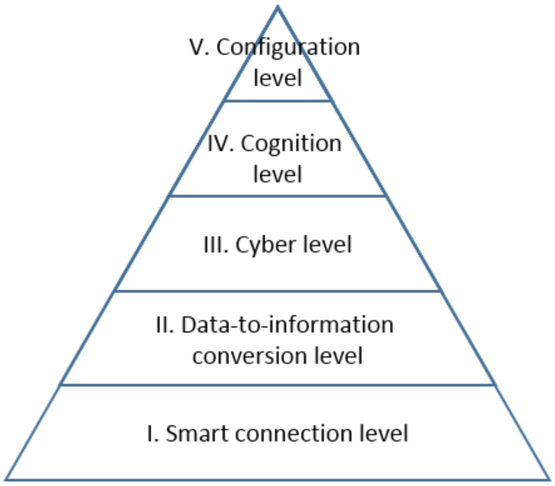

Figure 3.5: CPS framework adopted from Lee et al.[11]

The architecture furthermore maps applications and techniques to each level as well as attributes. The lowest level, the smart connection level, gathers data for condition monitoring whereas the configure level, the top-level, makes the machines self-configure and self-adaptive by receiving feedback from cyberspace to the physical space and acting upon it[11].

Cyber-physical production systems (CPPS) can be viewed as an applied version of CPS as proposed by Monostori[109].

Automation can be defined as the use of automatic equipment in a process such as manufacturing. The history of automation can be traced as far back as to the ancient Greeks and Chinese who used water and steam to power waterwheels and simple steam-powered reaction motors, respectively[110]. Nowadays, various processes are automated using for example conveyor belts and robots. With the advent of Industry 4, automation has become increasingly flexible. Collaborative robotics, often referred to as cobots and drones have emerged. Cobots emerged in late 20th century and are designed to be safe to work in the same environment as humans without any safe guards.

The term Digital twin was first introduced in 2003 by Grieves[111]. The initial concept included three parts, physical component, virtual component and connection between them[111]. The virtual component keeps a record of the performance of the physical part whilst also making predictions and optimises the part. Furthermore, data from multiple sources, such as sensors and domain knowledge, are integrated in Digital twins, creating more reliable and flexible production[89].

Augmented reality (AR) is a technology that provides the user with an altered view of the world. AR first appeared in the middle of the 20th century to enhance the guests' experience in cinema[112] AR augments an environment with computer-generated information in real-time[112]. AR can be used, for example, in maintenance to improve the operator's performance and aiding managers with decision making[113]. Gallegos-Nieto et al.[114] also showed that AR is beneficial for training operators on assembly tasks. As they noted, the benefits of using AR increases as the complexity of the assembly task increases[114].

Additive manufacturing (often referred to as 3D printing) creates physical components, defined by a CAD model, by joining or bonding materials together in a layer-by-layer fashion. Wong and Hernandez[115] noted that in comparison to traditional manufacturing methods, additive manufacturing is more flexible and more efficient which resonates well with the pull from industry of becoming more flexible and efficient[7]. The data flow for additive manufacturing processes is digital, that is, the process that takes a 3D model of a part and converts the raw materials into the final parts[59]. Even though today Additive manufacturing is a well-established manufacturing method, there are still concerns over the material strength and product quality. Additionally, manufacturing speed and often limited printing volume are still barriers for Additive manufacturing[59].

One of the key enablers of Industry 4 and relevant technologies is communication. The fifth-generation (5G) network is expected to support a massive number of connected devices[116]. The 5G network was initially rolled out in 2019 and is currently still being implemented in 2020[117]. Varghese and Tandur[118] proposed three major design requirements for the next generation communication standard. A majority of applications will require a compromise between these requirements:: latency, longevity and reliability. They also compared WiFi and 5G and concluded that a combination of different technologies is necessary to meet the standards of Industry 4.

One of the requirements for Industry 4 technologies is to keep the asset safe in the virtual world. Gartner[119] predicted that around 20 billion IoT devices will exist by the end of 2020. It is crucial to secure the data from any potential cyber threats. As CISCO[120] noted, more sophisticated technologies are necessary to secure the IoT architecture. Cyber security is therefore used in the context of Industry 4 to prevent unauthorised access to any manufacturing data[54]. IoT security differs from traditional IT security in several ways as Frustaci et al.[121] and Wang and Xu[122] noted. Customers cannot add security measures to the devices once they have been shipped from the manufacturer, thus the devices need to have built-in security as opposed to add-on security of traditional IT system. The size of typical IoT devices restricts both the hardware and software resources which limits the complexity of the algorithm on the device. The number of security guards is also smaller for IoT security and the devices are often located in open environments as opposed to traditional IT devices that are generally situated in closed environments[121].

As with IoT devices, CPS security is also a challenge. CPS security threats can be divided into five categories, that is physical, political, privacy, financial and criminal[123]. Humayed et al.[123] classified vulnerabilities of CPS into three types, cyber, cyber-physical and physical vulnerabilities. They furthermore identified five causes of vulnerability of CPS, namely isolation assumption, connectivity, openness, heterogeneity and number of stakeholders. They additionally reviewed security measurements such as communication controls, device attestation and connectivity controls[123].

3.3.3 Section summary

Numerous emerging technologies, such as IoT, 5G network, Big data and CPS enable the realisation of Industry 4. The majority of these technologies are not commonly used in industry yet and therefore need to overcome several barriers before they are implemented in industry.

In this section, various views in academia as well as industry and governmental on the required technologies for Industry 4 were explored. Even though the views of the three different groups share some commonalities, there is not a consensus on which technologies are required for the realisation of Industry 4. This may be due to a lack of general definition of Industry 4 as noted in the previous section and is an indication that a formal framework for the realisation of Industry 4 is needed.

3.4 International initiatives

Many countries have put forward their plan for Industry 4 to strengthen their manufacturing industries as well as to improve quality of life for their citizens. In

2019, the World Economic Forum ranked countries based on their Industry 4 competitiveness[124]. Below is the ranking of the top ten most competitive countries with regards to Industry 4:

1. Singapore
2. United States
3. Hong Kong
4. Netherlands
5. Switzerland
6. Japan
7. Germany
8. Sweden
9. United Kingdom
10. Denmark

Only Singapore, Hong Kong, Netherlands and Sweden moved up in the ranking from 2018, the other countries either dropped their rank or stood in the same place. Four main pillars formed the basis of the ranking, as seen in Figure 3.6, that is enabling environment (such as infrastructure and ICT adoption), human capital (i.e health and skills), markets (e.g. market size and financial system) and innovation ecosystem which includes business dynamism and innovation capability.

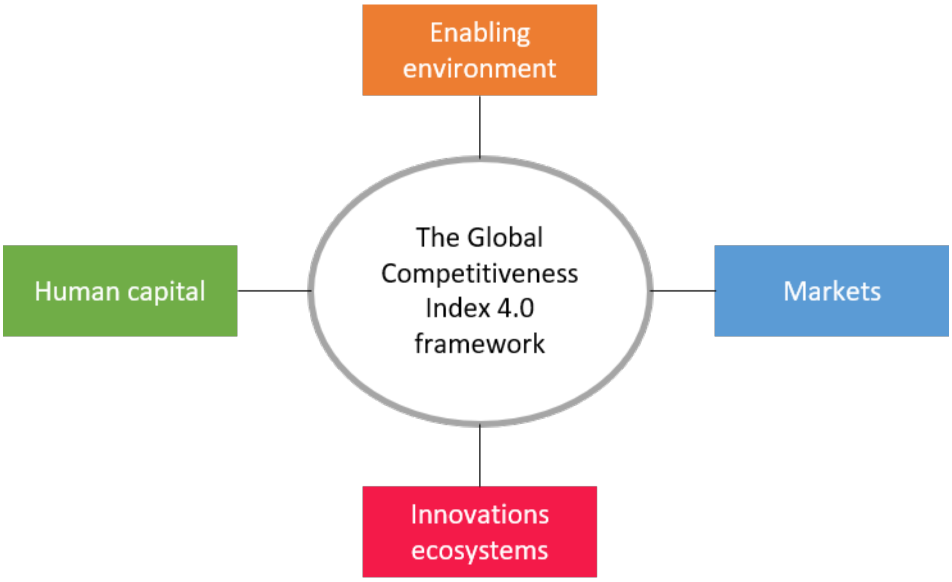

Figure 3.6: The Global Competitiveness Index 4.0 framework

This section explores various international initiatives with the aim of identifying characteristics of Industry 4 (see Chapter 4 for the analysis of this section). This section provides an overview of Industry 4 initiatives from Singapore, the United States, Hong Kong and Netherlands as they are the top four most competitive countries according to the World Economic Forum.

Furthermore, the German initiative is reviewed as Germany was the first country to put forward such an initiative. Finally, the Japanese and the UK agendas are reviewed as Japan has a different view on Industry 4 to the other countries and finally, UK as this research is based in the UK. The initiatives are discussed based on their Industry 4 competitiveness rankings by the World Economic Forum. The initiatives are presented in Subsection 3.4.1 and a summary is provided in Subsection 3.4.2.

3.4.1 Overview of international initiatives

The manufacturing sector in Singapore makes up close to 20% of the countries GDP. The sector was facing challenges such as increasing operational cost and weakening of the Singaporean currency. The government recognised the need to update the manufacturing sector[125]. They developed the Smart Industry Readiness Index in collaboration with TUV SUD that aims to guide companies through their transformation journey. The index consists of three building blocks of Industry 4, namely process, technology and organisation. Under those three building blocks are eight key pillars which are then mapped on to sixteen areas. The key pillars are mapped against the building blocks below:

- Process
  - Operations
  - Supply chain
  - Product life cycle
- Technology
  - Automation
  - Connectivity
  - Intelligence
- Organisation
  - Talent readiness
  - Structure and management

Singapore has furthermore developed a framework for prioritisation which consists of four key areas that companies must consider to achieve a holistic prioritisation. These four principles are: current state of Industry 4 maturity level within the company, impact on the company's profits, determine critical business objectives with regards to Industry 4 and share information and learn from other companies within the manufacturing industry [95].

The USA launched the Advanced Manufacturing initiative which aims to accelerate US advanced manufacturing. In 2012, the Advanced Manufacturing Partnership (AMP) presented a report on how to increase the competitiveness of manufacturing in the USA [4]. This report was followed by a more comprehensive report two years later which offered recommendations on how to achieve this goal. The recommendations are grouped into three categories, namely enabling innovation, ensuring the skill gap is filled and improving the business climate [8].

Hong Kong have proposed a roadmap towards Industry 4 for SMEs which consists of seven steps. The first step is to develop a digital strategy and roadmap. They recommend starting with small-scale pilot projects and then create a strategy and roadmap for Industry 4. Next step is the integration and coordination of digital infrastructure, followed by digital integration of vertical and horizontal processes, that is integration within the business as well as with the supply chain. The fourth step includes the utilisation of IoT and real-time data collection which feeds into step 5 which is data analytics. The sixth step of the roadmap is moving towards autonomous or self-optimised systems and finally, the seventh step is to formulate new business models where they encourage collaboration between partners in the value chain. They have moreover developed the i4.0 maturity model for SMEs. The model maps the path of Industry 4 development against degree of maturity which also reflects the value for the company. The model has 5 steps, from 0i to 4i. The initial step, 0i is a critical step that companies must take before starting the Industry 4 journey. Table 3.1 presents the 5 stages of the model:

Table 3.1: i4.0 maturity model proposed by Hong Kong

Level	Maturity level	Outcome
0i	Digitalisation and connectivity	
1i	Visibility	Increased availability of data
2i	Transparency	Increased data interpretation
3i	Predictability	Increased prediction based on data
4i	Adaptability	Data-based decision making

[8]Business climate can be defined as the environment that encompasses all the relevant entities needed for the operation of a business such as tax rates and governmental policies that affect businesses [126]

The Netherlands launched the Smart Industry initiative in 2014. The objectives of the initiative are to strengthen the position of the Dutch manufacturing industry and increase its productivity. The initiative focuses on three lines of action to realise the aim of Smart industry: using existing knowledge and disseminating it to businesses, acceleration through field labs and improve ICT conditions, knowledge and skills. The first line of action will supply businesses with both technological information as well as best practices. The second line of actions aims to create research centres which connect companies and academic institutions. Those centres will provide facilities for the development and deployment of technical solutions. The final action line aims to develop a research agenda in the field of Smart industry which combines both academia and industry alike. The three lines of action are furthermore divided into 14 action points.

Japan has a different view on the current evolution of industry. According to Japan, society has been through four evolutions, i.e. hunter-gatherer society, agrarian society, industrial society and information society [19]. Society is moving towards Society 5.0 which is the super-smart society. As opposed to focusing on industry, Japan is focusing on how to integrate digitalisation with people's lives. When implementing Society 5.0, the emphasis will be on four areas, that is healthcare, infrastructure, mobility and FinTech. According to the Government of Japan, Japan has a few advantages that make Society 5.0 possible, that is, abundance of data gathered from both healthcare as well as industry and the technological culture in Japan. These advantages are the enablers for Japan to achieve a smart society [19].

Germany was the first country to identify the next revolution of industry, that they called Industrie 4.0. They introduced Industry 4 or Industrie 4.0 as they refer to it in Hanover in 2011 as a governmental agenda to make Germany an international leader in innovation and manufacturing. The strategy can be summarised as: "building a network, researching two major topics, implementing three integrations and the achievement of eight objectives" [2]. The two researching topics are the development of Smart factories and Smart manufacturing. The three-way integration consists of vertical, horizontal and end-to-end integration. Amongst the eight objectives are safety, training, work organisation and resource efficiency. Furthermore, Germany has identified key technologies for Industry 4 which are Cyber-physical production systems (CPPS), Mobile Internet and Internet of things technologies, Cloud computing technologies and Big data and advanced analysis techniques [2].

The United Kingdom has released an industrial strategy for the fourth industrial revolution [127]. The industrial plan has five main elements to transform Britain's economy, that is: ideas, people, infrastructure, business environment and places [127]. The government wants to raise research and development investments in the UK and strengthen the educational system with a particular focus on science, technology, engineering and maths skills. They furthermore want to enhance the digital infrastructure and improve productivity by e.g. establishing partnerships between industry and government. As part of the industrial strategy, the government of the UK has set out the Grand challenges to make the UK a leader of the industrial revolution. The first set of the Grand challenges will focus on AI and data, clean growth, ageing society and future of mobility [127].

3.4.2 Section summary

An overview of governmental initiatives for advancing the manufacturing industry and other industries was given in this section. Seven international initiatives were explored, that is from Singapore, the United States, Hong Kong, Netherlands, Japan, Germany and the United Kingdom. Those countries were all amongst the top ten most competitive countries in Industry 4 according to the World Economic Forum. All of the initiatives apart from one focused on the manufacturing industry and how to strengthen it. Japan claims that society is moving beyond the information era, which they refer to as Society 4.0 and has chosen to focus, therefore, on making the society smarter [19]. The initiatives shared some similarities such as securing the talent pipeline.

3.5 Industry 4 frameworks

Industry 4 is an increasingly growing field within academia as noted in the introduction. In recent years, various frameworks for implementing Industry 4, applying the technologies and addressing various aspects of Industry have been developed. The term framework is used in this section as an umbrella term for a structured approach of implementing an aspect of Industry 4. The aim of this section is to give an overview of the frameworks that have been developed for Industry 4 to establish the current state of Industry 4 frameworks.

Subsection 3.5.1 presents the frameworks. The frameworks are categorised into organisational and technological frameworks. The organisational frameworks focus on implementing Industry 4 from an organisational point of view whereas the technological frameworks focus more on the technical aspects of Industry 4. The order of frameworks within each category is based on the publishing year of the respective papers. Subsection 3.5.2 provides a summary of the section.

3.5.1 Frameworks

Academics have different views on the requirements of Industry 4 and the manufacturing industry is requesting guidelines for the application of Industry 4.

Organisational frameworks

Choi et al.[78] identified that the implementation of a Smart factory requires a systematic and strategic approach. They developed a strategic plan and a systematic framework for the realisation of a virtual factory in a manufacturing environment. The plan has two approaches, that is the top-down approach, which involves the CEO's support, and the bottom-up approach which includes the design of the virtual factory as well as applying the relevant Industry 4 technologies. According to Choi et al.[78], both these approaches must be applied simultaneously. They also proposed an architecture of a virtual factory based on the technologies required and problems identified.

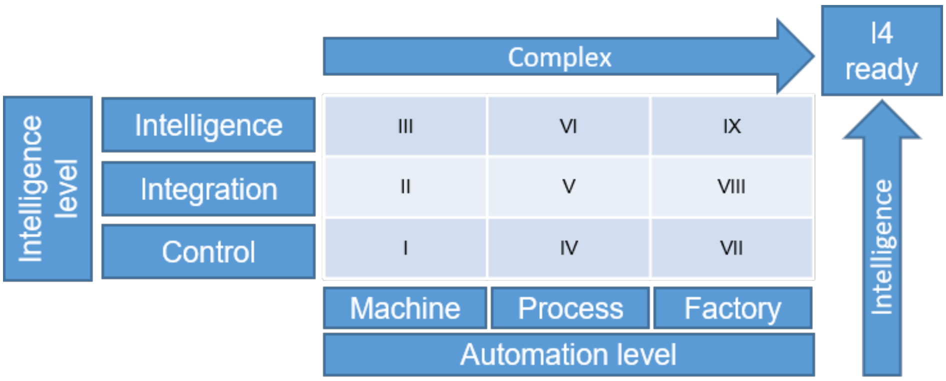

Figure 3.7: Framework for the implementation of Industry 4 (adapted from Qin et al.[128])

Qin et al.[128] developed a categorical framework for the implementation of Industry 4. The framework combines the intelligence level and the automation level, generating nine levels of manufacturing applications as shown in Fig. 3.7.

The intelligence level categorises technologies based on their level of intelligence into three groups, control, integration and intelligence level[128].

The framework allows for a better understanding of how to achieve the requirements of Industry 4 by mapping different levels of intelligence technologies, such as IoT and CPS technologies, to the automation level within production systems, which allows the factory to be connected and share data[128].

Ganzarain and Errasti[129] proposed a maturity model for Industry 4. The model has three process stages, namely envision, enable and enact. During the envision phase, a vision for Industry 4 is created and general Industry 4 understanding is developed. The enable stage encompasses identifying the requirements and relevant Industry 4 technologies. Finally, the enact stage involves preparing and implementing Industry 4. Furthermore, there are five maturity levels for each process stage which describe the maturity level of the organisation with regards to Industry 4. The first step is the initial step where a vision for Industry 4 does not exist. In the second step, a roadmap of strategy for Industry 4 has been developed. Step 3 involves defining key resources, value proposition etc. Transformation of the strategy into a project plan is the fourth step and finally, is the transformation of business model[129].

Schumacher et al.[130] identified 62 maturity elements of Industry 4 which they categorised into 9 dimensions. These dimensions are as following: technology, products, strategy, leadership, operations, customers, culture, people and governance. To assess the majority levels of Industry 4, they developed a three-step procedure. The first step includes a questionnaire which measures the level of maturity of the elements, followed by a calculation of the maturity levels of the nine dimensions. Finally, a report and graph showing the maturity of each dimension are created.

Bucker et al.[13] identified the need for a methodology for companies to implement Industry 4 and proposed an Industry 4 transformation metamodel based on the five universal elements derived by Gutzwiller[131], cited in Bucker et al.[13]. Furthermore, they developed an Industrie 4.0 framework which is the first technique of the metamodel. The framework is based on a human-technology-organisation (HTO) model (Fig. 3.8) and the design principles identified by Hermann et al.[56] and the interactions between them. The HTO model was chosen as it brings together all the required components of an organisation. The framework, shown in Fig. 3.9, is represented by a matrix with 24 fields which represent the interaction between subsystems.

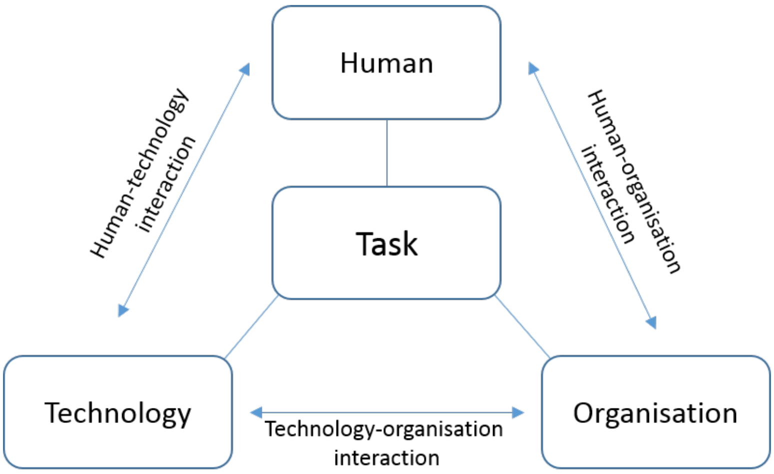

Figure 3.8: HTO model, based on Ulich[132]

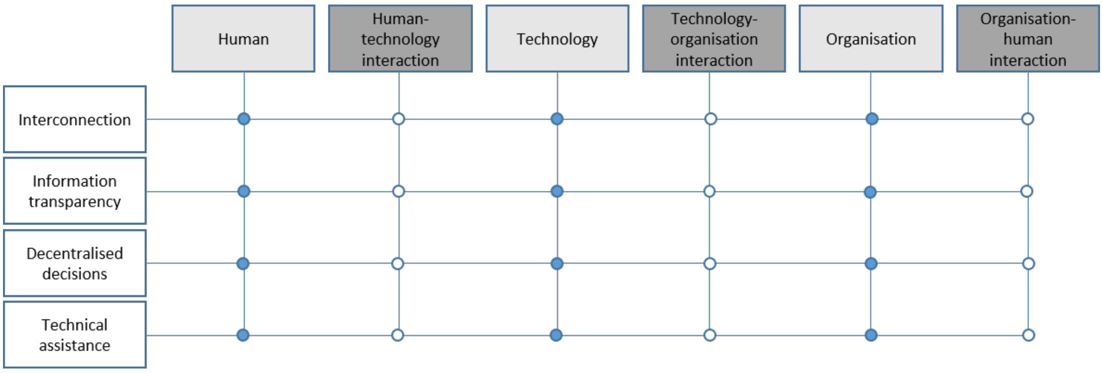

Figure 3.9: Industrie 4.0 framework (adapted from Bucker et al.[13])

Decentralised-decision making increases efficiency in human-technology interaction and shifts the focus of employees towards increased creativity and activities that add value. Moreover, it leads to autonomous decision making[13].

From an academic perspective, the foundation of design theory is design principles[133] which furthermore can be used to describe characteristics phenomena[134]. As Hermann et al.[56] discovered in 2016, design principles for Industry 4 do not exist. Hermann et al.[56], therefore, conducted a qualitative literature review and quantitative text analysis on Industry 4 and proposed four Industry 4 design principles to guide scientists and industry to navigate Industry 4. Those design principles are decentralised decisions, information transparency, interconnection and technical assistance. According to Hermann et al.[56], those principles generate a common understanding of Industry 4 as well as supporting academics in their research of Industry 4.

As Chien et al.[12] identified, the gap between the current state of most companies and Industry 4 readiness might be too big. They proposed a conceptual framework called Industry 3.5 to assist companies to realise Industry 4 and enable countries that struggle to implement Industry 4 to develop a strategy for Smart manufacturing. The framework has five features, namely digital decision, Smart factory, Smart manufacturing, smart supply chain and total resource management, furthermore, it uses Big data analysis, CPS and IoT.

Today, experienced managers currently perform most of the decision making in manufacturing. Digital decision making is required to enable flexible decisions and guide the users making better-informed decisions on complex manufacturing issues. Fast decisions should be based on high-quality analyses of manufacturing data[12].

Smart supply chain is required to improve its competitiveness and Big data analysis is the primary enabler to reach the goal. Smart manufacturing aims to improve manufacturing by e.g. increase flexibility, enhance quality and productivity. One of the aims of Industry 4 is a 3-way integration, total resource management is, therefore, necessary to integrate the resources with the operational strategies. Finally, Industry 4 aims to implement a Smart factory. As Industry 3.5 aids companies to implement Industry 4, its focus is on improving the existing manufacturing environment[12].

In 2017, Ferrera et al.[135] developed the MAESTRI total efficiency framework which is built on four key elements of overall efficiency, that is a management system, assessment tools, industrial symbiosis paradigm and IoT infrastructure. Industrial symbiosis is when waste that comes from an industrial process is reused for another industrial process as a resource. The framework combines the four elements into a platform where the central layer is an IoT platform which connects and enables data transfer between the shop floor and the organisation.

Uhlemann et al.[99] noted that Industry was facing difficulties implementing these technologies due to lack of standards and lack of certainty on the economic advantages of those investments. Uhlemann et al.[99], therefore, proposed an approach for the implementation of a Digital twin. The approach is based on multi-modal data acquisition and a model of the factory which shows how data is used to realise CPPS through a digital twin. The data acquisition relies mainly on two systems, that is sensor-based tracking and machine vision. The model for the realisation of CPPS shows how the production system, data layer and information and optimisation layers are connected.

Technological frameworks

Zhang et al.[136] proposed a framework for Internet of Manufacturing Things (IoMT) to improve the data flow between manufacturing equipment during production. The framework is made up of four layers, namely configuration of manufacturing equipment, sensing, data analysis and application services. They developed an interface that offers dual-way connectivity between the machine, workshop floor and enterprise layers to process the data in real-time.

Zawadzki and Żywicki[137] developed a framework that presents various techniques that aid smart design and manufacturing control for efficient mass customisation in a Smart factory. The framework connected suppliers and customers to a producer by smart product design, smart production control and automated production, enabled by Industry 4 technologies such as CPS and hybrid prototyping.

Romero et al.[138] introduced the term "Operator 4.0" which aims to build an effective human-machine relationship. They proposed eight different types of the Operator 4.0, which are based on connecting the operator with various Industry 4 technologies, such as Big data analytics to create an analytical operator and an operator with a wearable tracker which leads to a healthy operator. Moreover, they proposed a framework which illustrates the relationship between operators and CPPS. As a part of that framework, they identified three different strategies for supporting the operator in human-machine interactions, namely, based on critical events, measurement-based and model-based strategies[138].

An IoT-based framework for collaborative manufacturing was proposed by Lu and Cecil[139]. The key components of the framework are the cyber components, which are software-based and are responsible for e.g. design analysis and assembly planning and the physical components such which are responsible for many aspects of the manufacturing.

Smart factory can be seen as a step towards a "factory-of-things" which is closely related to IoT[140]. As IoT deals with physical objects as well as interacting with IT systems used at the manufacturing site, data is gathered from multiple resources. Shariatzadeh et al.[140] suggested an approach to integrate data in a Smart factory to ensure interoperability. The approach has two layers, namely the IoT platform and the PLM layer. To ensure interoperability between, application programming interface is used. The difference between the IoT platform and the

PLM is how the data is stored. The IoT platform collect large amounts of data which is stored in an unstructured way.

Masoni et al.[141] used off-the-shelf technologies to support remote maintenance (Fig. 3.10).

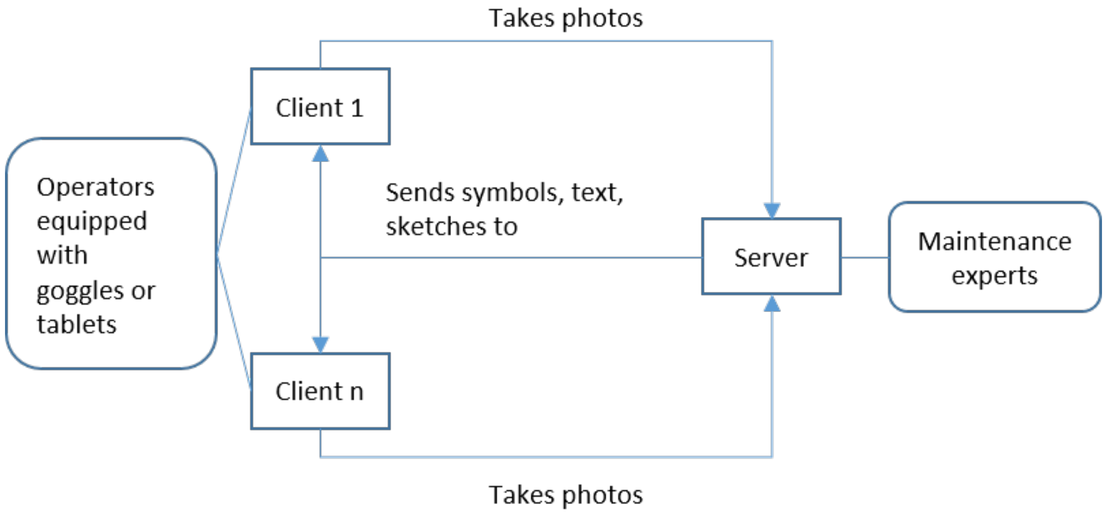

Figure 3.10: Remote maintenance support (adapted from Masoni et al.[141])

A client, an unskilled operator, takes photos of the equipment with either a tablet or goggles and sends them automatically through the system to the server, the maintenance expert. Those photos are then used as a reference for the maintenance expert to give the operator instructions for the maintenance. The expert can add text message or sketch on the photo before sending it to the client.

Penas et al.[108] identified the main issues regarding the design of CPS (see Section 3.7) and developed an approach to address those issues. The approach was an iterative process which consists of multi-scalable methods and tools. The methods and tools are divided into different domains which can be categorised into three main groups, that is system boundary definition, semantic interoperability and modelling. Data is gathered from different levels of the production, that is from the component level and then the machine level. The data is then analysed in on the production level (i.e. CPS), making the approach multi-scalable, meaning that the system can be changed depending on the required inputs and outputs.

Maintenance of equipment is an important element of Smart manufacturing as it affects the efficiency of the production and service life of the machines[142]. Wan et al.[142] developed a manufacturing solution that focused on active preventive maintenance as part of Industry 4 implementation which is built on Big data. The main focus of the solution is the collection of manufacturing data and its analysis.

AIMTEC (cited in Benešová and Tupa[20]) claim to have implemented Industry 4 in four stages. In the first stage, a digital representation of the factory is created in real-time by implementing an enterprise resource planning (ERP) system. The second step involves the horizontal integration of processes with automated equipment. In the third phase, data from the first two steps is analysed. The final step involves the integration of the whole system to reach autonomous manufacturing.

Zhong et al.[77] presented a framework for integrating intelligent manufacturing and Industry 4. The framework categorises the main research topics needed, that is smart design, smart machines, smart monitoring, smart control and smart scheduling.

Canito et al.[143] proposed an architecture for proactive maintenance in the machinery industry. The architecture consists of five layers, that is: data collection, database, Big data analytics, production management software and an intelligent user interface. The architecture encompasses everything from data gathering to the end user which is important as the knowledge created by analysing the data needs to be available to the relevant personnel.

Zheng et al.[60] developed a framework for Smart manufacturing systems within Industry 4. The framework maps typical Industry 4 problems (e.g. smart design, smart monitoring and smart scheduling) against issues related to data (e.g. data collection and Big data analysis) and proposes solutions for those difficulties. The general problems are mapped against data gathering and analysis as data is a major source of smartness in Industry 4 activities.

3.5.2 Section summary

Numerous frameworks for Industry 4 that cover various aspects of Industry 4 such as its implementation and frameworks that focus on certain areas within Industry 4 as CPS and IoT were reviewed in this section. The frameworks follow a structured approach, which as Choi et al.[78] noted though that a systematic and a strategic approach is required for the realisation of a Smart factory. However, the frameworks did not follow a formal, mathematical rigorous approach.

3.6 Case studies

Industry 4 has already been applied in Industry as the following case studies will demonstrate. This section explores the implementation of Industry 4 in various sectors with the aim of exploring the reasons for the implementation and how it was realised. Subsection 3.6.1 presents case studies from the automotive industry such as Harley-Davidson and Daimler Trucks and Subsection 3.6.2 presents case studies from the aviation sector. Subsection 3.6.3 provides an overview of implementation in the energy sector. Subsection 3.6.4 explores Industry 4 in the manufacturing sector. Companies presented in this subsection are e.g. Bosch Rexroth and Heidelberg. Subsection 3.6.5 presents a case study in the service sector and Subsection 3.6.6 provides a summary of the section.

3.6.1 Automotive industry

Daimler Trucks North America (DTNA), in Portland Oregon, specialises in customising trucks to customer needs and requirements in a mass production environment. To meet the needs of the market, they upgraded their factory in Portland. The new infrastructure needed to be implemented as quickly as possible as downtime was not an option and to minimise the impact on the production. DTNA decided to outsource the upgrade and partner with experts in the field. With the new system, managers can use their iPads to check the status of parts in real-time anywhere on the plant floor. The new infrastructure has reduced production issues, improved the conditions for the employees and increased the visibility for managers, which has enabled them to make faster decisions[5].

As the financial crisis hit in 2008, Harley-Davidson was facing the potential of ceasing manufacturing of their motorcycles. Their manufacturing site was based on Henry Ford's principles on mass manufacturing and was lacking flexibility and efficiency. They needed, therefore, to update their facility in collaboration with an integrator to meet customers' need. Harley-Davidson replaced manual assembly lines with automated guided vehicles (AGVs) that are driven by planning needs. As a part of the upgrade, connectivity in the factory was increased, providing the managers with real-time data so they can make faster and better decisions. The new factory needs fewer workers due to automation of the process, however, this has led to higher skilled and engaged workers. The upgrade of the factory has reduced costs by 7%, productivity has increased by 2.4% as well as the net margin which has increased by 19%[144].

Lamborghini decided to build a new Smart factory for a new car model. They created a strategic Industry 4 roadmap, including all the objectives they wanted to achieve. The factory is modular and with the use of robotics and sensors, it allows for a collaborative environment. Lamborghini uses AGVs to move the cars between work stations, which have both robotics and production workers. The data is collected from the factory floor and can be controlled remotely through a comprehensive IT platform. Lamborghini implemented a digital twin that integrates live production with the virtual world [145].

Volkswagen, the German automotive manufacturer, developed an industrial cloud in collaboration with Amazon Web Services. The aim of the collaboration is to increase productivity of their plants by gathering and analysing data from various sources such as machines, systems and plants across all the Volkswagen factories. It furthermore collects logistical data and the long-term goal is to integrate the entire supply chain in the cloud [146]. In 2020, the company started implementing the cloud in their factories and aims to roll it out in 18 factories by the end of the year [147].

3.6.2 Aviation industry

Rolls-Royce makes and services jet engines for commercial aeroplanes. They have been running their service plan, Power by the hour, for over 50 years [148]. It is in their interest to maximise the flying hours of the jet engine. As the volume of data coming from various parts of the aircraft is constantly increasing, Rolls-Royce decided to offer their customer a solution to analyse the data using a data analysis platform. The platform allows Rolls-Royce to analyse large datasets and accurately identify any operational deviation. The results are used to help the customers make necessary plans and understand what factors contribute to increased fuel efficiency [149].

GE Aviation is an aircraft engine manufacturer that faced challenges with manufacturing faults. They equipped their mechanics with a Wi-Fi-enabled torque wrench as well as smart glasses[9] which had software that transferred the step-by-step instructions on to the glasses. The introduction of the new manufacturing system was done through a consultancy. This resulted in a safer working environment as the mechanics no longer had to move to review a paper-based manual. The new system logs the torque values from the wrench and

[9]Smart glasses are glasses that are connected glasses that project information for the user [150]

prompts the workers to take photos for future reference. A pilot study on the new system showed that efficiency increased by 8-11%. 60% of the operators who participated in the study claimed that they preferred the new system to the traditional one and 85% believed that it would lead to decreased errors. Furthermore, an analysis performed by GE Aviation indicated that the new system could lead to reduced cost [151].

3.6.3 Energy and mining industry

BC Hydro is the main electric distributor in the province of British Columbia in Canada. In 2011 they started the Smart Metering programme where they substituted analogue meters with smart meters which monitor power consumption and create a network of meters that are connected to a monitoring system. The implementation ended at the end of 2015 when they had installed over 1.93 million smart meters which cover about 99% of their customers. With the new system, BC Hydro has increased efficiency by automated meter readings, enhanced customer service by more accurate billing and increased energy savings. Furthermore, they developed theft analytics software that uses information from the meters and detects energy theft which has reduced theft by more than 80%. The programme led to an increased profit of $235 million in its first five years [152].

Lukoil, a Russian oil and gas company, were looking to increase exports from a facility that is placed in Varandey and is the northernmost oil terminal in the world that is continuously operated. Due to its harsh environment, automation was needed to ensure safe and steady year-round operations. By automating the system, Lukoil can control every stage of the process and can detect potential errors and failures before they happen. The implementation of the automation system was done in cooperation with an integrator. This has reduced operating cost as well as energy use and process losses. Furthermore, the safety of the facility and working conditions for the employees have improved [153].

Training is a significant factor of the employees' safety, however, can be dangerous to train the employees on site. Lukoil, therefore, decided to buy a training simulator that is placed on land and allows the employees to train in similar conditions as offshore but in a safe environment. That has not only lead to increased safety of their workers but also better training [154].

The Kenya Pipeline Company (KPC), owned by the government of Kenya, provides a pipeline network of petroleum products for Kenya. In 2014, they wanted to optimise communication between the main control centre and the pipeline stations to reduce the frequent failures they were dealing with using the previous SCADA system. Another problem they were having was the long response time for the maintenance personnel, caused by traffic jams in Nairobi, to deal with a failure of the system. As they upgraded their control system, they increased the system uptime and reduced the response time to failures by giving local managers access to the system. The new system has automated leak detection that prevents theft and increases safety. This has led to increasing revenues, safety and time-saving [155].

3.6.4 Manufacturing

The Bosch Rexroth facility in Germany produces hydraulic valves for engineering equipment such as forklifts and tractors. The problem Bosch Rexroth was facing was that one of the manual production lines was struggling with keeping up to the standards of quality and customer demand. The line had to be flexible and deal with small batch sizes while producing six different valve types with multiple variants and even more parts.

The solution was to re-design and automate the production line using Industry 4 philosophies while keeping the employees in the loop. The production line was changed to flexible autonomous workstations and RFIDs employed to collect data. Since the new system was implemented, the logistical and set-up time has been reduced to zero and inventory days have decreased. It furthermore collects and processes data in real-time, allowing for fast decision-making. One main focus of the solution was on the employees. With the new system, each workstation is tailored to the needs of the individual (which are dependent on e.g. the individual's height, reach). It is user-friendly, provides flexibility and reduces errors. The implementation of the new system resulted in 30% stock reduction, set-up time has been eliminated and annual saving with the system is € 500.000 [6].

Leica Microsystems is a German company that specialises in designing and manufacturing scientific instruments as well as providing high-end customer service. However, the service they provided was reactive so they decided to shift to a proactive service model to minimise downtime of the equipment. After having implemented an IoT platform that allowed them to connect to the Leica instruments remotely, the uptime increased by 40% and service cost was reduced by 33% as a consequence of reduced on-site visits. 30% of the detected problem is now fixed remotely and service productivity has improved by 5%. It is not only Leica that sees the benefits of the new system, customers also benefit from increased uptime as well as increased productivity and faster service. The implementation of the new system was done by the provider of the system[156].

Lambert[157] identified so-called lighthouses which are leading manufacturing companies in Industry 4 implementation. The companies had some common capabilities that enabled the scale-up of the implementation. First of all, a strategy for Industry 4 must be in place as well as a business case. It is important as well to engage the workforce and offer necessary training for the new technologies and systems. Finally, the IoT architecture should be designed in such a way that it enables scale-up. Furthermore, the lighthouse companies shared five key value drivers, namely, Big data decision-making, agile systems, new business models, minimal implementation cost of use cases to address business challenges and user-friendly technology implementation[157].

Elekta, headquartered in Sweden, provides clinical solutions for treating cancer. The challenge Elekta faced was that they were unable to detect and solve problems as remote access to their complex devices was not available. The company, therefore, implemented an IoT platform that allows them to access the devices remotely and collect real-time data which allows them to predict maintenance and intervene before parts fail. This has resulted in 20% of service requests which can now be solved remotely and do not require an on-site visit. The system uptime has also increased, allowing for more patients to receive treatment. Furthermore, the implementation has led to improved product design as the company collects and analyses data from the machines. The company relied on an external source for the development and implementation of the software[158].

Stanley Black & Decker, headquartered in Connecticut, USA, is a leading manufacturer of products for industrial application such as power tools and monitoring systems. One of its largest manufacturing sites, placed in Reynosa, Mexico, has over 40 manufacturing lines, each producing multiple products. The plant has thousands of employees and produces millions of tools a year. Their challenge was how to manage production with such a high complexity, they also needed to reduce labour cost and increase productivity. In 2019, they implemented IoT to gather real-time information on any material on site, which resulted in an increased equipment effectiveness by 24% immediately. Furthermore, conditions for workers have improved due to better ergonomics of the line and labour efficiency has increased by 10%. The new system also enables faster decision making and provides better visibility for managers to react to production issues. A company that specialises in networking hardware oversaw the implementation of the new system [159].

Heidelberg is a German printing press manufacturer. As the printing industry is a competitive industry which aims to keep the price as low as possible, Heidelberg had moved towards digitalisation. The presses continuously send data to a Big data analytics system at Heidelberg which analyses the data and predicts failures, enabling predictive maintenance. Heidelberg outsourced the integration of the data analysis platform to a computer software company [160].

Procter and Gamble have a dish-washing liquid manufacturing in the Czech Republic. They were faced with the challenge of a shift in the market, leading to a significant drop in sales. They, therefore, decided to implement Industry 4 on their plant, using an inclusive vision which included all the employees. One part of their implementations was a digital performance management system which shows live key performance indicators but the system is also used for scheduling and tracking. They also implemented end-to-end supply chain synchronisation which, by analytical modelling and simulation, provides visibility of the entire supply chain. As a result of the changes the company made, they have seen an increase in productivity by 160% and the total cost has been reduced by 20% [157].

Whirlpool is aiming to become a sustainable company. One of their goals is to have no waste that goes to landfill in 2020. To reach the goal, they implemented a platform for data collection and analytics in collaboration with external experts. With the IoT and data analytics, Whirlpool can monitor their factory sites and their wastage, resulting in cost reduction as well as waste reduction [161].

3.6.5 Service industry

UPS is an international package delivery company that has decided to take advantage of the new technologies and expand their business. In 2013 they ran a pilot programme, offering 3D printing services. As the pilot was successful, they expanded their capabilities and partnered up with a 3D printing service provider. The service focuses on printing and delivering custom parts and is flexible enough to manufacture both one-off parts and batches of thousands of parts [144].

3.6.6 Section summary

The implementation of Industry 4 in various industries such as manufacturing and the aviation industry were reviewed in this section. Most of the companies implemented Industry 4 to resolve issues regarding e.g. manufacturing, competitiveness and safety. Companies such as Leica and Elekta used Industry 4 to achieve remote and predictive maintenance. The companies noticed increased efficiency due to increased data and data analytics. Most of the companies used an integrator to implement Industry 4 which indicates that companies lack specialist knowledge to implement the changes needed for Industry 4. While the case studies were selected to demonstrate Industry 4 adoption in industry, it could be argued that only few of them have reached Industry 4. The case studies demonstrate companies that are on their journey towards Industry 4 with an emphasis on automation.

3.7 Opportunities and challenges

This section explores the challenges and opportunities associated with the implementation of Industry 4 to investigate the characteristics of Industry 4 further. Subsection 3.7.1 provides an overview of the opportunities and applications of Industry 4 while Subsection 3.7.2 presents the challenges of Industry 4 in industry. A brief summary is provided in Subsection 3.7.3.

3.7.1 Opportunities and applications

Industry 4 has already started to affect many aspects of industry. This section focuses on opportunities and benefits of Industry 4 on various aspects of industries.

Wang et al.[8] identified various benefits of implementing Industry 4. They noted increased flexibility and productivity, due to automatic reconfiguration of equipment and optimisation of the process, enabled by Big data. Industry 4 also leads to more efficiency and transparency, which again is facilitated by Big data analysis. Industry 4 does not only benefit the technical aspect of companies, it also leads to increased profitability and better working conditions for employees[8].

KPMG[17] noted that the most significant value of Industry 4 is derived from the benefits that come with integrating the emerging technologies and their capabilities[17]. According to Almada-Lobo[162], Industry 4 will transform industry in three ways: the digitisation of production, automation and linking manufacturing sites to form a well-connected supply chain.

Lasi et al.[7] identified the effects implementing Industry 4 has on the organisation. First of all, it leads to changes in the manufacturing systems as they will become primarily IT-driven which will affect the companies both on a technological as well as an organisational level. Furthermore, it will allow for new types of business to emerge to account for changing scenery in the manufacturing industry.

Industry 4 can add benefits to all aspects of the business through, for example, data analysis as noted by Maier[57]. Among the benefits they identified were flexibility, productivity, quality, competitiveness and working conditions. They furthermore stated the impact Industry 4 will have on the workforce, however, as it requires new skills, new jobs will emerge. Industry 4 will also change the nature of employment as robots will substitute labour but will not replace[57].

Deloitte[163] identified six areas in which Industry 4 will affect industry. They were categorised into two groups, that is business operations and business growth. In the business operation category, Industry 4 will transform planning, factories and support. Production plans will use prediction and will be able to respond in real-time. Factories will become better connected and after-sale support will change. As for business growth, products and services will become smart, customers are better integrated in the business and engineers will have more data, leading to faster design processes[163].

Rojko[164] noted various benefits of adopting Industry 4. Firstly, it leads to better customer responsiveness. It also enables mass production of customised products and leads to increased flexibility. Furthermore, it leads to increased energy efficiency and better use of natural resources.

Process integration is an integral part of Industry 4, both within an enterprise as well as between different enterprises. It will lead to increased optimisation and real-time decision making[165]. Another trend accompanied by process integration is that companies move from selling end products to selling services[165]. Khan and Turowski[165] also mentioned the need for accessing the real-time data on mobile devices so employees can access the production outside the factory floor. The final scenario they discussed is predictive maintenance but by having a system that monitors the health parameters of the equipment, unplanned maintenance can be avoided.

Arica and Powell[166] proposed opportunities for manufacturing execution systems (MES) based on the key Industry 4 technologies identified by Posada et al.[84]. Amongst the opportunities they mention is the use of semantic technologies and intelligent robotics to predict faults and foresee unplanned events within the MES. Other opportunities include real-time decision making enabled by interactive AR user interfaces and the use of industrial Big data for advanced analysis for proactive decision making in MES.

As Thoben et al.[9] mentioned, Industry 4 can be applied in various scenarios depending on the enterprise in question. They reviewed use cases, including safe human-robot interaction and cyber-physical logistics system (CPLS). Secure human-robot interaction is crucial for Industry 4 scenarios where the market requires high productivity as one of the key enablers is the collaboration between robots and human workers. CPLS is a subsystem within CPS which aims to increase flexibility with autonomous decision making and solving errors in real-time autonomously which leads to a reduction in inventory.

Roland Berger identified five key drivers for the shift towards Industry 4, namely virtual factories, automated flows, smart machines, predictive maintenance and CPS[91]. They furthermore noted three ways for industry to develop, i.e. automation, obsolescence and Industry 4 where automation has high profitability but low asset turnover and obsolescence is the opposite. Industry 4, on the other hand, offers flexible production which leads to a balance of the two factors[91].

Big data can be used for various applications in an Industry 4 environment as Khan et al.[98] mentioned. Big data can be used to predict equipment failures and thus eliminate production failure. Production planning can also be enhanced by using Big data to predict future demand in the market. Moreover, feedback from customers can be gathered and analysed for the development of new products and increased customers' satisfaction. Finally, business intelligence (BI) relies on Big data to create business plans and strategies.

Industry 4 requires real-time data collection which IoT and CPS can possibly solve with its capabilities to gather data and connect to a centralised database[60].

There are several benefits associated with implementing a predictive manufacturing system, such as cost reduction, operational efficiency and product quality improvement[87].

Wu et al.[74] identified the potential impact of Cloud manufacturing on engineering design, production and marketing. The short term effects of CM were improved efficiency and reduced time-to-market and cost. If looking at the long-term benefits, CM will lead to collaborative design, distributed manufacturing and distributed manufacturing.

3.7.2 Challenges

General challenges

Even though Industry 4 offers great potential for industry as reviewed in Section 3.7.1, it comes with many challenges, both related to the technologies needed as well as the human and business aspects. Zhou et al.[62] identified four key challenges for the implementation of Industry 4, i.e the development of smart devices, digital manufacturing and the construction of the CPPS platform, which includes challenges related to the cooperation between various systems, CPS modelling and integration and verification of the system. Big data analysis poses as a challenge due its large and complex nature. Furthermore, it needs to be matured to be rolled out in industry on a large scale[62].

In 2016, Khan and Turowski[165] surveyed to discover the current challenges in the manufacturing industry concerning Industry 4. According to their survey, the main three challenges are: data integration, process flexibility and security. Data is currently generated and collected from different places, both within the company as well as outside. The data requires, therefore, new ways of storing (i.e. cloud storage), processing and management. Furthermore, real-time data is needed to make decisions in real-time to improve performance and minimise cost. With regards to security, severe measures are required to limit the threats caused by hacked and malfunctioning devices. Finally, customisation is becoming increasingly more important as the product life cycle is shortening which requires more manufacturing flexibility.

Maier[57] identified three limiting factors for the implementation of Industry 4 in the UK, that is lack of effective leadership, inadequate levels of adoption and lack of start-ups. As for the lack of leadership of digitalisation in the UK, the UK does not have a clear vision of the future due to lack of cross-sector national leadership. One example of that is shown in the network of technology centres in the UK but their capability is not fully exploited due to lack of coordination. The UK is behind other countries in overall productivity as they are behind in the adoption of digitalisation. Amongst the reasons are lack of business support and the barriers SMEs face with adoption such as lack of standards and cyber security. Finally, the UK is a leading country in research and innovation but the knowledge is under-leveraged to support start-ups[57].

As Deloitte[10] noted, implementing Industry 4 is easier in theory than practice. Industry 4 requires a shift in processes as well as mindset and balancing the emerging technologies and new business models with legacy operations can be challenging. This may be the reason why in recent surveys conducted by Deloitte, significant majority of companies' executives stated that Industry 4 was a top priority in their strategy[167] but only fraction of them are highly confident their companies are ready for the digital transformation[15].

KPMG noticed that a minority of organisations have reached the point of integrating technologies in the process of implementing Industry 4. Their analysis shows the entire enterprise must participate in the implementation of Industry 4 to reach its full benefits[17]. Vertical integration in the company is required before any advantage of Industry 4 within the value chain can be gained (Bischoff, 2015 as cited in Uhlemann et al.[99]).

BCG identified five main challenges companies will need to be overcome to implement Industry 4. First of all, data needs to be gathered and analysed in real-time and stored securely. Industry 4 must support operations by, for example, production control and AR for training. Automation of tasks is also a challenge which can be realised with for example digitalising the supply chain and finally, demand management[90].

Wang et al.[8] noted several technical challenges, including Big data in the manufacturing environment and its analysis and system modelling. Moreover, they identified cyber and property security as a challenge as data as well as physical properties such as machines are connected to the cloud. Another problem that they identified is the products move around the shop floor which requires a modularised, smart conveying system.

There are not only risks associated with the technical aspect of Industry 4 as Roblek et al.[21] noted, according to them, the main threat in the implementation process of Industry 4 may be related to the mindset. With IoT, increased connectivity will be introduced, which means that the mindset of enterprises must change to incorporate the change[168].

Benešová and Tupa[20] noted that Industry 4 must be implemented in industrial settings in stages to avoid problems associated with the implementation. Germany stated that to shift current manufacturing production to Industry 4, they need to follow a strategy which focuses on two main areas, i.e. data and CPS technologies and products[2].

Capgemini conducted a survey across 13 countries in just under 1000 manufacturing companies in 2019. The survey revealed that manufacturers are planning to increase the number of Smart factories by 40% in the next five years. However, only 14% of the companies claimed that their implementations of Smart factories were successful and about 60% stated that they are struggling to scale up their initiatives. There are two main challenges the manufacturers are facing regarding scaling up, that is the convergence of operational technology with information technology and lack of skills and capabilities. Not only are digital skills required, but multi-functional skills as well, such as manufacturing and maintenance and engineering and manufacturing[169].

When creating the Industry 4 roadmap for an organisation, it is crucial to align it with the business strategy[17]. Gates and Bremicker[17] further noted that having a well-defined strategy for Industry 4 adds value to the business by giving insight into its processes and improving visibility of the value chain.

Although Wang et al.[8] stated that Industry 4 will lead to better working conditions for employees, Industry 4 may also have a negative effect on the workforce as noted by Frey and Osborne[22]. They concluded that up to 50% of jobs will be replaced by automation by the emerging technologies. Moreover, Industry 4 requires retraining of employees which means that the company must have the resources to upgrade the skill set of their employees[20].

Technical challenges

Wan et al.[170] reviewed various challenges of CPS designs at different layers of the CPS architecture. As CPS involves multiple communication methods such as M2M, networking issues need to be resolved. Existing design and verification tools are not suited for the design of CPS as it requires the cooperation between various disciplines[170]. As with other Industry 4 technologies, security and privacy is a big challenge as data is no longer stored locally on the devices. Standardisation is another challenge as CPS require the usage of various technologies from different disciplines, new standards of greater scope than the traditional standards are therefore required[170].

Monostori[109] identified the research and development challenges related to realising CPPS. Amongst the challenges were the identification and prediction of dynamic systems, integration of real and virtual systems and human-machine collaboration.

When the different design elements are integrated into CPS, hidden problems emerge such as unknown interactions and conflicts between the components of the system[108]. Rajkumar et al.[64] listed several challenges related to CPS such as the need for reducing cost and testing and implementation time of complex CPS systems.

Uhlemann et al.[99] identified multiple difficulties that need to be overcome before realising digital twins for CPPS, most of them related to data. There is a lack of standardisation of data collection, the general implementation of Industry 4 is not advanced enough and data security is also a concern.

Manufacturing processes and its assets should be visualised in real-time but the current methods offer limited accuracy so new data modelling approach is needed to standardise data that comes in various formats. Future research should, therefore, investigate AR-enabled real-time visibility and cyber-virtualisation modelling[60].

Khan et al.[98] listed several challenges related to the usage of Big data in an Industry 4 environment. Firstly, the acquisition of automation data is difficult due to different technologies and equipment. Data transformation is a challenge as most of the data generated in industry is machine data that needs to be transferred into a suitable format. The data furthermore needs to be integrated into a single platform for fast decision making which is another challenge. The data also needs to be accessible in real-time and kept secure and private at all times. Finally, data analytics is a challenge as the data needed for the analysis comes from various sources and the data needs to be analysed in real-time. Scalability of analysis is another problem as the volume of data increases as the production increases[98].

Currently, data is mostly gathered manually on the factory floor, making it time-consuming both to collect the data as well as analysing and making decisions based on the data. Moreover, as manufacturing processes rely heavily on manual labour, efficiency is low[60].

Amongst the biggest challenges in Industry 4 is to make production systems with abilities that make them "self-aware", "self-maintain" and "self-predict". Nikolic et al.[87] pointed out the main issues with those systems. According to them, the biggest challenge is related to data followed by issues on uncertainty and lack of standards[87].

Armbrust et al.[101] ranked the critical challenges for Cloud computing. The top-ranked challenge involves the availability of the services provided by Cloud computing. They also noted challenges related to data such as its security, storage and transfer.

Automation will play an essential role in an Industry 4 environment as it enables flexible and complex manufacturing processes. Angerer et al.[171] outlined significant challenges when implementing multi-functional robotic cells, that is modelling, planning and simulation and the deployment to real-world systems.

Machine-to-machine communications play a key part in CPS and as M2M is a relatively new field, the technology presents several challenges. The integration of M2M requires a high level of security to prevent hackers from breaking into the system. M2M communications generate a significant amount of data that goes in the hand of more people. That will cause a change in some business processes and require more training for the employees. Integration is another challenge, both with regards to integrating M2M as well as with other systems[170].

Augmented reality offers great potential for industry but will be challenging to implement nevertheless. Nee et al.[172] noted four main challenges, namely accuracy, registration, latency issues and interfacing technology.

Even though IoT offers enormous potential, there is an increasing fear of technology. The control of the data captured by IoT is the biggest concern regarding the IoT technology according to Roman et al.[173].

Digital twins are among the ten strategic technology trends Gartner identified in 2018[92]. Tao and Zhang[89] identified a few challenges that relate to the implementation of a Digital twin. According to Tao and Zhang[89], a two-way connection must be established between the virtual and physical spaces. Building a virtual model of the shop floor is a fundamental problem due to the uncertainty and variability of the physical space. Thirdly, ensuring a seamless integration of the virtual and physical world is challenging as the two spaces are of different scales. Security is another challenge as the physical and virtual spaces must be kept safe from attacks[89].

Research challenges

There are a few research challenges associated with Industry 4. Thoben et al.[9] categorised the research challenges related to the adoption of Industry 4 into three groups, that is methodological, technological and business case research issues. The technological research issues are data related but problems associated with interfaces are also mentioned. Issues on data are divided into three groups, data security, data quality and data analytics. With regards to methodology, the following issues were identified: lack of reference models (i.e. standards and holistic models that cover all aspects of Industry 4), different requirements for visualisation due to diversity of the stakeholders, insufficient requirements engineering and service/app marketplaces as the overlap between research issues is significant. Finally, business case issues are divided into three groups, i.e. privacy issues, investment issues and servitised business models [9].

Miorandi et al. [174] classified the research challenges that need to be addressed to make IoT a commercially viable technology. For IoT to become commercially viable technology further research is required in areas of distributed systems technology and intelligence as well as computing, communication and identification technologies.

3.7.3 Section summary

This section gave an overview of the challenges and the opportunities that arise with Industry 4. Amongst the opportunities that were noted associated with increased connectivity and data flow, e.g. flexibility and optimisation of the process. Even though there are benefits of implementing Industry 4 as demonstrated in this section, companies and researchers face several challenges related to Industry 4. The challenges were divided into three groups, namely:

- General challenges: E.g. lack of effective leadership, the need for a shift in mindset and negative effects on the workforce.
- Research challenges: Various challenges related to technologies such as data and IoT as well as a lack of reference models.
- Technical challenges: Related to e.g the complexity of CPS, Big data, lack of standardisation of data.

It was apparent from the papers reviewed in this section that many challenges are associated with Industry 4, both technological as well as organisational and research-related challenges. This demonstrates the complexity of Industry 4 on multiple levels. Furthermore, as noted earlier in this chapter, there is neither a unity on the definition on Industry 4 nor which technologies are required for its realisation. Those challenges, combined with the lack of reference models as mentioned in this section, underpins the need for a formal, rigorous approach for describing and formally evaluating the implementation of Industry 4 solutions in manufacturing.

3.8 Formal logic

This section gives an overview of formal logics and axiomatic systems as this research answers whether Industry 4 can be described with mathematical reasoning. Formal logics and axiomatic systems allow for a consistent, rigorous approach which might aid with the implementation of Industry 4. Subsection 3.8.1 explores the different types of logic and their differences. It furthermore explores various applications of logics in engineering. Subsection 3.8.2 introduces axiomatic design and Section 3.8.3 provides a summary of the section.

3.8.1 Types of logic

Logic is one of the most ancient form for representing knowledge. It can be traced as far back as to Aristotle in ancient Greece. The foundation of modern logic was, however, laid in the 19th century by mathematicians such as K. Gödel, T. Skolem and G. Gentzen to name a few[175]. Formal logic is widely used in various fields of research such as philosophy, computer science and engineering. There are several types of formal logics such as propositional logic, first-order logic, computational logic and non-classical logic. The properties of these four logic types will be explored in this section.

It is worth noting that there are other types of formal logics such as modal logic and second-order logic, to name a few. A review of the full range of logics is not within the scope of this Thesis. The focus will, therefore, be on logics that are typically used to describe engineering systems.

Boolean algebra consists of six basic logic operations, that is AND, OR, XOR, NOT, NAND and NOR. The logic is the mathematical presentation for digital logic, used to build digital circuits[176]. Boolean algebra is, therefore, typically used in electronic engineering. However, it can be used for other applications as well such as calculating intersections between different parts of the model when modelling with ACIS[177].

Propositional logic can be defined as a logic that allows to reason whether statements are either true or false. Propositional logic uses five logical connectives to connect logical propositions[175]:

- negation: $\neg$
- conjunction: $\wedge$
- disjunction: $\vee$
- implication: $\rightarrow$
- bi-implication: $\leftrightarrow$

Below is an example of proposition, assume R and C have the following definitions:

R = "It is raining"

C = "It is cloudy"

then the following formula can be derived:

$$R \rightarrow C \tag{3.1}$$

which implies if it rains, then it is cloudy.

Propositional logic is limited in the sense that it cannot express general statements on similar examples, however, first-order logic has that benefit[175]. First-order logic is based on the existence of objects and their relations. It can be used to articulate facts on things in the world and even though it may not be feasible to describe the entire workings of the universe, it can be useful to understand it[96]. First-order logic provides the freedom of explaining the objects in question in ways that are suitable for the field[96].

First-order logic uses the same logical connectives as propositional logic, furthermore, it uses variables and quantifiers. There are two quantifiers: the existential quantifier $\exists$, read: "there exists" and the universal quantifier $\forall$, read: "for all". For the variable x, $\exists x$ means that there exists an x and $\forall x$ means that the statement is true for all x.

First-order logic is widely used in the field of engineering. Witherell et al.[178] used first-order logic to enhance techniques for engineering design knowledge management. They identified that three main issues in knowledge management could be resolved by using first-order logic. These three issues are:

1. verify knowledge occurrences within a framework
2. maintain consistency during the knowledge example generation
3. minimising redundancy in the knowledge example generation

For their work, they used description logic as well as Horn clause[178]. The first-order logic system was applied in two case studies, for the design of a simple beam and a medical device, respectively. By using Horn logic, knowledge acquisition was enhanced as well as knowledge management and knowledge validation[178].

In 2009 Wang et al.[179] developed a first-order predicate logic system for the modelling and analysis of manufacturing processes.

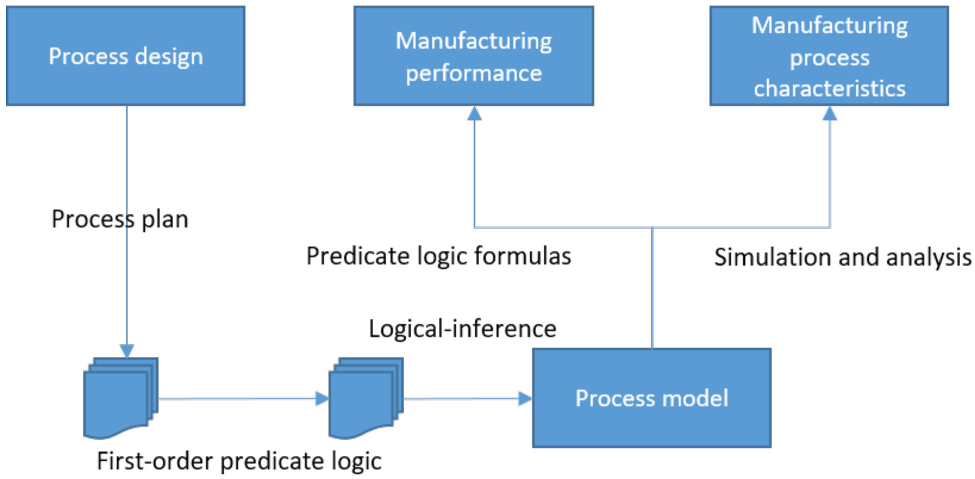

Figure 3.11: First-order logic framework for manufacturing process modelling (adapted from Wang et al.[179])

Figure 3.11 shows the modelling framework. The first step is to design the process plan, which is then translated into predicate logic formulas using first-order predicate logic. The process plan can then be created by applying logical inference. The framework can, furthermore, be used to identify bottlenecks within the process.

As with propositional logic, first-order logic can only express whether statements are true or false. Fuzzy logic allows descriptions of the world, as opposed to first-order logic, with a degree of truth, that is facts do not need to be entirely true or false[96]. A fuzzy logic statement can be for example: "It never rains in Glasgow" and might only be valid to a degree of 0.8. Fuzzy logic can be defined as a precise logic used to describe logical systems that are imprecise[180]. Fuzzy logic has, therefore, an advantage over bivalent logic (such as first-order logic) when real systems are described due to their imperfect and fuzzy nature[181]. As Zadeh[181] noted, fuzzy logic caused debate amongst scholars when Zadeh[182] published the first paper on fuzzy logic. Today, however, the importance of fuzzy logic is widely accepted[181].

Minsky[183], one of the first leaders in the field of artificial intelligence[184], used a high-level approach which included formal logic to describe a complex phenomena. He described the functionality of the brain in the book "Society of the mind". His approach was to describe the mind in a non-technical way by identifying small building blocks of the brain, called agents. He furthermore identified their characteristics and relationships between them[183].

Expert systems are computer programs designed for solving various problems in a specific domain[18]. Gupta and Singhal[18] described expert systems as: "An expert system is an interactive computer-based decision tool that uses both facts and heuristics to solve difficult decision problems based on knowledge acquired from an expert"[18]. The core of the workings of expert systems can be formulated as below:

$$expert\ system = knowledge + inference \tag{3.2}$$

where the knowledge base represents knowledge specific to the domain and the inference engine manipulates the knowledge using predefined algorithms. Knowledge systems are typically based on first-order logic. Majority of expert systems are written as programmes, using programming languages such as Prolog or LISP[175].

3.8.2 Axiomatic design

"Axioms are general principles or self-evident truths that cannot be derived or proven to be true, but for which there are no counterexamples or exceptions"[185]. The first examples of the use of axioms come from the Greeks and is Euclid's geometry considered to be the oldest example of the use of axioms. Ever since then, axioms have played a vital role in the development of natural science. For example, Sir Isaac Newton's axioms of mechanics are the foundation for modern engineering and science[185].

The axiomatic approach has also been used in applied engineering, such as in the Axiomatic design[185] which consists of two axioms, namely the independence axiom and the information axiom. The information axiom states that "the design world consists of four domains"[185] and identifies the domains required to be addressed in a design process. The four domains are: customer, functional, physical and process domain. The second axiom states that the information content must be minimised. That means that the amount of information needed to achieve the design goals is directly related to the quality of the design.

According to Suh[185], the goal of axiomatic design is to provide a scientific basis for design and improve design processes by giving designers tools and processes which are based on logic. He furthermore states that design benefits from having a scientific basis as to achieve its goals, it must have knowledge, experience, imagination and hard work which science can provide[185].

Even though Suh's[185] axiomatic design was developed for design it has also been applied in the field of engineering. Farid[186] adopted the approach for engineering design of systems. Rather than using a traditional top-down engineering approach, they proposed an iterative process based on Suh's[185] axiomatic design.

Axioms are used by mathematicians to describe the foundation of a domain, from which definitions can be derived from. Axioms and definitions can be used to prove theorems[96]. The terms definition and theorem will be defined in Section 5.2.1.

Logical systems are commonly evaluated based on two characteristics, namely soundness and completeness. For a system to be sound, every formula in a logical system must be proven to be true within the defined system. To meet that criterion, the proof needs to fulfil two conditions, that is the proof must be logically correct and the propositions must be true[50]. As opposed to soundness, completeness describes the adequacy of a system, that is, for a system to be complete, if and only if every theorem in the system can be proven within it[30]. With formal logic systems, completeness of the system is proven through formal proofs.

3.8.3 Section summary

This section provides an introduction to formal logic and provides examples of the use of such systems within engineering. Propositional logic, predicate logic and fuzzy logic were reviewed. Those three logics offer different capabilities ranging from the expression of whether a statement is true or false for a specific model (propositional logic) to more general statements about real-world imperfect models. Logics are widely used in the field of engineering as shown in the section. The axiomatic approach was explored. The axiomatic approach is used by mathematicians to describe the foundation of a domain, however, it can also be used in other fields such as engineering and design as Farid[186] and Suh[185] showed, respectively. The goal of axiomatic design is to provide a scientific basis for design[185].

3.9 Summary

This chapter has presented a review of Industry 4, aiming to provide an overview of the required factors to successfully implement Industry 4 in industry as well as the challenges and opportunities.

In Section 3.2, an overview of Industry 4 and related manufacturing concepts such as Cloud manufacturing and Smart manufacturing and their connections to Industry 4 was discussed. Various technologies and their relations to Industry 4 are reviewed in Section 3.3. The majority of the technologies are not commonly used in industry yet. Furthermore, it is apparent that there is a lack of unity on which technologies are needed for the implementation of Industry 4, both within each reviewed group as well as between them. Section 3.4 provided an overview of the international Industry 4 initiatives. The review revealed the importance of having a framework for the implementation of Industry 4 and including the human aspect. including the human aspect and Section 3.5 explores frameworks that have been developed for Industry 4. The frameworks focus on various aspects of Industry 4 such as the organisational aspect and technology aspect. None of the frameworks reviewed proposed a formal logical approach for the implementation of Industry 4. Multiple case studies in numerous sectors such as manufacturing and aviation are presented in Section 3.6. The case studies shared various commonalities such as the use of an integrator for the implementation. That indicates that companies are not ready or do not have the specialists themselves to implement Industry 4. Section 3.7 provided an overview of both opportunities and challenges associated with Industry 4. There are many technical challenges and opportunities within Industry 4, however, as the scope of Industry 4 covers not only technologies but the business and human aspect as well, and was shown to benefit these areas too. Finally, Section 3.8 discusses various types of logics such first-order logic and their applications. This section creates a basis for the selection of approach for the axiomatic universe which is presented in Chapter 5.

The review of the literature indicates that even though Industry 4 is a widely researched topic, a formal logical approach for the implementation of Industry 4 has yet to be proposed. As Choi et al.[78] noted, the realisation of Smart factories require a strategic and systematic approach. As noted in Section 3.2, Smart factories share commonalities with Industry 4 which is an indicator that Industry 4 also benefits from a similar approach. Gates and Bremicker[17] furthermore noted a that a well-defined strategy for Industry 4 adds value to the business.

In Chapter 4, the literature review is analysed and key characteristics of Industry 4 are identified. Those characteristics will provide a basis for the rule base presented in Chapter 5.

Chapter 4

Industry 4 analysis

4.1 Introduction

In Chapter 3, literature on Industry 4 was reviewed. Papers on various aspects of Industry 4 were presented and case studies on its implementation in industry were reviewed. It was observed from the literature reviewed in Chapter 3 that a general definition of Industry 4 is lacking. This chapter aims to analyse the literature presented in the previous chapter and identify its key characteristics. This chapter consequently addresses Objectives 1a-1c of this research which focuses on analysing the literature on Industry 4 to identify the key characteristics of Industry 4. The key characteristics provide the basis for the rule base presented in Chapter 5 and therefore Objective 2b which is the establishment of the dependencies between the key characteristics of Industry 4. The methodology employed for the analysis was outlined in Chapter 2.

This chapter is structured as follows: Section 4.2 provides an analysis of each section of the literature review (Chapter 3), in Section 4.3 the results of the previous are cross analysed to identify the key characteristics of Industry 4 that are within the scope of this Thesis. These themes are: data, business, technology, manufacturing and connectivity. Finally, Section 4.4 provides a summary of the chapter.

4.2 Analysis of Industry 4

This Section presents the analysis of the literature. Subsection 4.2.1 presents the word count analysis which is the first step of the analysis as detailed in the previous section, followed by the analysis of each section of the literature review, presented in Subsections 4.2.2-4.2.6. Subsection 4.2.7 provides a summary of the section.

4.2.1 Word count analysis

For the analysis, 96 papers reviewed in the literature review were analysed. All the academic papers and industrial reports were analysed, however, references from the internet were excluded as the aim was to focus on academic papers and reports. Figure 4.1 shows the 100 most frequently words used in these papers, identified by the software NVivo.

Figure 4.1: Word cloud from the word count analysis

Figure 4.2 shows the result of the word frequency with stemmed words, showing the 40 most frequently used words. As seen in the figure, the most frequently used word that appeared in the papers analysed is manufacturing, followed by industry, systems and data.

The word count analysis shows that the main focus of Industry 4 is on manufacturing which is in line with the original scope of Industrie 4.0 [2]. "Data" is

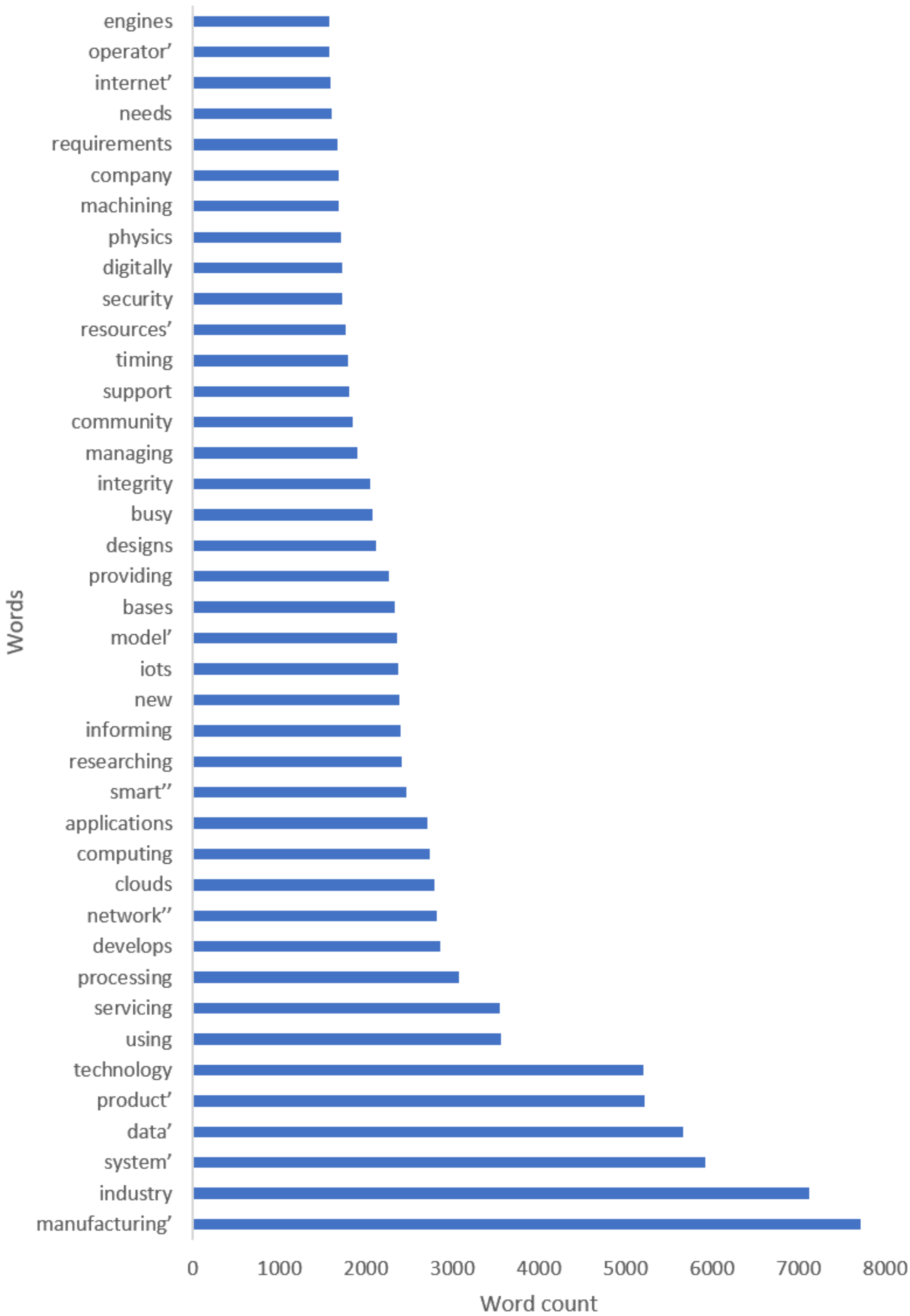

Figure 4.2: Word count using stemmed words

the fourth most used word in the papers reviewed. As with "manufacturing", that aligns with the original initiative of Industrie 4.0[2]. Industry 4 is heavily linked with technologies as the word count analysis shows "Technology" is amongst the top 10 most frequently used words in the reviewed papers. The term "servicing" ranks high in the word count analysis which is an indicator that Industry 4 allows industries to move towards new business models such as servitisation. The words "cloud" and "computing" appear next to each other which indicates that cloud computing has strong links to Industry 4. Even though Radziwon et al.[65] noted that the word "smart" is overly used both in academia as well as industry, therefore it is interesting to see that the word only ranks in 15th place in the reviewed papers.

The majority of the results of the word count analysis are in line with what was expected. Industry 4 focuses primarily on manufacturing as the analysis shows. The previous industrial revolutions also lead to changes in the manufacturing sector and it is, therefore, unsurprising that the current revolution focuses on manufacturing as well. As with its predecessors, technologies are evidently an integral part of Industry 4. Data, cloud computing and IoT are the most frequently mentioned technologies. The majority of the words are linked with technologies in one way or another, such as digitally, security and system. These technologies have been advancing fast in recent years, however, as noted in the literature review, the sector is struggling with implementing them. The word "system" appears amongst the most frequently mentioned words. That may indicate that the technologies are applied in a system rather than individually.

The word "automation" did not appear amongst the most frequently mentioned words which is an indicator that majority of the papers reviewed do not consider automation important part of Industry 4. It is also worth mentioning that analysis is not amongst the 30 most frequently used words, however, "processing" appears amongst the top 10 words. There are words that are associated with Industry 4, such as words related to finance, that did not appear in this analysis. In conclusion, this research focuses on Industry 4 within manufacturing settings and the selection of papers reviewed in the literature review therefore reflect that.

4.2.2 Key characteristics

The various definitions on Industry 4 found in literature reflect that there is no single unifying Industry 4 definition. The papers reviewed showed some commonalities in the definition of Industry 4. 40% of papers defined Industry 4 based on the value chain and as many papers said that the overall goal of

Industry 4 is to increase efficiency and productivity. Other papers assessed, dated between 2011-2020, mentioned increased flexibility and decentralisation.

Various papers noted some fundamental concepts of Industry 4. The most frequently mentioned concept was CPS with 75% of papers noting CPS as a fundamental concept of Industry 4. 50% of the papers reviewed said that smart factory, self-organisation and new systems in logistics were amongst the fundamental concepts of Industry 4.

As with the fundamental concepts, the papers reviewed in the literature review did not agree on a single, but multiple, benefits of Industry 4 as seen in Fig. 4.3. Real-time decision making was one of the most frequently mentioned benefits of Industry 4.

Most papers identified how Industry 4 can benefit the organisation, e.g. by increased flexibility, productivity and quality. Moreover, the papers noted that Industry 4 can also benefit people, e.g. by improving the work conditions and substituting people with robots. As KPMG noted in 2017, the most significant value of Industry 4 comes from implementing emerging technologies[17]. Finally, the authors identified that Industry 4 can benefit industry by enabling prediction and improving decision making.

The opportunities noted in the papers are enabled by the emerging technologies and especially connectivity and data processing. Optimisation, for example, is a result of more data being accessible for the managers while better conditions for employees is a consequence of, for example, increased data on the employee, allowing for the work environment to be adapted to the employee. It is important to consider the effects those opportunities have on the organisation and not only consider the effects they have on the manufacturing, but on the organisation as well.

As for challenges associated with implementing Industry 4, the papers reviewed in the challenges section in the literature review (Subsection 3.7.2) noted a wide range of challenges (Fig. 4.3). The most frequently noted challenges were related to security and general challenges associated with emerging technologies.

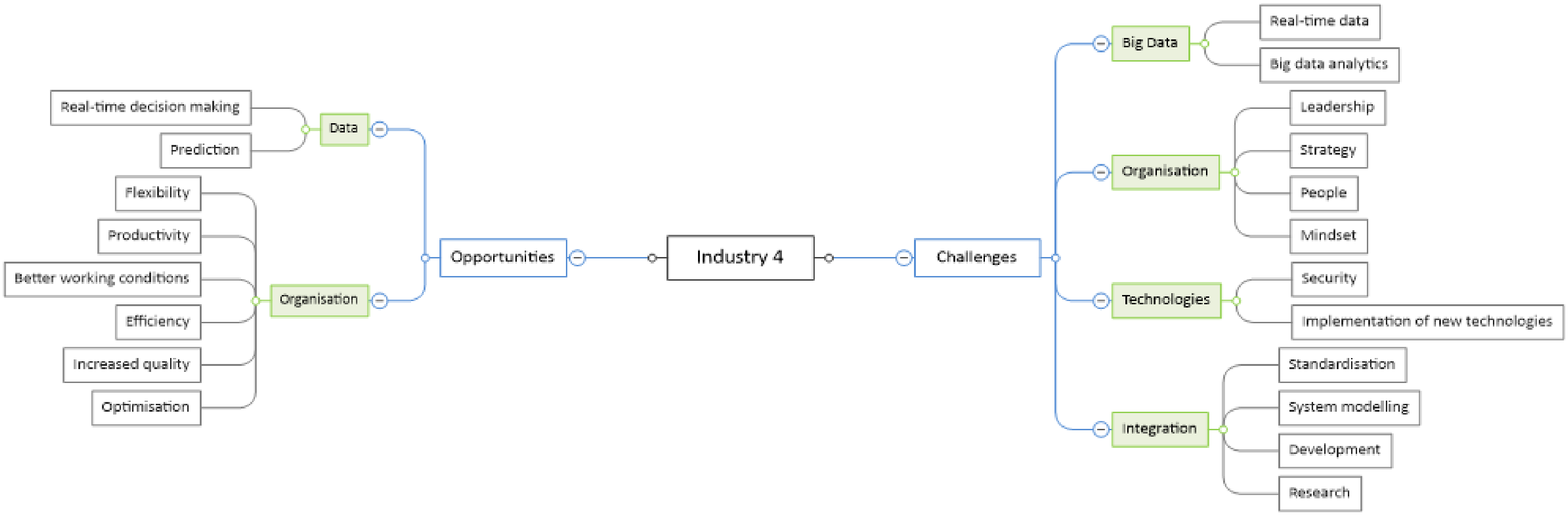

Figure 4.3: Benefits and challenges of Industry 4

Most of the challenges identified by the papers reviewed were related to technologies, e.g. automation, CPPS and development of smart devices. This remains in line with the fact that technologies are one of the main drivers of Industry 4. As expected, big data is a challenging factor for the implementation of Industry 4. Data integration, real-time data and big data analytics pose a challenge to companies adopting big data.

Many of the challenges were associated with industry, such as cost, lack of start-ups and poor adoption in organisations. Other challenges noted in this category were flexibility, standardisation and demand management. It was also noted that companies will face challenges associated with people, such as retraining the operators and changing the mindset of the employees and other stakeholders.

The emerging technologies have not widely been successfully implemented industry. Companies may therefore neither be aware of the best practices of implementing them nor know their capabilities. As noted above, companies face challenges with the mindset which also is part of the technology challenges.

It is apparent that Industry 4 poses a wide range of challenges upon organisations. That indicates that even though Industry 4 is enabled by emerging technologies, various of other factors need to be considered for the realisation of Industry 4 such as organisational and human factors.

4.2.3 Technology

The analysis of the technology section in the literature review revealed various views of which technologies are necessary for the implementation of Industry 4. Figure 4.4 illustrates the technologies noted in academic papers as the technological enablers for Industry 4. The sizes of the circles indicate the frequency of appearance of the technologies in the papers reviewed. Furthermore, each size of the circles has its own colour. The percentages of each technology indicate the percentage of papers noting that particular type of technology. As the papers frequently noted various technologies for the enabling of Industry 4, the percentages should not be added up. The same principles hold for Figures 4.5 and 4.6.

As seen in Figure 4.4, Big data was the most frequently mentioned technology, followed by IoT, then cloud computing and analytics. This indicates a comprehensive view of the usage of data within Industry 4 environments, that is

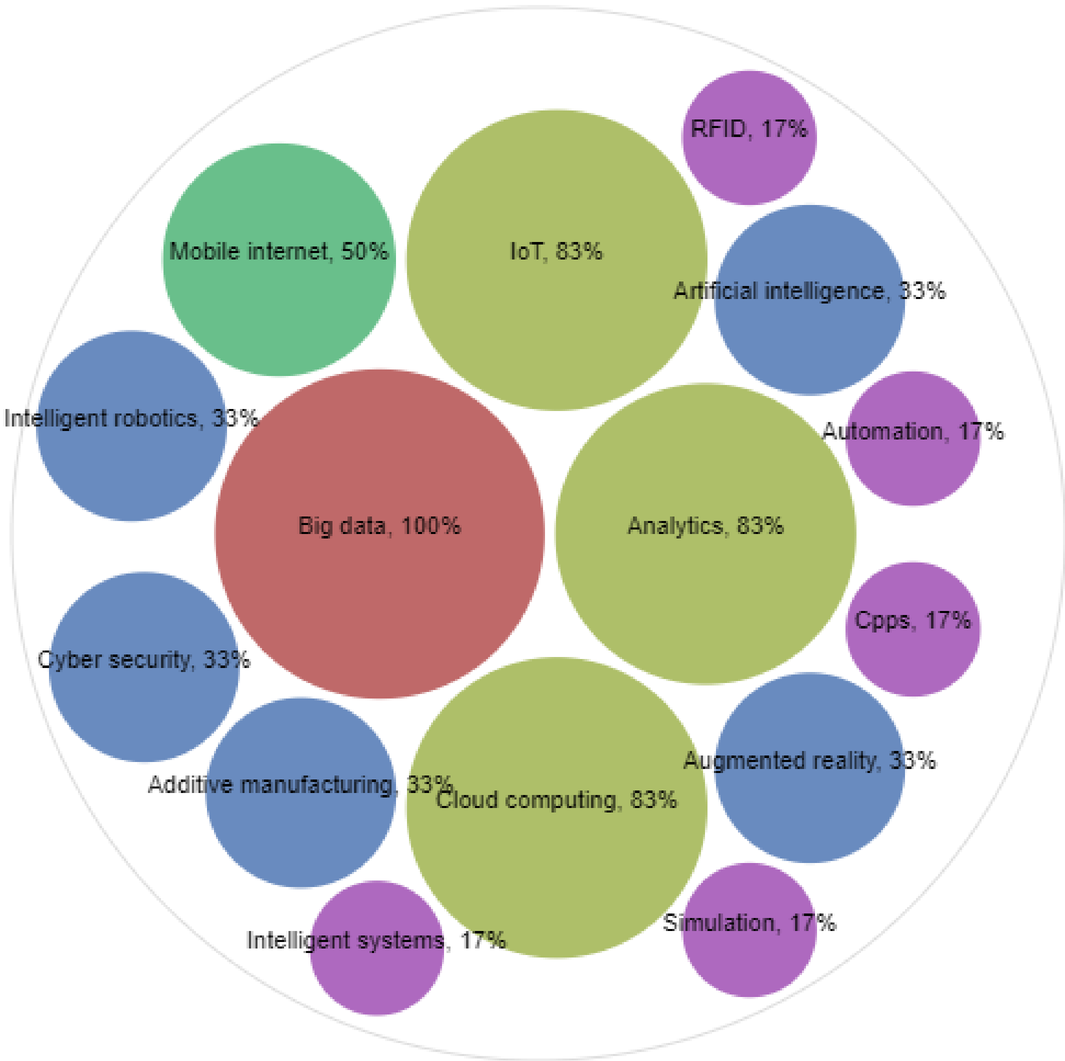

Figure 4.4: Most frequently mentioned technologies in academic papers (2011-2020)

the collection, analysis and storage of data. It is worth noting that cyber security ranks amongst the second least infrequently identified technologies even though the emphasis on data is high in the papers reviewed.

The technologies suggested in governmental agendas were also reviewed. Figure 4.5 shows the analysis of the technologies mentioned by governments in their initiatives for Industry 4.

Cloud computing, Big data, sensor, CPPS, AI and IoT were the most frequently mentioned technological enablers of Industry 4 in governmental reports across the world. There is more unity on which technologies are required, compared to the academic papers which is a contradiction to the findings of

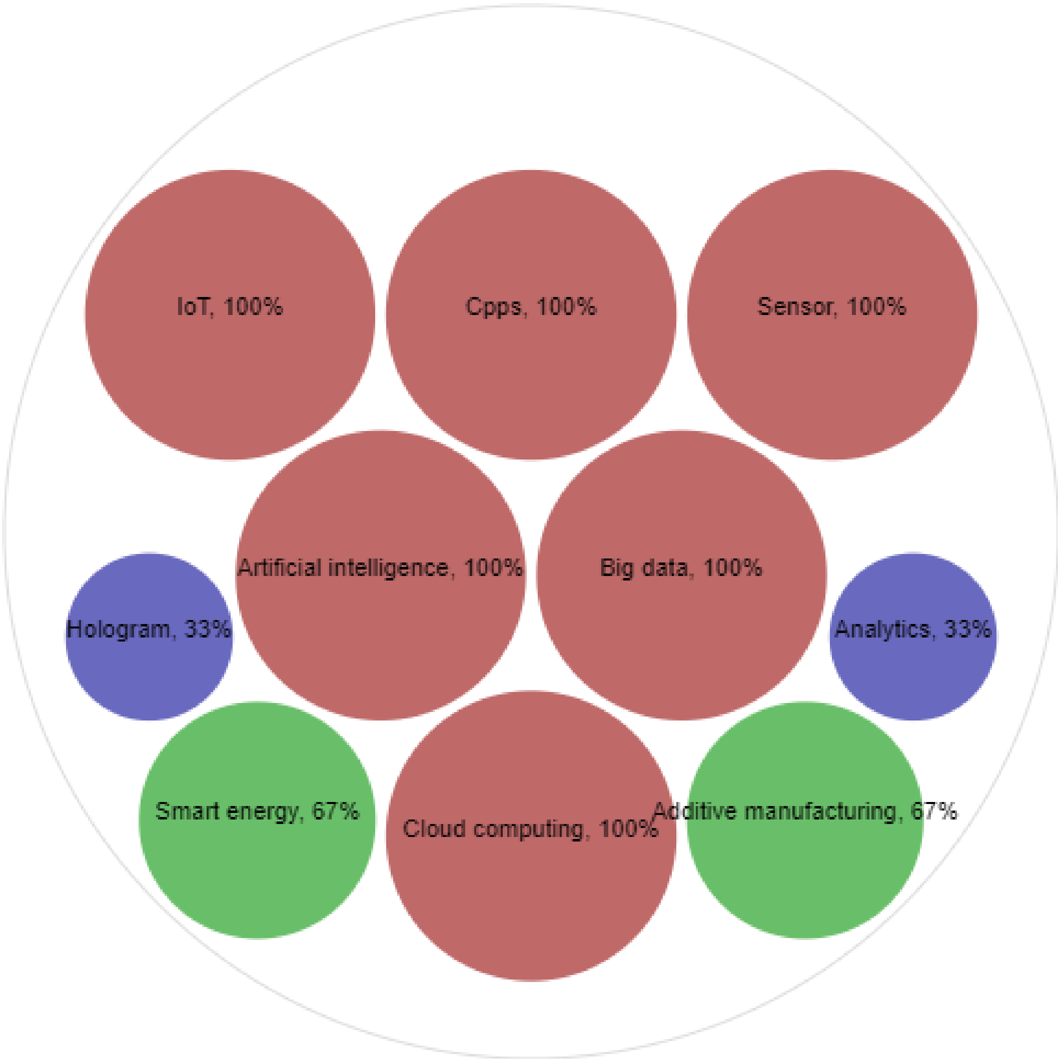

Figure 4.5: Most frequently mentioned technologies by governments

Castelo-Branco et al.[14] who noted that a shared understanding of Industry 4 had not yet been reached.

Figure 4.6 portrays the technologies noted as the key technological enabler for Industry 4 in industrial reports reviewed in the literature review. The analysis of the industrial reports revealed that additive manufacturing was the key technology enablers for Industry 4, followed by big data and analytics. This group was the only one out of the three groups that noted additive manufacturing as the key enabler as opposed to big data in the former two groups.

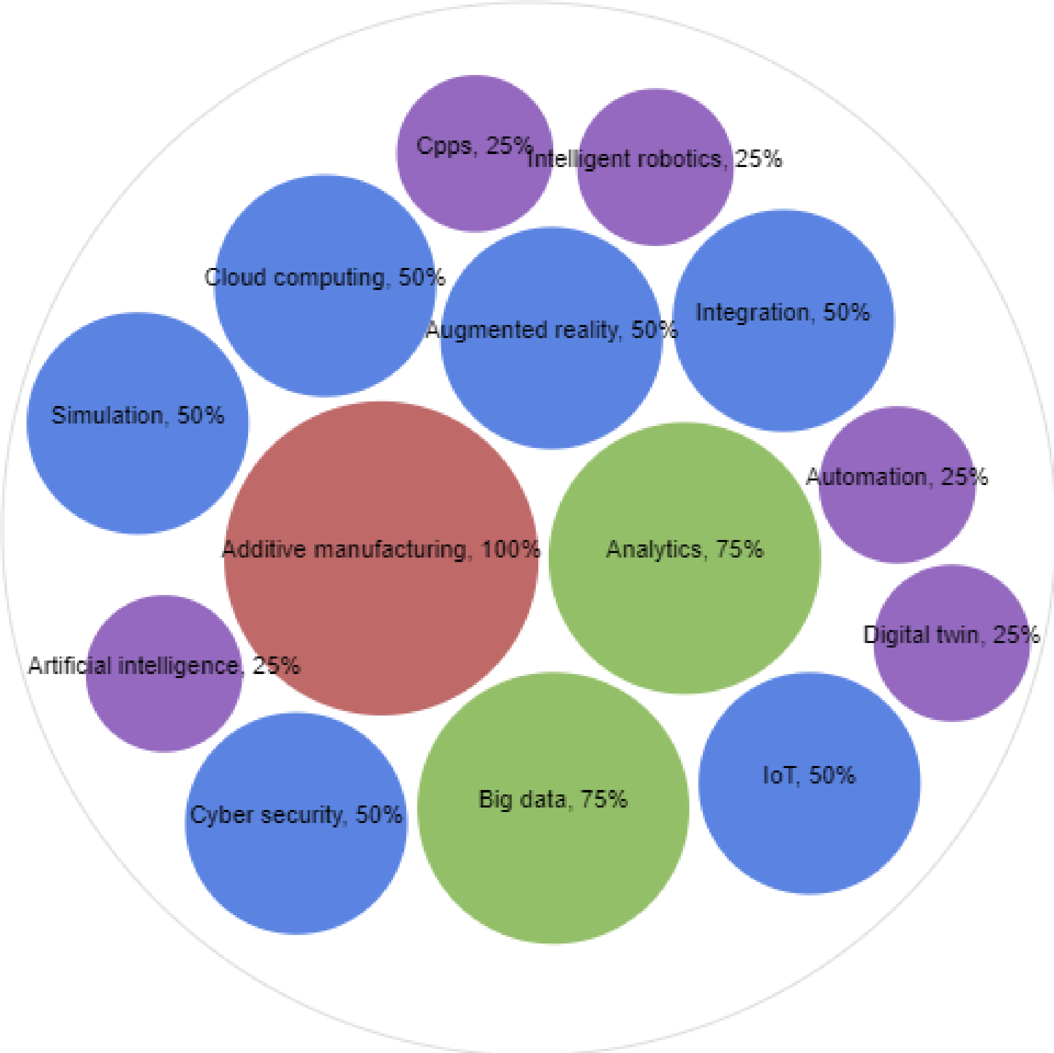

Figure 4.6: Most frequently mentioned technologies in industrial reports

The comparison of the three analyses against each other reveals that there is no apparent agreement on which technologies are required for the realisation of Industry 4. It is, however, apparent that big data plays an essential role in Industry 4 as it was the most frequently noted technology in both academic and governmental papers and the second most frequently mentioned technology enabler noted by industrial papers. Although big data ranks amongst the top it is worth noting that analytics is not amongst the most often noted technology in governmental agendas. IoT and cloud manufacturing are among the most often noted technologies in academic and governmental papers, however, those technologies are ranked in the third place among AR, simulation, cyber security and integration in industrial reports. Big data was, however, not the key enabler noted in the industrial reports which may explain why IoT and cloud computing are rated of lower importance in that group.

One of the most significant differences between academic papers and industrial reports was the difference in the importance of additive manufacturing. As previously stated, the industrial report put additive manufacturing forward as the key enabler whilst its importance in academic papers is lower. This might indicate a difference in the definition of Industry 4 between those two groups.

Based on the analysis and the comparative analysis of the technological enablers of Industry 4, the collection of data and data analytics is important for the realisation of Industry 4. As noted by all the groups, although their views of its importance differed, IoT was amongst one of the key technological enablers for Industry 4 as it enables data gathering. Cloud computing is, as stated in the literature review, one of the enablers of big data as it offers, for example, more computing power. It is, therefore, not surprising that it is among the most frequently noted technologies for Industry 4. Furthermore, that is in line with the increased decentralisation many authors noted as the key characteristic of Industry 4.

Even though the papers noted the importance of data and its related technologies, only a few papers noted Artificial intelligence as an enabler for Industry 4. Artificial intelligence technologies enable objects to become autonomous and enable them to make their own decisions which can result in a self-organised and reconfigurable system[187]. The lack of acknowledgement of Artificial intelligence is therefore not consistent with the notion of self-organisation as the key characteristics which 50% of the papers reviewed noted. Furthermore, automation ranked low amongst the technology enablers which also contradicts the notion that Industry 4 will lead to increased flexibility.

4.2.4 Framework analysis

In the framework section of the literature review (Section 3.5), a total of 20 different frameworks for Industry 4 or related initiatives were presented. The frameworks covered various aspects of Industry 4 such as the implementation of Industry 4, IoT, CPS, maturity of Industry 4 and maintenance as seen in Figure 4.7. It is worth noting that many of the frameworks focused on more than one theme.

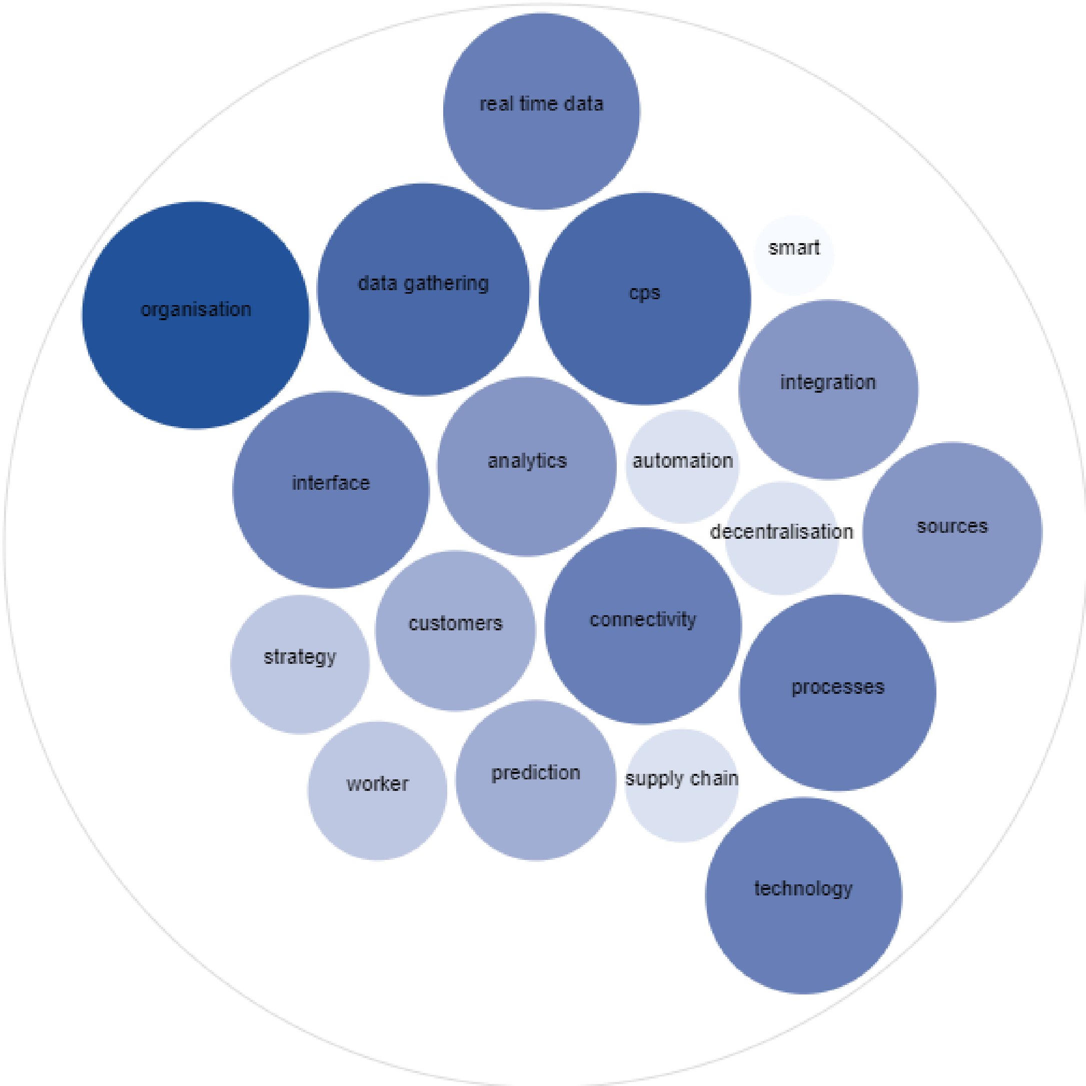

Figure 4.7: Most frequently noted themes in frameworks for Industry 4 from all papers in the literature review

Even though the frameworks addressed different aspects of Industry 4, they shared commonalities related to e.g. data, connectivity, organisations and technologies.

Organisation was the most frequent theme covered in the frameworks reviewed in the literature review. This emphasises the importance of the organisational part in the implementation process. 30% of the frameworks mentioned data gathering and CPS, followed by the terms real-time data, connectivity, technologies, interfaces and processes.

The frameworks mentioned the use of data, e.g. data gathering, analysis and real-time data. Chien et al.[12] used data in the framework that joins Industry

3 and 4 and Wan et al.[142] used big data analysis for preventative maintenance. Zhang et al.[136] developed a framework to improve data flow in a manufacturing setting which included data gathering and data analysis.

Connectivity was another common theme noted in the frameworks. Ferrera et al.[135] developed a framework where one of the four key elements was an IoT infrastructure and Chien et al.[12] proposed a framework to bridge the gap between Industry 4 and Industry 3 and part of that framework was related to IoT.

Table 4.1: Technologies in reviewed frameworks

Technologies	Percentage
Data	15%
IoT	7%
CPS	4%
Digital twin	1%
CPPS	1%
AR	1%
AM	1%

The majority of the frameworks reviewed in the literature review (Chapter 3) discussed the use of technologies as enablers for Industry 4. Table 4.1 shows the technological enablers for the frameworks. Technology was amongst the key elements in the methodology developed by Bucker et al.[13], the other two were organisations and humans. Choi et al.[78] developed a strategic plan for the implementation of a virtual factory and technologies were an important factor in that plan as it showed how to develop the relevant Industry 4 technologies for the execution of Industry 4. Other frameworks approached Industry 4 from a more technical point such as Masoni et al.[141] who used off-the-shelf technologies for remote maintenance and Lu et al.[79] who developed a framework for collaborative manufacturing using IoT.

As previously mentioned, the frameworks noted how Industry 4 uses data to improve maintenance. Other papers also mentioned how data can be used to improve processes as Romero et al.[138] and Shariatzadeh et al.[140] exhibited.

Even though Industry 4 is enabled by the emerging technologies, the analysis of the frameworks shows that it is important to consider the softer elements of Industry 4 as well, that is the organisational level as well as people. The frameworks also note the significance of including humans in the realisation of Industry 4. 20% of the frameworks mentioned customers and 15% of frameworks mentioned workers. That aligns with the HTO model which states that humans, technology and organisation should be considered both individually as well as interactively when new technologies are implemented[13].

As noted in the word count analysis, the term servitisation ranked amongst the top ten most frequently mentioned words in the papers reviewed. That was however not reflected in the frameworks. It is also interesting that the frameworks did not focus on decentralisation and supply chain which were amongst the key characteristics noted previously in this Section.

The analysis of the frameworks highlights the importance of data for the implementation of Industry 4 which is consistent with the technology analysis. It also shows the importance of technologies for the implementation of Industry 4. The technological themes in the frameworks more or less mirrored what was noted in the analysis of the technologies earlier in this section with connectivity and analytics ranking high. That indicates with the exception of CPS. CPS seemed to have more bearing in the frameworks than technology enablers indicated.

The analysis of the frameworks for the implementation of Industry 4 shows that multiple factors are necessary for the implementation. This indicates that even though the emerging technologies enable the realisation of Industry 4, other factors are needed as well. It also indicates that the technologies not only affect the manufacturing aspect of the business but can also be beneficial for the entire organisation.

Finally, even though Industry 4 is heavily linked with technologies, as both the analysis of this section as well as previous sections show, other factors need to be considered when Industry 4 is realised.

4.2.5 International initiative analysis

Seven Industry 4 related governmental initiatives were reviewed in Section 3.4. Those initiatives were from the governments of Singapore, the USA, Hong Kong, Netherlands, Germany, Japan and the United Kingdom. All the initiatives apart from the Japanese initiative focused on using the emerging technologies to strengthen the manufacturing industry whereas the focus in Japan is to create a smart society. That might indicate that different manufacturing cultures lead to different perception of Industry 4.

The strategies of those seven governments share similarities even though they differ as well. The key characteristic of the Japanese strategy is that people are the focal point, that is Japan has considered how the emerging technologies can improve the entire society. The other initiatives also discuss people but focus more on how Industry 4 can improve their work-life and the importance of education for Industry 4. The key people policies for the UK strategical plan for Industry 4 include technical education and retraining scheme and one of three pillars in the strategy of the US in securing the “talent pipeline” [127].

Singapore, Germany and Hong Kong all noted integration as part of their plan whereas the other four did not specifically mention integration. Part of Netherlands’s plan is to create a network of academic institutions and connected companies.

Other similarities are the focus on businesses, innovation and technologies. It is also worth noting the link between industry and academia in those strategies. The UK has set out the Grand challenges which bring industry and research together to improve the British industry. Part of Germany’s Industrie 4.0 strategy are two major research topics, that is a smart factory and smart manufacturing. This indicates that the main focus of Industry 4 and relevant initiatives is the implementation of new technologies to enhance the manufacturing sector.

Both Singapore and Hong Kong have developed frameworks and roadmaps to aid companies with the implementation. Those two countries were amongst the few countries that climbed up the World Economic Forum ranking in 2019. This might indicate that a formal structured approach is necessary for companies to implement Industry 4.

Those two frameworks share some similarities. Both note the importance of including the technology aspect as well as other aspects of Industry 4 in the implementation. They note the importance of the business aspect such as business objectives and strategy as well as the integration part of Industry 4. In addition to the implementation frameworks, Singapore and Hong Kong have also proposed models that focus on prioritisation and maturity, respectively. One of the elements in the Singaporean model is maturity.

From this, it can be inferred that a structured approach is required for the implementation of Industry 4. The approach should not only include the technology aspect but also the business aspect. Furthermore, different approaches may suit different organisations and different manufacturing cultures. As Berger[91] noted, different strategies lead to different results. They mapped the profitability of various countries against the asset turnover based on data from 2000 and 2014. The results of that analysis showed that countries that have made investments for their industries, like Germany and the US, have increased profits whereas countries that have under-invested suffer from shrunken profits[91]. It is therefore important for governments to invest in strategic transformations like Industry 4 to enhance their industries.

4.2.6 Case study analysis

Sixteen case studies from various industries were presented in Chapter 3. Although they were from different sectors, they share commonalities on the implementation of Industry 4.

Table 4.2 shows the reasons reviewed companies upgraded their factories and implemented new technologies and systems.

Table 4.2: Motivation for implementing Industry 4

Purpose	Percentage
Production issues	25%
Market needs	25%
Collect more data	13%
Security	13%
Cost	6%
Export	6%
New business model	6%
New factory	6%
Waste	6%

The main drivers for changes were to resolve manufacturing issues and to be able to meet market needs. Rexroth[6] was faced with manufacturing challenges caused by the variety of parts they make and used Industry 4 to solve their problem. Electric[155] wanted to reduce the frequent failures of the system they currently were using and Leica[156] were unable to detect and solve problems remotely. Other companies, such as Lamborghini, started their Industry 4 journey building a new factory which they built by having a strategy for the implementation of Industry 4.

The companies reviewed in the literature review used various enablers for the implementation of Industry 4 (Table 4.3)

Table 4.3 illustrates, the majority of the companies mentioned the use of data. Many companies reported faster decision making such as CISCO[5], Rexroth[6], World[144] which is a result of increased data. Some companies such as Leica[156] and Elekta[158] changed their products so that they can gather data from their

Table 4.3: Enabling technologies used in the reviewed industry cases

Enabler	Percentage
Data collection	94%
Integrator	75%
Real-time data	69%
Connectivity	63%
Analytics	25%
Automation	19%
Technologies	13%

products remotely while Whirlpool used the data for monitoring the factory floor[161].

The term real-time was mentioned by 75% of the companies, either in relation to checking the status of parts in real-time[5] or capturing data in real-time e.g. Electric[155] for monitoring of pipes, Rexroth[6] for faster decision making and Heidelberg[160] for monitoring their printers in real-time, allowing for predictive maintenance.

Another key element in which majority of the companies shared is connectivity. Leica[156], Elekta[158] and Heidelberg[160] used connectivity to remotely connect to their instruments. That allowed them to gather data, detect problems or maintain them remotely. GE[151] used WiFi-enabled tools that logged the data for quality control. CISCO[159] implemented connectivity on their factory site to increase productivity and allow for increased visibility. Hydro[152] implemented smart meters that enabled data collection to increase savings and efficiency by having an automated reading.

The integration and choice of technologies varied between companies as they were at different maturity levels before the implementation. Rolls-Royce was already collecting data so they focused on implementing a platform that analysed data in real-time. Other companies (such as Rexroth[6] and Electric[155]) did not collect data so they had to put the infrastructure in place to do so. Lamborghini and Harley Davidson used AGVs to move from typical, fixed manufacturing lines to more flexible manufacture[144,145]. CISCO[5] used tablets for the managers to monitor the shop floor and GE[151] equipped the workers with smart glasses, allowing them to go from paper-based work instructions to digital work instructions.

It is interesting to see that only 25% of the companies implemented data analytics and only 69% noted connectivity, even though 94% stated they collected data. This may either be caused due to the way the case was reported or because the companies did not analyse the data. Moreover, only 19% of the companies implemented automation. This may be driven by resistance of investing in robots due their cost and/or complexity. None of the case studies mentioned the use of cobots, however, a few companies implemented AGVs to transport goods in their factories.

The companies reported various benefits of the implementation of Industry 4 as seen in Table 4.4.

Table 4.4: Benefits of the implementation of Industry 4 in the reviewed industry cases

Results	Percentage
Manufacturing	63%
Finance	56%
Business	25%
Environment	19%
Predictive maintenance	19%
Remote control	19%
Security	19%

The main benefit of the implementation according to this analysis is for manufacturing. Within that group are increased efficiency, productivity and error detection. 56 % of the companies reported cost reduction, savings and increased net margin.

Although Industry 4 tends to focus on the technological aspect, it also affects the entire business as many of the case studies revealed. Procter and Gamble[157] included their employees from the very beginning of the implementation stage. Lukoil[154] recognised how dangerous it was for the company to train their employees at the rig so they moved the training facility on land and used the benefits of AR for training. Rexroth[6] made their new system user-friendly and flexible for the workers so that each workstation can be adjusted to the workers' needs. The companies also reported a need for higher-skilled workers[144] which is a consequence of the implementation of the Industry 4 technologies.

Table 4.5 maps the technologies used for the implementation against the benefits the companies reported. According to the analysis, connectivity brings the most significant overall benefits with the biggest impact on manufacturing. That is in line with what was stated above, i.e. manufacturing benefited the most from the implementation (Table 4.4).

Table 4.5: Benefits of the implementation of technologies in reviewed case studies

	Analytics	Automation	Connectivity	Integrator	Real-time data	Technologies
Business	0.00	0.33	0.30	0.25	0.18	0.50
Environment	0.25	0.33	0.10	0.25	0.18	0.00
Finance	0.50	1.00	0.50	0.58	0.55	0.50
Manufacturing	0.50	0.33	0.70	0.67	0.64	0.50
Predictive maintenance	0.25	0.00	0.20	0.25	0.18	0.00
Remote control	0.00	0.33	0.30	0.25	0.18	0.00
Security	0.25	0.33	0.10	0.08	0.27	0.00

Table 4.6: Comparison on technology enablers

	Analytics	Automation	Connectivity	Integrator	Real-time data	Technologies
Analytics		0.00	0.50	0.75	0.75	0.00
Automation	0.00		0.67	0.67	1.00	0.00
Connectivity	0.50	0.67		0.70	0.60	0.10
Integrator	0.75	0.67	0.70		0.67	0.08
Real-time data	0.75	1.00	0.60	0.67		0.00
Technologies	0.00	0.00	0.10	0.08	0.00	

Table 4.6 shows the correlation between different technologies that the companies chose for the implementation. Most companies, or 75% of the companies, implemented real-time data collection along with data analytics.

4.2.7 Section summary

In this section, the analysis of each section of the literature review is presented. A word count analysis was performed by the analysis software NVivo. The analysis illustrated that manufacturing, industry, system and data were the most frequently used words in the reviewed papers. It showed that technologies are an important aspect of Industry 4 and indicated that they should be implemented in a system. It also revealed that even though the technological aspect of Industry 4 is a fundamental aspect, other aspects must be considered as well, such as the organisational aspect as well as the human factor.

The analysis of the sections revealed the importance of data within Industry 4. It moreover showed that connectivity and emerging technologies are an important part of Industry 4. The analysis also showed that even though the main focus of Industry 4 is on manufacturing, it affects the entire organisation.

4.3 Clusters of Industry 4

Even though there is a lack of consensus in the field of Industry 4 as the analysis of the literature review revealed, there are certain themes that can be identified. The analysis of each section was clustered into the following themes that are within the scope of this Thesis:

- Data
- Technologies
- Connectivity
- Business
- Manufacturing

Within each theme, elements have additionally been identified. The elements will be introduced in this section, however, a detailed discussion on each element is presented in the following chapter. The elements identified feed directly to the theorems of the rule base presented in Chapter 5.

4.3.1 Data

Data was identified as a theme as it was one of the most frequently cited technology in the sections reviewed. Furthermore, it was the fourth most frequently noted word in the word count analysis. Data was the key technology enabler noted by two out of three groups in the technology section and was ranked second in the industrial reports. When analysing the key technologies implemented in the case studies, data was used by 94% of the companies. Finally, the most frequently noted challenges and opportunities for Industry 4 were linked to data and data analytics. The papers did not mention data directly, however, they noted real-time decision making and prediction which is a result of data and data analytics.

4.3.2 Connectivity

Connectivity is an important enabler of Industry 4 as revealed by the analysis. All the governmental agendas reviewed in the literature review noted IoT as a key technology enabler. Academic papers and industrial reports also mentioned IoT, 83% and 50 %, respectively. Connectivity was the companies reviewed in the case studies. It is worth mentioning that 94% of the case studies noted data collection but only 63% of the companies noted connectivity. Furthermore, 60% of the companies that implemented connectivity, used real-time data. As noted in the analysis of the case study, the information provided in the case study was sparse so the ratio in reality may be higher than shown in this analysis.

4.3.3 Technologies

Technologies were another theme noted in the analysis. For this analysis, technologies such as cloud computing, AR and automation were grouped. The clustering aims to identify the high-level themes rather than identify the key technologies of Industry 4. As with data, the word technology ranked high in the word count analysis (5th most frequently mentioned word).

4.3.4 Manufacturing

Manufacturing is the fourth theme that was identified in the analysis. That theme differs from the previous two in the sense that it is more implicit in the analysis than the other two. However, it was the most frequently used word in the papers reviewed according to the word count analysis. The challenges and opportunities focused on the manufacturing industry, noting increased flexibility (25% of the papers) and better working conditions for workers (25% of papers). 50% of the companies reviewed in the case study sections were in the manufacturing industry. However, many of the other companies such as in the automation and aviation also manufacture products. Manufacturing was, therefore, identified as the fourth theme which aligns with the original scope of Industrie 4.0.

4.3.5 Business

Industry 4 does not only affect the manufacturing, it also affects the whole company as the analysis of the literature showed. The fourth theme identified is, therefore, business. 37% of the papers reviewed in the challenge section noted challenges related to business specifically. Among the challenges they noted were related to leadership, mindset, strategy and loss of jobs. 50% of the papers reviewed in the opportunity section noted the business-specific impact such as increased optimisation, competitiveness and quality.

4.4 Summary

This chapter presents the analysis of literature reviewed in Chapter 3 and addresses Objectives 1a-c which is to identify key characteristics of Industry 4. Section 4.2 provides an analysis of each section of the literature as well as word analysis of the papers reviewed in the literature. Section 4.3 presents clustering of the analysis and identifies commonalities between different sections of the literature review. The section furthermore presents the themes and elements of Industry 4. Those themes are big data, connectivity, technologies, business and legacy factories and were identified in the previous section. It is worth noting that those themes do not provide a complete overview of the themes of Industry 4, only the themes that were within the scope of this Thesis.

The analysis of the literature review is the foundation for the rule base (Objective 2b) presented in Chapter 5.

Chapter 5

Rule Base for Industry 4

5.1 Introduction

Industry 4 is already being realised by multiple companies. Many companies are, however, struggling with implementing Industry 4, as various surveys noted in the literature review. One of the reasons, as outlined in the previous chapters, is the lack of clarity and direction. This chapter aims to establish a structured and purely formal logical way to guide industry through an objective and prescriptive approach and highlight the key characteristics of Industry 4. This chapter addresses Objective 2b, which is to establish the dependencies between the characteristics of Industry 4. Moreover, Objective 3a is addressed, which is the development of a system that enables automatic inference of the framework.

As outlined in Chapter 2, the rule base, that will be introduced in this Chapter, is based on the analysis of the literature review, as well as the case studies of successful Industry 4 implementations, conducted in Chapter 3. The rule base is constructed from axioms, theorems, lemmas, proofs and definitions. The axioms describe the core of Industry 4. The theorems in the rule base are based on the axioms and their derived theorems and can be grouped into five themes that were identified in the analysis. These themes are legacy factories, data, technology, connectivity and business.

This chapter is structured as follows: Section 5.2 explains the structure of the rule base, its components and the themes covered in the rule base. Section 5.3 introduces the rule base itself, which is composed of axioms, definitions, theorems and proofs. Furthermore, it provides an explanation and rationale for each theorem (referred to as the bridge in Figure 5.1). The bridge is based on literature review and its analysis and bridges the gap between those two chapters

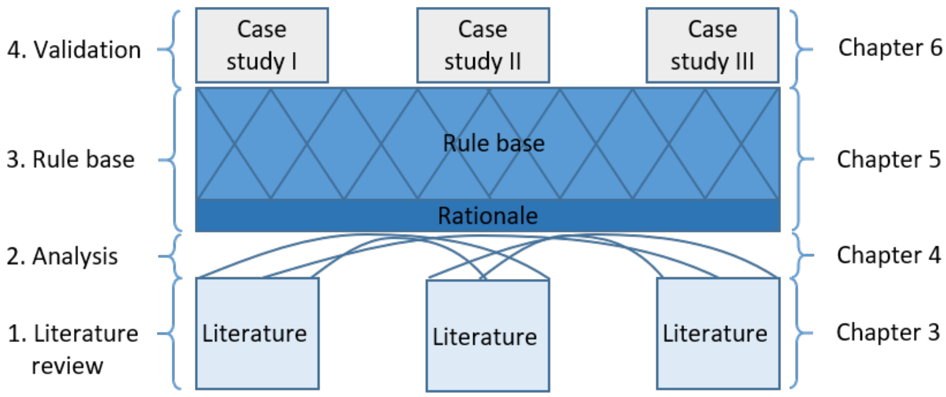

Figure 5.1: Overview of the Thesis

and the rule base. The expert system developed from the rule base is presented in Section 5.3. Finally, Section 5.5 provides a summary of the chapter.

The validation of the rule base is presented in Chapter 6. It was validated by performing three industrial case studies and academic expert validation. The development of the rule base is furthermore presented in the next chapter.

5.2 Overview of the rule base

In this section, the structure of the rule base will be explained and the theorems within each theme introduced. Subsection 5.2.1 explains the terminology used in the rule base. Subsection 5.2.2 provides an overview of the rule base and its themes. It furthermore presents the theorems within each theme and shows how they are interconnected. Subsection 5.2.3 gives an overview of the themes and their elements. Subsection 5.2.4 describes the origins of the axioms and theorems. Finally, a brief summary of the section is provided in Subsection 5.2.5.

5.2.1 Terminology

This section aims to explain the terminology used in the rule base. The terms universe, axiom, theorem, proof and definition, will be defined in this section.

Universe

The term *universe* exists in various disciplines such as astrology and philosophy. In philosophy, the term *universe of discourse* is used to discuss a class of fixed entities. As the research presented in this Thesis is in the field of engineering, the term is not fully embraced and only used to collectively describe Industry 4 solutions that can be tested, or generated, by the rule base.

Axioms

Encyclopedia of Britannica[188] defines an axiom as: "an indemonstrable first principle, rule, or maxim, that has found general acceptance or is thought worthy of common acceptance whether by virtue of a claim to intrinsic merit or on the basis of an appeal to self-evidence"[188].

In this Thesis, the axioms present the key elements of Industry 4 and were identified through the analysis in Chapter 4 of the literature review in Chapter 3. The axioms are the foundation of the entire rule base by which all the theorems are derived from. Subsection 5.3.1 provides a further justification and explanation of the axioms.

Theorems and lemmas

A theorem can be defined as a proven statement[189]. The rule base has 21 theorems and three lemmas[1] which are derived from the axioms, literature and definitions. The theorems and lemmas cover the Industry 4 space within a legacy factory, however, many of them can be applied in other settings as well. The theorems and lemmas fall into five main themes: data, connectivity, technologies, organisations and legacy factories which, as previously stated, were identified in the analysis of the literature review. Those themes constitute the scope of this research. The theorems and lemmas originate from the literature review as well as the author's interpretation.

Proofs

A proof can be defined as reasoning that demonstrates the validity of a statement[190]. The proofs for the theorems are proven by using two different approaches. The first part of the theorems are proven by applying first-order logic, as discussed in the literature review (Chapter 3). The rest of the theorems are proven by reasoning, based on literature and theorems in the rule base. This approach was adopted as the this research aims to answer whether Industry 4 can be modelled with formal logic for the implementation of Industry 4. By arguing the first part of the theorems in a formal logical way, that objective is

[1] The plural "lemmas" will be used instead of the equal alternative "lemmata".

fulfilled. The latter parts of the theorems will be reasoned in a formal logical way without using first-order logic for the reason stated previously as well as this research does not focus on pure logic, rather how it can be applied. The reasoning-based theorems could also be established by first-order logic, however, that would obscure the higher-level insight of these theorems.

Definitions

The purpose of the definitions is to explain further terms that are not commonly known or used in a specific way in this rule base. The definitions are derived from standards and literature. Some definitions are directly derived from standards while others use the combination of previously defined terms. Common terms are not defined in the rule base, refer to the glossary for common term (Page xii).

5.2.2 Structure of the rule base

The rule base is composed of axioms, theorems and lemmas as seen in Figure 5.2. The figure shows the interconnection between the axioms, theorems and lemma (Subsection 5.2.1 provides an explanation of the terminology) but does not contain the proofs (the rule base itself is presented in Section 5.3). The interconnection is derived from the proofs, that is the items within the rule base that the respective proofs are cited.

A colour code for the figure can be found in the bottom left corner of the figure. The output from each box was grouped together to minimise the number of lines in the figure. That causes a difference in thickness of lines. That difference is not of any significance to the figure other than it is thicker for boxes that have many outputs and thinner for boxes that have a few outputs.

The figure should be read from top to bottom, however, it is not a flow diagram even though it shares similarities. The axioms are on top as they are the foundation of the rule base.

The order of the Theorems within the rule base is based on their level of abstraction. The initial Theorems are elementary components of the rule base and provide a basis for the latter Theorems. They are proved using formal logic. They are followed by Theorems with an increased level of abstraction but are still proofed using formal logic. The level of abstraction increases towards the end of the rule base and those Theorems are still argued using formal logic, however, they are too complex for long formal proofs.

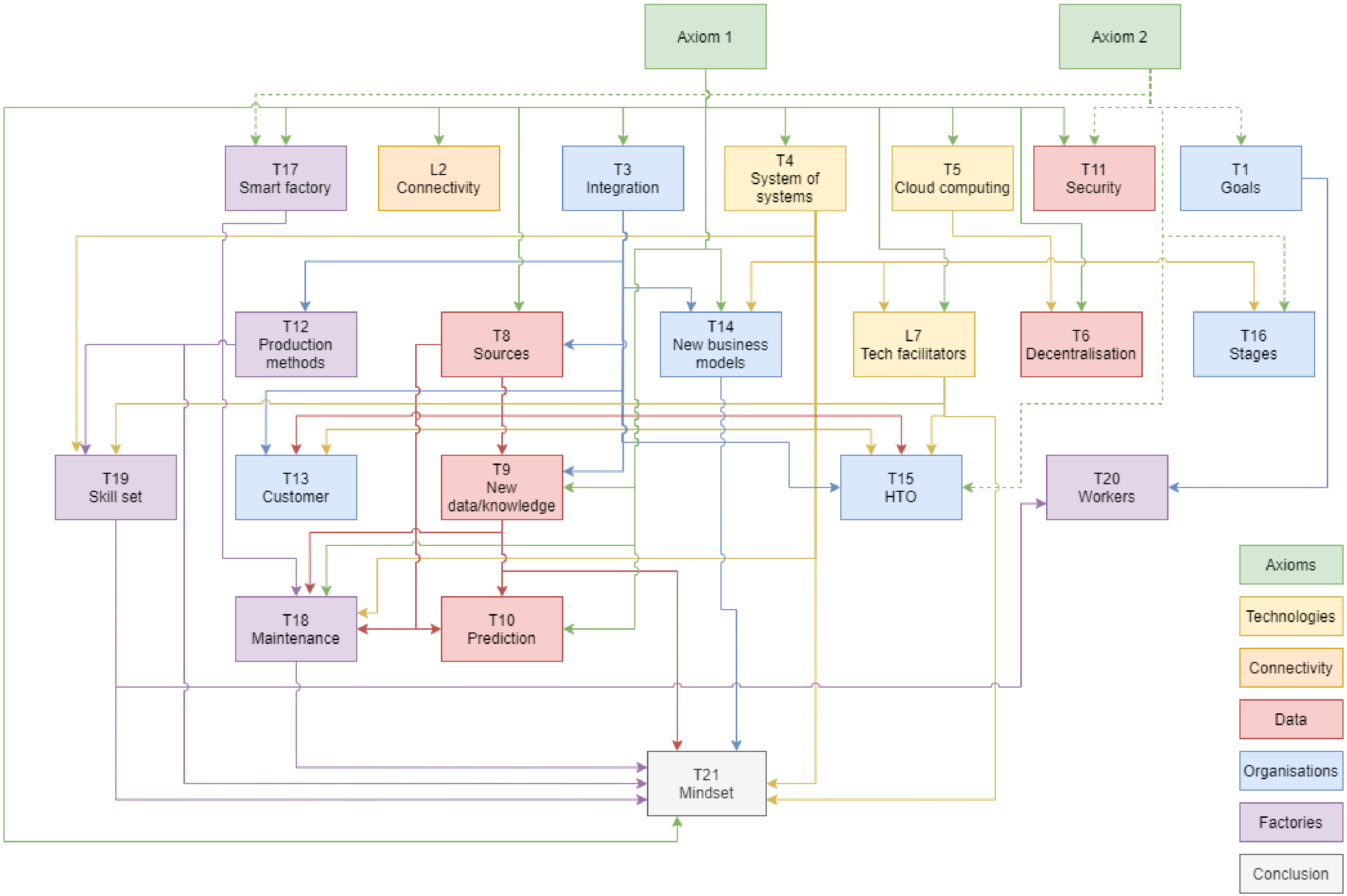

Figure 5.2: Overview of the rule base

5.2.3 Rule base themes

The elements of each theme will be introduced in this subsection. For further explanation of each element, see Subsection 5.3.2 which gives a thorough rational and explanation of each item.

Data theorems

The data theme consists of five theorem as seen in Fig. 5.2, shown in red in the figure. Data related theorems cover various aspects of data within Industry 4. These elements are:

- decentralisation of data
- data sources
- new knowledge[2]
- data prediction
- data security

All of which were identified in the analysis (Chapter 4). Below is a brief rationale for the identified elements. More detail is provided in Section 5.3.

Decentralisation was one of the key characteristics identified in the analysis of the literature (Subsection 4.2.2). Data sources was a derived theme from the literature analysis. The analysis showed the importance of data (word count analysis Subsection 4.2.1 and technology analysis Subsection 4.2.3). Furthermore, it was noted in the literature review by Khan et al.[98] that Industry 4 requires data from multiple sources. Security was amongst the most frequently noted words in the word count analysis (Subsection 4.2.1). It also frequently mentioned as an implementation challenge (Subsection 4.2.2).

Factory theorems

There are six theorems in the factory theme which address Industry 4 with regards to a factory setting. They can be divided into three subgroups:

- workforce
- equipment
- manufacturing

Fig. 5.2 shows the factory theorems in a purple colour.

[2]Knowledge is interpreted as a type of data as it is derived from data

The theorems in the factory theme are as follows: new production methods, smart factories, workers, skill set and maintenance.

Organisational theorems

The organisational theorems address the points in the Industry 4 space that relate directly to businesses and organisations.

The organisational theorems are five as seen in Fig. 5.2 (shown in a blue colour) and cover the following topics:

- goals and strategy
- 3-way integration
- customers
- new business models
- implementation approaches

The importance of developing an implementation strategy for Industry 4 was highlighted in the analysis of the international initiatives and case studies (Subsections 4.2.5 and 4.2.6. The three-way integration was not mentioned in analysis, however, it was discussed in details in the literature review, Chapter 3. Customers were noted as a theme in 20% of the case studies as noted in Subsection 4.2.6 of the analysis. New business models were noted in the word count analysis (Subsection 4.2.1) and in the the analysis of the case studies (Subsection 4.2.6). The implementation of Industry 4 was a common theme throughout the analysis of the literature.

Connectivity theorems

There is one connectivity theorem in the rule base (Fig. 5.2), shown in an orange colour. The connectivity theorem considers data flow within Industry 4.

Technology theorems

The technology theorems cover Industry 4 technologies on a high level (Fig. 5.2, yellow-coloured boxes).

The technology theorems address the following elements:

- system of systems
- cloud computing

- interfaces

Cloud computing was amongst the most frequently mentioned words in the word count analysis (Subsection 4.2.1) and it was amongst the most frequently noted technology enabler in the technology analysis (Subsection 4.2.3). Interfaces were noted as a theme in the technology analysis.

Conclusion theorem

The conclusion of the rule base is one theorem which states that Industry 4 requires a new mindset (Fig. 5.2).

It is important to note that even though this is the conclusion theorem of the rule base, the rule base has a scope to be expanded upon by incorporating factors of Industry 4 that are outside the scope of this research.

5.2.4 Origin of theorems

The origin of the theorems presented in this rule base is twofold, from analysis and the author's interpretation of the literature review and analysis.

The theorems from the analysis of the literature review are:

- Business goals
- Cloud computing
- Decentralisation of data
- Data prediction
- Data security
- Production methods

The theorems based on the author's interpretation of the literature reviewed are:

- Connectivity
- Three-way integration
- Recursive system
- Technology enablers
- Data sources
- New knowledge
- Customer role
- New business models
- Factors for the implementation of Industry 4
- Staged implementation of Industry 4

- Smart factory
- Skills gap
- Workers
- Maintenance
- Mindset

5.2.5 Section summary

The purpose of this Section was to provide an overview of the rule base to explain its structure and terminology. The rule base has five main components, axioms, theorems, lemmas, proofs and definitions, which were derived from the literature review (Chapter 3) and literature analysis (Chapter 4). Subsection 5.2.1 provides an overview of the terminology used in the rule base. Subsection 5.2.2 presents the structure of the rule base. The theorems, which are explained in Subsection 5.2.3, are based on the axioms, which were derived from the literature review. The theorems of the rule base can be divided into five groups, that is data, connectivity, manufacturing, business and technology. Those categories were derived from the analysis presented in Chapter 4. Finally, Subsection 5.2.4 provides a brief overview of the origin of the Theorems in the rule base. More details on the elements of the rule base are provided in the next Section which presents the rule base.

5.3 Formal logical rule base for Industry 4

This section presents the rule base, which addresses Objective 2b, to establish dependencies between the key characteristics. The section is structured as follows: Subsection 5.3.1 presents the axioms and related definitions as well as their rationale. Subsection 5.3.2 introduces the theorems, proofs and relevant definitions. Each theorem is provided with rationale which is based upon academic literature and industry based knowledge sources. The theorem is then presented along with its proof, followed by commentary on the theorem. Finally, Subsection 5.3.3 provides a summary. Refer to Appendix B for a fold-out list of the axioms, theorems and lemmas.

5.3.1 Axioms of Industry 4

This subsection presents the axioms of Industry 4 and the definitions associated with the axioms. The definitions clarify the terms used by the axioms and are therefore presented before the axioms.

Advanced data analytics

Advanced data analytics is the use of advanced technologies[3] to gather and analyse data in real-time. That is derived from the analysis in Section 4.2 where it was identified that analysis is important for Industry 4. 25% of the companies reviewed in Chapter 3 used data analytics as part of their Industry 4 implementation. The literature analysis furthermore suggests that data analysis is one of the most important technologies for Industry 4. The real-time aspect is important as it distinguishes Industry 4 from its predecessors, as discussed in the literature review[4].

Definition 1. *Advanced data analytics* is the use of technologies to gather and analyse data in real time.

Building blocks

The second definition states that Industry 4 is made up of *building blocks*. Building blocks are commonly used to describe sub-elements that make up a system. Desfray and Raymond[192] defined the term "building block" as: "the essential components of the architecture that constitute its skeleton"[192]. A building block will be used in this Thesis to describe the basic components of Industry 4. An example of a building block is, e.g. an RFID tag. This definition is needed as the second objective of this Thesis is to establish whether Industry 4 can be structured with mathematical reasoning.

Definition 2. A *building block* is a basic component that makes up Industry 4 within an industrial context.

[3] Advanced technology can be defined as: "a technology that is still immature but promises to deliver significant value, or that has some technical maturity but still has relatively few users. Among current examples: artificial intelligence, agents, speech and handwriting recognition, virtual reality and 3D visualization"[191]

[4] In this Thesis *real-time* refers to an immediate response of a system.

Interface

This definition states that an *interface* is a shared boundary between two, or more, building blocks in either, or both, the virtual and physical world. An example of a physical interface is a display unit that shows data (virtual world) to a human (physical world). Interfaces are enablers for integration.

Definition 3. An *interface* is a shared boundary between two or more building blocks in either, or both, the virtual and physical world.

Integration

Definition 4 states that *integration* is the act of connecting two or more building blocks. According to the Cambridge dictionary, "integration" is the act of combining one thing with another to form a unit [193]. In this Thesis, a unit equals a building block. As the analysis (Chapter 4) revealed, integration is critical for Industry 4. Integration will be discussed in this chapter in more detail.

Definition 4. *Integration* is the act of connecting two, or more, building blocks.

System

Definition 5 states that two or more building blocks integrated by an interface in a way that data can flow between them are called a *system*. There are many definitions of systems but systems are commonly defined as a set of interrelated components that collaborate towards a common objective [194]. The components of the systems in this Thesis are building blocks, as described above as they are the components of Industry 4.

Definition 5. Two or more building blocks integrated by an interface so that data can flow through them are called a *system*.

Connectivity

Definition 6 states that if data can be shared between systems, industry is said to be *connected*. Generally speaking, the verb to "connect" means to join together two entities. In an Industry 4 context, that definition of the term applies as well, however, it has a more specific meaning. When objects are connected in an Industry 4 context, the objects can share data, either in one or both directions. Connectivity plays a vital role in Industry 4 but it relates to one of two focus points of Germany's Industry 4 that is connected manufacturing facilities [2]. Connectivity was also one of the major themes identified in the analysis chapter (Chapter 4).

Definition 6. Industry is said to be *connected* if data can be shared between systems.

Axiom 1 (Data-driven industry). *Industry 4 is principally characterised by advanced data analytics within connected data-driven industry.*

For the purpose of this Thesis, Axiom 1 states that a key characteristic of Industry 4 is advanced data analytics within connected data-driven industries for improving competitiveness. That means that industries that adopt Industry 4 must be connected, gather data and process data. The axiom is the basis for developing the best practices for Industry 4, focusing on connectivity and advanced data analytics. The solution can be of any size, i.e. it can be a sub-solution or a solution for the entire organisation. This section will explain the axiom with references to the literature and literary analysis.

One of the most noted fundamental theme of Industry 4 was data (Chapter 4). As the analysis revealed, data needs to be gathered in Industry 4. Unlike its predecessors, Industry 4 gathers data in real-time and moreover, it analyses data and uses data to improve processes (see Industry 4 and related terms, Section 3.2. Many of the key benefits of Industry 4 are, therefore, directly linked to data and data analysis, such as process optimisation and increased flexibility and agility. The analysis of the case studies furthermore revealed that 88% of the companies gathered real-time data after implementing Industry 4 (see Case study analysis, Subsection 4.2.6). One of the most frequently mentioned benefits of Industry 4 according to the analysis (Chapter 4) is real-time decision making for improved competitiveness. To enable real-time decision making, real-time data is needed, among other factors. Zheng et al. [60] also noted that real-time data collection is necessary for most manufacturing companies.

The literature explained, for example, how cloud computing acts as an enabler for Big data as Big data requires more computing power than typical computers can offer. It is important to note though that the right data must be gathered, that is, data is purposefully gathered. Advanced data analytics, therefore, refers to using advanced technologies, such as Cloud computing and IoT, to process the data. As noted in the analysis (Chapter 4), 75% of the papers mentioned Big data analysis. It was furthermore pointed out as being one of the key technologies for Industry 4. Big data analysis was also one of the challenges pointed out in the analysis (Chapter 4), which indicates that analysis is an essential part of Industry 4. Although 94% of the case studies reviewed noted that data collection was an enabling factor, only 25% of the case studies stated that data analytics was an enabling factor. That might indicate that a low maturity level of the reviewed case studies.

To gather data for Industry 4, industry needs to be connected. Connectivity was amongst one of the themes noted in the analysis (Sec. 4.3). Connectivity is also one of the key commonalities that the case studies shared.

IoT was the second most frequently mentioned technology related to Industry 4. IoT aims to bridge the gap between the virtual and physical world and enable the transfer of data between things[104]. IoT is an enabling technology for Industry 4 that establishes connectivity.

Industry 4 does not only gather and analyse data, it also uses data to impact decision making and processes to improve productivity. It was a common theme across the analysis of the literature that within Industry 4, context data is a driver for decision making.

Axiom 2 (Improves competitiveness). *A principal characteristic of Industry 4 is its intend and ability to improve company competitiveness.*

The second Industry 4 axiom states that Industry 4 improves companies' competitiveness. Industry 4 will have positive effects on the companies that implement Industry 4 as the analysis revealed. This axiom will be defined in this section with references to the literature and its analysis.

The analysis of the case studies presented in the literature review (Subsection 4.2.6) revealed that all the companies noted positive effects of the implementation of Industry 4. Amongst the benefits they noted were decreased cost, increased productivity and efficiency and better decision making.

The papers reviewed noted various opportunities and benefits associated with Industry 4. Those benefits were similar to the capabilities the companies reported such as increased productivity and faster decision making. Even though the papers did not agree on the benefits of Industry 4, it was apparent that Industry 4 has the potential of benefiting companies in many ways.

Technologies of Industry 4 furthermore aim to help companies. With the increasing amount of data that comes with Industry 4 and decentralisation of data, the importance of cyber security becomes transparent. That was also highlighted by the papers in the technology section, which noted cyber security as one of the key technology enablers for Industry 4.

The initial Industrie 4.0 initiative was created by Germany to boost the German manufacturing industry[2]. Other governmental initiatives have similar agendas. The Japanese initiative, Society 5, even goes further to enhance the entire society in Japan[19].

As noted in the literature review, many challenges are associated with Industry 4. These challenges are linked to the organisational aspect such as leadership and the need for a strategy as well as challenges associated with various technical aspects related to data, implementation of new technologies and security. That does not necessarily mean that Industry 4 will not benefit companies, it will, however, come with challenges which may pose potential risks to the implementation. Companies will, therefore, need to consider that risk and weigh it up against the benefits of a correction implementation of Industry 4. The risk of implementing Industry 4 will not be further discussed as it is not within the scope of this Thesis.

5.3.2 Theorems

Business goals

Theorem 1 states that business goals and strategy need to align with Industry 4. That was apparent in the case studies reviewed in the literature review as all the companies implemented Industry 4 to accomplish their business goals. Lukoil, for example, aimed to increase exports from a certain facility and used Industry 4 technologies to achieve that goal[153]. Another example comes from the automotive industry. Harley Davidson was facing troubles after the financial crisis. To recover from the crisis they were facing, they updated their factory, using Industry 4 thinking, making the factory more connected and data-driven[144]. Lambert[157] gathered successful implementations of Industry 4 and one of the key things the companies shared was a strategic plan for the adaption. Schumacher et al.[130] identified 9 dimensions of Industry 4 and was strategy one of them.

Even though many authors did not identify goal setting in the literature review, it was identified as a commonality amongst the companies implementing Industry 4 as previously stated. It was noted as a challenge by 7% of the papers reviewed. Business goals and strategy are important for businesses as Locke[195] noted and since it was a common thread for the companies reviewed in Chapter 3, Theorem 1 is needed.

Theorem 1 is built on Axiom 1 and is the first theorem as the rule base covers the elements that are needed to implement Industry 4 in factories.

Theorem 1. *Business goals and strategy need to align with Industry 4.*

Assumption: $\forall x\ Axiom2(x) \rightarrow Goals(x)$
Proof.

1.	$\forall x\ Axiom2(x) \rightarrow HelpsCompanies(x)$	Axiom 2
2.	$\forall x\ HelpsCompanies(x) \rightarrow ImprovedStrategy(x)$	By definition of HelpsCompanies
3.	$\forall x\ ImprovedStrategy(x) \rightarrow Goals(x)$	hypothesis

Remark: This theorem should encourage companies to implement Industry 4 with a strategy and align the implementation to their goals. Industry 4 should be adjusted to the company's manufacturing processes, solutions may, therefore, vary between companies although the aim might be the same. As Chien et al.[12] noted, the gap between the current state of manufacturing maturity and Industry 4 may be too big for the company to benefit from Industry 4. Implementing Industry 4 in steps may thus suit companies of lower manufacturing maturity.

The assumption is that Axiom 2 which states that Industry 4 improves competitiveness implies that the company's goals and strategy need to align with Industry 4. The variable x is the organisation in question. The first step assumes that Axiom 2 implies that Industry 4 helps companies which Axiom 2 states. The second step implies that strategy is needed to help companies. The final step implies that strategy is built on goals. By applying logical eliminations, which are not shown, it is clear that Axiom 2 implies goals.

Connectivity

Lemma 2 states that connectivity enables data to flow between building blocks. As stated above, connectivity is important in Industry 4 and so is data. Data was the most frequently mentioned technology in the literature reviewed (Sec. 4.2). One of the main focal points of Industry 4 is connecting manufacturing facilities[2], meaning that the entire factory needs to be connected to allow data to flow. Building blocks, therefore, need to be able to share data enabled by connectivity.

The proof for Lemma 2 is based on Axiom 1, which states that things need to be connected and data-driven and the definition of connectivity.

Lemma 2. *Connectivity enables data to flow between building blocks.*

Assumption: $\forall x \, Axiom1(x) \rightarrow Connectivity(x)$
Proof.

1.	$Axiom1(x) \rightarrow Connected(x)$	Axiom 1
2.	$Connected(x) \rightarrow Connectivity(x)$	hypothesis

Three-way integration

Theorem 3 states that with Industry 4, industry will transition towards a 3-way integration. 3-way integration is one of the key focus areas of Industry 4 [2]. The integration involves *horizontal, vertical* and *end-to-end* integration[5] (refer to Subsection 3.2, Industry 4 and related terms, for further details). To realise the 3-way integration, multiple elements are required. The emerging technologies allow for the three-way integration by enabling connectivity that enables data to flow between relevant building blocks, e.g. suppliers and equipment.

The analysis of the case studies shows that the companies that implemented Industry 4 tended to only focus on the vertical integration, that is integration within the company. Procter and Gambler was the only company that implemented vertical integration by synchronising the supply chain [157]. Other companies, such as Harley Davidson [144] and Daimler [5], changed their production lines to enable them to manage increasing demand for customised products (vertical integration).

The 3-way integration is one of the factors that differentiates Industry 4 from its predecessors as it eliminates silos which is the current state in industry. The proof of Theorem 3 is based on the Axiom as the driver for the 3-way integration is the need for data and how that is linked with industry.

[5]Vertical integration refers to integration within the organisation, horizontal integration refers to integration within the supply and finally, end-to-end integration is the integration of the life cycle of the product.

Theorem 3. *With Industry 4, industry will transition towards a 3-way integration.*

Assumption: $\forall x\, Axiom1(x) \rightarrow Goals(x)$
Proof.

1.	$\forall x\, Axiom1(x) \rightarrow Connected(x)$	Axiom 1
2.	$\forall x\, Connected(x) \rightarrow Integration(x)$	Def 4
3.	$\forall x\, Integration(x) \rightarrow Horizontal(x)$	hypothesis
4.	$\forall x\, Integration(x) \rightarrow Vertical(x)$	hypothesis
5.	$\forall x\, Integration(x) \rightarrow End-to-end(x)$	hypothesis

Remark: This theorem provides a basis for many of the theorems to come. Although Industry 4 shares some commonalities with e-manufacturing, including a three-way integration, Industry 4 differs from e-manufacturing from a data perspective. In e-manufacturing, data tends to be gathered for monitoring purposes, whereas in Industry 4 data is gathered, analysed and then used to make informed decisions.

System of systems

A *system of systems* is defined in Definition 7. The difference between a system and a system of systems can be described by five characteristics: autonomy[6], belonging, connectivity, diversity and emergence[196]. def[197] defined systems of systems as: "a collection of systems, each capable of independent operation, that interoperate together to achieve additional desired capabilities"[197].

Definition 7. A *system of systems* is a group of systems that can act independently as well as interactively towards a common goal.

Theorem 4: System of systems

Theorem 4 states that Industry 4 is based on systems of systems.

[6] The application of autonomous systems of systems is dependent of numerous factors such as security as well as a shift in mindset. Implementing systems of systems may, therefore, not be feasible during the first phases of the implementation.

Theorem 4. *Industry 4 is based on systems of systems.*

Assumption: $\forall x\, Axiom1(x) \rightarrow SystemOfSystems(x)$
Proof.

1.	$\forall x\, Axiom1(x) \rightarrow Connected(x)$	Axiom 1
2.	$\forall x\, Connected(x) \rightarrow Integration(x)$	Def. 4
3.	$\forall x\, Integration(x) \rightarrow SystemOfSystems(x)$	hypothesis

Remark: The implications of this theorem are that as the building blocks (or systems) are connected, they can be seen as systems of systems. It allows for a structured classification of the systems and enables relevant communication between the building blocks[198]. As discussed earlier, one of the key characteristics of Industry 4 is data flow (Axiom 1) and therefore it is integral that systems can communicate with other systems.

Even though interoperability is an important component of Industry 4, it was interesting to see that the term did not appear often in the literature review. That might indicate a certain level of immaturity of the literature reviewed which demonstrates the requirement for the framework developed for the purpose of this Thesis.

Definition 8: Decentralisation

The term *decentralised* is defined in Def. 8 which states that a system that is moved from a centralised location is said to be decentralised (for the definition of centralised, see Glossary, Page xii). Decentralisation is an important factor in Industry 4 as it is one of the key characteristics identified in the analysis in Chapter 4. It is also the basis of Cloud computing which is one of the most important technologies for Industry 4.

Definition 8. A system which ownership is moved from a centralised location to a network of ownerships is said to be *decentralised*[7].

Cloud computing

Cloud computing is defined as a network of decentralised computers providing compute services that can be requested on-demand. That definition is based on

[7] This Thesis does not consider systems which do not have specific ownerships such as Bitcoin. The definition, therefore, focuses on decentralised systems that have specific ownerships.

the definition Mell and Grance[100] put forward for Cloud computing and is needed as Cloud computing is an important factor in Industry 4 as a major technology as noted in the analysis (Subsection 4.2.3).

Definition 9. *Cloud computing* can be defined as a network of decentralised computers providing compute services that can be accessed on demand.

Cloud computing is an Industry 4 enabler

Theorem 5 states that Cloud computing enables the computing of big datasets and their analysis. It was clear from the analysis of the literature review that data and data analysis is an integral part of Industry 4. As discussed in Chapter 4, Cloud computing is a network of decentralised computers that can be accessed on-demand and as big datasets require more computing power than normal dataset and Cloud computing they rely on Cloud computing. Cloud computing was noted as a key enabling technology by 71% of the papers reviewed.

The proof for Theorem 5 is based on Axiom 1 as Industry 4 is driven by data and the amount of data Industry 4 generates.

Theorem 5. *Cloud computing enables the computing of big datasets and their analysis.*

Hypothesis: $\forall x\ Axiom1(x) \rightarrow CloudComputing(x)$
Proof.

1.	$\forall x\ Axiom1(x) \rightarrow Data(x)$	Axiom 1
2.	$\forall x\ Axiom1(x) \rightarrow Connected(x)$	Axiom 1
3.	$\forall x\ Connected(x) \wedge Data(x) \rightarrow BigData(x)$	Literature definitions
4.	$\forall x\ BigData(x) \rightarrow CloudComputing(x)$	Literature definition

Remark: Although Cloud computing is noted as an Industry 4 enabler, it is worth noting that the implementation of Cloud computing depends on the company's requirements etc.

Industry 4 enables decentralisation of data

Here it is stated that Industry 4 enables decentralisation of data. Decentralisation is one of the principles of Industry 4[61] and as Lasi et al.[7] noted, processes need to become decentralised to allow for faster decision making (Section 3.2). Hermann et al.[56] furthermore noted decentralised decisions as one of the design principles of Industry 4. Faster decision making was the most frequently mentioned benefits of Industry 4, according to the analysis. 20% of the companies reviewed in the literature review noted faster decision making after the implementation of Industry 4. Cloud computing enables decentralisation of data as Hofmann and Rüsch[199] noted.

Axiom 1 and Cloud computing make up the basis of the proof of this theorem. A key characteristic of Industry 4 is data analytics in connected data-driven industry as Axiom 1 states. Theorem 5 is then used as Cloud computing enables Big data and finally, the definition of Cloud computing which states that Cloud computing is a network of decentralised computers is then used to finish the proof.

Theorem 6. *Industry 4 enables decentralisation of data.*

Hypothesis: $\forall x\ Axiom1(x) \wedge CloudComputing(x) \rightarrow DecentralData(x)$
Proof.

1.	$\forall x Axiom1(x)$	
2.	$\forall x CloudComputing(x)$	Theorem 5
3.	$\forall x\ Axiom1(x) \wedge CloudComputing(x) \rightarrow DecentComp(x)$	hypothesis (Def. 9)
4.	$\forall x\ DecentComp(x) \rightarrow DecentData(x)$	hypothesis

Artificial intelligence

Artificial intelligence is as an advanced technology in which computers or machines use data to "think" and "learn". That is based on the definitions on smartness and AI by Russell[96], Wang et al.[8] and Zhong et al.[77].

Definition 10. *Artificial intelligence* (AI) is an advanced technology in which computers or machines use data to "think" and "learn".

Industry 4 technologies

As noted in the analysis of the literature review, technologies are one of the key characteristics in Industry 4. There is, however, not a general consensus on which technologies are required for the realisation of Industry 4. Despite that, there were some commonalities amongst the papers reviewed such as Big data and IIoT. Definition 11 lists the *Industry 4 technologies*. They are as follows: VR, additive manufacturing, Big data and analytics, cyber security, IIoT, robots[8], artificial intelligence and autonomy.

Definition 11. Industry 4 technologies[9] utilise the following advanced technologies in this context in time are virtual reality (VR), additive manufacturing, Big data and analytics, cyber security, industrial internet of things (IIoT), robotics, artificial intelligence and autonomy.

Technology enablers

Lemma 7 states that Industry 4 technologies are the enablers of the interfaces. Various definitions are used to proof Lemma 7. These definitions are as follows: building block, interface and system. Those definitions are needed as they show how the technologies are connected to interfaces.

Lemma 7. *The Industry 4 technologies are enablers of the interfaces.*

Proof. Industry 4 is based on system of systems (Theorem 4). According to Def. 5, systems are building blocks integrated by interfaces so that data can flow through them. Axiom 1 states that Industry 4 is advanced data analytics which uses advanced technologies (Def. 1). Interfaces were defined as a shared boundary between building blocks that enable data transfer in systems (Def. 3 and Theorem 4). As Industry 4 uses advanced technologies and is built on system of systems, the Industry 4 technologies are enablers of the interfaces.

Industry 4 environment

Definition 12 states that an industrial environment where Industry 4 has been implemented is called an *Industry 4 manufacturing environment*. This definition is needed as the rule base discusses the properties of such an environment.

Definition 12. An *Industry 4 manufacturing environment* is an industrial environment where Industry 4 has been implemented.

Industry 4 data sources

Theorem 8 states that data from one or more sources must be gathered. According to the analysis of the literature review (Chapter 4), data from one, or more,

[8] It is worth noting that although robots are an integral part of the third industrial revolution, they still play an important role in Industry 4 as autonomous robots.

[9] This list of technologies is neither binding nor completed and susceptible to changes

sources is needed, including multiple sources on the factory floor, manufacturing equipment, processes, metrology, supply chain and even customers. That links to the 3-way integration[2] but for the realisation of the 3-way integration, data needs to be collected from various sources. The data can originate from various places such as IoT and enterprise[103].

The proof is based on the fact that data must be gathered and industry will move towards a 3-way integration with Industry 4 as the greatest potential of Industry 4 can be reached with a 3-way integration. As a consequence of that, data must be gathered from at least one source.

Theorem 8. *Data from one or more sources must be gathered.*

Proof. According to Axiom 1, data must be gathered from at least one source. Industry 4 furthermore will lead to a 3-way integration (Theorem 3) so for various building blocks to communicate, data must be sent between them, allowing them to make appropriate decisions. Data from at least one sources must, therefore, be gathered.

Remark: This is derived from the definition of connectivity (Def. 6) which states that industry is connected if data can be shared between systems. Since Industry 4 will move towards a 3-way integration which requires connectivity, data will be gathered and shared between systems. Data, therefore, needs to be collected from at least one source.

Knowledge

In literature, there is not a uniformity on the definitions of data, information and knowledge. Zins[200] gathered definitions of the previously mentioned terms from 57 scholars from all of the world. The outcome was the D-I-K model which includes the definitions of data, information and knowledge. According to that model, data is sense stimuli, such as loud noise from a manufacturing equipment. Information can be defined as empirical knowledge and is placed in between data and knowledge. Continuing with the example above, the information would know that the equipment has been turned on and is producing components. Finally, the content of a thought in a person's mind is defined as knowledge. It can either be non-empirical or empirical and has three conditions, i.e. i) the belief that it is true, ii) it can be justified and iii) it is or appears, to be true. The Oxford dictionary defines knowledge as: "Facts, information, and skills acquired through experience or education; the theoretical or practical understanding of a subject" [201]. The definition of knowledge is based on those two definitions.

Definition 13. Understanding of a subject gained through experience can be defined as *knowledge*.

New knowledge and Industry 4

As noted in the literature review (Chapter 3), Artificial Intelligence learns from experience[77]. One of the participants in Zins' study defined knowledge as "information scripted into relations with recipient experiences" [200]. That can be transferred to computers and artificial intelligence as they use data and information to create new knowledge.

The proof of this theorem is based on the need for data for Industry 4 and the fact that data is gathered from at least one source and requires real-time data. Industry 4 furthermore analysis of the data by using advanced technologies. The output of that analysis is new data but as it is context-based, it can be considered knowledge as knowledge is context-based data.

Theorem 9. *Industry 4 creates new knowledge.*

Proof. Industry 4 requires the collection and advanced analysis of data as Axiom 1 states. The analysed data is furthermore fed back to the relevant process. Industry 4 also leads towards a 3-way integration (Theorem 3) which requires the collection of data from one or more sources (Theorem 8). A large amount of data is, therefore, available to be analysed and used. When data is analysed and contextualised, new data is generated, which based on Def. 13 can be defined as knowledge as the system gains understanding of the subject through experience. Industry 4, therefore, creates new knowledge.

Data prediction

Industry 4 does not only gather and analyse data, it also enables prediction as many authors noted in the literature review. That was further reinforced by the analysis of the literature review (Chapter 4) as the prediction was identified as an element in the data theme. One of the opportunities noted in the literature review was the use of emerging technologies to predict machine failures[166]. Prediction can be used in a variety of applications, such as planning[163] and maintenance[91].

Many of the companies reviewed in the literature review (Chapter 3), gathered and analysed data for prediction. PTC [158] for example used predictive maintenance to improve their service process. PTC [160] also used predictive maintenance but they implemented technologies to their presses that allowed the presses to send data, enabling predictive maintenance.

Industry 4 predicts the future course of events by analysing data from production so Industry 4 creates new knowledge through prediction. Theorem 10 therefore states that Industry 4 predicts the future course of events.

Theorem 10. *Industry 4 enables the prediction of future course of events.*

Proof. Industry 4 gathers data from one or more sources (Axiom 1 and Theorem 8) and analyses it with advanced technologies (Axiom 1). By analysing the data, new data and new knowledge is created (Theorem 9). Now, AI is an advanced technology (Def. 10) which can apply "thinking" and "learning" to a dataset. Since AI applies "thinking", it can identify trends and therefore predictions can be made.

Cyber security

Definition 14 states that *cyber security* is the techniques used to protect internet-connected systems from harmful attacks[10]. The International Telecommunication Union (ITU) defined cyber security as: "Cybersecurity is the collection of tools, policies, security concepts, security safeguards, guidelines, risk management approaches, actions, training, best practices, assurance and technologies that can be used to protect the cyber environment and organization and user's assets" [202].

Definition 14. *Cyber security* is the technique of protecting internet-connected systems from harmful attacks.

Data security in Industry 4

Theorem 11 states that data must be secure. In an Industry 4 environment, data is stored at a decentralised location, meaning that the data is more vulnerable to cyber attacks. Special measures need, therefore, to be taken to ensure the security of the data. Cyber security was one of the main challenges identified in the analysis of the literature review. The data needs to be protected against cyber attacks as well as malfunctioning devices as Khan and Turowski [165] noted.

[10] In this Thesis harmful attacks is defined as attacks harmful to the enterprise.

Only 33% of the papers reviewed in the literature review (Chapter 3) mentioned cyber security as a key technology for Industry 4. None of the case studies in the literature review (Chapter 3) noted cyber security specifically. As the data is decentralised in Industry 4, it is prone to cyber attacks, especially since the data can hold valuable information on the companies and their processes. It is therefore essential that the data is stored in a secured manner.

The proof of this theorem is based on the fact that Industry 4 requires a 3-way integration which means that data flow between various sources. Data is furthermore decentralised, which makes it more vulnerable for cyber attacks. As there is a huge amount of decentralised data flows between multiple building blocks it must, therefore, be secured.

Theorem 11. *Data must be secure.*

Assumption: $\forall x\, Axiom1(x) \wedge Axiom2(x) \rightarrow Security(x)$
Proof.

1.	$\forall x\, Axiom1(x) \rightarrow CollectsData(x)$	Axiom 1
2.	$\forall x\, Axiom2(x) \rightarrow HelpsCompanies(x)$	Axiom 2
3.	$\forall x\, CollectsData(x) \wedge HelpsCompanies(x) \rightarrow SafeData(x)$	hypothesis
4.	$\forall x\, SafeData(x) \rightarrow Security(x)$	hypothesis

Remark: With Industry 4, data becomes increasingly available for multiple parties. That is enabled by e.g. decentralisation and the 3-way integration which has been discussed above.

Production method

The term *production method* is defined as the methods required to convert raw materials into finished goods.

Definition 15. A *production method* can be defined as a the methods required to convert raw materials into finished goods.

New production methods

Theorem 12 states that Industry 4 enables new production methods to emerge. As noted in the analysis (Chapter 4), Industry 4 allows new production methods to emerge. Industry 4 enables flexible production as Berger[91] noted. That is also reflected in the case studies which were analysed in Chapter 3 but increased connectivity enabled Harley Davidson[144] to move towards customisation of their bikes. DTNA also reported the need for customisation, which Industry 4 enabled them to do. Lasi et al.[7] noted that Industry leads to more customisation, which requires processes to move towards becoming more flexible than before. The three-way integration enables Industry 4 to gather information from different sources which means that manufacturing processes will have more data. That along with the Industry 4 technologies allows new production methods to emerge.

Theorem 12. *Industry 4 enables new production methods to emerge.*

Proof. The ultimate goal of Industry 4 is a three-way integration (Theorem 3) which includes suppliers and customers to be integrated into the production and life cycle of the product. Production methods include the processes needed to convert raw material to finished goods (Def. 15) and they will need to be integrated (Theorem 3). The integration along with increased availability to data and the Industry 4 technologies (Def. 11) allow new production methods to emerge.

Role of the customer in Industry 4

Theorem 13 states that the customer has an increased role in Industry 4. As noted in the analysis, customers will become a more integral part of the product life cycle due to quicker response times, increasing connectivity and integration. For example, Industry 4 enabled CISCO[5] to meet their customers' requirement and allow them to purchase customised trucks. Harley Davidson reported similar experience, implementing Industry 4 enabled them to manage increasing demand for customised products[144]. Lasi et al.[7] noted that customers are increasingly influencing the products they purchase and Deloitte[163] identified that customers are better integrated in the business.

The literature also noted the increasing integration of customers in the business[163]. Data can be for example gathered from the customers to feedback into the design process[98]. Therefore it is essential to take into consideration the new role of customers in Industry 4.

Theorem 13. *The customer has an increased role in Industry 4.*

Proof. Industry 4 requires data from multiple sources (Theorem 8). Theorem 3 states that 3-way integration, which means that customers need to be integrated into the systems of systems (Theorem 4). Data from customers is gathered so they have a role in Industry 4.

Servicitation

Servicitation is defined in Definition 16 as a business model which focuses on the service of a product. Organisations have been using this business models before the emergence of Industry 4, such as Rolls Royce with their Power-by-the-hour programme. However, more companies are moving towards servicitation with Industry 4.

Definition 16. Servicitation is a business model which focuses on the service of a product.

New business models

Theorem 14 states that Industry 4 allows for new business models to emerge. 6% of the case studies showed that new business models emerged with Industry 4. UPS took advantage of the readily available 3D printing technology and offered customers 3D printing service[144]. Heidelberg and Elekta offered customers predictive maintenance which benefited both the customers as well as the businesses[158,160]. Lambert[157] analysed commonalities among companies that are leading in Industry 4. They discovered that one of the key value drivers that the companies shared is new business models.

The word count analysis showed that servitisation was among the top ten most frequently used words in the papers. As stated in the analysis, that is an indication that Industry 4 allows companies to move towards servicitation. Moreover, the emergence of new business models was identified as a challenge by Deloitte[10].

Theorem 14. *Industry 4 allows for new business models to emerge.*

Proof. Industry 4 requires 3-way integration (Theorem 3), that means that more people will have access to data as data flows between building blocks in the network of systems of systems (Theorem 4). The availability of analysed data (Axiom 1) along with the emerging Industry 4 technologies (Def. 11) means that Industry 4 creates are new opportunities from which new business models can be made from.

Remark: Industry 4 brings increasing connectivity and emerging technology to industry. It therefore has the potential to change existing practices and even expand current practices. This Theorem is important as it encourages companies to consider the broader potentials Industry 4 can have.

Factors for the implementation of Industry 4

Humans, technology and organisations need to be considered simultaneously when implementing Industry 4. That is derived from Bucker et al.[13] who explored the use of the model for Industry 4. The analysis of the case studies reveals that many of the companies focused on those three categories when they implemented Industry 4. Rexroth[6] wanted to improve one of their production line that was struggling to keep up with the demand. They applied Industry 4 philosophy while involving their employees in the integration. Lukoil wanted to expand their production to a new side so they implemented new technologies to keep their workers safer. When the three-way integration is considered, it becomes apparent that is effectively made up of three components, that is humans, organisations and technologies. Therefore, the proof of this theorem is built on that as well as data from one or more sources is required.

Theorem 15. *Humans, technology and organisations need to be considered simultaneously when implementing Industry 4.*

Proof. Industry 4 will lead to a three-way integration and data from one or more sources must be gathered (Theorems 3 and 8). That means that various building blocks, such as technologies (Theorem 7), humans and organisation are involved in the implementation of Industry 4. Axiom 2 states that Industry 4 improves companies' capabilities, meaning that it will have positive effects on the companies that implement Industry 4. As Industry 4 is built on systems of systems (Theorem 4), the three groups will be part of those systems. Those three groups will therefore need to be considered simultaneously as they are part of the same systems.

Remark: This Theorem reflects what was noted in the analysis of the literature review (Subsection 4.2.2). The analysis noted various technical challenges associated with the implementation of Industry 4, however, there are also challenges related to the organisations as well as people. The consequences of this Theorem are that industry needs to consider these three factor simultaneously as they are intertwined. That is also reflected in the most successful international initiatives, such as the initiative that Hong Kong developed for Industry 4. It is also worth noting that the Industry 4 revolution is still taking place, Industry 5 has already started evolving. Experts claim that Industry 5 will put more emphasis on the human factor as customers will demand high-level of customisation of the products they purchase[203].

There are several barriers that accompany the implementation of Industry 4, including trust and leadership[22,204]. Another factor that requires attention is the culture in the organisation as Szymańska[205] noted. Those factors are not within the scope of this Thesis to discuss.

Implementation of Industry 4

Theorem 16 states that Industry 4 can be implemented in stages. That is derived from Benešová and Tupa[20] who noted that to avoid problems associated with the implementation, Industry 4 must be implemented in stages. The gap between Industry 3 and 4 can also be too big as Chien et al.[12] identified so they developed a framework for adapting Industry 3.5 which aims to bridge the gap.

As Industry 4 is built on systems of systems it can be implemented in stages which is the basis of the proof.

Theorem 16. *Industry 4 can be implemented in stages.*

Proof. Axiom 2 states that Industry 4 improves companies' capabilities. Industry 4 is based on systems of systems (Theorem 4) and can, therefore, be implemented in stages.

Remark: The implications of this theorem are that even though there should be a strategy for Industry 4, it can be implemented in stages.

Smartness

The term *smart* is defined in Definition 17. As Radziwon et al.[65] noted, there is not a general consensus on the definition of the word smart within the context of Industry 4. The working definition used in this Thesis of the term smart is based on literature review.

Definition 17. A building block that is connected and shares data with a system that analyses the data and can affect and predict the behaviour of the building block based on the data analysis is called *smart*. Furthermore, it must comply with the Industry 4 Axioms.

Smart factories in Industry 4

Theorem 17 states that in order for a factory to be smart, it must be connected, collect real-time data and analyse the data. The data must also be used to improve the production. Smart factories are one of the fundamental concepts of Industry 4, according to Lasi et al.[7] and Roblek et al.[21], it is also one of two research themes for the German initiative Industrie 4.0. MacDougall[63] defined smart factories as the connection between virtual and physical worlds. One of the characteristic of a smart factory is flexibility as Radziwon et al.[65] and Shrouf et al.[66] noted which is enabled by connectivity and data analytics.

Theorem 17. *For a factory to be smart, it must be connected, able to collect data in real-time and the output of the analysis in real-time. It furthermore must use the analysed data to improve the production.*

Proof. The definition of smart (Def. 17) states that a smart building block must comply with the Axioms of Industry 4.

Impact on maintenance

Theorem 18 states that Industry 4 will change maintenance. Increased connectivity and integration, data and data analysis allow for a shift in maintenance towards predictive maintenance. It was highlighted both in literature as well as the case studies that maintenance will change with Industry 4. Many of the companies, presented in the case studies, had implemented predictive maintenance such as Elekta[158]. Predictive maintenance was also noted as one of the opportunities associated with Industry 4[91]. Three of the frameworks reviewed in the literature review focused on the change of maintenance, both remote maintenance and predictive maintenance. It is, therefore, apparent that Industry 4 will have an impact on maintenance. The foundation of the proof is the previously mentioned enablers, that is connectivity, data and analytics.

Theorem 18. *Industry 4 has started to change maintenance.*

Proof. A factory is smart if it is connected and can share data (Theorem 17). One part of the integration is the vertical integration, that is the integration of the factory to enterprise planning. That means that the machinery in the factory is a part of the system of systems (Theorem 4). As Industry 4 needs data from multiple sources (Theorem 8), data is gathered from the machinery. Now, the data is analysed (Axiom 1) and new knowledge is created (Theorem 9) so new knowledge is formed on the factory and the machinery. With new knowledge on the machinery, prediction can be made on the failure of the machinery which changes the maintenance.

Remark: Maintenance is an integral part of manufacturing which must be included as part of the implementation of Industry 4.

Legacy machinery

Def. 18 states that machinery that lack connectivity to connect to Industry 4 technologies is called *legacy machinery*. Jónasdóttir et al.[206] defined legacy machinery as: "machine equipment that is not yet I4 [Industry 4] ready and typically requires upgrading through Internet connectivity to allow access to advanced I4 technology"[206].

Definition 18. Machinery that lacks connectivity to connect to the Industry 4 technologies is called *legacy machinery*.

Legacy equipment upgrading

Definition 19 states that any legacy equipment is smart if it is connected, monitored and predicted. Data and connectivity is an integral part of Industry 4 as explained earlier in this chapter. Data is currently widely gathered manually on the shop floor[60] and legacy equipment is still widely used within the manufacturing industry. A few companies in the case study review upgraded their manufacturing lines such as Harley Davidson that upgraded the connectivity in their factory[144]. With the emerging technologies, legacy equipment can be upgraded as Jónasdóttir et al.[206] showed.

Definition 19. Legacy equipment is called smart if it is connected, monitored and predicted.

Skills gap

Theorem 19 states that Industry 4 requires a shift in the workers' skill set. It was noted in the analysis that Industry 4 requires new skills, for example, education is one of the pillars in Britain's strategy for the fourth industrial revolution and[57] also noted the requirement for a new skill set. Skills gap was noted as one of the challenges associated with Industry 4 in the literature review. The companies reviewed in the case studies noted the need for higher-skilled workers due to the implementation of advanced technologies. Furthermore, the importance of training people was also noted in the analysis of the international initiatives as many of them included education and academia as part of their plans. The emerging technologies and systems provide the basis for the proof of this theorem.

Theorem 19. *Industry 4 requires a shift in the workers' skill set.*

Proof. Industry 4 is built on systems of systems (Theorem 4). Systems are made up of integrated building blocks which can be in either, or both, the physical or virtual world (Def. 4 and 5). Humans are part of the physical world and can therefore be considered a building block. Lemma 7 states that the Industry 4 technologies are enablers of the interfaces. The Industry 4 technologies are emerging technologies which are not yet widely used in industry. As the technologies are the enablers for the interfaces, the workers will need to adapt to the new interfaces and shift their skill set. Furthermore, Industry 4 enables new production methods to emerge (Theorem 12) which may require workers to adopt new skills.

Impact on people in the factory

Theorem 20 states that Industry 4 will affect workers. As noted in the analysis, Industry 4 will replace workers but will not necessarily make them redundant even though some authors stated the opposite in the literature. By automating tasks, Industry 4 will make factories safer for workers as they will no longer be required to do repetitive or dangerous tasks. That was also reflected in the case studies where two companies noted improved working conditions for their operators[5,159]. It was also noted in the literature review that Industry 4 will lead to a higher-skilled workers and the redundancy of workers. It is therefore clear that Industry 4 will affect workers, both in positive ways as well as negative.

The proof is based on that Industry 4 must comply with the business goals and strategy which directly affects workers. The analysis of the literature review revealed that Industry 4 could improve conditions for workers.

Theorem 20. *Industry 4 will affect workers.*

Proof. The implementation of Industry 4 must align with the business strategy and goals (Theorem 1), as workers are part of the business, it will affect the workers. Furthermore, as Theorem 19 showed, it will affect the skill set of the workers.

Remark: This Theorem states that workers will be affected. That is important as it was proved in Theorem 15 that humans, technology and organisations must be considered simultaneously. The consequences of this Theorem are that as Industry 4 affects workers, that must be considered simultaneously with the organisation and technologies. Industry 4 will affect workers in various ways as discussed earlier and it is worth noting that workers could also affect the implementation of Industry 4.

New mindset

The analysis of the literature shows that Industry 4 requires a change in mindset. Theorem 21, therefore states that Industry 4 requires a new mindset. One of the main risks is associated with changing the mindset so Industry 4 must be implemented with a changed and correct mindset. The change of mindset can be explained with a simple analogy of a laptop. If a laptop was given to a person who had never seen a laptop before, he or she could make the simple mistake of writing with the pen on the screen. This example nevertheless shows the importance of applying a new mindset to new technologies.

A few papers reviewed in the literature review (Chapter 3) noted the requirement of changing the mindset when Industry 4 is applied. Deloitte[10] pointed out that the mindset needs to be shifted and Roblek et al.[21] stated that the main risk of implementing Industry 4 is linked to the mindset. The implementation of IoT will furthermore require a change in mindset as Bach et al.[168] noted. That is in line with the findings of Mittal et al.[207] who identified research gaps for Industry 4. They concluded that Industry 4 requires a change in mindset. None of the case studies mentioned a shift in the mindset specifically, however, as limited information was given in the case studies, that may not be an accurate description. It is also worth noting that in the Made Smarter review, leadership was one of the focal points as the review revealed that the leadership required information on the new opportunities Industry 4 brings[57]. The proof if this theorem is a consequence of the entire rule base and concludes the rule base.

Theorem 21. *Industry 4 requires a new mindset.*

Proof. Industry 4 is driven by data (Axiom 1) which is put into use by systems of systems (Theorem 4) which have interfaces facilitated by emerging technologies (Lemma 7). The data gathered and analysed creates new knowledge (Theorem 9). The new knowledge will change maintenance and the workers' skill set (Theorems 18 and 19). Furthermore, Industry 4 requires 3-way integration which along with the Industry 4 technologies, allows for new business models to emerge (Theorem 14). Finally, Industry 4 enables new production methods to emerge (Theorem 12). It is therefore clear that Industry 4 introduces novel concepts to industry which require a new mindset to exploit the benefits of these new concepts fully.

Remark: The implications of this Theorem are complex in its nature. It means that the Industry 4 technologies cannot be used by intuition without having changed the mindset to Industry 4. Research in management on mindset emphasise the importance of mindset. Smith and Saint-Onge[208]noted the imbalance that can occur during innovation phases if pre-existing mindset is applied to the development. That is in line with what was noted earlier regarding the implementation emerging technologies. The mindset does not only apply to the emerging technologies, it also applies to Industry 4 as a whole. As noted in this rule base, Industry 4 requires a shift as it has the potentials for new business models to emerge and connect organisations in new ways (i.e. three-way integration).

5.3.3 Section summary

This section presents the rule base for Industry 4. The rule base is composed of axioms, definitions, theorems, lemmas and proofs which were derived from the literature review and its analysis. The two axioms of Industry 4 describe the principal characteristics of Industry 4. The first axiom states that Industry 4 is principally characterised by advanced data analytics within connected data-driven industry and while the second axiom states that a principal characteristic of Industry 4 is its intend and ability to improve company competitiveness. Followed by the axioms are the theorems and lemmas, 21 in total. The theorems and lemmas cover the high-level aspects needed for the implementation of Industry 4. The first theorems in the rule base can be described as being trivial, however, they are crucial building blocks for the rule base. The level of abstraction increases as more theorems get introduced. The theorems were proven by using formal first-order logic and formal logic. Formal logic was deemed sufficient for the more abstract theorems as discussed in Section 5.2.

Rationale for the each item in the rule base was presented in this Section. The rationale was based on the literature review and its analysis. The section aimed to bridge the gap between the analysis of the literature and the rule base itself. The rule base was translated into an expert system which is introduced in next Section.

5.4 Practical application

The rule base was translated into an expert system to enable practical application of the rule base. The expert system was used to validate the rule base (see Chapter 6). The expert system is detailed in this section. Subsection 5.4.1 provides a short overview of expert systems as well as the rationale for using an expert system and its benefits. Subsection 5.4.2 details the practical application of the rule base as an expert system and Subsection 5.4.3 provides a summary of the section.

5.4.1 Background

Expert systems are computer programs used for problem solving in a specific domain[18]. Expert systems are based on two main components, that is knowledge and inference and are commonly based on first-order logic. Programming languages such as Prolog and LISP are widely used for these applications[175].

The rule base developed for the purpose of this Thesis can be described as a knowledge base for the implementation of the rule base for Industry 4. Furthermore, it uses first-order logic. The benefits of using an expert system for the rule base are multiple. First of all, it enables an automatic inference of the rules and enables the rule base to be applied in practical settings. It also enables validation (see Chapter 6) and satisfies the demand for automation and objectiveness. As the rule base has both knowledge as well as inference as its based on first-order logic, it can be translated to an expert system.

Programming languages such as Prolog and LISP are the two main languages used for the programming of expert systems. Various programming languages have been derived from those languages such as Scheme, Clips (both derived from Lisp) and Racklog (derived from Prolog). Further detail of these languages will not be given as this Thesis does not focus on the theory of software but rather uses software as an enabler. For the purpose of developing an expert system for the rule base, the programming language CLIPS was chosen. It was chosen as it is commonly used for programming expert system and offers forward chaining rules.

5.4.2 Expert system

The expert system is solely built on the rule base from Section 5.3. The program gathers facts from the user through a user interface and uses those facts to make inferences as seen on Fig. 5.3.

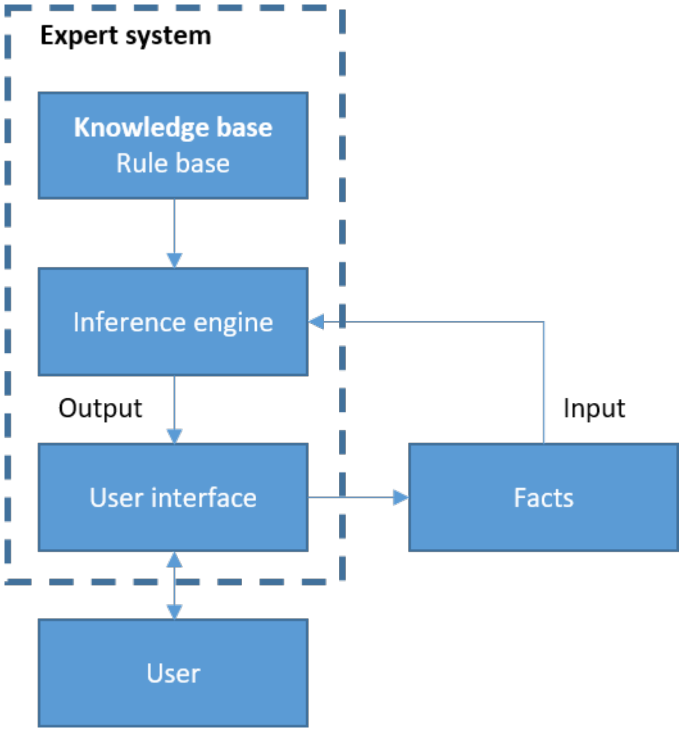

Figure 5.3: Overview of the expert system

The expert system has three components, that is functions, facts and rules. The majority of the expert system is based on facts and rules whereas the functions are used to set up the system. Three predefined constructs were used for those components and are further defined below.

The functions are used for the program to enable the expert system to ask two types of questions, that is either a yes/no question or a question where other values are permitted. Both types of questions store the answer under a predefined variable that is associated with the question.

The facts used in this expert system are both predefined facts which are used to establish the axioms and facts that are derived from the user via the user interface. The facts derived from the user are gathered by asking the user questions and prompting the user to answer them using predefined words. The user is prompted to either input yes or no for the yes/no questions or specifically defined words for the other questions. [11]

Examples are shown below of the yes/no questions and value questions, respectively.

```
Are the systems recursive (yes/no)?
What is the body's type (factory/object)?
```

The final part of the expert system is the rule part. The rules are composed of four parts, that is the header, patterns, THEN arrow and finally actions. Two types of actions are used in the expert system, `assert` which prompts the user to enter an answer and `printout` which prints out a message.

As Figure 5.3 shows, the rule base provides the knowledge base for the expert system. Figure 5.4 shows in more detail how the rule base is translated in the expert system. The Theorems provide a basis for the questions that the user interface asks the user. The proofs on the other hand provide the inference engine with the rules the inference engine. The proofs and the facts (the answers to the questions from the user) enable the inference engine to provide advice to the user.

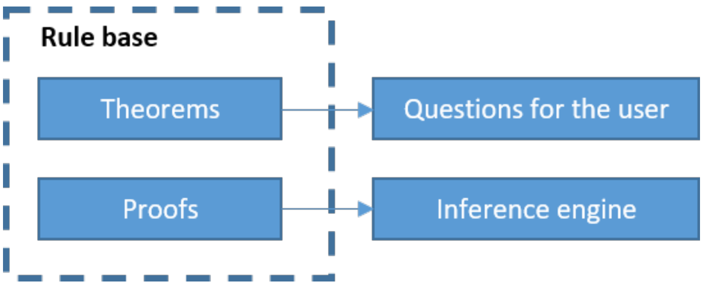

Figure 5.4: Explanation of how the rule base maps to the expert system

The proofs can be divided into two groups based on the methods used, that is formal first-order logic (used to proof the former part of the rule base) and formal logic (used to proof the latter part of the rule base). The former method lends itself well to be translated into an expert system as the expert system uses first-

[11]The question function has been removed from this Thesis. However, it can be found e.g. from https://courses.washington.edu/css482/examples/auto.clp

order logic. The latter part of the proofs can also be translated into an expert system. The expert system checks whether the Theorems cited in the proof are fulfilled or not in the same manner as for the first-order logic proofs.

Below are two examples that show how the first-order logic proofs and the logical proofs are translated, respectively.

Theorem A. *The implementation of Industry 4 aligns with the business goals and strategy.*

Assumption: $\forall x\, A2(x) \rightarrow Goals(x)$

Proof.

1.	$\forall x\, Axiom2(x) \rightarrow HelpsCompanies(x)$	Axiom 2
2.	$\forall x\, HelpsCompanies(x) \rightarrow ImprovedStrategy(x)$	By definition
3.	$\forall x\, ImprovedStrategy(x) \rightarrow Goals(x)$	hypothesis

Theorem B. *Industry 4 enables the prediction of future course of events.*

Proof. Industry 4 gathers data from one or more sources (Axiom 1 and Theorem 8) and analyses it with advanced technologies (Axiom 1). By analysing the data, new data and new knowledge is created (Theorem 9). Now, AI is an advanced technology (Def. 10) which can apply thinking and learning to a dataset. Since AI applies thinking, it can identify trends and therefore predictions can be made.

The rules are in two parts within the program, that is firstly the facts are gathered from the user using the `deffrule` and secondly the expert system makes inferences which are based on the Theorems in the rule base. It is worth noting that the user can be an expert, however, that is not necessary.

Below are examples of the two parts of a rule. For the entire code for the expert system, see Appendix C. Firstly is the gathering of facts which prompts the user to input whether data is stored securely. The latter example is the inference part of the rule which evaluates the facts and provides the user with a response.

```
(defrule data-security ""
   (data-gathered yes)
   =>
   (assert (data-secure (yes-or-no-p ''Is the data stored in
   a secure way (yes/no)? "))))

(defrule Theorem17b
```

```
8     (data-gathered yes)
9     (data-secure no)
10    =>
11    (printout t ``Data must be stored in a secure way'' crlf))
```

Line 1 defines the header of the rule while line 2 includes the pattern or facts needed for this rule. Line 3 is the THEN part of the rule. Lines 4-5 represent the action part of the rule, which in this case asks the user whether data is stored securely and prompts the user to give a yes/no answer. In the same manner as line 1, line 7 defines the header of the rule and lines 8-9 provide the facts needed to be asserted for the rule. Line 10 is the THEN part of the rule and finally, line 11 prints out a message on the user interface stating that data must be stored in a secure way.

For the latter part of the rules, that is the inference part, has two, or more, parts which explore different outcomes. If the condition that fulfils the rule is met, such as if the user stated that data is gathered in a secure way, then it establishes that the Theorem on data security holds, otherwise it prints out a message stating that data needs to be stored in a secured way.

Following is the structure of the program. Firstly, the functions of the expert system are defined, that is the questions. Secondly, the facts that are required for the Axioms are defined, followed by the definition of the Axioms. The facts for the Theorems are then gathered and finally the rules are defined which give the user an answer for based on the facts provided.

The expert system provides a platform for automatic inference and hence enable practical applications of the rule base. Part of the validation were industrial case studies which tested the practicality aspects of the rule base. The expert system provided a basis for that part of the validation. For further details, see Chapter 6.

5.4.3 Section summary

This section outlines the expert system that was developed on the basis of the rule base presented in this chapter. A brief overview was given on expert systems and rationale for the selection of the approach provided. The expert system was then outlined. It has three main components, that is functions, facts and rules. The expert system gathers facts from the user through a user interface and uses that set of information to make inferences. Based on those inferences and the facts, it provides the user with responses. The expert system provides a basis for part of the validation which is discussed in Chapter 6.

5.5 Summary

This chapter presented a rule base for the implementation of Industry 4 in a manufacturing setting. The rule base is based on an axiom, theorems, lemmas and definition and is based on the analysis presented in Chapter 4. The rule base establishes the interconnections between the characteristics and elements, which is Objective 2b. Section 5.2 provides an overview of the rule base and creates a link between the analysis (Chapter 4) and the rule base itself which is introduced in Section 5.3. This link has been referred to as the bridge in this Thesis. The bridge discusses every item in the rule base, provides a rationale for the existence of the item as well as explains the proof. Section 5.3 includes the rule base which covers Objective 2b of this Thesis. The theorems are built on the elements identified in Chapter 4 in addition to other theorems and lemmas that were regarded necessary to form a complete rule base for Industry 4 within the scope of this Thesis. The rule base focuses on five themes identified in Chapter 4, that is: data, connectivity, legacy factories, organisations and technologies.

The expert system that was developed for the rule base, and consequently addresses Objective 3a, was introduced in Section 5.4. Expert system are typically based on first-order logic and are based on two parts, facts and rules. The rule base, therefore, lends itself to be translated to an expert system. The components of the expert system were detailed and an example of its workings was provided. The expert system was used for the case study part of the validation. The program for the expert system can be found in Appendix C.

The rule base was validated by an academic expert as well with a paper-based case study and a case study in a manufacturing company in the UK. An explanation of the validation process and the results of the validation can be found in Chapter 6.

Chapter 6

Rule base evaluation

6.1 Introduction

The rule base developed in Chapter 5 describes Industry 4 in a formal logic way with a focus on factories with legacy equipment. The rule base identifies the building blocks of Industry 4 and connects them while approaching Industry 4 from a high level. As discussed in Chapter 1, this research aims to answer whether Industry 4 can be describe with mathematical reasoning. To answer this question, a rule base was created based on an analysis of the literature review (Objective 2b). The purpose of the evaluation is to establish whether Industry 4 can be described using a formal logic approach (Objective 3). This chapter aims to evaluate the rule base based on three aspects, that is applicability, utility and validity.

The chapter is structured as follows: Sections 6.3 and 6.4 present the review of the expert and the case studies, respectively. The expert review and case studies are assessed based on their validity, utility and applicability in Section 6.5. Finally, Section 6.6 provides a summary of the chapter.

6.2 Evaluation approach

The evaluation approach is summarised in this section, however, for further details, refer to the Research approach, Chapter 2.

To fulfil Objectives 3b-c, the rule base was evaluated by an academic expert and by performing two independent case studies. The expert review aimed to confirm the soundness and completeness of the rule base. The expert was selected based on his expertise. The feedback the expert provided for the evaluation was used to improve the rule base. Figure 6.1 exhibits the procedure followed for the expert review.

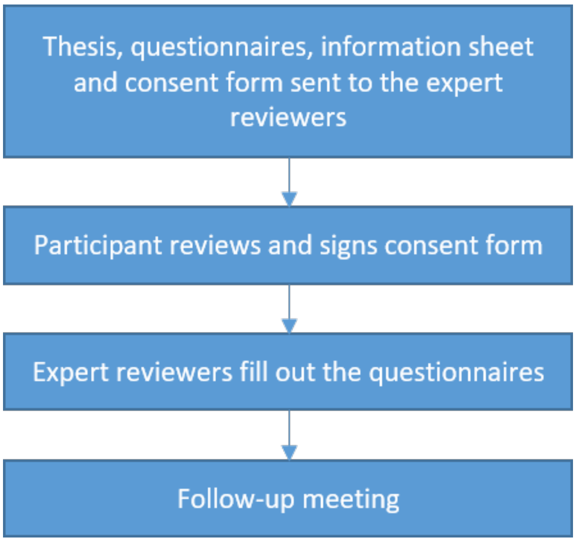

Figure 6.1: Expert review procedure

As for the case studies, the first case study was a paper-based study on an Industry 4 device. The latter case study was performed at a manufacturing company in the UK. The aim of the two case studies was to evaluate the applicability and utility of the rule base. The software developed based on the rule base was applied for both case studies (see Chapter 5). For the first case study, the information required for the software was gathered and put into the software. The latter case study followed a different approach. Here, interviews were conducted for those case studies (Figure 6.2).

As seen in Fig 6.2, each case study participant was asked to review and sign a consent form. A short introduction to the thesis and the task in hand was then given by the researcher. The participants were given four sets of questionnaires (these questionnaires can be found in Appendix D):

- Information about the participant
- Current state of manufacturing
- Future state of manufacturing
- Feedback

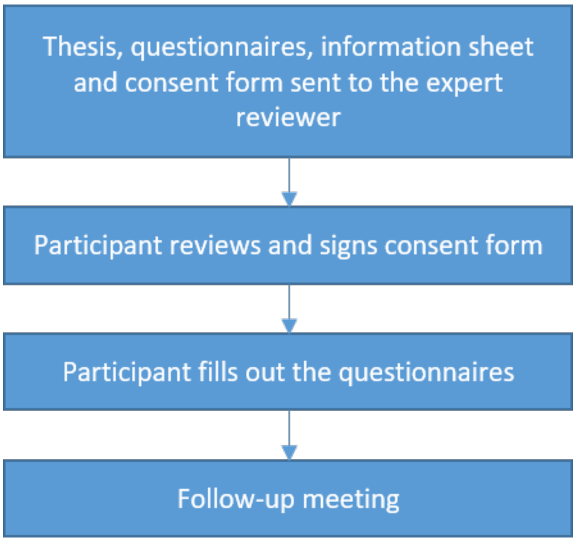

Figure 6.2: Case study procedure

The answers from the participants were put in the expert system and the expert system gave relevant feedback based on the input from the user. Figure 6.3 shows the workings of the expert system with relation to the rule base. For every Theorem p, where p is an integer between 1 and 21, in the rule base, the expert system asks the user a question which prompts the user to answer. Based on the premises of the respective theorem (that is Axiom n and Theorem m, where n is an integer from 1 to 2 and m is an integer between 1 and 20), the expert system provides the user with feedback. One example for each case study is presented to demonstrate the workings of the interaction between the rule base and the expert system.

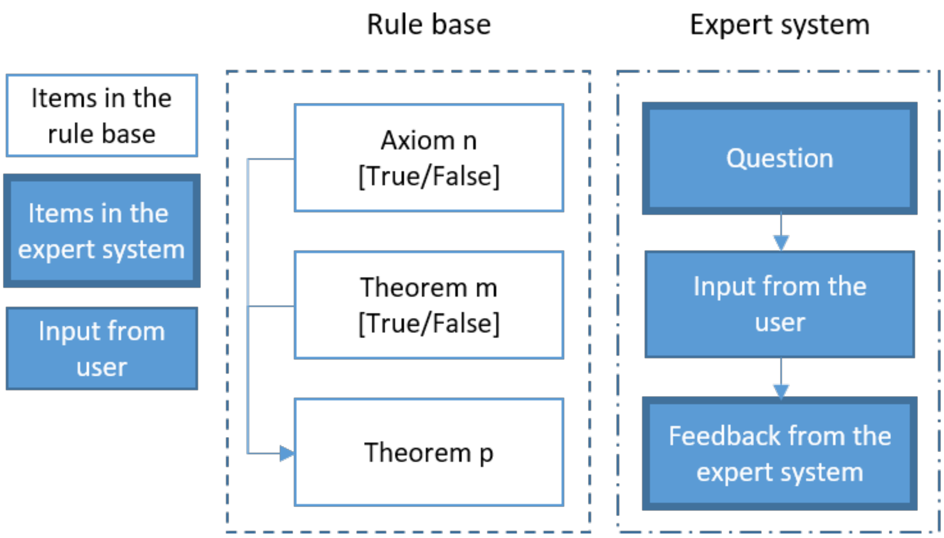

Figure 6.3: Case study procedure

6.3 Expert review

The expert is an academic with over 15 years of experience in the field of data, connectivity, analytics and visualisation. Moreover, the expert has significant industrial experience and has led numerous Industry 4 projects. The expert's field of expertise is Industry 4 technologies and the value they have to offer, including applied visualisation, IIoT and AI and analytics.

The expert stated that the rule base has the potentials to "allow evaluation of a proposed implementation/solution for completeness". According to this expert, the goal of Industry 4 is to "improve productivity and competitiveness through the adoption of digital technologies in manufacturing". The expert claimed that the implementation of Industry 4 requires a structured approach that follows a formal logic approach. Finally, the expert proposed that the rule base could be used to assess the completeness of a proposed implementation/solution.

When asked to assess the soundness of the rule base, the expert marked all the theorems and proofs as being sound apart from the following:

- Theorem 3: Integration
- Theorem 4: Systems of systems
- Lemma 7 and its proof: Technology facilitators
- The proof of theorem 9: New knowledge
- Theorem 16 and its proof: Implementation stages

The theorems listed above were reviewed based on the feedback the expert provided. All changes have been incorporated in the rule base, the changes confirmed by the expert to be sound and the final rule base used in this Thesis. Following are the changes made based on the feedback.

Theorem 3: Integration. The lack of soundness was caused by a misunderstanding. The expert commented on the difference between horizontal integration and end-to-end integration. That was resolved by adding a footnote which explains the difference between the three types of integration.

Theorem 4: System of systems. The expert stated that Industry 4 systems required autonomy as the definition of a system of systems states. The expert also added that very few Industry 4 systems have autonomy due to lack of trust and security. After a conversation with the expert, a footnote that explains that organisations should strive towards autonomous systems of systems, however, it may not be feasible to implement the autonomous part of the systems of systems straight away as it requires a change in mindset.

Lemma 7: Technology facilitators. The expert stated that the definition of the term *technology* may not always hold, however, after a discussion on the matter, it was decided that there was no need to change the definition. The same goes for the feedback on whether technologies facilitate interfaces or the other way around. After having consulted with the expert, it was decided to keep the original version of the lemma.

Theorem 9: New knowledge. The proof was not sound. The wording of the proof has been changed as the expert suggested and is therefore now sound.

Theorem 16: Implementation stages. The theorem was incomplete and therefore not sound. The theorem was completed as well as the proof and deemed complete.

In the version provided to the expert, Digital Twin was isolated as a key theme. As the expert noted, a Digital Twin is a tool to contextualise data. It was decided to exclude Digital Twins from the rule base as the rule base does not focus on technologies and to maintain consistency in the level of granularity in the rule base. Finally, the expert questioned where the products come into the rule base. The rule base focuses on the manufacturing side rather than products. However, that will be noted for future work.

The proofs follow logical reasoning to an extent according to the expert. The expert provided feedback on which proofs required revision as seen above. That feedback has been incorporated in the rule base included in this Thesis.

6.4 Case studies

The case studies provide practical application examples of the rule base. The case studies aimed to evaluate the applicability and the utility of the rule base (see Chapter 2 for the definitions of the terms). For the first case study, the rule base is used to describe the device whereas, for the second case study, the rule base is used as an assessment tool of an Industry 4 solution.

The first case study was paper-based whereas the second was conducted in a manufacturing company in the UK. Case study 1 was based on an EPSRC project done at the University of Strathclyde[206]. The project aimed to develop equipment for a legacy equipment upgrade. Case study 2 was conducted at an international company in the UK. For the second case study, two manufacturing research and development engineers were interviewed.

Subsections 6.4.1 and 6.4.2 present case studies 1 and 2, respectively. The subsections provide an introduction to the selected cases, followed by the outcome of the software. Finally a discussion on selected questions, and therefore theorems, is presented. For detailed discussion on the applicability and utility of the rule base, refer to Section 6.5.

6.4.1 Case study 1

The first case study was performed as an initial test of the rule base. The aim was to test the workings of the rule base in a limited scope. The first case study was based on an EPSRC project that aimed to upgrade legacy equipment (Figure 6.4). The equipment developed during the project, referred to as BAUTA, enables legacy machinery to gain connectivity and be controlled remotely. The device can be attached to a controller and solenoids used to press the buttons on the controller[206]. The idea of BAUTA was to demonstrate how advanced HMI should be designed and implemented for upgrading legacy machine tool equipment.

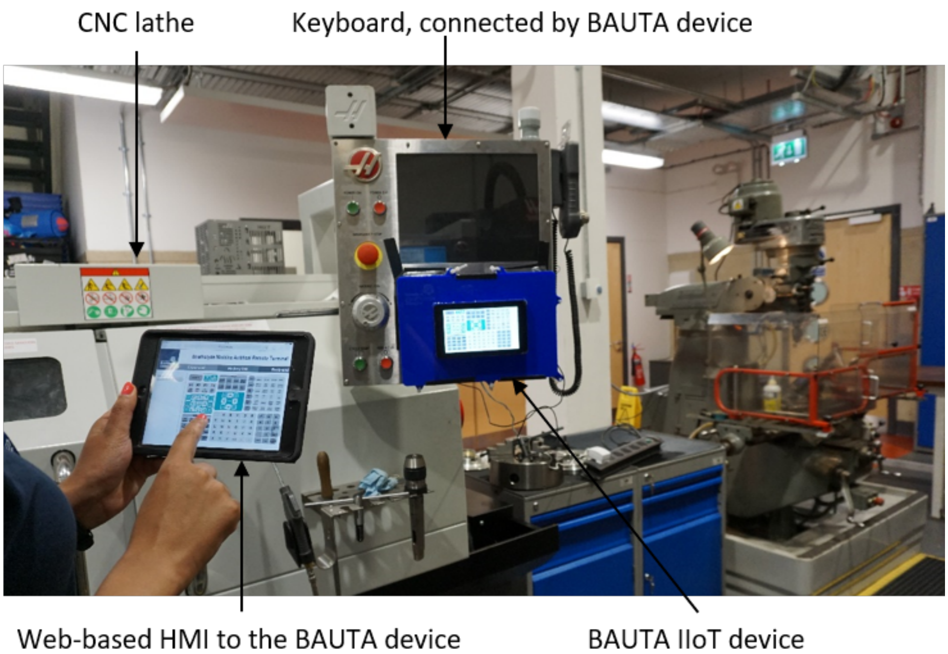

Figure 6.4: BAUTA

The device was selected for an initial test of the rule base. The outcome of the expert system can be found in Appendix E. For the evaluation of the rule base, the workings of the following questions for case study 1 will be further discussed:

Q1: Has the factory/object been integrated at all?

Q2: Is data used from one or more sources?

Q3: Is data stored in a secure way?

Q4: Has the impact of Industry 4 on production methods been considered?

The first question, regarding integration, was answered negatively. The question is linked to Theorem 3 which proof is based on Axiom 1 which is assumed to be true. Even though the premise for the theorem is true, a negative answer to the question prompted the expert system to provide the user with the feedback that integration is required for Industry 4. The question was answered negatively as even though the device had been connected to the equipment, the three-way integration was not considered for the implementation of this version of the device.

The second question, regarding data source, was answered affirmatively as Figure 6.5 shows. However, as the proof for that theorem (Theorem 8) is based on Axiom 1 and Theorem 3 which is the integration theorem, the theorem behind that questions is false (as the integration question was answered negatively by the user, see question 1). The expert system therefore provided the user with the feedback that integration is needed even though the question on data sources was answered affirmatively. The system, therefore, gave the rule base higher weight than the answer of the user as the rule base had a premise that was false.

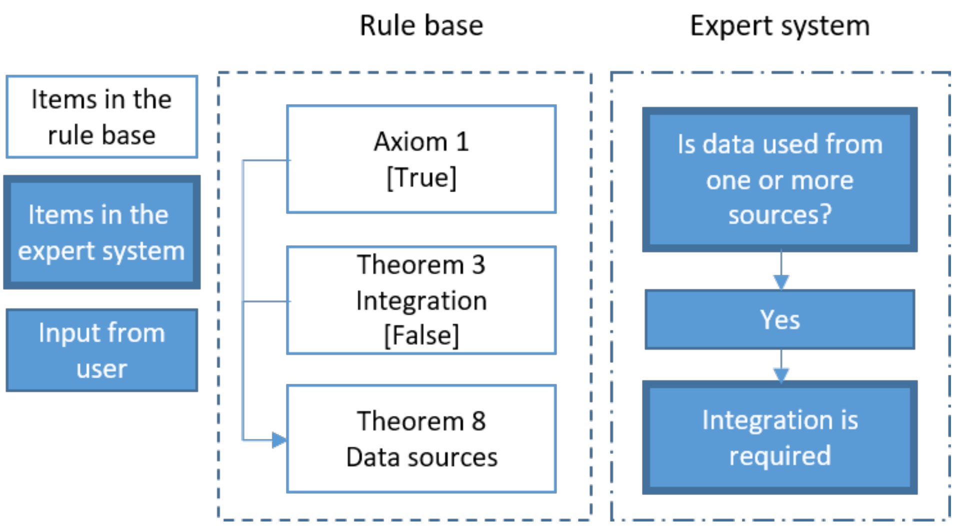

Figure 6.5: Workings of question 2, case study 1

The third question, whether data is stored in a secure way, was answered affirmatively by the user. The respective theorem is proved based on the two axioms. As the axioms are assumed to be true for the case studies and the question was answered affirmatively, the expert system provided no feedback to the user.

The impact on production methods is the final questions which details will be further discussed. That question was answered with a no. When a question is answered negatively, the expert system places the answer in a higher priority order than the proof for the respective theorem and provides the user with feedback that is irrespective of the rule base. For example, in this instance, the proof of the respective theorem is based on the integration theorem, to which the user had given a negative answer. However, the expert system provided the user with the feedback that Industry 4 enables new production methods to emerge.

Prior to the outcome of the expert system, the device is considered to be Industry 4 compatible. It was concluded from the assessment that the device itself is not Industry 4 compatible nor did it make the CNC lathe Industry 4 compatible as five questions in the expert system were answered negatively. However, it can be inferred that the device enabled Industry 4 compliance. The outcome of the expert system can, moreover, be used to improve the design of the device with respect to Industry 4. For example, the device was not integrated to the system of systems so future work could include adding that feature to the design of the system.

6.4.2 Case study 2

For the second case study, a manufacturing company was selected. The company was selected as they plan to implement Industry 4 to increase efficiency. The company is a representative candidate as they are at the beginning of their journey to Industry 4 integration and require a high-level overview of what is needed for the adoption of Industry 4.

The company is a supplier of mechanical parts for another large international company. The company buys pre-fabricated parts and assembles them on site. The assembly relies heavily on manual assembly lines, although some level of automation has been adopted in the assembly process. The company is looking for opportunities to improve competitiveness and efficiency through the implementation of emerging technologies.

For the evaluation, two employees, a principal and a senior engineer with a thorough knowledge of the manufacturing processes were interviewed. The engineers are also working on what a future factory would look like so they know both the current processes as well as the future state of manufacturing at the company. Employee A has worked for the company for 12 years while employee B has worked for about there 3 years.

Industry 4 has great potentials as the employees noted. They stated that when Industry 4 was first introduced, people focused on "the shiny solutions". As employee A noted, people did not fully understand the problem and consequently did not understand the roadmap to the solution. When asked about barriers that the company is facing regarding the implementation of Industry 4, employee B noted culture, the ageing workforce and lack of infrastructure.

Appendix E includes the outcome of the software with the answers from the employees regarding the implementation of Industry 4 at the company they work for. As with case study 1, four questions were chosen for further discussion in this Thesis. Detailing every question was deemed not necessary for the evaluation as the case studies focused on the utility and applicability of the rule base, not the workings of every theorem. The workings of the selected questions for Case study 2 will not be detailed in figures as Case study 1, for further details, refer to Figure 5.2 in Subsection 5.2.2. The chosen questions are as follows:

Q1: Has connectivity been established?

Q2: Has the impact of Industry 4 on customers been considered?

Q3: Has the impact of Industry 4 on skills been considered?

Q4: Has the impact of Industry 4 on mindset been considered?

The first question to be detailed is related to connectivity. The employees stated that data connectivity had not been established. As the proof of the relevant theorem, the connectivity theorem, is based on Axiom 1, the expert system responded with the statement: "Connectivity needs to be established".

The participants responded affirmatively to the question on the impact on customers (Theorem 13) as seen in Figure 6.6. The expert system, however, provided the user with the responses that integration is required for customers to be involved, system of systems is required for customers to be involved and data from one or more sources is required for the involvement of customers. The proof of the respective theorem is based on that Industry 4 will transition towards a three-way integration (Theorem 3) and is based on a system of systems (Theorem 4). The proof is also based on that Industry 4 uses data from multiple sources, to which the participants replied with a no. As the participants responded with a no to all of the related questions, the expert system provided the user with the

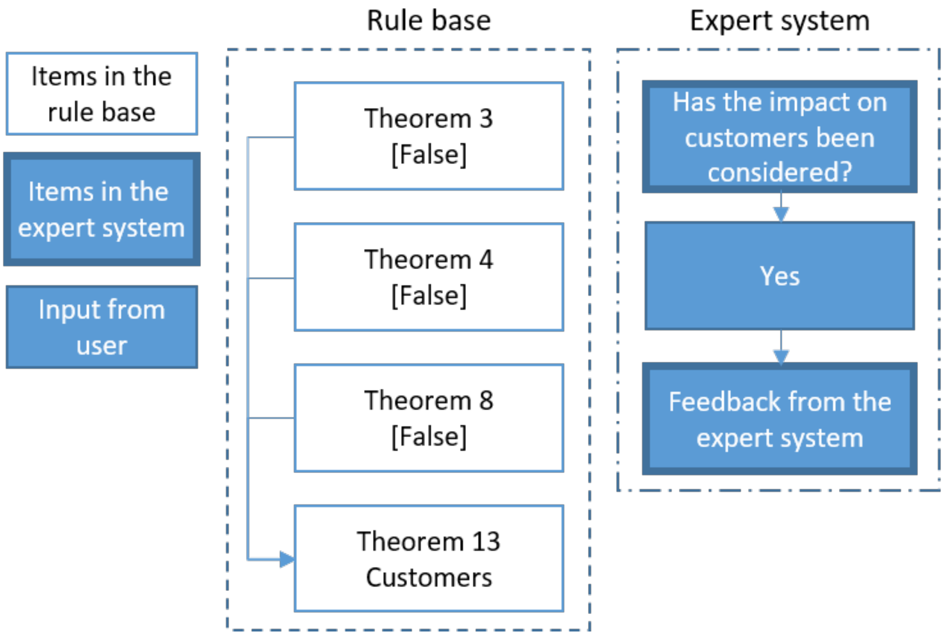

Figure 6.6: Workings of question 2, case study 2

feedback that they needed to address integration, system of systems and gather data from one or more sources.

The third question which will be further discussed is on the impact of Industry 4 on skills. The participants responded affirmatively to that question. The system, however, provided the users with the responses that a system of systems is required and new production methods should be considered. The proof to the respective theorem (Theorem 19) is based on the system of systems theorem and the new production method theorem. As the participants responded with a no to the questions that are linked to those theorems, the expert system provided the feedback that system of systems is required and new production methods should be considered.

Finally, the participants stated that the impact of Industry 4 on the mindset was still to be considered. As before, as the participants responded to the question with a no, that answer overwrites the rules in the expert system and prompts the system to respond with the statement that Industry 4 requires a new mindset. The proof of the respective theorem, Theorem 21, concludes the rule base and is therefore based on several theorems in the rule base, such as the theorems on systems of systems and new business models. Had the participants responded to the mindset question affirmatively, the mindset theorem had been deemed false as the participants answered a number of question with a no, including the theorems on integration and new production methods. The expert system, therefore, would have provided relevant feedback.

The second case study demonstrated that the rule base can be applied in a manufacturing company. The participants answered twelve questions with a no which implies that the company has not reached Industry 4 yet. The answers from the expert system were in line with how the participants viewed Industry 4 within the organisation. The results from the expert system can guide the company on how to navigate the implementation of Industry 4 and help them understand Industry 4. The key characteristics are mapped in the rule base and the expert system is based on the rule base. The expert system provides the user with feedback on what features of Industry 4 have not been addressed and, therefore, helps the company to navigate Industry 4.

6.5 Evaluation of the case studies

This section evaluates the rule base against the four evaluation aspects, that is completeness, soundness, utility and applicability. Subsections 6.5.1 and 6.5.2 discuss the soundness and completeness of the rule base, respectively. Subsection 6.5.3 reviews the utility of the rule base and Subsection 6.5.4 discusses its applicability.

6.5.1 Soundness

As discussed in Section 6.3, the expert reviewed the soundness of the rule base. The expert assessed the rule base sound with the exception of for Theorems 3, 4, 7, 9 and 16. These theorems and their respective proofs were reviewed and edited based on the feedback. The rule base presented in this Thesis is thus considered being sound.

6.5.2 Completeness

The expert stated that the axioms captured the key attributes of Industry 4. The expert agreed that data, connectivity and analytics are the key attributes of Industry 4 which lead to greater insight about processes and therefore actionable decisions. The expert stated that the action based on insight was lacking in the axioms, meaning that action based on the data gathered and analysed was missing. However, Axiom 1 states that "Industry 4 is principally characterised by advanced data analytics within connected data-driven industry". The final part of the axiom, data-driven industry, refers to the action based insight the expert was referring to. The axiom was, therefore, deemed complete.

As for the completeness of the rest of the rule base, the expert stated that the rule base was complete. The expert questioned whether decentralisation was necessary and where the analysis comes into the rule base. In the version provided to the expert, "processing" was used instead of "analysing". That was changed in the version featured in this Thesis. The expert noted that supply-chain integration "does not really come through". That was misinterpretation as supply-chain integration is referred to as horizontal integration in the rule base. The expert, furthermore, noted that the proofs followed logical reasoning to an extent. The expert provided feedback on where the proofs should be improved. The version of the rule base presented in this Thesis features the improved version of the rule base where the logical reasoning of the proofs has been improved upon.

The case studies were evaluated after the rule base was reviewed based on the feedback from the expert. As the rule base was not developed for a device, no meaningful conclusion on its completeness can be drawn from case study 1. The participants in the second case study that the questionnaire that they were provided with was complete with regards to the implementation of Industry 4. The questionnaire contained questions from the expert system. As the expert system was based on the theorems in the rule base, it can be inferred that based on that feedback, the rule base is complete.

6.5.3 Utility

To address the issue of implementing Industry 4, the utility of the rule base was evaluated. In this Thesis, the term utility is referred to as the usefulness of the rule base (refer to Chapter 2 for further details).

Case study 1 showed the usefulness of the rule base on a small scale. It showed that the rule base can be used to evaluate the Industry 4 level of a device. It can also be used to improve the design as the rule base provides the user with high-level feedback on how to improve the design.

The employees of the company in Case study 2 stated that a high-level framework, like the rule base presented in this Thesis, would be beneficial for the implementation of Industry 4 at the company. Employee A stated that it allowed the transformation to be mapped out with all the required factors and variables. That is valuable as the company is starting their digital journey and it is, therefore "easy to miss something". Employee B noted that the rule base would "allow people to take a step back from their view of Industry 4" and consider the bigger picture. They also noted that the implementation of Industry 4 required a high-level framework that "drives the needs and details the needs". The employees stated that the rule base identified all the required factors required for a high-level approach. They mentioned that the rule base is broad enough and especially noted the value of considering "the mentality culture" as it can often be overlooked. From the employees' responses, it can be inferred that the rule base is useful for the company to assist them in identifying the key factors needed to implement Industry 4.

The two case studies detailed in this chapter demonstrate the utility of the rule base.

6.5.4 Applicability

To evaluate the extent to which the rule base can be applied, the applicability of the rule base was evaluated. Even though the first case study was paper-based, it shows that the rule base can be applied on a device to assess the level of Industry 4 implementation. It is worth noting that some of the questions, and therefore theorems, did not directly apply to the first case study, such as the skill set and worker theorems, however, the aim of the first case study was to apply the rule base on an example for an initial evaluation.

Case study 2 demonstrated that the rule base can be applied in a manufacturing company. Employee A and B found the questions relevant to the company and stated that it could be applied in the company to aid the implementation of Industry 4. The two case studies, therefore, exhibit that the rule base can be applied both on a device scale as well as in a manufacturing company.

6.6 Summary

This section discussed the four aspects of the rule base that were evaluated in this research, that is soundness, completeness, utility and applicability. The completeness and soundness of the rule base were evaluated through expert review. The review revealed that six of the theorems and their respective proofs required further work. Those theorems and proofs were updated based on the feedback from the reviewer. The reviewer stated that the rule base was complete. Based on that, the version of the rule base that is presented in this Thesis is both sound and complete. As for utility and applicability, two case studies were performed to assess those aspects of the rule base. The first case study was paper-based, using a device that was designed to upgrade legacy equipment. The second case study was done at a manufacturing company in the UK. The outcome of the two case studies revealed that the rule base can be applied to a device as well as in a manufacturing company. They furthermore exhibited the utility of the rule base.

Chapter 7

Critical discussions

As noted in the literature review, Chapter 3, Industry 4 has yet to be commonly defined. Moreover, industry is struggling to implement Industry 4. The research documented in this Thesis aimed to address these issues by developing a formal logic framework for the implementation of Industry 4. A rule base which uses an axiomatic approach, presented in Chapter 5, was developed to answer the research question. The rule base was evaluated through case studies and an expert review, as presented in Chapter 6. This chapter presents the discussions of the research. Section 7.1 presents the research findings, research methods are reflected upon in Section 7.2 and the overall approach is discussed in Section 7.3.

7.1 Research findings

This section will reflect upon the findings of the analysis of the literature review (Subsection 7.1.1), followed by a discussion on the rule base that was developed for this Thesis (Subsection 7.1.2).

7.1.1 Key characteristics of Industry 4

The key characteristics were identified in Chapter 4. The analysis led to the identification of five main characteristic clusters. These clusters are data, technologies, connectivity, business and manufacturing.

Lasi et al.[7] and Maier[57], amongst others, have identified the key characteristics of Industry 4. However, the key characteristics of Industry 4 were identified in this Thesis by analysing a broad scope of literature from various sources, including academic papers, industrial reports and Industry 4 case studies.

Industry 4 is a growing field, both in academia as well in industry and on a nation-wide scale. It is, therefore, important to include literature from every aspect of Industry 4, as was done in this research, to identify the key characteristics of Industry 4.

The analysis is a cornerstone of the rule base as the categories of the rule base are based on the clusters identified in the analysis. Furthermore, many of the theorems in the rule base were identified in the analysis of the literature. The theorems aid companies to identify the high-level factors of Industry 4 they need to consider before starting considering the technological aspect of Industry 4.

The key characteristics enable organisations to implement Industry 4 as they pinpoint the factors required. They facilitate further research and could be used to identify new parts of Industry 4 or even factors that are outside the scope of Industry 4. The emergence of new characteristics could indicate that industry is moving on from Industry 4 towards the next revolution. Japan has already moved on to what they refer to Society 5 [19] and industry is already speculating how the next revolution will entail [203,209].

The key characteristics could have been identified through other means, such as by interviewing key personnel in the field. However, identifying the key characteristics through a literature review was considered a better approach considering that it allowed the researcher to gather information from a wider perspective. That is important as to realise Industry 4, the effort of various actors is required as discussed earlier in this section.

The disadvantage of the analysis is that it was carried out by one researcher, that is the author of this Thesis. The analysis may, therefore, be biased. However, that concern was mitigated in the expert evaluation where the expert was asked whether the rule base contained all the required clusters. Due to the constraints of this PhD research, the analysis does not give a comprehensive analysis of Industry 4. The literature review focused on Industry 4 in a manufacturing setting, and in-depth review of Industry 4 with regards to, for example supply chain and distributed systems (blockchain) was therefore not included.

7.1.2 Formal logic rule base for Industry 4

As identified in the literature review (Chapter 3), enterprises are struggling to successfully implement Industry 4 and there are many challenges associated with Industry 4. A rule base for the implementation of Industry 4 was, therefore, developed to address this issues. The rule base presented in Chapter 5 formalises the implementation process by offering a formal logic rule base. The rule base is based on two axioms which were identified through the literature review and its analysis. The rule base furthermore has 21 theorems which are derived from the literature and proved in a logical way. By using an axiomatic approach with formal logic, the rule base creates a space to create and evaluate solutions, referred to as the universe in this Thesis.

Various frameworks have been proposed for the different aspects of Industry 4. However, Industry 4 has not been modelled with formal logic before. First-order logic can be used to articulate facts and provide an understanding of the facts[96]. First-order logic has been widely used within the field of engineering to resolve issues and deepen understanding as noted in the literature review. By using logic, the rule base it lends itself to be cast to a digital solution as exhibited in this Thesis. The rule base was translated into an expert system which allows for automated inference of the rules.

The rule base is based on an axiomatic approach, like the axiomatic design methodology by Suh[185]. As Adams[210] noted, the axiomatic design methodology has several critical attributes. Amongst these attributes are consistency, rigorous, neutrality, transportable and guide to action. These attributes were proposed by Adams and Keating[25] amongst four others to evaluate sustainability of a methodology. As the axiomatic design methodology, the rule base presented in this Thesis meets these criteria. The rule base is based on formal logic which ensures that the results are consistent. The rule base uses an axiomatic approach and formal logic which ensure rigour. As for neutrality, the rule base is designed in such way that it tries to minimise external influences by being transparent and strive to eliminate bias. As the case studies show, the rule base can be applied to a variety of domains, which fulfils the transportable attribute. Finally, the rule base can be used to guide companies with the implementation of Industry 4 as case study 2 exhibits.

The evaluation of the rule base demonstrated that Industry 4 can be modelled with formal logic. The expert, who has years of experience both in industry and academia, stated that the rule base was sound and complete. As the participants in the second case study noted, the rule base is beneficial for the implementation of Industry 4 in the company they work for and it ensures that all the relevant factors are considered. That is in line with what Adams[210] stated about the axiomatic design methodology as discussed above.

Compared to existing frameworks, such as the 5C architecture developed by Lee et al.[11] and the RAMI4.0 framework[58], the rule base shares some similarities. For example, RAMI4.0 is built on three dimension, that is the product life cycle, business layer and the hierarchical level which may be interpreted as the connectivity level[58]. The rule base considers all these factors, although it approaches it from a different angle to RAMI4.0. The axioms encompass the three dimensions of the RAMI4.0 model as the axioms both incorporate the connectivity aspect as well as the business aspect of Industry 4. The axioms cover those aspects on an abstract level, however, the theorems cover them on a less abstract level. As for the 5C framework, Axiom 1 states that Industry 4 is in connected, data driven industry which is the basis of the 5C framework. However, as the rule base identifies the key factors for the implementation of Industry 4, it cannot be compared to the 5C framework on a detailed level.

The rule base offers numerous opportunities. The rule base can both test solutions for Industry 4 compatibility guide companies with the implementation of Industry 4 as demonstrated with the case studies (Chapter 6). It can do so either manually or in an automated way through the expert system. Furthermore, the rule base could create new Industry 4 solutions if it was combined with artificial intelligence. It could also be used to identify the boundaries of Industry 4 and, therefore, identify new trends that are beyond Industry 4.

The rule base identified the links between the key characteristics through the proofs. That can guide and influence future research by creating a map of the relationships between the characteristics of Industry 4.

The rule base is in its nature modular and expandable. That was partially demonstrated the first case study where only part of the questions in the expert system where applicable. However, the rule base can be changed so it is more applicable to be applied to devices. Moreover, the extent of the rule base can be extended to other industries as well as extend the initial scope of the rule base within the manufacturing industry. That could include incorporating different elements of Industry 4, such as more details on the supply chain as well as distributed systems.

A feature of the rule base is that it uses first-order logic which only accepts either true or false values. The world, and Industry 4, however, is not binary, and other types of logics may have been better suited for the application of the rule base. The primary focus of the research conducted for this Thesis was on

Industry 4 and whether it could be described using formal logic. The logic of choice was, therefore, first-order logic.

As discussed in the section above, the scope of the literature reviewed was limited, resulting in a limited scope of the rule base. However, it was considered not within the scope of the Thesis to include every aspect of Industry 4. The rule base, therefore, focuses on Industry 4 within a manufacturing setting.

7.2 Research methods

As discussed in Chapter 6, two main research methods were applied for this research, that is data collection and data interpretation. The advantages and disadvantages for each methods are discussed below. Subsections 7.2.1 and 7.2.2 discuss the literature review and its analysis, respectively. The case studies are discussed in Subsection 7.2.3 and a discussion of the expert review is presented in Subsection 7.2.4.

7.2.1 Literature review

The rule base was developed based on a thorough literature review which was presented in Chapter 3. Literature was gathered from four main sources, that is academic papers, industrial case studies, governmental initiatives and industrial reports. The literature review was analysed in Chapter 4 to identify the key characteristics of Industry 4.

The strength of the literature review is that papers from various sources were reviewed. In typical literature reviews conducted for PhD research, researchers focus on academic sources. In this Thesis, however, a broader scope of sources was considered. By reviewing papers from various sources, a more holistic view of Industry 4 was gained as it is both a research field in academia and has an increasingly growing existence in industry.

Due to the vast scope of Industry 4, the literature investigate in this research cannot be completely exhaustive. The scope of the literature review was limited to Industry 4 in manufacturing environments and international initiatives, and was comprehensive within the scope. By limiting the scope to manufacturing environments, enabled the researcher to investigate that aspect of Industry 4 in a more thorough manner.

The literature review was performed by one researcher, that is the author of this Thesis, which are natural limitations of a Thesis. The process followed for the literature review was primarily non-systematic, as discussed in Chapter 2. The literature review may, therefore, be subject to bias, however, as the rule base was evaluated by an independent reviewer which mitigated the risk of bias to an extent. It is worth mentioning that the pragmatist view on ethics and values allows the researcher to be biased as discussed in Chapter 2. Nevertheless, the literature review could have been addressed in a more rigours manner by following a systematic review process and/or involving another researcher. A systematic literature review aims to minimise the bias by following a rigorous process to gather and analyse academic papers on a predefined topic. The process is transparent and replicable by other researchers. Due to the extent of papers required to be reviewed for systematic reviews, they typically require more than one researcher. That would have been difficult as PhD researchers typically have limited access to resources.

By not following a systematic process enabled the researcher to review a broader scope of literature types as the literature was not limited to high-quality journal papers. As Industry 4 is both an academic as well as industrial topic, various types of literature are required to be investigated to acquire an in-depth review of the topic. The decreased scope of Industry 4 presented in this Thesis allowed the PhD researcher to focus more on the various aspects of Industry 4 within manufacturing.

7.2.2 Literature analysis

The literature review was analysed in Chapter 4 to identify key characteristics of Industry 4. The analysis led to the identification of five main clusters of Industry 4 and influenced the axioms and theorems in the rule base.

The analysis was performed by the PhD researcher alone and may, therefore, be biased. However, as the worldview of pragmatism was adopted for this research which allow the research to be influenced by the researcher's beliefs and doubts.

Multi-methods were used for conducting the analysis, that is both statistical analysis of the literature review as well as word analysis of the papers reviewed in the literature review. The results of those two approaches were compared against each other.

The literature review includes both an exploration of the literature within the field as well as an analysis of the literature gathered. A total of twenty different frameworks and sixteen case studies were reviewed in the literature review. About 50 papers were reviewed on concepts, benefits, barriers and believes on Industry 4. In this Thesis, the analysis of the literature was conducted separately to the gathering of the literature. That was done to allow for more in-depth analysis of the literature to address Objective 2a, which was to analyse Industry 4 literature to identify its key characteristics.

7.2.3 Case studies

Two case studies were performed to evaluate the rule base. The first case study was paper-based while the second one was performed at a manufacturing company. The case studies aimed to evaluate the applicability and utility of the rule base.

The first case study was primarily performed as an initial evaluation of the rule base. As the case study was paper-based, it provided limited scope. Furthermore, as the case study was conducted on a device, it could only evaluate parts of the rule base. However, it allowed for an initial evaluation that exhibited that the rule base can be applied on a device level with some limitations.

The second case study that was performed at a manufacturing company in the UK provided a more in-depth evaluation of the rule base. That case study evaluated the entire rule base as opposed to the first one that did not do so as the rule base was developed to be applied to manufacturing companies.

The advantage of performing the case studies on both a device level as well in a company is that the evaluation displayed the potentials of the rule base. Even though the rule base has been evaluated, it might be beneficial in the future to perform more case studies in different sectors and different sized companies. The company that participated in the second case study is a large enterprise. More evaluation is therefore required to exhibit that the rule base can be applied in SMEs as well.

7.2.4 Expert review

The soundness and completeness of the rule base were evaluated by a field expert. The expert was provided questionnaires to complete. Following the completion of the questionnaires, the PhD researcher had a meeting with the expert to follow up on any questions and minimise the risk of any confusion. The advantages of the expert review are that the expert has years of experience in the field of digital technologies and is an independent reviewer.

An alternative method to expert review could have involved an expert workshop or involving more than one expert. An expert workshop would have led to more breadth of evaluation and could be considered for future evaluation.

7.3 Overall approach

This research addressed the research question whether Industry 4 can be described with formal logic for the implementation of Industry 4 as it is not yet formally defined, and industry is having difficulties with successfully implementing Industry 4. The research is, therefore, guided by a research problem identified in the literature, and it aims to develop a practical solution to the problem. The worldview of pragmatism was, therefore, adopted for this research owing to the reasons mentioned above. Pragmatism allows for adopting a wide scope of methods, including quantitative and qualitative as well as multi-methods. The research conducted for this Thesis used various methods and was primarily qualitative, although quantitative methods were also used.

A pragmatist recognises that the world can be understood and interpreted in several ways. A wide range of literature was selected for the literature review, that is academic papers, industrial case studies and reports as well as governmental reports. That led to a broad view of Industry 4 which allowed the researcher to analyse Industry 4 to identify its key characteristics. The key characteristics formed the basis of the rule base.

The rule base developed in Chapter 5 provides a practical solution for the future implementation of Industry 4 as it can test and describe Industry 4 solutions. The rule base was evaluated with two different methods, that is an expert review and case studies.

The methods used in this research were selected on the basis that they provided a means to form practical solution to a known problem. For example, the analysis led to the identification of key characteristics of Industry 4 and the evaluation methods demonstrated the applicability of the rule base. As noted in the literature review, Industry 4 was not formally defined yet and industry was having difficulties implementing it. The evaluation methods demonstrated that the rule base is useful for the implementation of Industry 4 in manufacturing environments. The methods, therefore, contributed to a practical solution and demonstrated the relevance of the solution developed in this research.

Pragmatism focuses on problem solving, with a special emphasis on outcomes and solutions that are practical. A pragmatist researcher is, furthermore, reflexive and the research is influenced by the researcher's doubts and believes. The rule base presented in this Thesis provides a practical solution to resolve issues with the implementation of Industry 4. The research was also influenced by the researcher's doubts and believes, which is reflected in, for example the theorems, and selection of literature. Based on that, and reasons mentioned above, this research successfully followed the worldview of pragmatism. Moreover, pragmatism proved to be a suitable philosophical stand for the research presented in this Thesis.

Chapter 8

Conclusions

The research presented in this Thesis creates a formal logic framework for the description and implementation of Industry 4.

The primary and secondary contributions to knowledge are:

Contribution 1: Rule base for describing and evaluating formally the implementation of Industry 4 solutions in manufacturing.

Contribution 2: Key characteristics of Industry 4

The Thesis is concluded in this chapter by a summary of the research approach (Section 8.1), contributions (Sections 8.2-8.4) and the evaluation of the rule base (Section 8.5). Advantages and disadvantages of the research and proposed future work are presented in Sections 8.6 and 8.7, respectively.

8.1 Research approach

The research presented in this Thesis aimed to answer a research question related to a research problem. Pragmatism was, therefore, adopted as a worldview for this research, as discussed in Chapter 2. The research methodology adopted for this research was mainly qualitative and multi-methods.

The primary source of data was literature on Industry 4, both academic papers as well as industrial and governmental reports. The literature review was analysed using both analytical software as well as a statistical approach. The analysis led to the identification of the key characteristics of Industry 4. The outcome of the analysis was used as the basis for the development of the rule base. The rule base was evaluated based on its soundness, completeness, utility and applicability through case studies and an expert review.

8.2 Review of Industry 4

Existing research and knowledge on various aspects of Industry 4 was reviewed in Chapter 3. Industry 4 and related terms were reviewed in Section 3.2 followed by an overview of emerging technologies and their relevance to Industry 4 (Section 3.3). Various international initiatives related to Industry 4 and existing academic frameworks for the implementation of various aspects of Industry were presented (Sections 3.4 and Section 3.5, respectively). Case studies on the implementation of Industry 4 in industries were examined as well as the benefits and barriers associated with Industry 4 (Sections 3.6 and 3.7).

The review of the literature Industry 4 led to the identification of issues associated with Industry 4 and its implementation, which this research aims to address. The literature review revealed that although various industries have already started implementing Industry 4, they are struggling. Furthermore, the definition of Industry 4 and its key characteristics have not yet been widely accepted. Consequently, the literature review conducted for this research addressed Objective 1a-c, that is to identify issues industry and academia are facing with regards to Industry 4.

The research question was defined based on the issues detailed above; that is: *whether Industry 4 can be modelled with formal logic for the description and implementation of Industry 4.*

8.3 Analysis of Industry 4

The literature from Chapter 3 was analysed in Chapter 4 to identify the key characteristics of Industry 4 (Objectives 1a-c). The analysis led to the identification of five key themes that were consequently addressed in the rule base. These themes are data, technologies, connectivity, business and manufacturing. The outcome of the analysis moreover identified sub-themes that were transferred to theorems and lemmas in the rule base.

8.4 Axiomatic Universe for Industry 4

To answer the research question, a rule base for the implementation of Industry 4 was developed through a literature review and literature analysis. The rule base, which is presented in Chapter 5, focuses on manufacturing environments and uses formal logic and an axiomatic approach.

The rule base is based on axioms, theorems and lemmas. Two axioms were identified through the literature review and its analysis, and they are the basis of the rule base. The first axiom states that Industry 4 is principally characterised by advanced data analytics within connected data-driven industry. The second axiom states that a principal characteristic of Industry 4 is its intend and ability to improve company competitiveness. Based on the outcome of the analysis, 21 theorems and lemmas from the themes discussed in the previous section. The theorems and lemmas were a result of the findings of the analysis as well as the author's interpretation of the literature review and its analysis. The development of the rule base addressed Objective 2b which focused on establishing the dependencies between the characteristics identified in the analysis to form a framework.

The rule base was developed using an iterative process. The knowledge gained from the literature review and the analysis was used to identify links between the characteristics. Each version of the rule base was then reviewed the by PhD researcher and an academic field expert. The rule base presented in this Thesis is based on the findings of the evaluation (Objective 3d).

An expert system that was based on the rule base was developed for a practical application of the rule base. The expert system was programmed using the programming language CLISP which a dialect of the Lisp programming language. The system asks the user a set of questions which are based on the theorems and lemmas in the rule base and provides the user with answers based on the user's input. Consequently, the creation of the expert system addresses Objective 3a which was to establish automatic inference of the rule base.

The rule base formalises Industry 4 by identifying the key characteristics of Industry 4 and establishes dependencies between the axioms and other elements of Industry 4.

8.5 Evaluation of the rule base

The rule base was evaluated by an academic expert (Section 6.3) and by performing two case studies (Section 6.4). The expert was provided with questionnaires to evaluate the rule base. The first case study was a paper-based case study using a device for upgrading legacy equipment, whereas the second case study was performed at a manufacturing company in the UK. The software developed in Chapter 5 was used for the evaluation of the case studies.

The evaluation of the rule base fulfils Objectives 3b-c. The case studies performed for the evaluation applied the rule base in presentative industrial setting and the rule base was improved upon based on the feedback from the academic expert.

To evaluate the rule base, four characteristics of the rule base were assessed:

- **Soundness**: Refers to which degree the theorems and their respective proofs are true.
- **Completeness**: Refers to the adequacy of the rule base, that is whether it encompasses the key characteristics of Industry 4.
- **Utility**: Refers to the usefulness of the rule base, that is how successfully it helps with the implementation of Industry 4.
- **Applicability**: Refers to the extent the rule base can be applied.

The findings of the evaluation were provided in Chapter 6 and discussed in details in Chapter 7. The major findings of the evaluation with regards to the rule base's soundness, completeness, utility and applicability are provided below:

Soundness:

- Expert A found the majority of theorems and lemmas to be sound.
- The theorems the expert found not to be sound were revised according to the feedback and are now considered being sound.

Completeness:

- The expert found the rule base to be complete.
- The case studies, although not designed to evaluate the completeness of the rule base, demonstrated that the rule base is complete.

Utility:

- The case studies exhibited the usefulness of the rule base.
- Case study 1 showed that the rule base can be used to describe an Industry 4 device, whereas case study 2 demonstrated that the rule base can be used to test an Industry 4 solution.
- The participants in case study 2 stated that a rule base would be beneficial for the implementation of Industry 4 in the organisation.

Applicability: Case study 1 showed that the rule base can be used to describe an Industry 4 device, whereas case study 2 demonstrated that the rule base can test an Industry 4 solution with respect to its Industry-4 compliance.

Based on the feedback from the expert reviewer, the rule base was reviewed and appropriate changes made on the rule base. The version presented in this Thesis is the reviewed version. Chapter 6 discusses the changes that were made on the rule base after the evaluation.

8.6 Advantages and limitations

The advantages and disadvantages of the research were discussed in Chapter 7, however, a brief overview will be provided in this section to fulfil Objective 4 which was to determine advantages and limitations and explore potential future work. The key characteristics have been identified in this research which will help both companies and academics alike to implement and research Industry 4. The rule base enables companies to identify the key factors needed for the implementation of Industry 4.

An expert system was developed for a practical application of the rule base. The system enables an automated inference of the rule base, resulting in improved utility of the rule base. Even though there are benefits of using an expert system for this application, expert systems have their limitations. They work best on problems that have predefined scope and unlike technologies such as AI, they cannot "think" for themselves, leading to the system to be static. That might lead to wrong decision making by the system if there is an error in the knowledge base. The expert system, moreover, relies on the input from the user to be right. If the user inputs inaccurate information, the system will give the user feedback based on the information provided to the system. Moreover, it only takes yes/no answers, which is due to the selection of logic which leads to a finite number of answers. Finally, the system only provides the user with answers if the user answered any of the questions negatively.

As the rule base approaches Industry 4 from a high level and focuses on the bigger picture, it may not influence directly which technologies should be implemented. Rather, it identifies the higher-level characteristics of Industry 4 that companies should consider before embarking on their Industry 4 journey. Once those factor have been identified and considered, lower-level factors, such as technologies, can be considered.

As discussed in Chapter 7, the rule base is modular and expandable. Elements of Industry 4 that were not included in this research due to its scope can, therefore, be incorporated. Moreover, the rule base can be changed so that it can applied in different scenarios, such as other industries and on a device level.

For the development of the rule base, first-order logic was used. For this research, that was deemed sufficient. However, first-order logic is limited as it only accepts absolute answers, that is either true or false. That restricts the user input as the reality might not be binary and may lead to the outcome of the rule base to not be as accurate as desirable. Other types of logics, such as fuzzy logic provide the option of taking values that are, to some degree, true.

An axiomatic approach has the advantages of providing a guide to action with a rigorous, consistent system, however, there are limitations to using the approach as well. As Gödel noted, there are truths in axiomatic systems that cannot be proved[31]. For the axiomatic universe for Industry 4, that means that there are solutions that cannot be proved with the rule base, even though they are within the space.

Another limitation to the work presented in Thesis is only one expert review was conducted to evaluate the soundness and completeness of the rule base. As only one expert review was conducted, the expert was carefully selected to limit the risk of having only one expert. However, a limitation of the expert review is that the expert may have been biased or misunderstood aspects of the rule base. Moreover, as the expert was from an academic background, the expert might lack knowledge of e.g. industrial culture, challenges and limitations to evaluate the soundness and completeness of the rule base.

8.7 Future work

The rule base was evaluated by an academic field expert and two case studies, a paper-based case study and one conducted at a manufacturing company. The applicability of the rule base is therefore limited to the manufacturing sector and device application. Further research is required to assess the broader applicability of the rule base.

The rule base is based on the five themes identified in the analysis (Chapter 4). As the literature review focused on the application of Industry 4 in a manufacturing setting, other aspects of Industry 4 were not examined, such as Cryptocurrency, sustainability and people (though people were included in the rule base to some extent). The rule base is therefore limited to the manufacturing aspect of Industry 4.

Future work could include expanding the scope of the rule base and therefore expanding the applicability if the rule base. It could also involve using a more advanced type of logic, such as fuzzy logic, which allows for a broader scope of input. The software could be developed further by, for example, adding a database with answers from other companies and their Industry 4 solutions. Moreover, by adding artificial intelligence to the software, the system could provide the user with possible solutions. Finally, domain experts could update the rule base, that is the axioms and theorems.

With regards to the evaluation of the rule base, future work could include performing more expert reviews with experts from both academia and industry. It could also include using the rule base to propose a device or technology, in an addition to the evaluation that was done for this research.

As demonstrated in this Thesis, the rule base can successfully model Industry 4 and guide companies with the implementation of Industry 4. The potentials of the rule base can be expanded even further with the proposals of future work listed in this section.

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Appendices

Appendix A

The table presented in this appendix is the result of the word count analysis which is portrayed in Section 4.2.1. The word count analysis was done in NVivo and provides the 100 most frequently used words in the papers reviewed.

Word	Length	Count	Weighted Percentage (%)	Similar Words
manufacturing'	14	7712	1.25	manufactur, manufacturability, manufacture, manufactured, manufacturer, manufacturers, manufacturers', manufactures, manufacturing, 'manufacturing, manufacturing', manufacturing''
industry	8	7122	1.15	industrial, industrialization, industrialize, industrialized, industrials, industrie, 'industrie, industries, industries', industrious, industry, industrys
system'	7	5919	0.96	system, system', systeme, systemic, systemically, systemization, systemize, systems, systems'
data'	5	5663	0.92	data, data', data'can
product'	8	5225	0.84	product, product', production, productions, productive, productively, productivity, productivity', products, products'
technology	10	5207	0.84	technologi, technologic, technological, technologically, technologies, technologies', technology, technology', technology''6
using	5	3558	0.58	use, 'use, use', use'', used, useful, usefulness, uses, using
servicing	9	3546	0.57	service, service', serviceability, serviced, servicers, services, services', services'', servicing
processing	10	3073	0.50	process, process', processed, processes, processes', processes', processing
develops	8	2857	0.46	develop, develop't, developed, developer, developers, developing, development, development', developments, develops
network''	9	2814	0.46	network, network', network'', networked, networking, networks
clouds	6	2792	0.45	cloud, cloud', cloud'', clouding, clouds
computing	9	2742	0.44	comput, computation, computational, computationally, computations, compute, computed, computer, computers, computes, computing, computing''
applications	12	2714	0.44	applicability, applicable, applicant, applicants, application, applications, applications', applicators
smart''	7	2475	0.40	'smart, smart, smart', smart'', smartly, smartness, smartness', smarts, smarts'
researching	11	2414	0.39	research, researched, researcher, researchers, researchers', researches, researching
informing	9	2400	0.39	inform, informal, information, informational, informative, informed, informer, informing, informs
new	3	2383	0.39	new
iots	4	2381	0.38	iot, iot@, iots
model'	6	2362	0.38	model, model', modeled, modeling, modelization, modelled, modelling, models, models'
bases	5	2341	0.38	base, based, based', bases, basing
providing	9	2269	0.37	provid, provide, provide'', provided, providence, provider, providers, providers', provides, providing
designs	7	2113	0.34	design, designated, designation, designations, designed, designer, designer'', designers, designers', designing, designs
busy	4	2085	0.34	busi, business, business', business'', businesses, businesses', busy
integrity	9	2048	0.33	integr, integrability, integral, integrate, integrated, integrates, integrating, integration, integration', integrations, integrative, integrator, integrators, integrity
managing	8	1908	0.31	manag, manage, manageable, managed, management, manager, managers, managers', manages, managing

community	9	1845	0.30	commun, communic, communicate, communicated, communicates, communicating, communication, communicational, communications, communicativeness, communities, communities’, community
support	7	1808	0.29	support, support’, supportability, supported, supporter, supporters, supporting, supportive, supports
timing	6	1790	0.29	time, time’, timely, times, timing, timings
resources’	10	1769	0.29	resource, resourced, resourceful, resources, resources’, resources’’, resourcing
security	8	1727	0.28	secur, secure, secured, securely, secures, securing, securities, security
digitally	9	1721	0.28	digit, digital, digitalization, digitalization’, digitalize, digitalized, digitally, digitization, digitize, digitized, digitizing
physics	7	1714	0.28	physical, physicalizing, physically, physics
machining	9	1691	0.27	machin, machinability, machine, machined, machines, machines’, machining
company	7	1684	0.27	companies, companies', companies’, company, company’suse
requirements	12	1676	0.27	require, required, required’, requirement, requirements, requires, requiring
needs	5	1607	0.26	need, needed, needing, needs
internet’	9	1595	0.26	internet, internet’, internet’’, internets
operator’	9	1582	0.26	oper, operability, operable, operate, operated, operates, operating, operation, operational, operationally, operations, operations', operations’, operative, operatives, operator, operator’, operators, operators', operators’
engines	7	1580	0.26	engine, engineer, engineer’, engineered, engineering, engineers, engineers’, engines
works	5	1569	0.25	work, work’, worked, working, works
controls	8	1567	0.25	control, controllability, controllable, controlled, controlled’, controller, controllers, controlling, controls
devices’	8	1447	0.23	device, device’, devices, devices’
level’	6	1428	0.23	level, level’, levelled, levels
including	9	1419	0.23	include, included, includes, including
innovators	10	1388	0.22	innov, innovate, innovated, innovating, innovation, innovation’, innovations, innovative, innovatively, innovativeness, innovativity, innovator, innovators
users’	6	1360	0.22	user, users, users’
standards’	10	1314	0.21	standard, standardization, standardizations, standardize, standardized, standardizes, standardizing, standards, standards’
challenging	11	1312	0.21	challenge, challenged, challenger, challengers, challenges, challenging
enabling	8	1300	0.21	enabl, enable, enabled, enablement, enabler, enablers, enables, enabling
differs	7	1270	0.21	differ, difference, differences, different, differently, differing, differs
futures	7	1245	0.20	futur, futur’, future, future’, futures
things’’	8	1229	0.20	’things’, thing, thing’, things, things’, things’’
environments	12	1217	0.20	environ, environment, environments
interns	7	1206	0.20	internal, internal’, internally, international, internationally, interns
highly	6	1203	0.19	high, highly
connects	8	1181	0.19	connect, connect’, connected, connecting, connection, connections, connectivity, connects

increasingly	12	1175	0.19	increase, increased, increases, increasing, increasingly
real	4	1149	0.19	real, reales
sensors	7	1141	0.18	sensor, sensored, sensorization, sensorized, sensors, sensors’
advancing	9	1140	0.18	advance, advanced, advancement, advancements, advances, advancing
virtualized	11	1117	0.18	virtual, virtuality, virtualization, virtualize, virtualized, virtualizes, virtualizing, virtualizing’’, virtually, virtually’
making	6	1115	0.18	make, makes, makes’, making
values	6	1110	0.18	value, value’, valued, values, valuing
accessing	9	1103	0.18	access, accessed, accesses, accessibility, accessible, accessing
intelligent’	12	1097	0.18	intelligence, intelligence’, intelligences, intelligent, intelligent’, intelligently, intelligible
one’	4	1092	0.18	one, one’, ones
implements	10	1062	0.17	implement, implementable, implementation, implementations, implemented, implementers, implementing, implements
factory’	8	1057	0.17	factories, factories’, factory, factory’
invests	7	1026	0.17	invest, invested, investing, investment, investments, invests
improving	9	1021	0.17	improv, improve, improved, improvement, improvements, improves, improving
automation	10	992	0.16	autom, automate, automated, automates, automating, automation, automations
big	3	988	0.16	big
relations	9	974	0.16	relate, related, relates, relating, relation, relational, relations, relations’, relative, relatively
strategy’	9	972	0.16	strategie, strategies, strategy, strategy’, strategy’’
example	7	969	0.16	example, examples
costs	5	957	0.15	cost, costing, costly, costs
sectors	7	939	0.15	sector, sector’, sectoral, sectors
cps	3	927	0.15	cps
solutions	9	924	0.15	solution, solutions
capable	7	918	0.15	capabilities, capabilities’, capability, capable
cyber’	6	914	0.15	cyber, cyber’, cyberize, cyberizing
approach	8	911	0.15	approach, approach’, approached, approaches, approaching
platforms	9	909	0.15	platform, platform’, platforms
world’	6	908	0.15	world, world’, worlds
enterprising	12	906	0.15	enterprise, enterpriser, enterprises, enterprises’, enterprising
changing	8	905	0.15	chang, change, change’, changed, changes, changes’’, changing
analysis	8	899	0.15	analysis, analysis’
keys	4	894	0.14	key, keyes, keying, keys

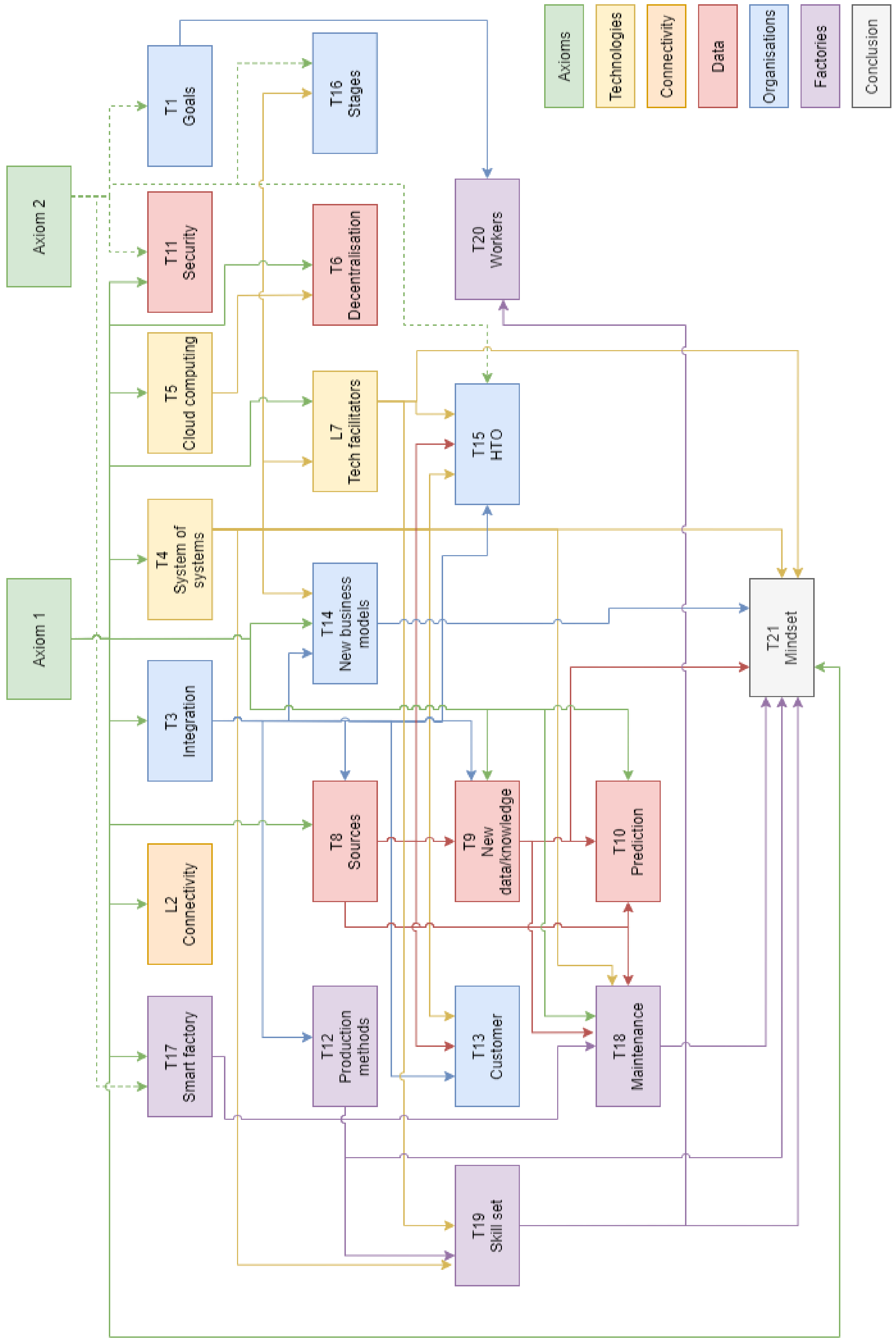
performs	8	894	0.14	perform, performance, performances, performed, performer, performers, performing, performs
customs	7	886	0.14	custom, customer, customers, customers’, customization, customization', customizations, customize, customized, customizing, customs
additives	9	883	0.14	addit, addition, additional, additionally, additions, additive, additively, additives
creating	8	871	0.14	create, created, creates, creating
robots	6	865	0.14	robot, robotic, robotics, robotics’, robotization, robots, robots’
collaborators	13	864	0.14	collaborate, collaborated, collaborates, collaborating, collaboration, collaborations, collaborations’, collaborative, 'collaborative, collaboratively, collaborator, collaborators, collaborators’
markets	7	863	0.14	market, market’, marketable, marketed, marketer, marketers, marketing, markets
interacts	9	861	0.14	interact, interacting, interaction, interaction’’, interactional, interactions, interactive, interactively, interactivity, interacts
architectures	13	850	0.14	architectural, architecture, architectures
tools	5	842	0.14	tool, tooling, toolings, tools, tools’
current	7	833	0.13	current, currently, currents

Appendix B

This appendix features a list of the items in the rule base for reference.

Axiom 1 Data-driven industry
Axiom 2 Improves competitiveness

Theorem 1: Business goals
Lemma 2: Connectivity
Theorem 3: Three-way integration
Theorem 4: System of systems
Theorem 5: Cloud computing is an Industry 4 enabler
Theorem 6: Industry 4 enables decentralisation of data
Theorem 7: Technology enablers
Theorem 8: Industry 4 data sources
Theorem 9: New knowledge and Industry 4
Theorem 10: Data prediction
Theorem 11: Data security in Industry 4
Theorem 12: New production methods
Theorem 13: Role of the customer in Industry 4
Theorem 14: New business models
Theorem 15: Factors for the implementation of Industry 4
Theorem 16: Implementation of Industry 4
Theorem 17: Smart factories in Industry 4
Theorem 18: Impact on maintenance
Theorem 19: Skills gap
Theorem 20: Impact on people in the factory
Theorem 21: New mindset


Axiom 1
Axiom 2
T1 Goals
T11 Security
T5 Cloud computing
T4 System of systems
T3 Integration
L2 Connectivity
T17 Smart factory
T16 Stages
T6 Decentralisation
L7 Tech facilitators
T14 New business models
T8 Sources
T12 Production methods
T20 Workers
T15 HTO
T9 New data/knowledge
T13 Customer
T19 Skill set
T10 Prediction
T18 Maintenance
T21 Mindset
Axioms
Technologies
Connectivity
Data
Organisations
Factories
Conclusion

Appendix C

This appendix presents the expert system which is detailed in Chapter 5 and provides a basis for part of the validation (Chapter 6).

```
;; ===== ;;
;; Facts ;;
;; ===== ;;

(deffacts axioms
   (axiom1)
   (axiom2))

;; ====== ;;
;; Axioms ;;
;; ====== ;;

(defrule Axiom-1
   (axiom1)
   =>
   (assert (Axiom1)))

(defrule Axiom-2
   (axiom2)
   =>
   (assert (Axiom2)))

;;; ========= ;;;
;;; Functions ;;;
;;; ========= ;;;
```

```
;; ========= ;;
;; Questions ;;
;; ========= ;;

[Removed code, please refer to
https://courses.washington.edu/css482/examples/auto.clp
for the function.]

;;; ================== ;;;
;;; Collection of facts ;;;
;;; ================== ;;;

;; ========== ;;
;; Production ;;
;; ========== ;;

(defrule new-mindset ""
   (not (mindset ?))
   =>
   (assert (mindset  (yes-or-no-p "Has the impact of Industry 4
   on skills been considered (yes/no)? "))))

(defrule new-people ""
   (not (people ?))
   =>
   (assert (people (yes-or-no-p "Has the impact of Industry 4
   on people been considered (yes/no)? "))))

(defrule new-skills ""
   (not (skills ?))
   =>
   (assert (skills (yes-or-no-p "Has the impact of Industry 4
   on skills been considered (yes/no)? "))))

(defrule new-maintenance ""
   (not (maintenance ?))
```

```
   =>
   (assert (maintenance (yes-or-no-p "Has the impact of
   Industry 4 on maintenance been considered (yes/no)? "))))

(defrule new-stages ""
   (not (stages ?))
   =>
   (assert (stages (yes-or-no-p "Will Industry 4 be fully
    implemented (yes/no)? "))))

(defrule new-hto ""
   (not (hto ?))
   =>
   (assert (hto (yes-or-no-p "Are humans, technology and
    organisations considered simultaneously (yes/no)? "))))

(defrule new-businessmodels ""
   (not (businessmodels ?))
   =>
   (assert (businessmodels (yes-or-no-p
   "Has the impact of Industry 4 on new business models
   been considered (yes/no)? "))))

(defrule new-customer ""
   (not (customer ?))
   =>
   (assert (customer (yes-or-no-p "Has the impact of
   Industry 4 on customers been considered (yes/no)? "))))

(defrule new-production ""
   (not (production ?))
   =>
   (assert (production (yes-or-no-p "Has the impact
   of Industry 4 on production methods been
   considered (yes/no)? "))))
```

```
;; ==== ;;
;; Data ;;
;; ==== ;;

(defrule data-security ""
   (not (security ?))
   =>
   (assert (security (yes-or-no-p "Is data stored
   in a secure way (yes/no)? "))))

(defrule data-prediction ""
   (not (prediction ?))
   =>
   (assert (prediction (yes-or-no-p
   "Is data used for prediction (yes/no)? "))))

(defrule data-sources ""
   (not (sources ?))
   =>
   (assert (sources (yes-or-no-p
   "Is data from one or more sources gathered (yes/no)? "))))

(defrule data-decentralisation ""
   (not (data-decentralised ?))
   =>
   (assert (data-decentralised (yes-or-no-p
   "Is data decentralised (yes/no)? "))))

(defrule determine-cloud-computing ""
   (not (cloud-computing ?))
   =>
   (assert (cloud-computing (yes-or-no-p
   "Has cloud computing been implmented (yes/no)? "))))

;; ================= ;;
;; Recursive systems ;;
```

```
;; ================= ;;

(defrule systems ""
   (not (systems ?))
   =>
   (assert (systems (yes-or-no-p "Are the systems
    interconnected(yes/no)? "))))

;; ==================== ;;
;; Goal and integration ;;
;; ==================== ;;

(defrule integration ""
   (not (integrated ?))
   =>
   (assert (integrated (yes-or-no-p "Has the factory/object
   been integrated vertically, horizontally
   and end-to-end (yes/no)? "))))

(defrule connectivity""
   (not (connectivity ?))
   =>
   (assert (connectivity (yes-or-no-p "Has connectivity
   been established in the factory (yes/no)? "))))

(defrule businessalign""
   (goal yes)
   (strategy yes)
   =>
   (assert (businessalign (yes-or-no-p
   "Does the strategy and goals align with the business goals
   and strategy (yes/no)? "))))

(defrule strategy""
   (not (strategy ?))
   =>
```

```
   (assert (strategy (yes-or-no-p "Is there strategy
   in place for the implementation of I4 (yes/no)? "))))

(defrule goal""
   (not (goal ?))
   =>
   (assert (goal (yes-or-no-p "Are there goals in place
    for the implementation of I4 (yes/no)? "))))



;;; ======== ;;;
;;; Theorems ;;;
;;; ======== ;;;

; --------- ;
; Theorem 1 ;
; --------- ;

(defrule Theorem1a
   (Axiom1)
   (goal yes)
   (strategy yes)
   (businessalign yes)
   =>
   (assert (Theorem1)))

(defrule Theorem1b
   (goal no)
   =>
   (printout t "You need to establish goals
   for the implementation" crlf))

(defrule Theorem1c
   (strategy no)
   =>
   (printout t "You need to establish a strategy
```

```
   for the implementation" crlf))

(defrule Theorem1d
   (businessalign no)
   =>
   (printout t "The goals and strategy need to
   align with the business" crlf))

; --------- ;
; Theorem 2 ;
; --------- ;

(defrule Theorem2a
   (Axiom1)
   (connectivity yes)
   =>
   (assert (Theorem2)))

(defrule Theorem2b
   (connectivity no)
   =>
   (printout t "Connectivity needs to be established" crlf))

; --------- ;
; Theorem 3 ;
; --------- ;

(defrule Theorem3a
   (Axiom1)
   (integrated yes)
   =>
   (assert (Theorem3)))

(defrule Theorem3b
   (integrated no)
   =>
```

```
   (printout t "Industry 4 requires integration" crlf))

; --------- ;
; Theorem 4 ;
; --------- ;

(defrule Theorem4a
   (Axiom1)
   (systems yes)
   =>
   (assert (Theorem4)))

(defrule Theorem4b
   (systems no)
   =>
   (assert (notTheorem4))
   (printout t "Industry 4 requires recursive systems" crlf))

; --------- ;
; Theorem 5 ;
; --------- ;

(defrule Theorem5a
   (Axiom1)
   (cloud-computing yes)
   =>
   (assert (Theorem5)))

(defrule Theorem5b
   (cloud-computing no)
   =>
   (assert(notTheorem5))
   (printout t "Industry 4 requires cloud computing" crlf))

; --------- ;
; Theorem 6 ;
```

```
; --------- ;

(defrule Theorem6a
   (Axiom1)
   (Theorem5)
   (data-decentralised yes)
   =>
   (assert (Theorem6)))

(defrule Theorem6b
   (data-decentralised no)
   =>
   (assert (notTheorem6))
   (printout t "Industry 4 requires decentralisation" crlf))

(defrule Theorem6c
   (notTheorem5)
   =>
   (assert (notTheorem6))
   (printout t "Cloud computing is required
   for decentralisation" crlf))

; --------- ;
; Theorem 7 ;
; --------- ;

(defrule Theorem7a
   (Theorem4)
   =>
   (assert (Theorem7)))

(defrule Theorem7b
   (notTheorem4)
   =>
   (assert (notTheorem7)))
```

```
; --------- ;
; Theorem 8 ;
; --------- ;

(defrule Theorem8a
   (Axiom1)
   (Theorem3)
   (sources yes)
   =>
   (assert (Theorem8)))

(defrule Theorem8b
   (notTheorem3)
   (sources yes)
   =>
   (printout t "Integration is needed" crlf)
   (assert (notTheorem8)))

(defrule Theorem8c
   (sources no)
   =>
   (printout t "Data not gathered from 1 or more sources" crlf)
   (assert (notTheorem8)))

; --------- ;
; Theorem 9 ;
; --------- ;

(defrule Theorem9a
   (Axiom1)
   (Theorem3)
   (Theorem8)
   =>
   (assert (Theorem9)))

; --------- ;
```

```
; Theorem 10 ;
; --------- ;

(defrule Theorem10a
   (Axiom1)
   (Theorem8)
   (Theorem9)
   (prediction yes)
   =>
   (assert (Theorem10)))

(defrule Theorem10b
   (notTheorem8)
   (prediction yes)
   =>
   (printout t "Data must be gathered for prediction" crlf)
   (assert (notTheorem10)))

(defrule Theorem10c
   (prediction no)
   =>
   (printout t "Data must be used for prediction" crlf)
   (assert (notTheorem10)))

; --------- ;
; Theorem 11 ;
; --------- ;

(defrule Theorem11a
   (Axiom1)
   (Axiom2)
   (security yes)
   =>
   (assert (Theorem11)))

(defrule Theorem11b
```

```
   (security no)
   =>
   (printout t "Data needs to be secure" crlf)
   (assert (notTheorem11)))

; --------- ;
; Theorem 12 ;
; --------- ;

(defrule Theorem12a
   (Theorem3)
   (production yes)
   =>
   (assert (Theorem12)))

(defrule Theorem12b
   (notTheorem3)
   (production yes)
   =>
   (printout t "Integration is required for
   new production methods to emerge" crlf)
   (assert (notTheorem12)))

(defrule Theorem12c
   (production no)
   =>
   (printout t "Industry 4 enables new production
   methods to emerge" crlf)
   (assert (notTheorem12)))

; --------- ;
; Theorem 13 ;
; --------- ;

(defrule Theorem13a
   (Theorem3)
```

```
   (Theorem4)
   (Theorem8)
   (customer yes)
   =>
   (assert (Theorem13)))

(defrule Theorem13b
   (notTheorem3)
   (customer yes)
   =>
   (printout t "Integration is required for
   customers to be involved" crlf)
   (assert (notTheorem13)))

(defrule Theorem13c
   (notTheorem4)
   (customer yes)
   =>
   (printout t "System of systems is required for
   customers to be involved" crlf)
   (assert (notTheorem13)))

(defrule Theorem13d
   (notTheorem8)
   (customer yes)
   =>
   (printout t "Data from one or more sources is
   required for the involvement of customers" crlf)
   (assert (notTheorem13)))

(defrule Theorem13e
   (customer no)
   =>
   (printout t "Customers should be considered
   for the implementation of Industry 4" crlf)
   (assert (notTheorem13)))
```

```
; --------- ;
; Theorem 14 ;
; --------- ;

(defrule Theorem14a
   (Axiom1)
   (Theorem3)
   (Theorem4)
   (businessmodels yes)
   =>
   (assert (Theorem14)))

(defrule Theorem14b
   (notTheorem3)
   (businessmodels yes)
   =>
   (printout t "Integration is required for
   new business models to emerge" crlf)
   (assert (notTheorem14)))

(defrule Theorem14c
   (notTheorem4)
   (businessmodels yes)
   =>
   (printout t "System of systems is needed for
   new business models to emerge" crlf)
   (assert (notTheorem14)))

(defrule Theorem14d
   (businessmodels no)
   =>
   (printout t "New business models should be considered" crlf)
   (assert (notTheorem14)))

; --------- ;
```

```
; Theorem 15 ;
; --------- ;

(defrule Theorem15a
   (Axiom2)
   (Theorem3)
   (Theorem4)
   (Theorem7)
   (Theorem8)
   (hto yes)
   =>
   (assert (Theorem15)))

(defrule Theorem15b
   (notTheorem3)
   (hto yes)
   =>
   (printout t "Integration is required" crlf)
   (assert (notTheorem15)))

(defrule Theorem15c
   (notTheorem4)
   (hto yes)
   =>
   (printout t "Systems of systems are required" crlf)
   (assert (notTheorem15)))

(defrule Theorem15e
   (notTheorem8)
   (hto yes)
   =>
   (printout t "Data from one or more sources is required" crlf)
   (assert (notTheorem15)))

(defrule Theorem15f
   (hto no)
```

```
   =>
   (printout t "Humans, technology and organisation
   should be considered simultanesously" crlf)
   (assert (notTheorem15)))

; --------- ;
; Theorem 16 ;
; --------- ;

(defrule Theorem16a
   (Axiom2)
   (Theorem4)
   (stages yes)
   =>
   (assert (Theorem16)))

(defrule Theorem16b
   (notTheorem4)
   (stages yes)
   =>
   (printout t "Systems of systems are required for
   the implementation of Industry 4" crlf)
   (assert (notTheorem16)))

(defrule Theorem16c
   (stages no)
   =>
   (printout t "Industry 4 should be implemented in stages" crlf)
   (assert (notTheorem16)))

; --------- ;
; Theorem 17 ;
; --------- ;

(defrule Theorem17a
   (Axiom1)
```

```
   (Axiom2)
   =>
   (assert (Theorem17)))

; --------- ;
; Theorem 18 ;
; --------- ;

(defrule Theorem18a
   (Axiom1)
   (Theorem4)
   (Theorem8)
   (Theorem9)
   (Theorem17)
   (maintenance yes)
   =>
   (assert (Theorem18)))

(defrule Theorem18b
   (notTheorem4)
   (maintenance yes)
   =>
   (printout t "Systems of systems are required" crlf)
   (assert (notTheorem18)))

(defrule Theorem18c
   (notTheorem8)
   (maintenance yes)
   =>
   (printout t "Data from one or more sources are
   required for maintenance" crlf)
   (assert (notTheorem18)))

(defrule Theorem18f
   (maintenance no)
   =>
```

```
   (printout t "The impact of Industry 4 on maintenance
   should be considered" crlf)
   (assert (notTheorem18)))

; --------- ;
; Theorem 19 ;
; --------- ;

(defrule Theorem19a
   (Theorem4)
   (Theorem7)
   (Theorem12)
   (skills yes)
   =>
   (assert (Theorem19)))

(defrule Theorem19b
   (notTheorem4)
   (skills yes)
   =>
   (printout t "Systems of systems are required for
   Industry 4" crlf)
   (assert (notTheorem19)))

(defrule Theorem19d
   (notTheorem12)
   (skills yes)
   =>
   (printout t "New production methods should be
   considered" crlf)
   (assert (notTheorem19)))

(defrule Theorem19e
   (skills no)
   =>
   (printout t "Industry 4 requires new skill set" crlf)
```

```
   (assert (notTheorem19)))

; --------- ;
; Theorem 20 ;
; --------- ;

(defrule Theorem20a
   (Theorem1)
   (Theorem19)
   (people yes)
   =>
   (assert (Theorem20)))

(defrule Theorem20b
   (notTheorem1)
   (people yes)
   =>
   (printout t "Goals and strategy are required for
   the implementation of Industry 4" crlf)
   (assert (notTheorem20)))

(defrule Theorem20c
   (notTheorem19)
   (people yes)
   =>
   (printout t "Industry 4 requires new skillset" crlf)
   (assert (notTheorem20)))

(defrule Theorem20d
   (people no)
   =>
   (printout t "Workers need to be considered for the
   implementation of Industry 4" crlf)
   (assert (notTheorem20)))

; ---------- ;
```

```
; Theorem 21 ;
; ---------- ;

(defrule Theorem21a
   (Axiom1)
   (Theorem4)
   (Theorem7)
   (Theorem9)
   (Theorem12)
   (Theorem14)
   (Theorem18)
   (Theorem19)
   (mindset yes)
   =>
   (assert (Theorem21)))

(defrule Theorem21b
   (notTheorem4)
   (mindset yes)
   =>
   (printout t "Industry 4 requires systems of systems" crlf)
   (assert (notTheorem21)))

(defrule Theorem21e
   (notTheorem12)
   (mindset yes)
   =>
   (printout t "New production methods should be considered" crlf)
   (assert (notTheorem21)))

(defrule Theorem21f
   (notTheorem14)
   (mindset yes)
   =>
   (printout t "New business models should be considered" crlf)
   (assert (notTheorem21)))
```

```
(defrule Theorem21g
   (notTheorem18)
   (mindset yes)
   =>
   (printout t "Industry 4 requires a shift in maintenance" crlf)
   (assert (notTheorem21)))

(defrule Theorem21h
   (notTheorem19)
   (mindset yes)
   =>
   (printout t "Industry 4 requires new skillset" crlf)
   (assert (notTheorem21)))

(defrule Theorem21i
   (mindset no)
   =>
   (printout t "Industry 4 requires a new mindset" crlf)
   (assert (notTheorem21)))
```

Appendix D

This Appendix includes the questionnaires provided to the participants in the case study 2.

General questions on the participant and Industry 4

1. In which industry is the company?
2. How long have you worked at the company?
3. What is your job title?
4. In which department do you work?
5. How do you envision Industry 4 at the company?
6. What barriers do you foresee during the implementation process?
7. What are the benefits of Industry 4 for the company?
8. Are there any drawbacks of implementing Industry 4?
9. Are there any risks associated with Industry 4 and its implementation?
10. Will Industry 4 change the manufacturing processes in the company? And if yes, how?
11. Will Industry 4 affect the entire company? And if yes, how?
12. Would a framework help implement Industry 4? If yes, how?
13. What part of the implementation process would a framework be beneficial?

Current state of Industry 4 at the company

Item	Question	Yes	No	Comment
1	Has the impact of Industry 4 on mindset been considered?			
2	Has the impact of Industry 4 on people been considered?			
3	Has the impact of Industry 4 on skills been considered?			
4	Has the impact of Industry 4 on maintenance been considered?			
5	Will Industry 4 be implemented in stages?			
6	Are humans, technology and organisations considered simultaneously?			
7	Has the impact of Industry 4 on new business models been considered?			
8	Has the impact of Industry 4 on customers been considered?			
9	Has the impact of Industry 4 on production methods been considered?			
10	Is data stored in a secure way?			
11	Is data used for prediction?			
12	Is data from one or more sources gathered?			
13	Is data decentralised?			
14	Has cloud computing been implemented?			
15	Are the systems interconnected?			
16	Has the factory/object been integrated vertically?			
17	Has the factory/object been integrated horizontally?			
18	Has the factory/object been integrated end-to-end?			
19	Has the factory/object been integrated at all?			
20	Has connectivity been established in the factory?			
21	Does the strategy and goals align with the business goals and strategy?			
22	Is there strategy in place for the implementation of I4?			
23	Are there goals in place for the implementation of I4?			

Feedback

1. Did any of the questions surprise you? If yes, which ones?

2. Was there anything missing? If yes, explain please.

Appendix E

This Appendix includes the results from the expert system for case studies 1 and 2.

Case study 1

Are there goals in place for the implementation of I4 (yes/no)? n
You need to establish goals for the implementation
Is there strategy in place for the implementation of I4 (yes/no)? y
Has connectivity been established in the factory (yes/no)? y
Has the factory/object been integrated vertically, horizontally and end-to-end (yes/no)? n
Industry 4 requires integration
Are the systems interconnected(yes/no)? y
Has cloud computing been implmented (yes/no)? n
Industry 4 requires cloud computing
Cloud computing is required for decentralisation
Is data decentralised (yes/no)? y
Is data from one or more sources gathered (yes/no)? y
Integration is needed
Is data used for prediction (yes/no)? y
Data must be gathered for prediction
Is data stored in a secure way (yes/no)? y
Has the impact of Industry 4 on production methods been considered (yes/no)? n
Industry 4 enables new production methods to emerge
Has the impact of Industry 4 on customers been considered (yes/no)? y
Integration is required for customers to be involved
Data from one or more sources is required for the involvement of customers
Has the impact of Industry 4 on new business models been considered (yes/no)?

y
Integration is required for new business models to emerge
Are humans, technology and organisations considered simultaneously (yes/no)?
y
Integration is required
Data from one or more sources is required
Will Industry 4 be fully implemented (yes/no)? y
Has the impact of Industry 4 on maintenance been considered (yes/no)? y
Data from one or more sources are required for maintenance
Has the impact of Industry 4 on skills been considered (yes/no)? y
New production methods should be considered
Has the impact of Industry 4 on people been considered (yes/no)? y
Industry 4 requires new skillset
Has the impact of Industry 4 on mindset been considered (yes/no)? n
Industry 4 requires a new mindset

Case study 2

Are there goals in place for the implementation of I4 (yes/no)? y
Is there strategy in place for the implementation of I4 (yes/no)? n
You need to establish a strategy for the implementation
Has connectivity been established in the factory (yes/no)? n
Connectivity needs to be established
Has the factory/object been integrated vertically, horizontally and end-to-end (yes/no)? n
Industry 4 requires integration
Are the systems interconnected(yes/no)? n
Industry 4 requires recursive systems
Has cloud computing been implmented (yes/no)? y
Is data decentralised (yes/no)? n
Industry 4 requires decentralisation
Is data from one or more sources gathered (yes/no)? n
Data not gathered from 1 or more sources
Is data used for prediction (yes/no)? n
Data must be used for prediction
Is data stored in a secure way (yes/no)? y

Has the impact of Industry 4 on production methods been considered (yes/no)? y

Integration is required for new production methods to emerge

Has the impact of Industry 4 on customers been considered (yes/no)? y

Integration is required for customers to be involved

System of systems is required for customers to be involved

Data from one or more sources is required for the involvement of customers

Has the impact of Industry 4 on new business models been considered (yes/no)? n

New business models should be considered

Are humans, technology and organisations considered simultaneously (yes/no)? n

Humans, technology and organisation should be considered simultanesously

Will Industry 4 be fully implemented (yes/no)? y

Systems of systems are required for the implementation of Industry 4

Has the impact of Industry 4 on maintenance been considered (yes/no)? n

The impact of Industry 4 on maintenance should be considered

Has the impact of Industry 4 on skills been considered (yes/no)? y

Systems of systems are required for Industry 4

New production methods should be considered

Has the impact of Industry 4 on people been considered (yes/no)? n

Workers need to be considered for the implementation of Industry 4

Has the impact of Industry 4 on mindset been considered (yes/no)? n

Industry 4 requires a new mindset