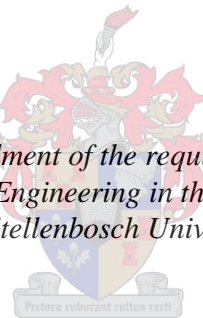# A framework for implementing Industrie 4.0 in learning factories

by

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Thesis presented in fulfilment of the requirements for the degree of Master of (Industrial) Engineering in the Faculty of Engineering at Stellenbosch University

Supervisor: Mr. Konrad H von Leipzig

March 2017

Declaration

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March 2017

Abstract

Globalisation and resource scarcity have drastically increased the intensity of competitive manufacturing, forcing companies to deliver on higher expectations with less staff and minimal resource usage. This situation has ushered forth a new industrial revolution, *Industrie 4.0*.

This new revolution, analogous to coined phrases such as smart factories and the internet of things, has given way to exponential advances in technologies. The implementation of these technologies, should in theory, enable firms to reduce the negative impact of their operations on their triple bottom line and improve efficiencies. However, whilst the implementation of these technologies provides seeming and logical improvements; how to implement them, with what, and where is still largely unclear and can lead to total abolishment due to the lack of knowledge. A decision support framework is proposed in this thesis for aiding companies, specifically small and medium enterprises (SMEs), and learning factories in their implementation efforts towards Industrie 4.0.

Industrie 4.0 is broken down into basic levels corresponding to those found in learning factories and SMEs. These levels are put forward as dimensions of the framework, ranging from objects and technologies to Industrie 4.0 applications in SMEs and competencies taught in learning factories, offering the user a visual representation of the practical implementations needed for Industrie 4.0.

This framework can be used in three different ways. The first, is a greenfield design, aimed at new learning factories who wish to develop industry related competencies and skills. In this greenfield design, the framework suggests implementation guidelines for the user based on the targeted competency criteria that the user seeks to develop through an Industrie 4.0 perspective. The second, an Industrie 4.0 greenfield design, is for the case where a user seeks to implement Industrie 4.0 concepts with the purpose of enhancing traditional operations in SMEs or showcasing the possibilities of Industrie 4.0 in learning factories. The third application is for redesigning the current operations within a learning factory or SME with Industrie 4.0 in mind. The Industrie 4.0 redesign is aimed at learning factories and SMEs who wish to implement Industrie 4.0 concepts using the infrastructure and equipment they already have.

The decision support framework is implemented in two learning factories, representing the two extreme cases of the framework, namely the Industrie 4.0 redesign and the greenfield design. The framework is applied in a technologically-advanced environment in Germany, and successfully allows for the incorporation of three distinct Industrie 4.0 applications in an already well-established learning factory. For further validation, the framework is applied at the Stellenbosch University learning factory to showcase the case where the complete design of a learning factory is commenced with the aim of incorporating Industrie 4.0 into the desired learning competencies.

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Uittreksel

Globalisering en skaarsheid van hulpbronne het drasties die intensiteit van mededingende vervaardiging laat toeneem, en dwing maatskappye om op 'n hoër verwagtinge met minder personeel en minimale gebruik van hulpbronne af te lewer. Hierdie situasie het ingelui tot 'n nuwe industrile rewolusie, *Industrie 4.0*.

Dié revolusie, analogies aan frases soos slim fabrieke en die internet van dinge, het vooruitgang gegee tot eksponensiële tegnologiese vordering. Die implementering van hierdie tegnologie, sal in teorie, maatskappye in staat stel om die negatiewe impak van hul bedrywighede op hul "tripple bottom line" te verminder en doeltreffendheid te verbeter. Maar terwyl die implementering van hierdie tegnologie oënskynlike en logiese verbeteringe bied; hoe om dit te implementeer, met wat en waar is nog grootliks onduidelik en kan lei tot totale afskaffing as gevolg van die gebrek aan kennis. 'n Besluit ondersteuning raamwerk word voorgestel in hierdie tesis vir die ondersteuning van maatskappye, spesifiek klein en medium ondernemings (KMOs), en leerfabrieke in hul implementeringspogings teenoor Industrie 4.0.

Industrie 4.0 word afgebreek in basiese vlakke wat ooreenstem met diè wat in die leer van fabrieke en KMO voorkom. Hierdie vlakke is voorgesit as dimensies van die raamwerk, en wissel van voorwerpe en tegnologie tot Industrie 4.0 toepassings in KMO en vaardighede geleer in leerfabrieke, en bied die gebruiker 'n visuele voorstelling van die praktiese implementering nodig vir Industrie 4.0.

Hierdie raamwerk kan op drie verskillende maniere gebruik word. Die eerste is 'n "greenfield" ontwerp, wat gemik is op nuwe leerfabrieke wat bedryfsverwante bevoegdhede en vaardighede wil ontwikkel. In hierdie "greenfield" ontwerp, dui die raamwerk implementeringsriglyne vir die gebruiker aan, wat gebasseer is op die geteikende bevoegdheid kriteria wat die gebruiker wil ontwikkel deur 'n Industrie 4.0 perspektief. Die tweede, 'n "Industrie 4.0 greenfield" ontwerp, is vir die geval waar 'n gebruiker Industrie 4.0 konsepte wil implementeer met die doel van verbetering aan tradisionele bedrywighede in KMOs of vir diè wat klem wil lê op die moontlikhede van Industrie 4.0 in leerfabrieke. Die derde toepassing is vir die herontwerp van die huidige bedrywighede binne 'n leerfabriek of KMO met Industrie 4.0 as raamwerk. Die Industrie 4.0 herontwerp is gemik op leerfabrieke en KMOs wat Industrie 4.0 konsepte wil implementeer slegs met die infrastruktuur en toerusting waaroor hulle reeds beskik.

Die besluit ondersteuning raamwerk is geïmplementeer in twee leerfabrieke, die twee uiterste gevalle van die raamwerk, naamlik die produksie 4.0 herontwerp en die "greenfield" ontwerp. Die raamwerk is toegepas in 'n tegnologies-gevorderde omgewing in Duitsland, en maak suksesvol voorsiening vir die oprigting van drie afsonderlike Industrie 4.0 toepassings in 'n reeds gevestigde leerfabriek. Vir verdere bekragtiging, is die raamwerk toegepas op die Universiteit Stellenbosch leerfabriek die geval waar die volledige ontwerp van 'n leerfabriek in aanvang neem, met die doel om die integrasie van Industrie 4.0 in die gewenste leer vaardighede ten toon te stel.

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List of Acronyms

BCG: the Boston Consulting Group

BMBF German federal ministry of education and research

ERP: Enterprise resource planning

ESBLLF: ESB Logistics Learning Factory

CPS: Cyber-physical system

CPPS: Cyber-physical production system

DAAD: German academic exchange service

IoS: Internet of services

IoT: Internet of things

IP: Internet protocol

IPv6: Internet protocol version six

KPI: Key performance indicator

LLC: Learning lean concepts

LPS: Chair of production systems

LRE: Learning for resource efficiency

LMO: Learning for management and organisation

M2M: Machine-2-machine

NSF: National Science Foundation

MES: Master execution system

PLC: Programmable logic controller

RFID: Radio frequency identification

SaaS: Software as a service

SLF: Stellenbosch Learning Factory

SME: Small and medium sized enterprises

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CHAPTER 1

Introduction

1.1 Background

Small and medium-sized enterprises (SMEs) are estimated to contribute to more than 95% of enterprises across the world, and account for approximately 60% of private sector employment [11]. A country such as Japan, for example, has the highest proportion of SMEs among the industrialised countries, accounting for more than 99% of total enterprises [23]. In South Africa, it is estimated that 91% of the formal business entities are SMEs [3]. Estimated data for 2012 illustrate the importance of SMEs' contribution to employment, shown in Figure 1.1, where SME 100 indicates SMEs that employ less than 100 people, and SME 150 less than 150 people and so on. In Europe alone, SMEs account for 99.8% of all enterprises, employ 67% of all workers and contribute to 58% of gross value added (GVA). The contribution of SMEs are equally important in low-income countries as it is in high-income countries like those in Europe, as is shown in Figures 1.1 and 1.2 where SMEs contribute to 65% of gross domestic product (GDP), and almost 80% of all employment [15].

SMEs are also major contributors to innovation in economies, greatly due to the collaboration with the larger corporate sector. SMEs that become fundamental parts in the supply chains of larger businesses become motivated to innovate and improve upon their own human and technological capital [10], thus improving their own productivity and performance. SME contributions to global GDP account for 52% of private sector value added, which provides a reasonable estimate for the sectors global economic contribution and importance [10].

SMEs greater labour intensity means that job creation entails lower capital costs than in larger firms [44], which is particularly important for developing countries and economies with high unemployment. Moreover, according to the Edinburgh group [66], SMEs are generally more common in rural areas than larger businesses, especially in developing countries, SMEs thus

TABLE 1.1: *SME contribution to employment by region - Cumulative median values [66].*

Median across regions	SME 100	SME 150	SME 200	SME 250	SME 300	SME 500
Africa	54.77	63.79	68.15	76.85	80.56	85.11
East Asia and Pacific	56.79	61.58	67.42	65.70	71.34	71.34
Europe and Central Asia	44.71	53.08	59.46	66.32	67.48	75.47
Latin America	53.72	56.71	64.36	67.77	70.99	78.26
Middle East and North Africa	31.20	48.1	36.63	57.31	58.56	62.3
North America	41.73	39.34	41.99	NA	59.27	56.58
South Asian Region	56.68	65.29	73.63	78.00	80.26	88.55

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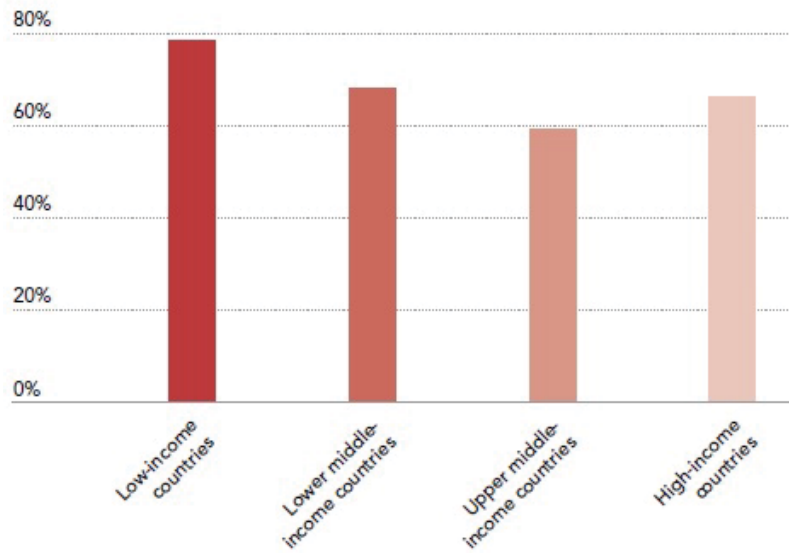
FIGURE 1.1: *Contribution of SMEs to employment by income categories [66].*
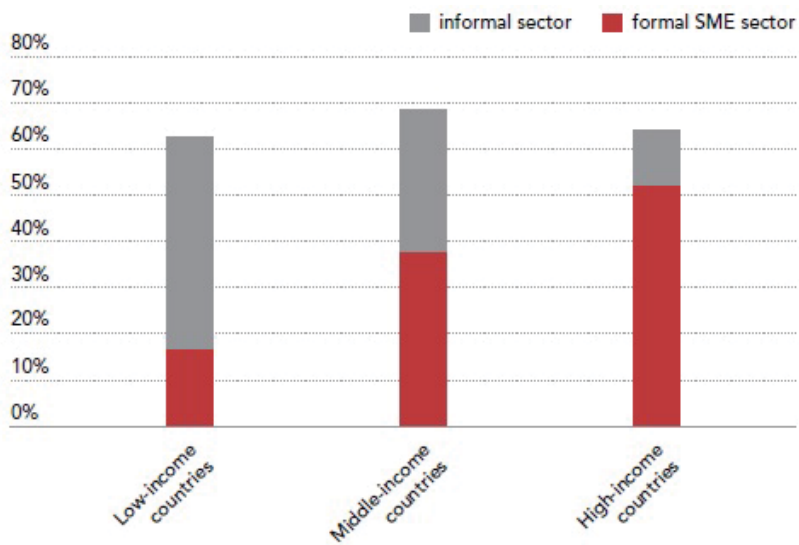
FIGURE 1.2: *Contribution of SMEs to GDP by income categories [66].*

provide much-needed employment in rural areas. SMEs can become the drivers for long-term development and sustained growth in developing countries. The reason for this, according to Fjose et al. [26] is when growth increases and manifests, SMEs gradually assume key roles in industrial development and restructuring. They then satisfy increasing local demand for services, allowing increased specialisation, and furthermore provide support for larger enterprises with services and inputs.

South Africa, for example, as an emerging economy relies greatly on their manufacturing sector for growth, as it is the second largest contributor to the total GDP [69]. According to van der Merwe et al. [74] the industries which comprise this sector get their top tier workers from the universities, and upon employing them, they find that some university graduates are still incapable and unproductive during their early period of employment. Some of the graduates receive a cultural shock from the work environment in industry. They become a liability during the early phases of their employment, which at times deters some industries from promptly engaging university graduates upon exiting the university. Industry at times goes an extra mile to train them so that they reach a level on which they would be productive. However, not all industries are forthcoming to take up this burden. Van der Merwe et al. [74] further states that industries would rather employ an experienced person than newly graduated university students. Fortunately, learning factories are paving the way for teaching the fundamentals of industry related concepts within a controlled and direct goal orientated manner [39]. They allow the implementation of concepts so as to practically teach and provide understanding of theoretical ideologies without the accompanying industrialised expenses a company would have. Some learning factories have, since their inception, shifted and divided their focus, from a pure teaching tool, to become industry leaders with regards to innovation and developments [24].

"Led by the internet is an industrial digital information age, which will forever change the way we live, work and produce" – *Dr. Benno Bunse, Chairman/CEO Germany Trade & Invest [18]*

Open source architectures together with high-speed networks and smart infrastructures that are able to communicate with each other, are ushering forth a degree of transformation, not seen since the first industrial revolution. This radical change was coined by the German government in 2011 at its first mentioning, as Industrie 4.0, referring to the fourth industrial revolution. This revolution is part of Germany's High-Tech Strategy 2020 Action Plan, and will change the way companies and businesses across all sectors operate [46].

A core element of Industrie 4.0, according to Festo Didactic head *Dr. Daniel Boese* [19], is that there will be a shift in the skills required to support various elements of the changes in industry. He further notes that the complexity of Industrie 4.0 will mean that schools, training and further education institutions will have to cooperate closely with industry during training and education, so as to better prepare students for industry once they leave the education system.

Many learning factories have been established around the world with the aim to bridge the gap between university education and real-world experience in an effort for graduates to be more capable and contribute to a company from the start of their employment. Industrie 4.0, however, is changing the landscape of SMEs, and learning factories need to follow suit if they wish to proactively reduce the inexperience gap that initiated them. It is for this reason that this thesis looks at developing a framework to act as decision support for learning factories and SMEs who wish to implement Industrie 4.0.

1.2 Thesis scope

This thesis involves two main elements. The first element entails the analysis of literature regarding Industrie 4.0 and learning factories, as mentioned above, and the analysis of existing learning factories.

The second element involves the design and development of a decision support framework that is able to provide assistance to a user who wishes to implement Industrie 4.0 within their SME or learning factory. The framework can provide decision support for the development of a new learning factory aimed at teaching specific competencies, or a learning factory that wishes to demonstrate the possibilities of Industrie 4.0 concepts, or an SME that wishes to enhance current activities through the implementation of Industrie 4.0. The aim of the framework is not to provide the user with a step by step guide to either of the three cases mentioned, but rather to provide recommendations towards achieving the desired outcomes. Through the use of the framework, the user is able to discern which implementations are readily available, which require investment in capital, and which are infeasible for a specific application or environment. This thesis is limited in scope to the development, creation, testing, and demonstrating of the framework. The development of the framework and concept demonstrators are adequately documented so that future users can utilise and possibly extend the framework to a tailored implementation framework.

1.3 Thesis aim and methodology

The aim of this thesis is to provide decision support to users, learning factories and SMEs, who wish to implement Industrie 4.0. A detailed flow diagram of the methodology followed is shown in Figure 1.3. As shown in the diagram, a thorough analysis of literature pertaining to Industrie 4.0 and its components, as well as the aims and make up of learning factories is conducted. This literature, as well as a research initiative by the Fraunhofer Institute [63], form the basis for the identification of the dimensions included in the framework, as well as the elements within each dimension for the incorporation of Industrie 4.0 within a learning factory or SME. All possible user states for the framework are considered, and the dimensions compiled in such a way that the framework accommodates all states, and provides the user with a suggested map for achieving the desired output specific to that user instance. The framework is validated in the ESB Logistics Learning Factory at Reutlingen University in Germany, representing a technologically matured environment, as well as in a technologically infant environment, namely the Stellenbosch University Learning Factory. These two use cases represent the two more extreme user instances of the framework, thus providing a good validation of the framework, and are used to perform a second iteration of the framework development to incorporate any missing elements identified in the applications.
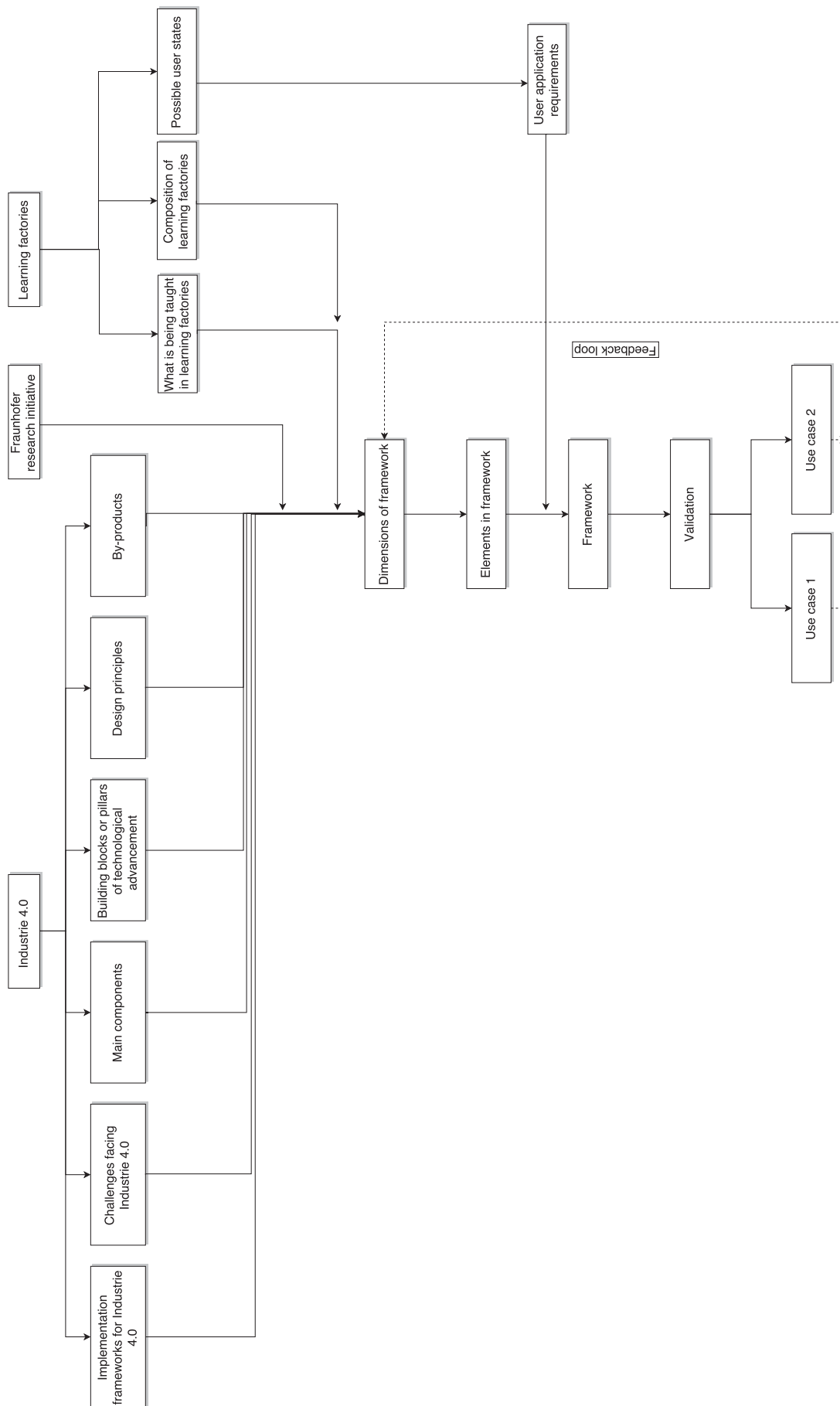
FIGURE 1.3: *Methodology roadmap of thesis.*

1.4 Thesis objectives

The following objectives are pursued in this thesis:

    I To *conduct* a thorough analysis and documentation of the literature related to this thesis, more specifically:

        (i) Industrie 4.0 and its components,

        (ii) practical implementation methodologies for Industrie 4.0, and

        (iii) learning factories in general and their role in research and education for industry.

    II To *collect* data and information regarding learning factories thorough practical visits to numerous learning factories in Europe and South Africa.

    III To *analyse* the gathered information from Objective II, more specifically:

        (i) to identify groupings of commonalities between learning factories, and

        (ii) form a link between the groupings and the literature in Objective I(i)

    IV To *propose* a modular and generic framework capable of taking as inputs the desired outputs of a user instance and propose a methodology and design criteria for achieving the outputs.

    V To *develop* and *create* the proposed generic framework of Objective IV, more specifically:

        (i) to interpret and present relational maps of the information of Objectives I–III, and visually representing it by means of tree diagrams, and

        (ii) to create a visual representation of the proposed framework.

    VI To *perform* case studies on two different application criteria, based on two different learning factories that formed part of the pursuit of Objective II.

    VII To *recommend* sensible follow-up work related to the work in this thesis which may be pursued in future.

1.5 Thesis organisation

This thesis is partitioned into six chapters. Chapter 2 focusses on the literature pertaining to Industrie 4.0 and learning factories. The chapter starts in Section 2.1 with an introduction to Industrie 4.0, followed by a discussion on historic industrial revolutions in Section 2.2 and leads into Section 2.3, which discusses the main components that comprise Industrie 4.0. This is followed in Section 2.4 by a discussion on the subcomponents and supporting elements of Industrie 4.0. The section on Industrie 4.0 is then concluded by reviewing the potential benefits, challenges and implementation methods of Industrie 4.0. The section on learning factories is started in Section 2.10, with a discussion on the origin and driving force that lead to learning factories, and is followed by a discussion of the current standing of learning factories around the world in Section 2.10.3. This discussion leads into and concludes with Section 2.10.4, where the physical composition of learning factories are discussed.

Chapter 3 contains the documentation of the development of the framework. The focus of this chapter is on the development and presentation of the developed framework. The chapter opens in Sections 3.1 to 3.4 with detailed steps on how the framework was developed and concludes in Section 3.5 with guidance on using the framework.

Chapter 4 describes one of the two use cases of this thesis. The use case in Chapter 4 concerns the ESB Logistics Learning Factory, mentioned earlier. The chapter opens with a brief description of the learning factory and the current operations within the learning factory. The remainder of the chapter provides a detailed documentation of how the framework is applied to the ESB Logistics Learning Factory and implementation of Industrie 4.0 realised.

Chapter 5 describes the second of two use cases in this thesis. The use case in Chapter 5 deals with the Stellenbosch University Learning Factory, mentioned earlier. As with Chapter 4, this chapter opens with a brief description of the learning factory and its operations. The detailed description of the framework application starts in Section 5.1 and continues with the framework results before concluding with the implementations made in Section 5.2.

The final chapter of this thesis, Chapter 6, contains a summary of the work presented in this thesis and an appraisal of the contributions of the thesis. The thesis closes with recommendations for future work.

CHAPTER 2

Literature study: Industrie 4.0 and learning factories

Two topics are discussed in this chapter, the first being the new industrial revolution, Industrie 4.0, and the second is an emerging teaching tool called learning factories. This chapter gives the reader an overview of the findings in these two fields.

2.1 Industrie 4.0

Industrie 4.0 is a term for the current trend of automation and computerisation in manufacturing technologies. It is a very popular and extensively discussed topic in social groups, industry as well as in the academic field. Since its first mentioning in 2011 by the German federal government, it has become a top priority for many research centres, universities and companies, especially in Germany [32]. The reason being, is that it has been estimated that the benefits of Industrie 4.0 will contribute as much as €78 billion to the German gross domestic product by 2025 [12]. With the popularity of this concept as a research topic, and the fact that for the first time in history an industrial revolution is being predicted a priori, academics and practitioners have obscured the true meaning and definition of Industrie 4.0 [13]. Although there is no single definition upon which "experts" agree, there still exist many overlapping concepts and criteria, which have been aggregated and discussed in this chapter.

2.2 Historical industrialisation

The first industrial revolution, according to Bauernhansl et al. [64], was the mobilisation and mechanisation of production using water and steam power. Bauernhansl et al. [64] further explains that the second industrial revolution introduced mass production aided by the discovery and development of electric power. The third industrial revolution termed the digital age, is generally accepted, by multiple sources [12, 17, 62] as the period dating from the 1970's to the early 21st century. It saw the introduction of micro electronics and electrical devices, enabling technologies like cell phones, tablets, the World Wide Web and digital information transfer. The first three industrial revolutions can be summarised, in respective order, as the results of mechanisation, electricity and lastly information technology (IT). According to Kagermann et al. [37] it is the introduction of the internet of things (IoT) and services (IoS) into the

manufacturing environment that is ushering a fourth industrial revolution. Figure 2.1 is a time line, depicting the approximate dates of each of the industrial revolutions.
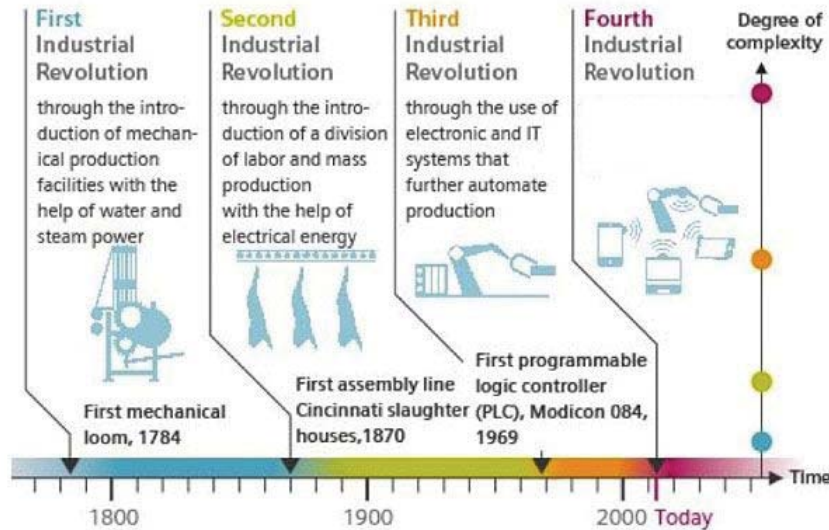
Figure 2.1: *Industrial revolution time line, adapted from [37].*

Industrie 4.0 is a collective term for a high technological strategy developed by the German government, which aims to not only promote, but drastically improve computerisation and industrialisation [64]. Industrie 4.0, in itself is a term that combines and captures contemporary automation, data exchange and manufacturing technologies. Some of these technologies have been combined into terms such as the internet of things and the internet of services, and cyber-physical systems (CPSs). The IoT, explained further in Section 2.3, is generalised for how all electronic devices are connected to the internet, and can be accessed and act as sensors or actuators. The IoS is similar, but in this case it is services like Twitter [80] that are offered to the "things" from the IoT, through the internet. Finally, to superficially describe CPSs, it is the cyber world where the IoT, IoS, mechanical devices and people converge. Hermann et al. [34] describe Industrie 4.0 as follows: "Within the modular structured smart factories of Industrie 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralised decisions. Over the IoT, CPSs communicate and co-operate with each other and humans in real time. Via the IoS, both internal and cross-organisational services are offered and utilised by participants of the value chain".

Figure 2.2 is a visual depiction of Industrie 4.0 within a factory environment. From this figure, a few things are noticeable, which are discussed in more detail in subsequent sections. Firstly there are no human labourers perform manual work within the factory, as most work steps, from the start of the manufacturing process right to the end product, have been automated. The second takeaway from this figure is that production information is collected through sensors equipped on all machines, which in turn produces big data, which is stored on a decentralised cloud and is then used to derive insights and performance measurements indicators in real-time. Thirdly, the high level of autonomy and introduction of 3D printing allows for high levels of customisation, where the user can select customised parts from the decentralised point like the internet, as shown on the right hand side on the figure. The fourth point is the complete integration of suppliers, manufacturers and end customers, indicated by the horizontal red and black arrows from left to right on the figure. The fifth and final point, which is not discussed in the subsequent sections, as it falls outside the scope of the project, is the resources of the future, shown at the bottom of Figure 2.2. These include mostly renewable energy sources focused on sustainability
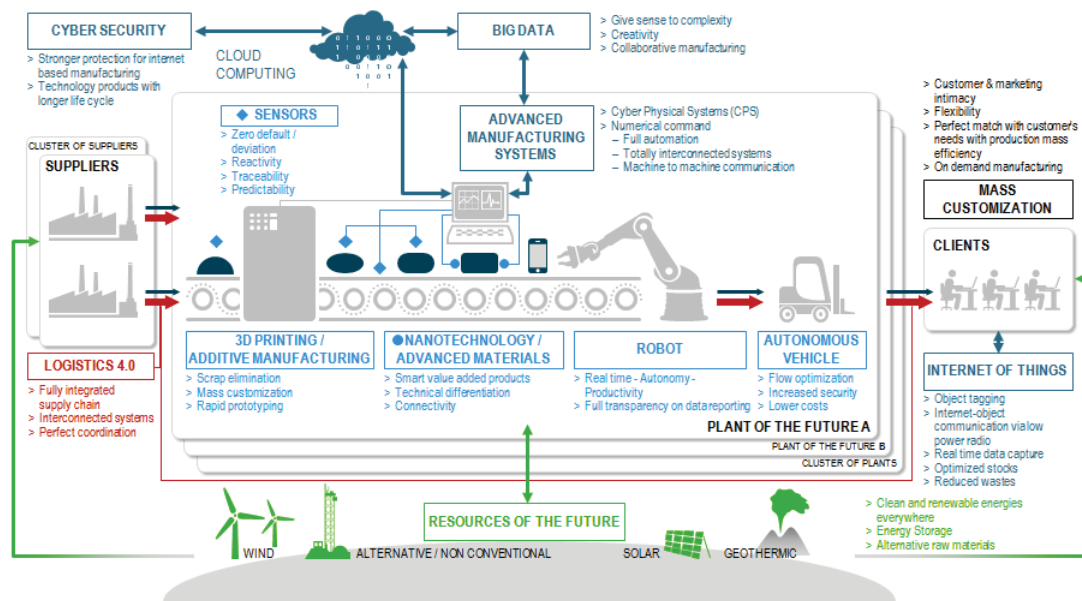
FIGURE 2.2: *Industrie 4.0 ecosystem [14].*

and low environmental impacts.

2.3 Industrie 4.0 main components

A literature analysis performed in 2015 by Hermann et al.[34], in an attempt to define Industrie 4.0, provided quantitative evidence for identifying the central aspects of Industrie 4.0. The first step was to identify key words associated with the concept of Industrie 4.0. For this, Hermann et al. [34] included the English translation, Industry 4.0 in addition to its German counterpart Industrie 4.0. The authors searched six distinct databases (CiteSeerX, ACM, AISeL, EBSCOhost, Emerald Insight, and Google Scholar), emerging with the results shown in Table 2.1.

Following their identification of key associative words, Hermann et al. [34] identified 51 publications that addressed Industrie 4.0. Using these 51 publications they performed a backwards and forwards search of each publication and aggregated the results, as shown in Table 2.2. After further consideration, they narrowed the list to four main components of Industrie 4.0, by ruling out the remainder of the list. The authors decided that machine-to-machine and smart products are not considered as independent Industrie 4.0 components. In similar fashion, in line with Bauernhansl et al [13], Hermann et al. [34] regarded big data and cloud computing as data services which utilise the data generated by Industrie 4.0 instances, and not as independent Industrie 4.0 components. The four remaining components, IoT, CPSs, IoS, and smart factories are discussed in the following section.

2.3.1   Internet of things

A clear definition of the IoT has not yet been established and accepted world wide, but there is a strong agreement on what the IoT stands for, encompasses and how it should theoretically work. According to Kagermann et al. [37], the IoT is a manifestation that allows "things" (robots and machines) and "objects" (smart phones, laptops, and tablets) to interact with each

TABLE 2.1: *Industrie 4.0 keyword associations [34].*

Keyword 1	Keyword 2
Industry 4.0	Cyber-physical systems
(Industrie 4.0)	*(Cyber-physikalische systeme)*
	Internet of things
	(Internet der Dinge)
	Internet of Services
	(Internet der Dienste)
	Smart factory
	(Intelligente fabrik)
	Smart product
	(Intelligentes produkt)
	Big data
	Cloud
	M2M (machine-to-machine)

TABLE 2.2: *Industrie 4.0 components [34].*

Search term	Number of publications in which search term occurred
Cyber-physical systems	46
Internet of things	36
Smart factory	24
Internet of Services	19
Smart product	10
Machine-to-machine	8
Big data	7
Cloud	5
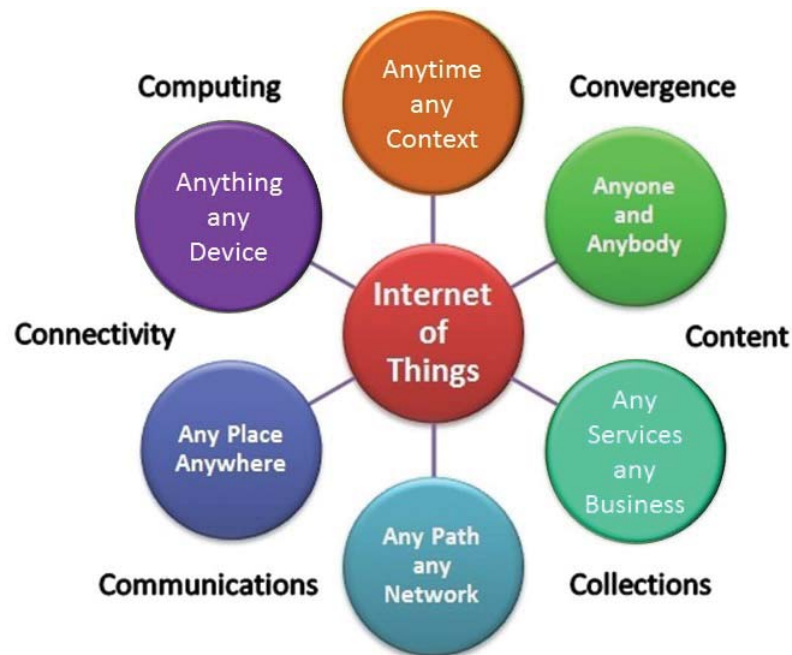
FIGURE 2.3: *Internet of things [70].*

other and cooperate by sharing information to reach common goals. Another basic definition for the IoT is that it is a dynamic network infrastructure with self configurable capabilities based on communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities with which they all cooperate with each other through unique addressing schemas [70].

Figure 2.3 gives a description of the vastness of the IoT. Sundmaeker et al. [70] explains that the IoT allows people and things to be connected at any time, any place with any thing and anyone, using any path or network with any service. If this were the case, all the implicit factors (convergence, content, collections, communications, connectivity, and computing) as shown in Figure 2.3 would be addressed.

The technologies for the IoT, according to Sundmaeker et al. [70] are as listed in Table 2.3. The enabling building blocks in Table 2.3, shown on the left are essential for the development of the IoT, whereas the synergistic technologies shown on the right are supporting technologies of the building blocks. Hermann et al.[34, 71] and have stated that these building blocks are essential to creating an Industrie 4.0 environment, which is true, but Sundmaeker et al. [70] have described it as essential for creating the IoT, which in turn is a foundational part of Industrie 4.0.

Sundmaeker et al.[70] propose a unique view on the definition of "things" in the phrase *internet of things*, by classifying them into five functional domains. The functional domains are listed in Table 2.4. The functional domains, ascend in increasing complexity as the domain number increases. The first functional domain covers the most basic characteristics of technology within the IoT. In this domain, "things" will communicate, be unique and be connected between the real and virtual world. In the second functional domain, the increased complexity of "things" to the point of inserting some sort of intelligence are discussed, as shown in the second row of Table 2.4. The statement made that a "thing", "competes for resources and services, and is subject to selective pressures", is not discussed in detail, leaving grey areas as to exactly what this entails and what the implications are or could be. Domain three humanises "things", by describing them

Table 2.3: *Technologies of the IoT [70].*

Enabling building blocks	Synergistic technologies
Machine-to-machine interface	Geo-tagging/geo-caching
Microcontrollers	Biometrics
Wireless communication	Machine vision
RFID technology	Augmented reality
Energy harvesting technologies	Mirror worlds
Sensors	Telepresence and adjustable autonomy
Actuators	Life recorders and personal black boxes
Location technology	Tangible user interfaces
Software	Clean technologies

as having social characteristics, but in a machine manner. In domain three, "things" are able to not only communicate but perform decision based communication. It should be noted that decision based communication is based on coded algorithms and not intuitive decision making, as humans do. Domain four discusses how "things" can be versatile in the sense that they can alter themselves to meet different demands and complete different tasks. This requires them to be context aware, be able to extract patterns, and make probability based decisions. Domain five boarders on artificial intelligence, in the sense that "things" from this domain posses human like qualities. Although Sundmaeker et al. [70] make use of the term "intelligence" in their descriptions, it should be noted that, as mentioned previously, true artificial intelligence can not yet be achieved practically.

2.3.2   Cyber-physical system

According to Kagermann et al. [37], an important component of Industrie 4.0 is the fusion of the physical and the virtual world, which is made possible by CPSs. Lee et al. [43] describes CPSs as "the integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa."

Hermann et al. [34] recognises three general development stages of any CPS. These development stages are further broken down by Lee et al. [43] into five steps, and are described below. In the first development stage described by Hermann et al., the CPS includes identification technologies which allow entities within the CPS to have unique identification. In the second stage, entities within the CPS, which their own unique identification, have equipped sensors and actuators that allow data capture and actions based on captured data. In the third and final stage, the CPS is comprised of entities with multiple sensors and actuators, they possess data analysing capabilities, and according to Bauernhansl et al. [13] entities are network compatible so that data can be shared throughout the CPS. This three stage definition given by Hermann et al. is supported by Plass [56] who describes CPSs as physical systems with inherent partial intelligence, and ability to make decisions provided by embedded software which gathers data via sensors and uses actuators to influence the system and environment, analyse and store data, and actively or reactively interact with the physical or virtual digital world, by being connected to each other via digital communication channels and as well as with global networks.

It should be noted that in the description given by Plass [56] above, the systems are described as being able to possess a form of intelligence. Other authors and sources, such as Venkatasub-

TABLE 2.4: *Functional domains for "things" in the IoT [70].*

Functional domains	Things
Domain 1: Functional characteristics	• Real or virtual entities • Unique identity • Non-intrusive • Use communication protocols to communicate with other things and CPS • Exchanges information between real and virtual world
Domain 2: Common characteristics	• Uses services as interfaces • Competes for resources and services and is subject to selective pressures • Sensor attachments enable interaction with environment
Domain 3: Social characteristics	• Decision based communication with other things, computing devices and people • Can collaborate to create groups or networks • Can initiate communication
Domain 4: Aware and autonomous characteristics	• Versatile autonomy • Can negotiate, understand and adapt to their environment • Can extract patterns from the environment or learn from other things • Can make decisions through reasoning capabilities • Can selectively evolve and propagate information
Domain 5: Self replication and control	• Can create, manage and destroy other things

ramanian [76], and Bauernhansl et al. [13] also use this concept as well as the term "smart" interchangeably. The actual fact is that this is impossible at this stage with the current technology, as this would imply that the systems possess some form of artificial intelligence, as noted by Russel and Norvig in their book [60] and in their article [61] on artificial intelligence. Smart objects are defined by the IPSO Alliance [7] as being small computers with a sensor or actuator and a communication device, embedded in objects such as thermometers, car engines, light switches, and industry machinery. They enable a wide range of applications in areas like home automation, building automation, factory monitoring, smart cities, health management systems, smart grid and energy management, and transportation. For this reason, the term "smart" or concept of intelligence is, for the purpose of this project used to indicate that the object of the discussion possesses data retrieval through sensors, data transmission through Wi-Fi or Bluetooth, and can communicate and form part of the CPS through incorporated network technologies.

CPSs first evolved from mechatronic devices that have incorporated communication capabilities and connectivity. The focus of CPSs is on a combination and coordination between physical and computational elements, differing from the IoT, which is in rudimentary form, focused on connectivity and communication. The ever growing use and incorporation of sensors and networked machines in industry, increases the generation of high volume data, also known as big data. According to Wolf [81] it is this increase along with advances in technology that has paved the way for CPSs.

It should be noted that Industrie 4.0 is still in its initial stages, which then holds true for all its components. Since the CPS is then in its initial stage of development, Lee et al. [42] have proposed a framework to clearly define, design and implement a CPS. The framework by Lee et al. [42] makes use of the 5C level architecture, as seen in Figure 2.4. The 5C framework is a five step process, with the steps as described in the following sections.
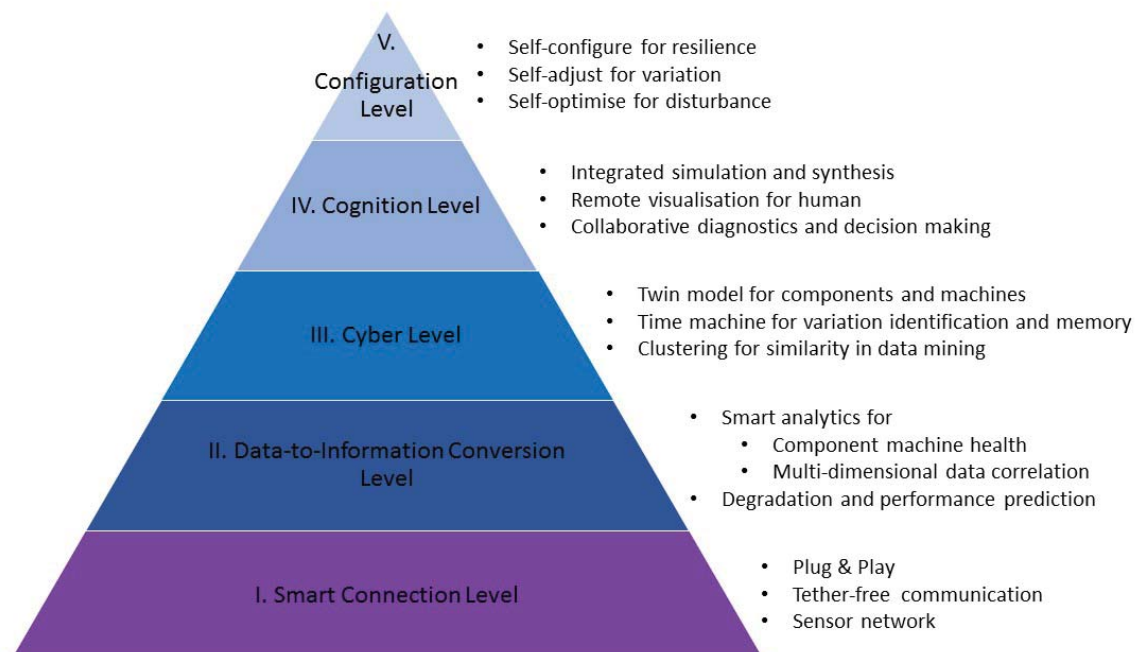
Figure 2.4: *CPS 5C architecture [42].*

Step 1: Smart connection

The first step involves acquiring reliable data from machines and components. Lee et al. [42] mention that provision needs to be made for various types of data acquired and in doing so, a seamless method for managing the various types of data needed is required. In a practical sense, this step would therefore involve the connecting of physical devices and the recording of data from them.

Step 2: Data-to-information conversion

Step two of this framework deals with the conversion of data extracted from connected devices, into usable information. The technology, techniques and methods required for this conversion, have already been developed in dealing with the big data boom. Lee et al. [42] states that this second step brings self-awareness to machines as they are now able to receive, and generate useful information.

Step 3: Cyber level

The focus of step three, the cyber level, is to create a central point to which all data is transferred. Such grouped information allows not only the measurement of individual machine performances, but also the comparison and evaluation of generations of machines.

Step 4: Cognition

The cognition level, step four, deals with the visual packaging and display of the outputs of previous steps in order to provide the user with decision support. In this step, the data analyses need to be presented in such a way that it transfers acquired knowledge to users and provides visual decision support.

Step 5: Configuration

The fifth and final step involves the feedback loop from the cyber system to the physical system. This step links the decisions made by the users in step four and connects them with steps one to three, hence commencing another iteration of the process.

A practical example

To provide a more detailed context of the five steps described, a practical example of a machine-operated assembly line is considered. In this example a product is manufactured in five stages, with a machine designated to each step. Figure 2.5 represents such a scenario in terms of the 5C framework.

Corresponding to the first level of the framework, each of the five machines is connected to one another by means of sensors. This allows for constant connectivity and exchange of data between the machines, as well as with the server. The raw machine data is converted to useful data, such as the assessment of each machine's health and work rate, which in turn is represented by step two of the framework. For explanatory purposes, the case is considered in which machine two requires maintenance within the following week, and cannot be used for manufacturing

in that time. The monitoring between machines represents a CPS in which this known event is communicated in a timely manner and an adaptive analysis is conducted. This step, which represents the third step in the 5C process, results in the CPS determining the possible scenarios for manufacturing the following week's production orders, based on the information that machine two cannot be used. These alternative scenarios could include the rearrangement of orders, or the transfer of manufacturing steps to another machine until the maintenance on machine two is completed. In step four of the 5C process, these alternative scenarios are packaged visually and sent to the user as decision support. Not only is the user provided with the alternative scenarios, but also receives the costs and potentially time delays associated with each, such that prioritisation can be given depending on which aspects are most important. The user can thus quickly and easily compare options based on the information provided by the CPS, and can make a decision regarding which scenario to implement. This decision is fed back into the CPS in a feedback loop containing the practical measures and actions to be followed. This completes the fifth and final step in the process, and initialises a second iteration of the process.

The continuous execution of this process ensures that all information is constantly available and problems pre-empted allowing for quick decision making to take place. This results in a resilient control system in which information processed by the CPS itself is used by the user to apply required preventative and corrective measures.
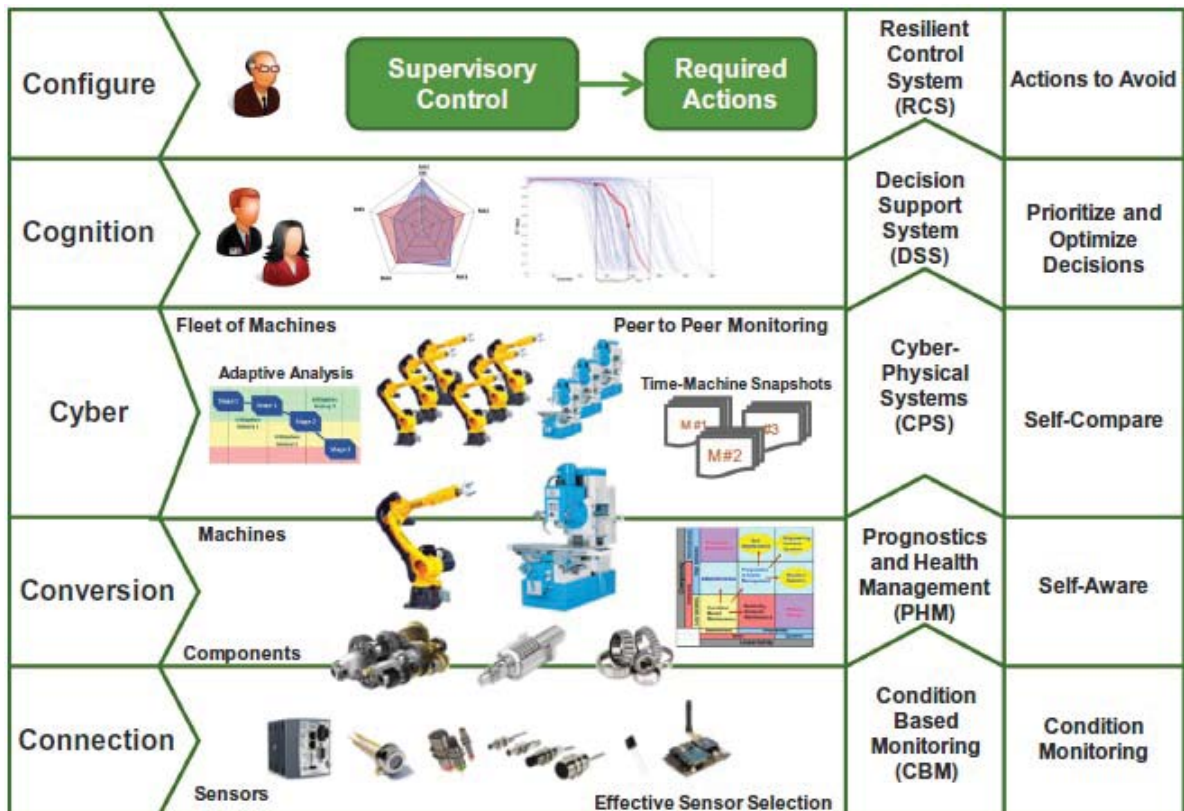
FIGURE 2.5: *5C framework techniques and applications [42].*

2.3.3   Smart factory

The smart factory is described by Herman et al. [34] and Kagermann et al. [37] as a factory that assists people and machines in the execution of their tasks. This is achieved by passive background systems, called calm systems, that can take in context information such as position and status of an entity, hence the name context-aware. The systems described by Kagermann et al. [37] accomplish their tasks by taking in information from the physical and virtual world and the unity of these two worlds is called a CPS [46], as described in Section 2.3.2. It is important to note that a smart factory contains a CPS and it is through this that calm systems, and the hardware and software of a smart factory, are able to communicate and send information between machines and humans. It thus follows that the smart factory is the embodiment of Industrie 4.0.

2.3.4   Internet of services

The IoS, according to Hermann et al. [34], enables service vendors to offer their services via the internet. An example of this scenario would be an instant text or notification service such as Twitter [80] that is incorporated into the shop floor of a manufacturing plant. These services are offered and combined into value-added services by various suppliers, such as a Twitter auto-notification shelf, and are communicated to users as well as consumers and accessed by them via various communication channels.

The goal of the IoS according to Terzidis et al. [72], is to use the internet for new ways of value creation in the services sector. In other words, the IoS aims to make services tradable in a digital
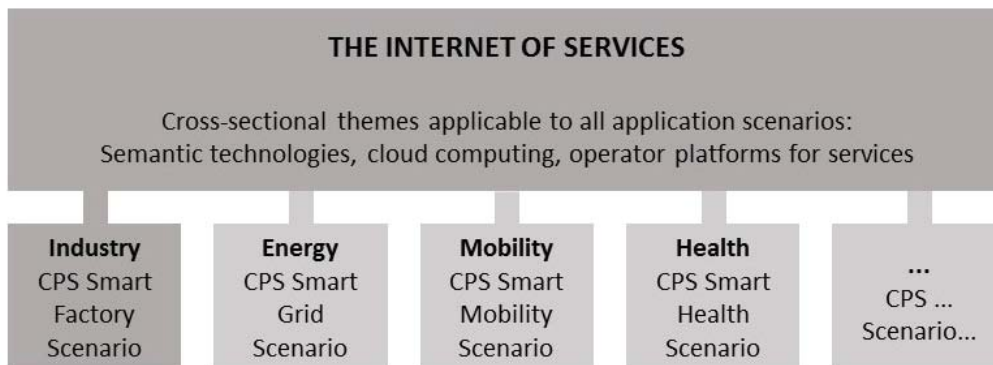
Figure 2.6: *Internet of services [37].*

medium. From an IT perspective, the concept of a service refers to a technical understanding of software functions provided as web services. In a broader sense, the concept of a service entails more than technical capabilities that are invoked by computer program interfaces. Throughout literature there is not such a strong agreement on the concept of the IoS as there is with the IoT. There are, however a few sources that describe the supposed function or need that the IoS does/should fulfil. Plass [56] describes the IoS as the development of networking and communication within the IoT which then produces vast amounts of data known as big data and is accessed via the cloud. Figure 2.6 describes the domain of the IoS and its application field, but for the purpose of this project, only the relevance to industry, the smart factory, is considered. Kagermann et al. [37] and Hermann et al. [34] describe the IoS as the enabling technologies that allow service vendors to offer their services via the internet. In such a system, the IoS consists of participants, an infrastructure for services, business models and the services themselves. In a factory, for example, this is done by making use of modular assembly stations that can be flexibly modified or expanded. In this situation, assembly stations and automated guided vehicles offer their services forming part of and defining the IoS.

2.4 Industrie 4.0 building blocks or pillars of technological advancement

The building blocks which are commonly referred to as pillars of Industrie 4.0 or technological advancement, can be considered as the supporting tools or technologies that are enabling the advancement to Industrie 4.0. These technologies have already been developed, but require alteration and improvement in some cases so that they can be tailored for the specific needs of user instances. According to a study by the Boston Consulting Group (BCG) [62] they are already used in industry, but are often found in isolated cases. It is the integration of all of these technologies that will transform industry and lead to Industrie 4.0:

- big data analytics,

- embedded electronics,

- simulation,

- cyber security,

- cloud computing,

- additive manufacturing,

- augmented reality,

- digital factory, and

- communication technology.

These technologies are discussed in more detail in the sections that follow.

2.4.1 Big data analytics

According to Manyika et al. [47], big data refers to datasets whose size is beyond the ability of typical database software tools to capture, store, manage and more importantly, analyse. McAfee et al. [49] further explains that big data is not just analytics applied to these big data sets, which could not be done before due to technological constraints, but is a movement that seeks to glean intelligence from data and translate that into business advantages. With big data, there are three key differences from traditional data; volume, velocity, and variety. Volume referring to the size of the datasets as described by Manyika et al. [47], velocity to the rate at which the data is generated, and variety to the different types of data collected.

Today the manufacturing sector is finding itself inundated with increasing amounts of data from various sources, and there is a need to gather all that data, collate and organize it in a coherent manner, and use the analytics provided by these data sets to support managements decision-making. Businesses cannot afford to ignore the data coming in, as it might prove to be very useful when it comes to optimization of production quality and service, reduce energy consumption, and improve efficiencies in the production process. For example, data can be collected from the various phases of the production process. These large amounts of data can be analysed in correlation with each other in order to identify phases with redundant processes that may be streamlined.

According to Hilbert [35] and Anastasia[6] there are six Cs in big data and big data-analytics with respect to the Industrie 4.0 environment. They are:

- connection, referring to the connection between sensors and networks,

- cloud computing,

- cyber, which involves the model and the memory capacity of the system,

- content and context,

- community, data sharing and collaboration between and among stakeholders, and

- customisation: How can the system and data be translated and transformed to produce different results?

2.4.2 Embedded electronics

The embedded electronics referred to in this project is electronics whose functionality has been implemented in hardware and software within specific system constraints such as power consumption, real-time demands and size. The relevance of this to the project is that these electronics

form a vital part of Industrie 4.0, because of the evolving functionality of embedded electronics, where they are no longer reliant on manual external stimulus but are reactive to sensory awareness through CPSs and form part of the IoT.

The use of robots in the manufacturing process is no longer novel; however, robots, too, are subject to improvements and evolution, as Fuller [27] describes the increasing complexities of end actuators (hands) of robots. Robot manufacturing companies are designing these robots to be more autonomous and interactive. An example, noted during a visit to Volkswagen South Africa, is the KUKA [59] painting robot, which is able to automatically exchange nozzles, paints and optimise spraying cycles which were all previously done manually.

The electronics that form part of the IoT and Industrie 4.0 according to Sundmaeker et al. [70] is open source programmable logic controllers (PLCs) that have been integrated with different modules and add ons, allowing it to be connected to the internet and a companies CPS and infrastructure. For SMEs, incorporating automation and Industrie 4.0 in the sense that a large company like the Toyota manufacturing company do, would have seemed impossible 5 to 10 years ago due to the lack of affordable and flexible technology. Fortunately nowadays companies like Arduino [8], Sparkfun [68] and Raspberry Pi [58] have enabled SMEs to purchase low cost, highly flexible PLCs and other hardware that will allow the integration and ultimately the incorporation of the IoT and Industrie 4.0 [70].

2.4.3   Simulation

Simulation tools like those of Technomatix [65] and Simio [67] have allowed companies to effectively simulate processes, testing alternatives and feasibility of projects or endeavours [6]. This allows companies to reduce trial and error costs as well as setup and implementation times. As computing power increases so does the accuracy and validity of the simulations and simulation software used, to a point where the 3D representations are no longer just simulations, but live stream representations of the company. This is achieved through the incorporation of the collected data of all "things" present within the environment that is to be simulated. This escalating effect is further explained in the digital factory concept.

2.4.4   Cyber security

As more and more companies are going online, there is an increasing demand for higher cyber security [70]. Considering the amount and nature of data or information that are uploaded or shared in networks, industrial systems are becoming increasingly vulnerable to threats. To address this, cyber security measures have to be put in place. According to Gasser [28], cyber security is the protection of information systems from theft or damage to the hardware, the software or to the information they contain.

2.4.5   Cloud computing

According to Mell and Grance [51], cloud computing is a model for enabling ubiquitous, on demand network access to a shared pool of computing resources such as networks, servers, storage and services. According to Armbrust et al. [9] cloud computing services can be rapidly provisioned with minimal management effort and require very little service provider interaction. Cloud computing could also be described as software as a service (SaaS), in which case the definition supports a very popular service, Google Drive [30]. In Google Drive, apart from

providing a data storage service, other software is also on offer, for example Google sheets, Google slides, and Google docs.

The large data sets involved in Industrie 4.0 means data sharing will become more prominent. The usual cloud-based software that a manufacturing company may have been using in the past may no longer be enough to hold all that data. Due to the continuous efforts of developers, cloud technologies are improving, and becoming more enabled for manufacturing and production systems. This point is emphasised in Section 2.3.2, where the large data sets associated with machines need to be readily accessed and converted into information providing insights and decision support to management of a company. In conjunction with the 5C framework of Lee et al. [42] in establishing a CPS, Mell and Grance [51] propose five points that are essential for storing and using the data through a cloud based service:

- on-demand self-service: A consumer can be provided with dynamic computing capabilities, such as server time and network storage, as it is needed without requiring human interaction with each service provider.

- broad network access: Capabilities are available over the network and accessed through standard devices and software that promote use by heterogeneous client platforms e.g mobile phones, tablets, laptops, and workstations.

- resource pooling: The provider's computing resources are pooled to serve multiple consumers using a multi-tenant model. This can be seen with e.g. Google Drive [30], that offers data storage, and a text editor and calculation worksheet.

- rapid elasticity: Capabilities can be elastically provisioned and released, in some cases automatically, to scale outward and inward adapting to demand. The consumer is generally unaware of changes in the system capabilities.

- measured service: Cloud systems automatically control and optimize resource use by implementing metering capability at some level appropriate to the type of service e.g. limited online storage space.

2.4.6   Additive manufacturing

Customisation of products is one way for manufacturers to improve customer satisfaction [62]. Fortunately, additive manufacturing is making this possible, as it enables manufacturers to come up with small batches of products that are customized in ways that offer more value to end users, while reducing cost and time inefficiencies for the manufacturer [62]. Companies have just begun to adopt additive manufacturing processes such as 3D printing, which they mostly use for prototyping and production of individual components [62]. With Industrie 4.0, these additive manufacturing methods will be widely used to produce small batches of customized products that offer construction advantages, such as complex, lightweight designs [38]. High-performance, decentralised additive manufacturing systems will reduce transport distances and stock on hand, as processes such as 3D printing has moved from being only applicable to polymers and metals to a broad range of materials, including glass, biocells, sugar and cement. According to the BCG [62], the maximum size of 3D printing has increased by more than tenfold from the 1990s, and this has led to increased possibilities for large scale rapid prototyping for companies in all manufacturing sectors.

2.4.7 Augmented reality

According to the BCG [62] augmented reality based systems are still currently in their infancy, but will in future form a large part of the support systems of companies. The BCG further explains that companies will use these technologies to provide workers with real-time information to improve decision making and work procedures. Taking this concept further, McKinsey and Company [50] state that this will be used in the form of virtual training for new and current employees, although the BCG [62] notes that some companies have already employed virtual training systems, where employees are taught how to handle emergencies or interact with physical objects using virtual representations thereof.

2.4.8 Digital factory

The digital factory is a bridge between a real factory and a virtual copy of the factory [16]. The digital factory is in essence a live simulation of the real factory, which incorporates live sensor data from the real factory. The digital factory can be used to perform highly accurate simulations of changes and/or alterations that are under investigation [32].

The digital factory is a generic term for the convergence of digital network models, methods and tools like simulation and 3D visualisation [40]. The main goal of such a system is to improve integrated planning, evaluation and continuous improvement efforts of processes, structures and resources of the real factory. Figure 2.7 shows the relationship between a virtual factory, a digital factory and a real factory, together with the associated processes. The virtual factory is merely a representation of the real factory, in which planning can be done, much like a 3D model of the real factory [75]. It contains data from the real factory, such as actual factory sizes and process flow times. The digital factory also contains simulation software whereby it can simulate scenarios with regards to changes that could potentially be implemented, and that have been deemed feasible from the virtual factory. The digital factory provides an almost real scenario for any potential changes, so that it can be subject to evaluation and feasibility before implementation in the real factory.

The digital factory has the following core objectives:

- industrial improvement,

- improving planning quality,

- improvement of communication,

- standardisation, and

- data management.

According to Bracht and Masurat [16], industrial improvement is achieved by avoiding bad investments, accelerated market introduction time of new products through integrated product and process planning via highly detailed and accurate simulations. The planning quality is improved by very much the same method as the industrial improvement, as it is possible to simulate and view any complex scenarios, depending on the complexity and refinement of the simulation software used. Communication is improved, by the use of cloud computing, and illustrative representations of complex problems. Data management is drastically improved, also by the use of cloud computing as well as integrated enterprise resource planning (ERP), and master execution systems (MES).
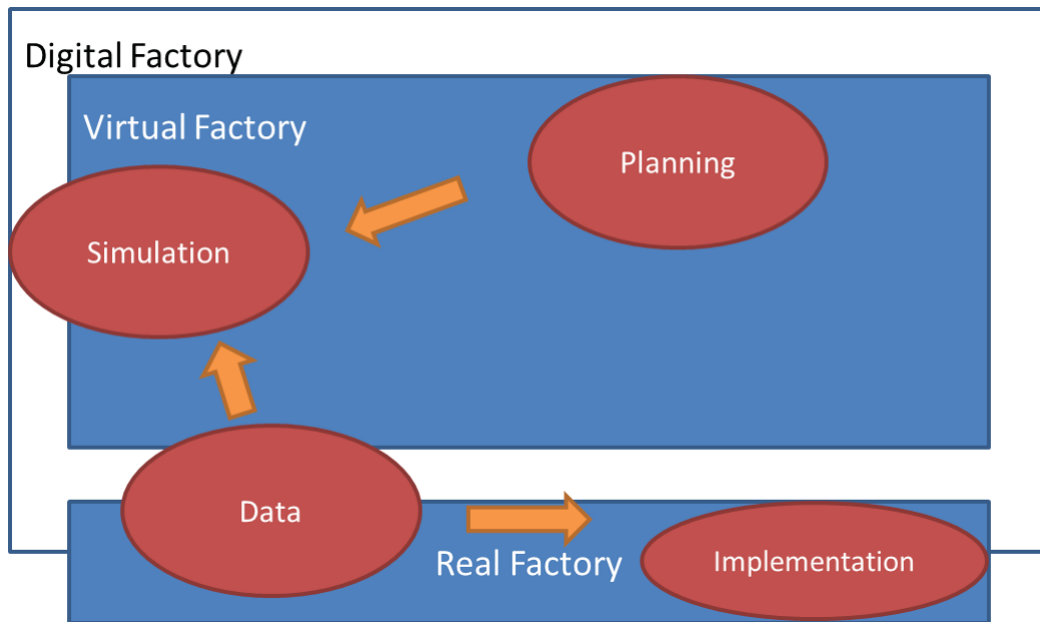
FIGURE 2.7: *Intersection between a virtual, digital and real factory [75].*

2.4.9   Communication technology

It is estimated that by the year 2020, there will be over 50 billion devices connected to the internet [25] . This increase in devices places a demand on the amount of internet protocol (IP) addresses that are required as well as a more efficient, fast and reliable communication protocol. This has lead to the development of the Internet Protocol version six (IPv6), and the broadening of Wi-Fi technologies. The IPv6 was developed because of the exhaustion of the IP addresses in the IPv4. This new development will allow for a far greater number of devices within the connected world [25].

2.4.10   Industrie 4.0 building blocks or pillars of technological advancement in summary

This section discussed nine components deemed essential to the advancement of current technological endeavours, or are building blocks to Industrie 4.0. These components are essential for the main components of Industrie 4.0, discussed in Section 2.3, to exist. The implementation of the main components of Industrie 4.0 will inherently contain some of the building blocks listed in this section. The following section discusses seven key principles that should be considered when designing for Industrie 4.0.

2.5   Design principles

According to Hermann et al. [34], there are six fundamental design principles that are evident in any Industrie 4.0 environment. These design principles are not only evident in Industrie 4.0 environments, but also assist companies in identifying and implementing Industrie 4.0. Kagermann et al. [37] in a paper titled "Recommendations for implementing the strategic initiative Industrie 4.0", do not discuss specific design components for Industrie 4.0 as Hermann et al. [34] does, but do list general guidelines for implementing Industrie 4.0 by providing use cases as

examples of what can or should be done to achieve or implement Industrie 4.0. These guidelines are on a more company wide strategic level as they provide support and detail to achieving the vertical and horizontal integration of companies and supply chains, as discussed in Section 2.6. The design principles outlined by Herman et al. [34], are supported by Sundmaeker et al. [70], except for the explicit importance made of standardisation, which has lead to the inclusion of a seventh design principle. These are discussed in more detail in the sections that follow

2.5.1   Interoperability

According to [71] interoperability means that all entities (workpiece carriers, products, assembly stations, humans) within a manufacturing environment are able to communicate with each other. Put in different terms, it means that all "objects" and "things" that form part of a CPS have compatible communication protocols and can accept messages coming to and from each other. This also implies that once communication has been performed and data exchanged, the "objects" or "things" are able to convert the data into information, as indicated in the second level of the 5C framework, and act on it.

2.5.2   Virtualisation

Virtualisation as explained by Hermann et al. [34], is the capability to monitor any physical process within a working environment, by linking live sensor data to plant simulation software and having the sensors read live process status data into the software. This scenario will give any manager the ability to have an overview of the entire plant from his/her smart device.

2.5.3   Decentralisation

Decentralisation refers to the ability of CPSs within smart factories to make decisions on their own. Hermann et al. [34] and Hompel et al. [36] explain that the rising demand for individualised or custom products has made centralised control increasingly difficult and less feasible. The reason for this, according to Hermann et al. [34] and Hompel et al. [36], is because centralised control reduces the speed of decision making systems in addition to reducing the ability to customise individualised products. This has also given rise to the need for embedded computers in the CPS to make decisions on their own. This decision making should, however, not be regarded as a form of artificial intelligence in the same context that humans make decisions, but in the sense of embedded electronics, so decision making is the mere conditional execution of functions. An example of this would be the process sequencing initiated by radio frequency identification (RFID) as a part moves through a working environment.

2.5.4   Real-time capability

Real-time capability refers to a system's capability to capture, extract and analyse data, and provide the derived insights immediately. For organisational purposes this means that data needs to be collected and analysed or be analysable in real-time [34]. An example of such a situation would be a machine failure, whose tasks are then immediately rerouted to other machines and the necessary changes to the production speeds and schedules are then automatically implemented [13].

2.5.5   Service orientation

According to Hermann et al. [34], the service orientation design principle of Industrie 4.0 is very much just the incorporation of the IoS into the working environment of a company. It is the ability of "objects" and "things" to connect to and have access to services provided in the CPS and the smart factory via the IoS. These services are, however, not limited to internal company borders and can be offered by other, third party participants [13], like that of Twitter [80] feeds for process updates. Hermann et al. [34] explains further that in the future smart factory, all CPS services and functionalities are offered as an encapsulated web service, and because of this product specific processes can be orientated and customised according to customer specific requirements, and hence batch/lot size one can be achieved.

2.5.6   Modularity

Modularity refers to the flexibility and adaptability of systems to changing requirements and external inputs, by replacing and/or expanding individual modules [34]. The description of this design principle, however valid, is very vague and a better description, by example, is provided by Sundmaeker et al. [70]; the modularity of a system is its capability to adapt or be adapted to fit different external inputs or differing requirements. This can be done by plug and play modules for actuators on specific robots as current actuators are not needed, the interchangeability of algorithms within the systems as well as communication versatility.

2.5.7   Standardisation

Plass [56] states that the need to standardise and determine the collaboration mechanisms and information to be exchanged should form part of the design and implementation considerations of an Industrie 4.0 environment. Sundmaeker et al. [70] further support this in the book titled "Vision and challenges for realising the internet of things", where there is constant mention, in numerous chapters, of the need to standardise communication protocols and channels, frameworks, and data standards, to name a few.

2.5.8   Concluding the design principles

The seven design principles introduced above by various authors are a generalised, yet practical and important part of implementing or designing for Industrie 4.0. All seven principles overlap, in the sense that one can not exist in an Industrie 4.0 environment without the other. Each of the principles form a core part of the definitions of the main components of Indsutrie 4.0, as described in Section 2.3. Successful implementation of Industrie 4.0, adhering to the design principles will have great effects on a company and its supply chain, these effects are discussed in the following section.

2.6   Industrie 4.0 by-products

The characteristics described in this section are not design considerations as described in 2.5, but are a by-product of the successful implementation of Industrie 4.0 as identified by Plass [56].
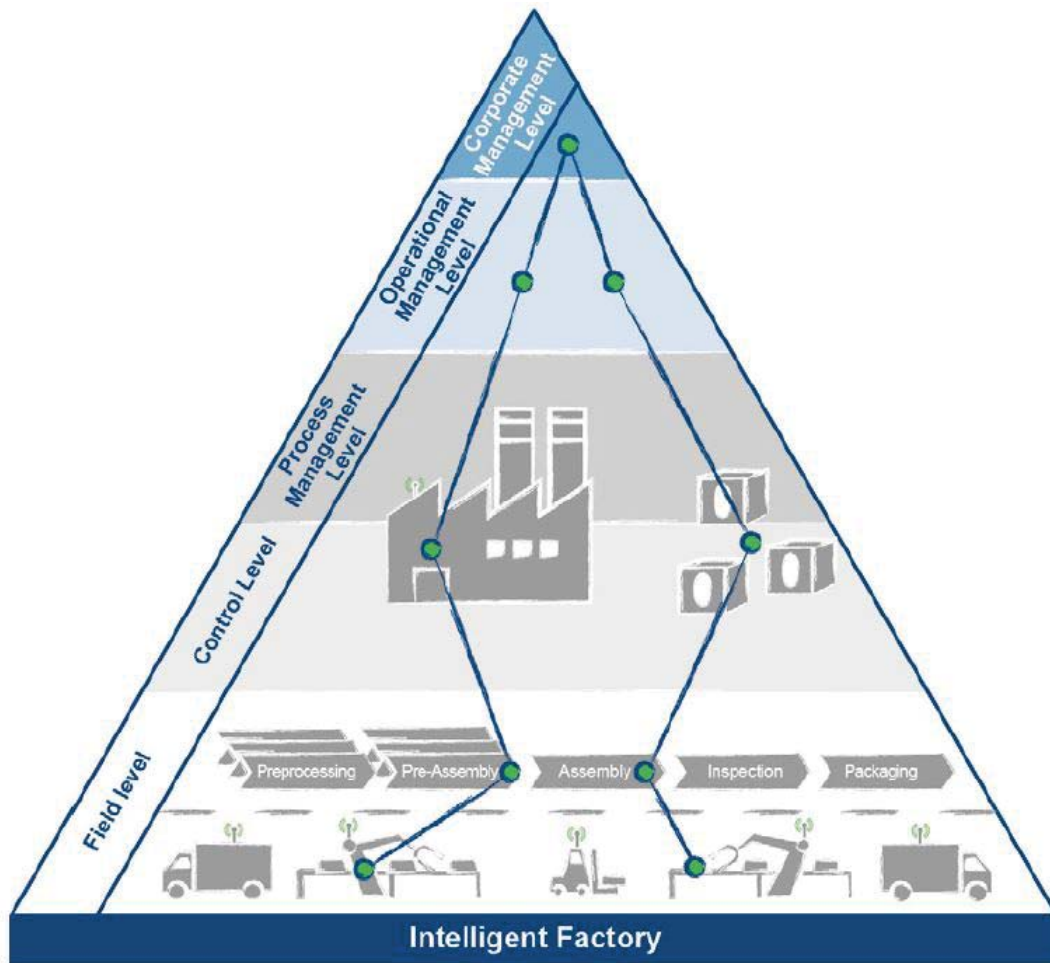
FIGURE 2.8: *Vertical integration within a company [56].*

2.6.1   Vertical integration of smart production systems

Factories that have implemented Industrie 4.0 cannot function on their own, with a top down approach, where commands are driven from a management level and translated and pursued down the hierarchical structure of the company [56]. The interconnectivity of all entities within an Industrie 4.0 factory creates the vertical integration of the production system as seen in Figure 2.8. Figure 2.8 depicts the process whereby links are formed from a corporate management level at the top of the pyramid, to the field level or shop floor. The essence of vertical networking according to Plass [56], stems from the use of cyber-physical production systems (CPPSs) which allows factories and manufacturing plants to react quickly and appropriately to variables, such as demand levels, stock levels, machine defects and unforeseen delays.

2.6.2   Horizontal integration through global value chain networks

Horizontal integration in Industrie 4.0 links the factory, supplier and distributor into an Industrie 4.0 supply chain [71]. Figure 2.9 indicates such a relationship between the factory, supplier and the distributor. Within a horizontally integrated supply chain, each entity is both a transmitter and receiver, because it transmits real-time data about its process and products to concerned external parties (supplier or distributor), and receives real-time data from either the supplier or
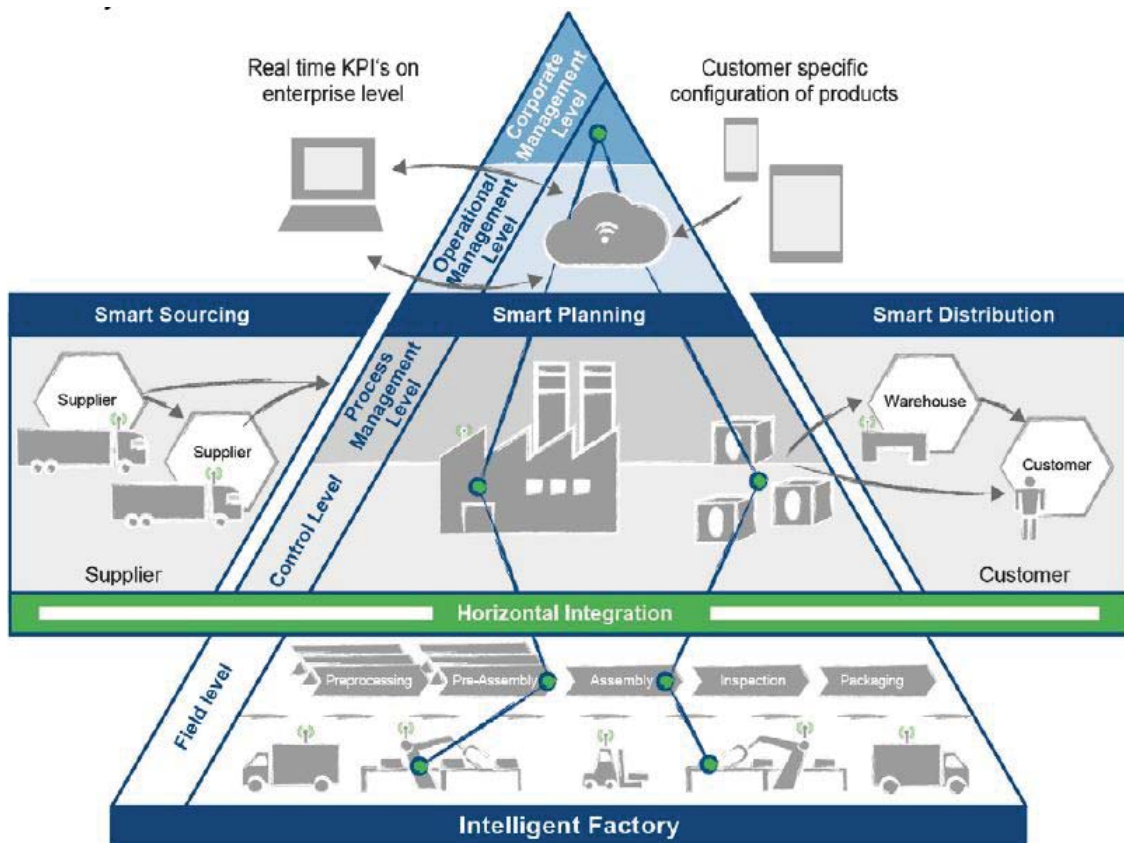
FIGURE 2.9: *Horizontal integration in the supply chain [56].*

distributor. This horizontal integration, according to Plass [56], will facilitate the establishment and maintenance of networks that create and add value. According to Kagermann et al. [37] the horizontal integration of supply chains allows the creation of a value network on a strategic level, and provides end-to-end integration across the entire value chain on the business process level. This means that the horizontal integration forms cooperation between companies and addresses sustainability of relationships and business practises [37].

2.6.3 Through-engineering across the entire value chain

Through engineering in the case of Industrie 4.0 refers to two distinct aspects, as described by Plass [56]. The first being the involvement of all departments in the entire product life cycle of a product and the second is the shift of the customer decoupling point right to the point of source. The meaning of the first aspect is that a product is subject to alteration and adaptation throughout its entire life cycle, from sourcing to design and manufacture, to delivery. The second aspect is the involvement of the customer throughout this entire process, where the customer can make constrained decisions throughout their product's life cycle that will change the nature and characteristics of their product. This gives rise to the concept of batch size one. A comparison to traditional decoupling points found in manufacturing is depicted in Figure 2.10, clearly showing the lengthened involvement of the customer throughout the product life cycle.
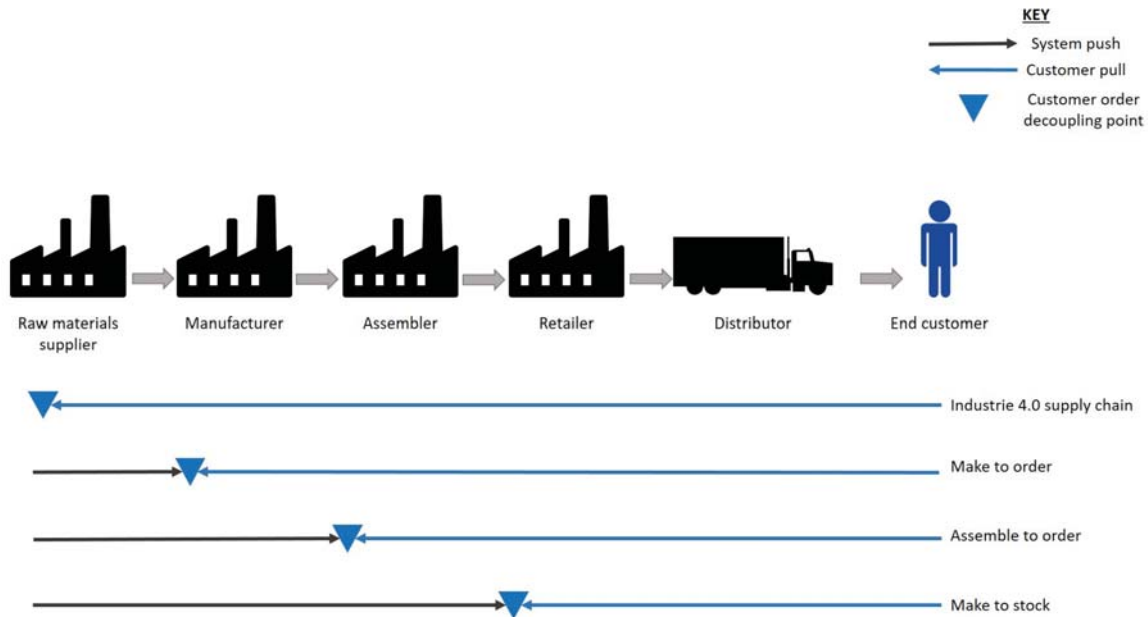
Figure 2.10: *Customer order decoupling point in an Industrie 4.0 supply chain, adapted from [56].*

2.6.4 Acceleration through exponential technologies

Business operations, particularly those involved in manufacturing, entail the use of many technologies, most of them already existing and operational for a long time. However, technologies are evolving by the day, becoming better and smaller, and in some cases bigger [6]. This builds on the previous characteristic, whereby for example, Plass [56] states that changes can be implemented on a product by rapid 3D printing of parts as needed.

2.6.5 The by-products of Industrie 4.0 in summary

As stated previously, the successful implementation of Industrie 4.0 will have many by-products on a company and its supply chain. The company and its supply chain will become more connected and co-operate on company wide levels, to reduce overall costs and operational efficiencies. Since the entire supply chain of a company could be affected, the effects could be wide ranging, influencing entire economies. Some of these potential effects have been studied by various companies, the results of which are presented and discussed in the following section.

2.7 Benefits of Industrie 4.0

The potential benefits of Industrie 4.0 are widespread, from a reduction in production costs to reductions in time to market introductions of new products. Many companies are performing their own case studies and analyses on the estimated benefits of Industrie 4.0. Of these, two notable analyses are those of McKinsey and Company [50] and he BCG [62]. The most important of the findings in their analyses are discussed in the following sections.
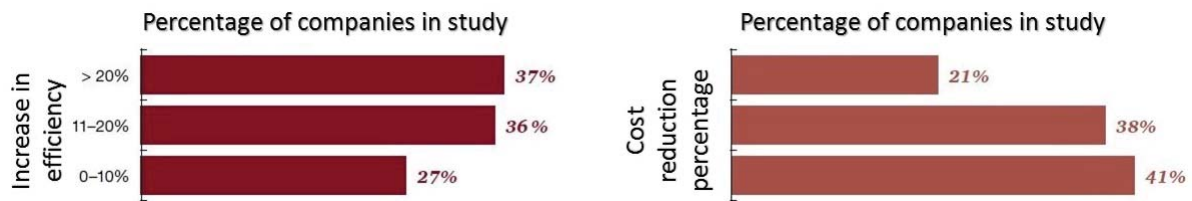
FIGURE 2.11: *Cumulative increase in efficiencies and associated cost reductions of Industrie 4.0 [38].*
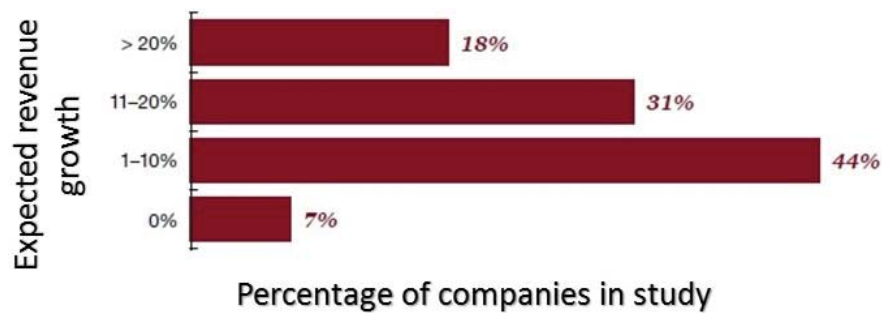
FIGURE 2.12: *Expected cumulative revenue growth in the manufacturing sector over the next five years, adapted from [38].*

2.7.1   Increased productivity

As stated by McKinsey and Company [50], there will be a large increase in all operational efficiencies with the use of data levering to improve processes. Of these, one of the most notable improvements will be in productivity levels in the manufacturing sectors. Studies conducted by Koch et al. [38]in the year 2014 in Germany show that operational efficiencies will increase by an average of 3.3% annually for the following five years leading to an average annual reduction in costs of 2.6%. In fact, the BCG study [62] stated that in the automotive industry alone, productivity is expected to increases by 10–20%, once Industrie 4.0 is fully implemented. An excerpt of the increases in efficiencies and corresponding cost reductions are depicted in Figure 2.11.

2.7.2   Increased revenue

With the increase in productivity, the manufacturing sector will also see an increase in its revenues, as depicted in Figure 2.12. Industrie 4.0 is seen as one of the major drivers for the growth of revenue levels, even as its implementation will also require significant investments by businesses. According to Koch et al. [38] cost-benefit analyses will show that revenue will increase faster and higher than the costs incurred to automate or digitise the manufacturing process in terms of Industrie 4.0.

2.7.3   Delivery of better customer service

According to Koch et al. [38], that with Industrie 4.0 concepts and methods applied, logistics and statistics are generated and collected in an automated manner, so responses are faster. The business immediately knows if an adjustment has to be made, or what adjustments are required, and can thus respond faster to the needs of customers. Due to the involvement of the
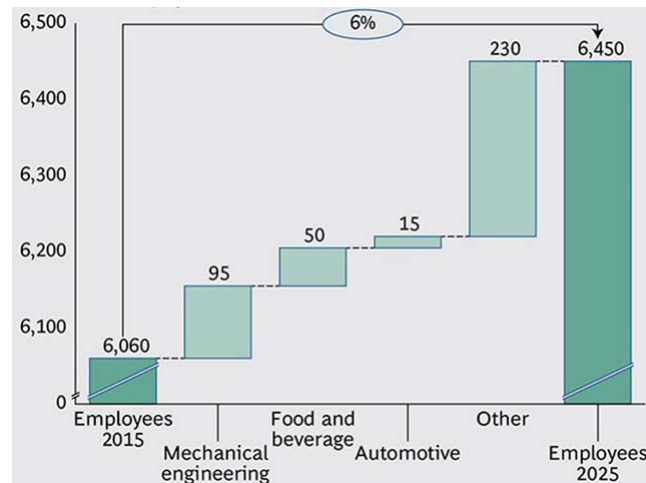
FIGURE 2.13: *Employment increase per sector in Germany [62].*

customer throughout the whole production process as mentioned in Section 2.6.3, a higher level of customisation, and thus customer service delivery, is possible.

2.7.4   Employment

The study by the BCG [62] on Industrie 4.0's impact on German manufacturing, found that the growth it stimulates will lead to a 6% increase in employment over the next ten years. The expected increases per sector can be seen in Figure 2.13. The study also noted that the demand for employees in the mechanical engineering sector may rise even more, by as much as 10% during the same period. In the short term, the trend toward greater automation will displace some of the often low-skilled labourers who perform simple, repetitive tasks. At the same time, the growing use of software, connectivity, and analytics will increase the demand for employees with competencies in software development and IT technologies, such as mechatronics experts with software skills.

2.7.5   Industrie 4.0 benefits in summary

Overall it can be seen that the benefits of Industrie 4.0 will have a large impact on certain sectors across Europe, more specifically the manufacturing sector in Germany. If the figures discussed above hold true, and the rest of the world follow suit to the European manufacturing sector, the world could see a drastic shift in resource, monetary and employment terms. Although this section creates a promising picture for the future of Industrie 4.0, there are some challenges facing its implementation. These challenges are discussed in the following section.

2.8 Challenges facing the implementation of Industrie 4.0

Work done by Koch et al. [38] identified challenges for companies moving towards Industrie 4.0. These challenges are supported by other works such as the study by the BCG [62], Anastasia [6] and Merkofer et al. [52]. Figure 2.14, displays the identified challenges for companies, as well as ranks the importance for the companies posed in the study done by Koch et al. [38]. From Figure 2.14 the two most important challenges for companies are the unclear economic
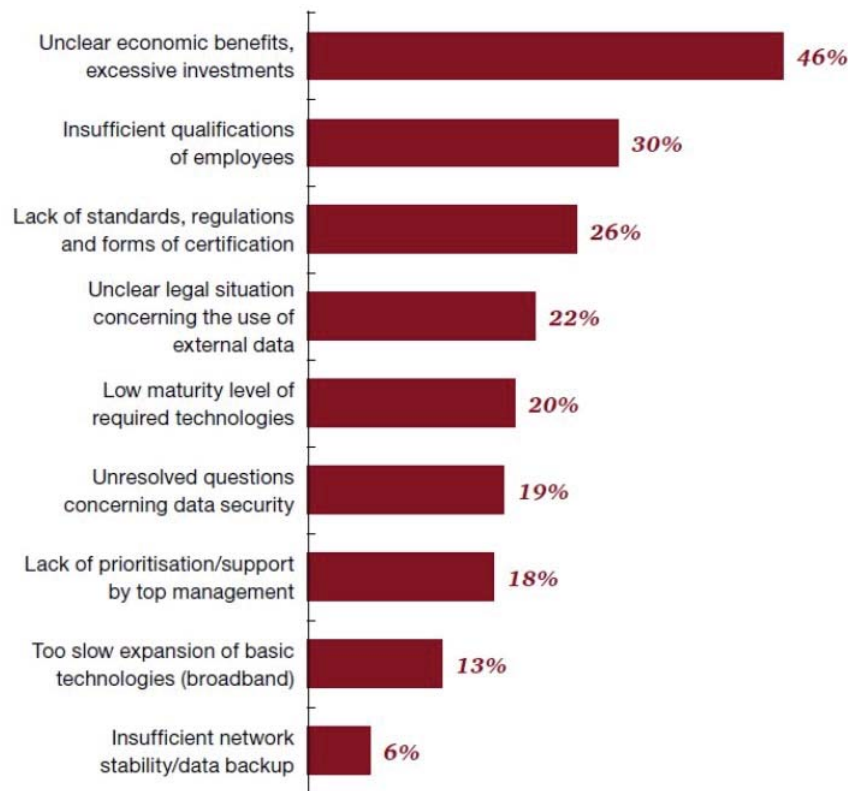
FIGURE 2.14: *Challenges facing Industrie 4.0 [38].*

benefits and excessive investments, and insufficient qualifications of employees. Other authors, such as Venkatasubramanian [76] and Kagermann et al. [37] believe data security to also be one of Industrie 4.0's main concerns. These three challenges are discussed in further detail in the sections which follow.

2.8.1 Unclear economic benefits and excessive investments

A study in 2014 by Koch et al. [38] analysed companies, and found that until 2019, these companies will invest, on average, 3,3% of their annual revenues in Industrie 4.0 solutions. PWC then rated this as equivalent to nearly 50% of the planned new capital investments and equates it to more than €140 billion in the European industrial landscape. Another study by the BCG [62], has estimated that manufacturing companies in Europe will invest €250 billion in the next ten years in order to adapt processes to incorporate Industrie 4.0.

2.8.2 Insufficient qualifications of employees

According to Koch et al. [38], there will be a large shift in the skills requirements of workforces from all economic sectors. The list below indicates the three main challenges and concerns that will be faced with regards to employees with the change brought about by the implementation of Industrie 4.0.

- lack of skill sets,
- displacement of low-skilled workers, and

- standardisation across industries.

The increase in IT and computers within manufacturing sectors will place a greater demand on workers skilled in programming and electronics [38]. Koch et al. [38] further explains that low-skilled workers with repetitive jobs will be replaced by robots as tasks become ever more standardised and automated. The realisation of which could lead to a great reluctance to change and adoption by large portions of the working force in many industrial sectors. This issue of reluctance could be especially prominent in countries such as South Africa where SMEs provide such a large part of the manufacturing sector, as discussed in Chapter 1.

2.8.3 Data security risks

The increasing amount of on-line data handling by companies, puts them at a greater cyber risk. Kagermann et al. [37] emphasized that digital safety and security are two critical factors that need to be considered for the success of Industrie 4.0, to such an extent that security needs to be a key design consideration for Industrie 4.0. Koch et al. [38] also identified data security as a challenge facing Industrie 4.0, although it is not of top for companies in their findings.

2.8.4 The challenges facing Industrie 4.0 in summary

The study outlined by Koch et al. [38] gave a clear indication of what companies feel are the challenges facing Industrie 4.0, of which the two main concepts were discussed. Other sources also made mention of the increased data security risk, as a result of the increased use of the the internet. From the studies conducted and discussed in the above sections, it would seem that the benefits are worth pursuing, and as such the implementation of Industrie 4.0 is discussed in the following section.

2.9 The implementation of Industrie 4.0

As previously mentioned, Industrie 4.0 will provide benefits in a wide varying number of sectors and in significant amounts, to the companies who wish to pursue it. As such, whether to pursue an Industrie 4.0 transformation should not be a debate. A suitable methodology for implementation of Industrie 4.0 is however, less clear. In order to accomplish this, a framework or implementation methodology of some sort is required to steer implementation efforts. Research was performed to identify and use such a framework, but it proved fruitless, as most of the frameworks only address implementation of Industrie 4.0 on meta levels, such as the one shown in Figure 2.15 which helps organise the implementation efforts from a theoretical standpoint. Other methodologies were even less applicable, such as the reference architecture model for Industrie 4.0 (RAMI4.0) which was proposed by Adolphs et al. [5]. The purpose of RAMI4.0 is to present the definitive characteristics mentioned in Chapter 2 of Industrie 4.0 in a single model [5]. This, then rules out the use of the model as a framework or methodology for the implementation of Industrie 4.0.

The use of simulation software and digital factory models, as discussed in Section 2.4.3 and Section 2.4.8 respectively, is useful for testing new alternatives or scenarios before implementing them in the real factory. Their use for implementation scenarios have however, proved less useful in the case of Industrie 4.0, where the final state still remains latent. A simulation or digital model also does not provide companies with the necessary change in employee behaviours or
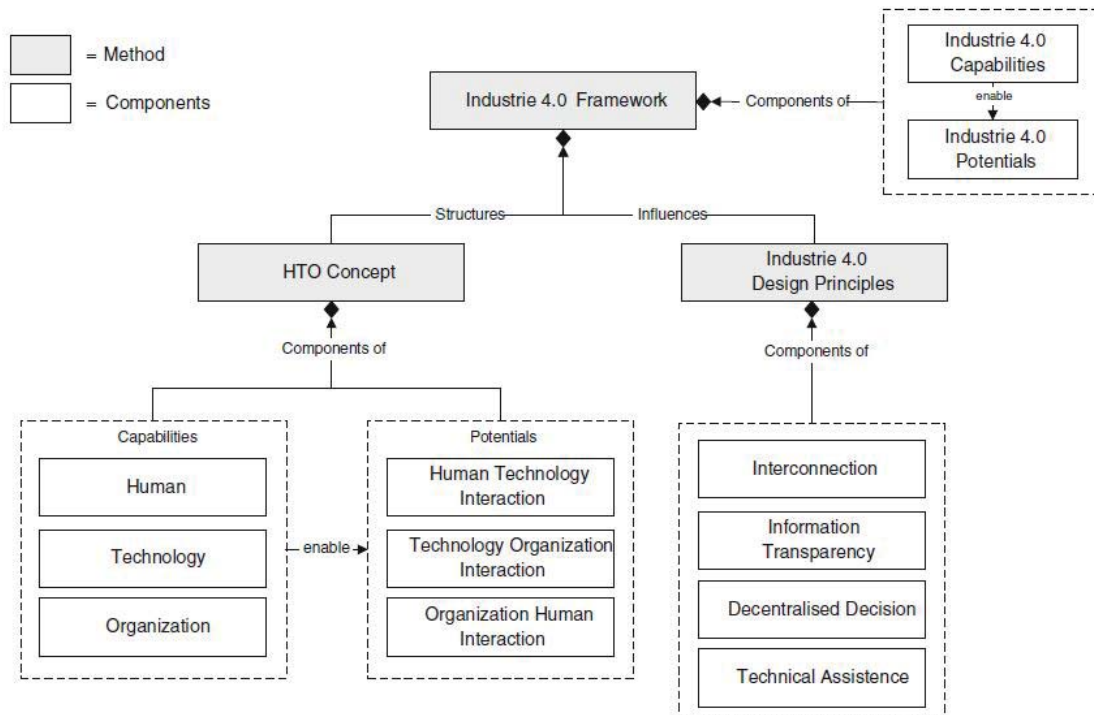
FIGURE 2.15: *Metamodel of the Industrie 4.0 framework [17].*

skills development, which was noted by companies as one of the top implementation challenges discussed in Section 2.8. Since Industrie 4.0 also incorporates, to a large extent, new technologies or applications thereof, it is a difficult concept to simulate. A different form of testing scenarios is thus called for, since the trial and error costs of implementing such technological changes directly on site, would be, simply put, unaffordable.

CIRP, a production engineering research organisation, uses learning factories as research and testing tools for experimental work and showcasing. Such a learning factory is a small scale factory, in which production of a product takes place, in order to showcase methods taking place in an actual factory, and provides both hands-on training for employees, but also allows for the experimental implementation of new methods without the costs of disrupting actual production lines. Learning factories are, as mentioned by Cachay et al. [21], almost risk free tools and environments where users, which comprise of industry participants and students, can learn how industry related concepts work as well as try out new ideas. As such, the idea for this thesis was to implement Industrie 4.0 concepts within learning factories so that the benefits and possibilities can be showcased to industry partners, as well as to students. This will allow students and/or companies to physically see the effects that Industrie 4.0 can have on a production environment, without having to carry the costs themselves. It will allow them to experiment with various scenarios in practice, before determining the more suitable implementation for their specific case.

Stellenbosch University, more so the Industrial Engineering department, works very closely with CIRP and is arguably on the forefront of design, optimisation, machines, and systems. The department is currently embarking on the journey of creating such a learning environment in the form of its own learning factory. Industrie 4.0 is altering the landscape of the industrial environment, and so learning factories should adopt the next industrial revolution and provide an exemplary environment where users can learn and experiment with the technologies and how

they work. In the following section, learning factories are discussed in terms of their composition, and their applicability to showcasing a complex new and unknown topic such as Industrie 4.0.

2.10 Learning factories

According to Abele et al. [2], a learning factory is a factory environment, where all processes and technologies inside it are base on real industrial sites, more specifically SMEs. Learning factories provide a reality-conform production environment as a learning environment where only minor abstractions are possible, providing participants with a practical learning experience. Learning factories are discussed in more detail in this section.

2.10.1   The global problem that led to learning factories

According to Lamancusa et al. [41], prior to 1950, practical arts dominated the engineering curricula. The main focus was to produce graduates who could be immediately useful to industry. This could have been as a result of the second world war, which created a scarcity of practical graduates. In addition to foundational studies in physics and calculus, students developed visualisation and graphical skills, and acquired direct knowledge of materials in foundries, machine shops, and test laboratories from field trips.

Lamancusa et al. [41] states that the publication of the Grinter report [33] in 1956 and the launch of the Sputnik in 1957 are widely acknowledged to have transformed the engineering education in the United States. The curricula changed, and books became more focused on calculus and science. The increase in enrolments and decreased budgets made mass lectures more feasible and hands-on, practical work less attractive. Increased computing power and simulation software with decreased computer costs rendered prototyping and practical work obsolete. During this same period, the United States government made a large amount of funds available for research, without equal funding for the expansion of infrastructures [31]. The result: Hands-on, practical labs became research and generic computer labs. The combined effect of the above mentioned was that students spent far less time "doing" engineering, and created a dependency on computerised applications.

Throughout industry, urgent challenges range from implementing new technologies over demographic change to volatile business environments in general [2], and in order for companies to withstand the international pressures and survive the highly competitive market environment, they need to continuously develop their manufacturing processes, their production equipment, as well as their operational and organisational processes [21]. Companies need to develop these criteria, so that they can quickly act and adapt to new market conditions [2], and this is dependent on the ability of the employees on all hierarchy levels to act self-organised in unknown situations and to find creative solutions [1, 4]. Therein lies the problem, because traditional teaching methods showed limited effects, according to Abele et al [2] for developing these competencies in employees. Fortunately learning factories are attempting to breach this gap.

In 1994, the National Science Foundation (NSF) in the USA awarded Penn State University a grant to develop and establish a "learning factory". It was during this time that the term was coined and patented. It referred to an interdisciplinary hands-on engineering design approach with strong links and interactions to industry [4]. This program run by Penn State University was awarded the National Academy of Engineering's Gordon prize for innovation in engineering in 2006 [2]. Since then, the use of learning factories has increased, particularly in Europe.

2.10.2 Evolving learning factories

The increased use of learning factories in Europe was funded by the German government through the German Academic exchange Service (DAAD) and the German Federal Ministry of Education and Research (BMBF) under a project called the European Network of Innovative Learning Factories (NIL) [24]. According to NIL [24], the goal of this project is to significantly contribute to an internationally recognised standard of the learning factory, so as to support international mobility enabling innovative educational programs that will enhance the quality of existing and future learning factories.

The rapid increase of funding made available and the high success of the learning factories stimulated the academic world and became a topic of general conversation, which lead to its popularity as a research topic. The numerous research efforts have produced a variety of topics, ranging from the validation of the successes of learning factories, to design and implementation methodologies, and improvement and expansion processes. Work done by Cachay et al. [21], for example, was aimed at investigating the learning success of engineering students in learning factories. The results showed increased learning successes of over 20% by control and experiment groups writing pre and post tests. Other works, such as by Matt et al. [48], and Chachay and Abele [20] sought to validate the practicality of the learning factory concept by incorporating it into lectures, as well as providing industry partners from SMEs the opportunity to qualify and further train their personal.

Work done by the above mentioned authors showed that the concept of the learning factory was promising, but there was a lack of literature regarding the setting up of learning factories and defining what is to be taught within the learning factory. Abele et al. [2], then proposed a seven dimension morphology for defining a learning factory. The morphology requires the user to identify critical aspects ranging from the operating model, covering the nature of the operating institution, to the didactics of the learning factory. This proposed morphology aided in the establishing and sustaining of learning factories and was then built upon by Wagner et al. [78] in a learning factory classification scheme. How learning factories are sustained and what their processes are is discussed in the following sections.

2.10.3 What is being taught in learning factories

Learning factories implemented around the globe, can be generalised into three forms, categorised in terms of their main teaching objectives. To date, learning factories are focused on teaching lean principles, resource efficiency and management and organisation [39]. These three objectives are discussed in further detail in the sections that follow.

Learning factories for lean principles

As previously stated, since the inception of learning factories, their popularity has grown around the world. The Penn State University alone has already conducted over 1800 projects with industry partners [55]. At first, learning factories concentrated mainly on the aspects of lean management and process improvement [39], which can be contributed to the work of the Toyota manufacturing company, evident in Liker [45], as it was the pioneering work of waste removal and manufacturing management. Figure 2.16 displays the strategic learning concepts, that are converted from theory into practice at the Chair of Production Systems (LPS) learning factory at the Ruhr-University of Bochum learning factory. This strategic learning concept is aimed at teaching the lean principles developed by the Toyota manufacturing company.
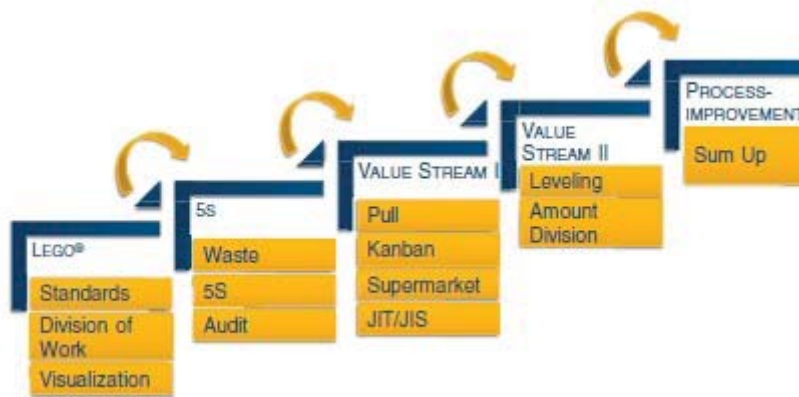
Figure 2.16: *Lean strategic learning concepts (LLC)[39].*

Figure 2.17: *Learning factories for resource efficiency: Strategic learning concepts [39].*

Learning factories for resource efficiency

The rapidly changing industrial environment and the demands created by Industrie 4.0, outlined in Chapter 2, has led to the rising significance of resource efficiency [39]. According to Kreimeier et al. [39], this has caused the need to include resource efficiency training into learning factories. The Ruhr-University of Bochum has developed a didactic concept of sensitisation for the design of energy-and-resource efficient production processes [39]. This learning factory for resource efficiency (LRE), addresses strategic concepts according to the model shown in Figure 2.17, for the identification and assessment of process-inherent potentials and how participants can transfer concepts learnt to their own company and processes.

The Institute of Production Management, Technology and Machine Tools (TU Darmstadt) had one of the earliest implementations of a learning factory in Europe [2, 21]. This learning factory started off mainly as a learning factory for teaching lean principles. Since then, it has been developed into a more holistic learning factory, including research efficiency as part of the learning factory package. Kreimeier et al. [39] describe how the LRE operates. In this description, the authors notes that the aim of the exercises performed in this LRE is to understand the information path from the signal to the finished key performance indicator (KPI), so that production processes can be tracked and optimised using the measured data. They further explain that during the data analysis step in the LRE, data is collected and analysed from the installed measurement sensors. The data collection then makes it possible to directly

FIGURE 2.18: *Teaching concept of the learning for management and organisation (LMO) [77].*

evaluate the processes, but the valid distribution of sensors and allocation of measuring points is an essential step to create a survey space and to build up KPIs [34, 39]. For this reason, this workshop/LRE teaches the participants how to acquire essential data and how to develop well-based KPI's and optimisation measures [39].

Learning factories for management and organisation

The third accepted and taught inclusion under the topics covered in learning factories is management and organisation, as described by Wagner et al. [77] and Kreimeier et al. [39]. The aim of this topic, according to Wagner et al. [77], is to show that the education of trainees in the field of management of workers' participation, can reduce the overall operating costs of projects. Hence the underlying concepts taught, is that of the importance and value of social communicative and interdisciplinary skills [77]. The strategic concept developed by Wagner et al. [77] as shown in Figure 2.18 is the management and organisational skills that are mainly focused on in this specific learning factory.

2.10.4 Composition of learning factories

Various learning factories were analysed and studied by Industrial Engineering students from Stellenbosch University, in order to segment the individual parts that make up a learning factory. Among these learning factories were the ESB Logistics Learning Factory at Reutlingen University and Darmstadt Learning Factory in Germany, the Budapest University Learning Factory in Hungary, the Vienna Learning Factory in Austria, and the Split Learning Factory in Croatia. For the purpose of this project, the following definitions were created for the elements of a learning factory, as identified during the analyses of the various learning factories.

System nodes

A system node is defined as a user instance which can be altered or changed in some manner to serve a purpose or function within a system process. It is the culmination of smaller objects. System nodes can be seen as a point of convergence of information, processes, materials, and resources. An example could be an assembly station in an assembly line manufacturing children's toys. The assembly station is a convergence point of information, processes in the form of

FIGURE 2.19: *Kitting station at the ESB Logistics Learning Factory at Reutlingen University.*

assembly, materials and resources in the form of human labour. As can be seen in Figure 2.19, an example of a system node in a learning factory, is the kitting station, which is composed of smaller objects which have been grouped and programmed to fulfil a process related goal. The kitting station in this example is where all the parts of the product being manufactured are placed in a "basket" and sent along a conveyor to its designated assembly point.

Objects

An object is the smallest physical element that can be part of, enhance or alter a process function (system node), but cannot be a process function on its own. Objects found in a learning factory are the smallest physical element that can function on their own. An example of an object is a low cost micro-controller such as the Arduino [8] or any PLC. An example of such a device is shown in Figure 2.20, where the Arduino [8] microcontroller (left), has been equipped with a low cost RFID reader, enabling RFID recognition. The Ardunio will in this case be the object, as it can not be a process on its own, but can enhance or alter a process function.

Technologies and software

Technologies and software refers to those required for objects and system nodes to function properly. It is somewhat intrinsic to the previous two groups, since objects can generally not function without software or technologies and in some cases objects can even be classified as technologies themselves. It has been separated into a different group because many objects and system nodes can posses different types of technologies or software, which in turn can be altered through different programs or methods to create "new" objects.
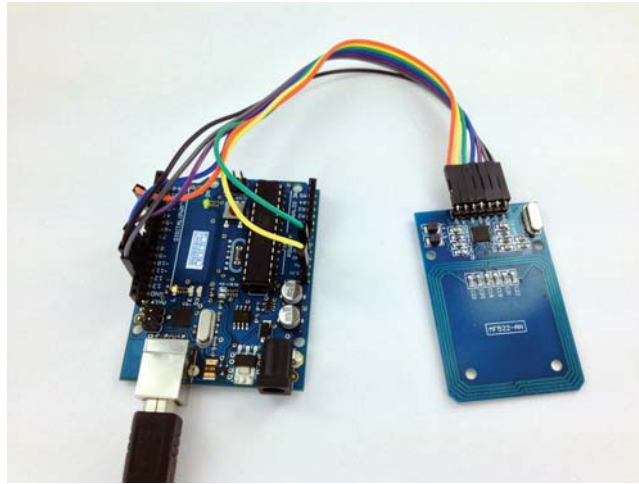
FIGURE 2.20: *Arduino microcontroller (left), with RFID module (right).*

2.11 Conclusion

After an analysis of the state of the art on Industrie 4.0, as well as learning factories, it becomes evident that such learning environments can provide a cost efficient teaching playground for industry partners looking to implement Industrie 4.0 (amongst many other things). The idea of showcasing Industrie 4.0 in the learning factory, is by no means a method to replace what is currently being taught in learning factories, as discussed in Section 2.10.3, but rather to provide an enhancement of such environments, analogous to how Industrie 4.0 promises to enhance current manufacturing environments and methods in industry.

Whilst literature provided a thorough background and understanding of Industrie 4.0 and learning factories, no clear framework exists for combining the two. Although general methodologies for designing and developing learning factories do exist, none provide the necessary implementation steps for incorporating Industrie 4.0. It is thus the aim of this thesis to develop such a framework which will provide a clear and practical methodology for implementing Industrie 4.0 into the learning factory environment. This framework shall allow for the adaptation of Industrie 4.0 to enhance the relevant methods taught in the specific learning factory.

CHAPTER 3

Industrie 4.0 framework development

The preceding chapter highlighted two main concerns that became apparent throughout literature. The first being the lack of methodology or guidance towards identifying the areas that need to be addressed in implementing Industrie 4.0, and the second problem is not knowing how to practically implement Industrie 4.0 once the areas have been identified. These two main concerns can be broken down into three main questions that are relevant to learning factories and SMEs in general. These questions are:

1. With what I have: How can I implement Industrie 4.0?

2. I want to have a specific Industrie 4.0 "inventions": What do I need to attain them? and

3. I want to teach specific courses or competencies in the learning factory: What do I require to implement it?

The framework developed in this thesis attempts to answer the three questions posed above, with specific focus on South Africa. It aims to not only provide decision support for complete design, with a focus on Industrie 4.0 (greenfield design), but also for the redesign of existing SMEs or learning factories, who wish to incorporate Industrie 4.0 with the elements that they currently have (Industrie 4.0 redesign). The third deduced application of the framework then, is for already existing learning factories who wish to enhance their current operations with the addition of specific Industrie 4.0 applications (Industrie 4.0 greenfield design).

The development of the framework was completed in four subsequent steps. The first two steps, gaining a holistic understanding of learning factories and insight into Industrie 4.0, was described in Chapter 2. The third step was to fill the framework dimensions with relevant elements from literature, outlined in Chapter 2, so that the framework may be tailored to fit a broad spectrum of learning factories and SMEs. The final step, was to manifest a link between steps one, two, and three, so as to create a usable and methodological framework. These steps are described in more detail in the subsequent sections.

3.1 Step 1: Understanding learning factories

In order to fully understand learning factories, a research study was conducted and summarised in Chapter 2, along with visits to learning factories in Europe and South Africa. The research
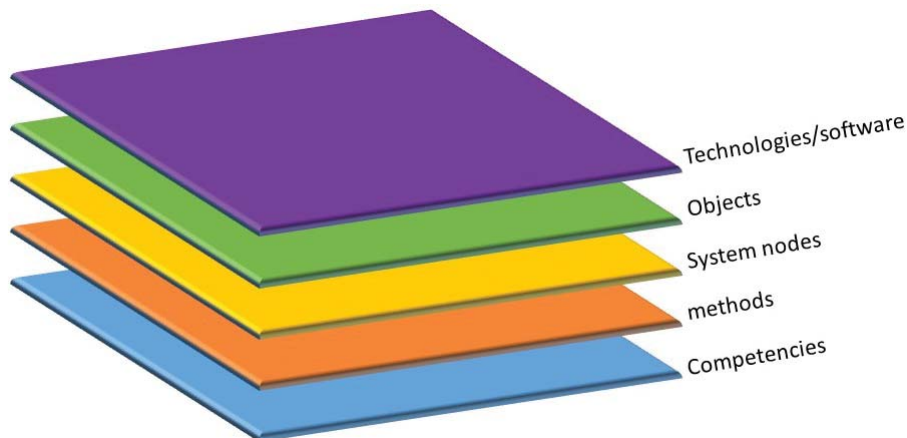
FIGURE 3.1: *Initial dimensions for framework.*

study helped identify the core competencies that are being taught in learning factories throughout the world. Work done by Kreimeier et al. [39] and Abele et al. [2] list courses that are being taught in learning factories. These courses were translated into competencies taught in learning factories. The courses and hence competencies have been explained and listed in Section 2.10. These competencies form the first level of the framework. Together with the research study, learning factory visits allowed the identification of groups of elements typically found in learning factories and SMEs, since learning factories are representations of SMEs. These groups of elements were used to classify dimensions for the framework. The first dimension contains those competencies taught in learning factories which are relevant to Industrie 4.0. A *competency* is defined in this project as the development of a targeted, industry related ability, which can be taught through various applications. The second dimension, *methods*, is defined as comprising of multiple objects and system nodes that, together form a function. This leads to the third dimension, *system nodes*, which are user instances which can be altered or changed in some manner so as to serve a purpose or function within a system process. *System nodes* are the culmination of smaller objects. The fourth dimension are these *objects*, which are the smallest physical elements that can be part of, enhance or alter a process function, but cannot be a process function on their own. The fifth and final dimension is *technologies and software. Technologies and software* are defined as the requirements for objects and system nodes to function properly.

The dimensions were aligned in such a way, as seen in Figure 3.1, that it reads from the bottom up as: Certain competencies can be taught through certain methods using certain system nodes, containing specific objects, which are enabled by specific technologies and software. From the top down, the order would read: Which technologies, software and objects can be applied to certain system nodes to obtain specific methods that allows the teaching of certain competencies in a learning factory. In an SME, it would stop at the methods dimension, as a specific method would be the implementation desired, and no competencies are taught.

3.2 Step 2: Gaining insight into Industrie 4.0

Chapter 2 highlighted some of the numerous benefits that could be obtained from the incorporation of Industrie 4.0, and as mentioned in the concluding section, it can be seen as an enhancement tool for operations. Industrie 4.0 then consolidates current technologies, software, objects and methods into packages. As such, incorporating a new dimension, Industrie 4.0 ap-
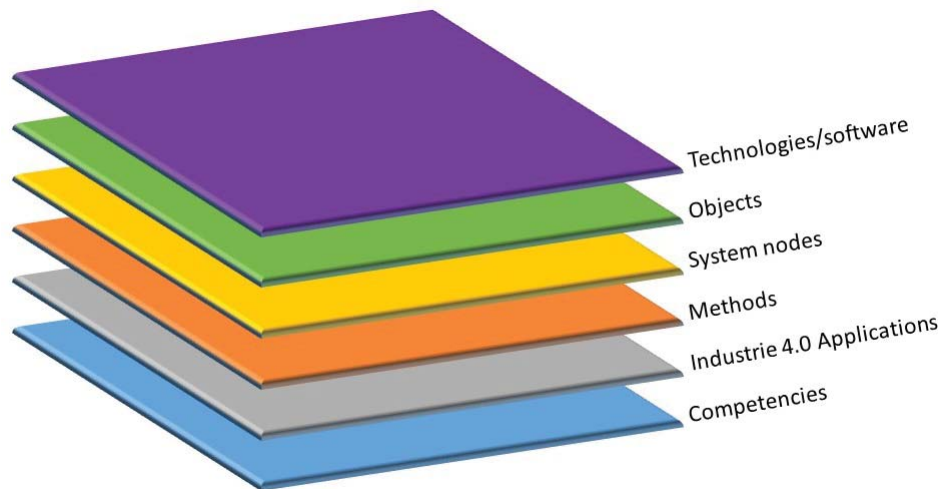
FIGURE 3.2: *Final dimensions for framework.*

plications, into the framework between the competencies and methods dimensions, enables the framework to capture these packages, and make them attainable. This additional dimension formed a link between the competencies taught dimension and the rest of the dimensions, as can be seen in Figure 3.2.

3.3 Step 3: Populating the dimensions

3.3.1 Competencies

The competencies dimension was populated firstly a priori by considering literature published relating to learning factories, as discussed in Section 2.10. The dimension was then further populated and altered from experience after attending specific courses at various learning factories throughout Europe. The following list depicts all the competencies that are included in this framework.

- design for assembly,

- design for manufacture,

- ergonomic design,

- lean tools,

- low cost implementation,

- visual management,

- systems thinking, and

- smart logistics.

3.3.2   Industrie 4.0 applications

A research initiative by the Fraunhofer institute [22, 63] regarding classifications of Industrie 4.0, in large, provided the elements for the Indsutrie 4.0 applications dimension. This dimension's development was further supported by Wan et al. [79] in a paper discussing the enabling technologies of Industrie 4.0. In the Fraunhofer research initiative, however, they have labelled the Industrie 4.0 applications as "Industrie 4.0 use cases". The definitions for Indsutrie 4.0 use cases and Industrie 4.0 applications are synonymous, although the label of "application" implies that it is a tool. The list below, indicates all the identified Industrie 4.0 applications included in the framework, with a brief discussion of each in subsequent sections.

- collaborative work,

- digital factory,

- smart manufacturing,

- smart products,

- human movement optimisation,

- big data analytics,

- intelligent transport, and

- real time work visualisation.

Collaborative work

In contrast to manual or automated work, collaborative work is the hybrid workstation, where robots and humans work in collaboration. For this framework, collaborative work is defined in three distinct cases:

- true collaborative work,

- cooperative work, and

- assistive work.

The case where the human and the robot work simultaneously on the same product is true collaborative work. When the robot and the human worker work on the same product, but not simultaneously, it is defined as cooperative work. The final case is when either the robot or the human has the sole purpose of assisting the other with their work. An example of the latter case could be a robot that holds tools or a part of a product for a human worker to work on.

Digital factory

As described in Chapter 2, the digital factory is a virtual representation of the physical factory and its processes. It allows for simulations and a general overview of the state of the physical counterpart.

Smart manufacturing

In this framework, smart manufacturing is defined as a subset of manufacturing that employs computerised control over processes. This subset of manufacturing aims to take advantage of information and manufacturing technologies to enable flexibility and adaptability in physical processes.

Smart products

Smart products are hybrid products with physical realizations, and digital and informations technology capabilities that provide the following characteristics:

- situated: Recognition and processing of situational contexts,

- personalised: Tailoring to buyers' and consumers' needs,

- adaptive: Change according to consumers' needs and affects,

- pro-active: Can initiate production sequences and control production variances,

- location aware: Retrieve information regarding where they are and how far they are along the production process, and

- network capable: Ability to communicate and bundle with another product or product sets.

Human movement optimisation

Human movement optimisation is an application that could be addressed through multiple methods such as simulation and workplace organisation. This application involves improving workplace conditions and environments for humans, so that improved outputs can be realised.

Big data analytics

Ensuing the literature discussed in Chapter 2 regarding big data; the analytical tools, methods and programs used to create value from the gathered data is an important application/function for realising Industrie 4.0 in the working environment. As such, it was deemed a necessary addition to the Industrie 4.0 applications dimension.

Intelligent transport

Intelligent transport is defined in this framework as a transport method that adheres to the following:

- contains a data communication mechanism (wired or wireless),

- possesses a form of programmable computational technologies, and

- contains sensory technologies.

TABLE 3.1: *Common manufacturing methods in learning factories.*

Methods	
Efficient resource management	Real time work-data visualisation
Additive/reductive manufacture	Product memory
KPI tracking	Synchronised material supply
Real time KPI tracking	Self execution system (SES)
Smart work sequencing (SWS)	Simulation
Workplace organisation	Standardisation
Automation	

Real time work visualisation

Real time work visualisation is defined in this framework using literature from work done by the Toyota motor company [45] as well as that of Posada et al. [57] in realising the importance of visual computing. Real time work visualisation is the visual representation of KPIs relevant to the production process or deemed necessary by management. The visual representation is also not bound to solely being for KPIs, but can also be any type of measured or measurable aspect.

3.3.3   Methods

The methods dimension is defined as comprising of multiple objects and systems nodes that together form a function in the production environment. It is also the first level that can be used to perform a defined purpose. As mentioned previously, for an SME the method dimension would be the desired implementation to serve a defined purpose or improvement. The methods dimension was populated using the information from the Fraunhofer research initiative, available literature, and learning factory and company visits. Table 3.1 lists all the methods that were deemed applicable to the framework.

3.3.4   System nodes

A system node is defined as a user instance which can be altered or changed in some manner to serve a purpose or function within a system process. A system node is the culmination of smaller objects. The system nodes dimension serves the purpose of tailoring the framework to cater for the specific processes that occur within a learning factory or SME. The list below shows common system nodes that have been included in this framework. It is important to note that these system nodes are general and relevant to modern manufacturing i.e. post third industrial revolution, otherwise the list of system nodes would be extremely extensive and out of context for this framework.

- commissioning,

- warehouse,

- rework,

- transport system,

- manufacturing machining,

TABLE 3.2: *Objects found in learning factories.*

Objects	
Wi-Fi routers	Barcode scanner
Conveyor(mechanical/automated)	Transfer skid
Smart conveyor	Computer
Supermarket	3D printers
Programmable logic controllers (PLC)	Microcontrollers
Mechanical transfer trolley	Smart transfer trolley
Heavy machinery: CNC, lathe etc.	Robots: Stationary
Robots: light mobile	

- E-kanban,

- kanban,

- palletisation station,

- assembly station,

- product design station, and

- quality check.

3.3.5 Objects

Objects are the smallest physical element that can be part of, enhance or alter a process function, but cannot be a process function on its own. An example of a process function could be a picking and packing process, at a picking station, where the objects would be the transfer skid where the parts will be placed on, and the transfer trolley or conveyor where the transfer skid is placed on. System nodes are typically made up of objects. The objects dimension was populated in the same manner as the system nodes and methods dimensions. Table 3.2 lists the objects identified for this framework.

3.3.6 Technologies/software

Technologies and software are required for objects and system nodes to function properly. The technologies/software dimension was populated by considering each of the elements in the objects dimensions and determining what they require to function properly. The technologies and software applicable to Industrie 4.0, the identified system nodes and objects are listed in Table 3.3.

3.4 Step 4: Connecting the dimensions

The connections between the dimensions were determined in two separate iterations, with the aim of answering the three questions posed at the start of this chapter. The first iteration, consisting of five steps, was performed by individually considering each of the competencies in the competency dimension and relating them to the other dimensions. The first step considered each of the competencies and related them to relevant Industrie 4.0 applications. An illustration

Table 3.3: *Enabling technologies/software.*

Technologies/software	
Sensors	3G/4G/LTE
Track and trace	Barcode
Bluetooth	Ethernet
Augmented reality	Wi-Fi
Advanced materials	Near field communication (NFC)
Harware specific software	Smart labels
3D printing	Open source software (OSS)
Cloud computing	

of the first step is provided in Figure 3.3a. The second step, shown in Figure 3.3b, was to take each of the identified Industrie 4.0 applications, from step one, and relate them to applicable methods. The third step was linking the identified methods and system nodes, shown in Figure 3.3c. The fourth step was identifying which objects are required to fulfil each specific method in each specific, identified system node, as shown in Figure 3.3d. The final step was to link the objects to their enabling technologies/software in terms of their other required dimensions, Figure 3.3e. The linking process, when visualised, much like that of Figure 3.3, portrays a tree diagram, as shown in Figure 3.5. This process was then repeated for each identified competency.

(a) Competencies and Industrie 4.0 applications.

(b) Industrie 4.0 applications and methods.

(c) Methods and system nodes.

(d) Methods and system nodes.

(e) System nodes and technologies/software.

FIGURE 3.3: Expansion of layers in framework.
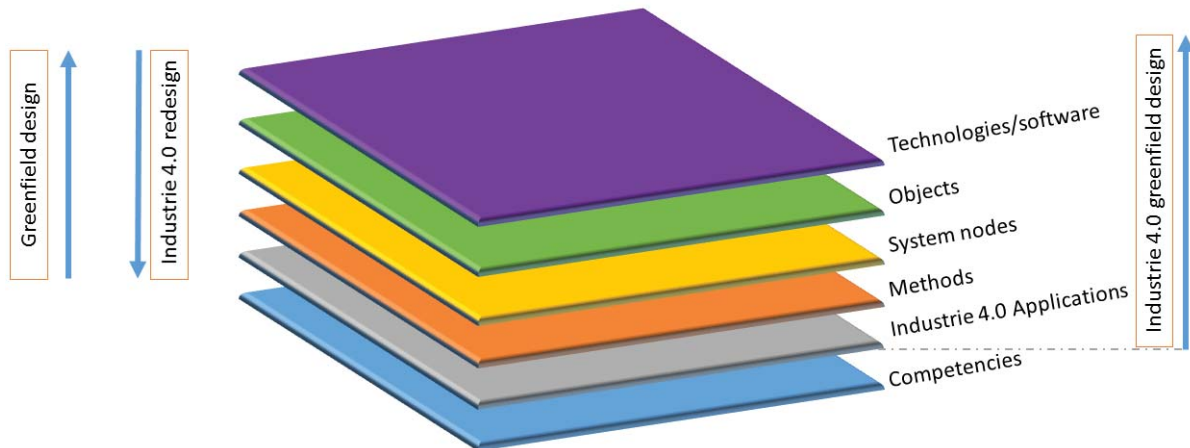
Figure 3.4: *Flow of framework applications.*

The second iteration was performed by considering the Industrie 4.0 applications as the starting point. This would be the typical case for an SME, who would wish to implement some form of Industrie 4.0 and would want to know what is required. In this iteration each individual Industrie 4.0 application was considered separately, and the associated methods determined. After the associated methods were determined, each method was individually considered and its applicable system nodes identified. The related objects were then identified and finally their enabling technologies/software. This process is very much like that of the first iteration, but where the aim of the framework is to provide a requirements roadmap for implementing a specific Industrie 4.0 application as opposed to a learning factory competency.

The two connecting iterations provided three distinct applications of the framework. The first is a greenfield design, applicable only to learning factories, that allows users to design a learning factory based on the core competencies that will be taught in their learning factories. The second application is an Industrie 4.0 greenfield design. This is for users who wish to incorporate Industrie 4.0 into already existing SMEs or learning factories. The third application of the framework is an Industrie 4.0 redesign. This redesign starts at the top of the framework and works downwards, by considering which technologies/software the user has available, then the available objects, applicable system nodes and methods and then finally which Industrie 4.0 application can be achieved and competencies taught. The Industrie 4.0 greenfield design is generally initiated by considering a desired Industrie 4.0 application, dimension two in the framework. This would typically be used for enhancing current operations in terms of SMEs, or for showcasing the possibilities thereof in learning factories. The flow of the three applications can be seen in Figure 3.4.

3.5 Using the framework

In order for the user to make proper use of the framework, he/she needs to identify which one of the three functions of the framework is required, namely:

1. a greenfield design of a learning factory,

2. an Industrie 4.0 redesign of an existing learning factory or SME, or

3. the enhancement of current operations within a learning factory or SME using Industrie 4.0.

The next steps depend on the required function, and are described in the subsequent sections. There are, however, some general considerations. The first being that there is a specific colour coding scheme that the user will use to identify feasible implementation routes. The green colour in the colour coding scheme is for elements that the user has available, but has not yet implemented it. The blue colour is for elements that are available and are already implemented in some manner. The orange colour is for elements that are required, and could be acquired by the user. Lastly, the red colour is reserved for elements that are infeasible to the user and cannot form part of the current user instance. A branch is only deemed completely feasible or implementable once a straight path can be drawn between all connecting elements, containing only green, blue and/or orange elements. This concept is further explained in the subsequent sections.

3.5.1   Greenfield design

If the user requires a greenfield design of a learning factory, with the aim of incorporating Industrie 4.0 applications into the learning factory, the framework would be followed from the competencies dimension upward to the technologies/software dimension. In such a case, the user would decide on the core competencies to be taught or displayed in the learning factory. Once these core competencies have been determined, the user considers the tree diagrams provided in Appendix A, displaying the connections between the competencies and the relevant remaining dimensions. Figure 3.5 shows a branch of one of the tree diagrams for the *lean tools* competency. The dimensions are listed at the top of the figure. The user will, in this case, work from the left to the right of the tree diagram and use the indicated colouring scheme shown. Only once the user is able to follow a direct path from left to right, containing only green, blue and/or orange elements, then that competency is ready to be taught or implemented in the learning factory, using the specified Industrie 4.0 application. Infeasible branches contain red elements. These are indicative that the user is not able to meet the requirements for the specific branch of the competency, and hence that it cannot be implemented or used to further teach the competency.

3.5.2   Industrie 4.0 redesign

When there already is an existing learning factory, and the user requires decision support in redesigning the learning factory so as to incorporate Industrie 4.0 elements, an Industrie 4.0 redesign is required. Using the same tree diagram as in the greenfield design example, the user will now start from the right hand side of the tree diagram, as shown in Figure 3.6, and work towards the left, applying colouring as explained previously. This method will assist the user in determining what is currently on hand, and what can be done with it. As mentioned previously, only once the user can follow a direct path from the technologies/software dimension to the Industrie 4.0 applications and competencies dimensions, containing only green, blue and/or orange items, can the related Industrie 4.0 application and competencies be implemented. The reason for ultimately working through to the competencies dimension, is because this application of the framework is intended for the enhancing of current operations and/or competencies taught through redesigning and implementing Industrie 4.0 applications.

3.5.3   Industrie 4.0 greenfield design

The third application of the framework considers the case where the target implementation is a specific Industrie 4.0 application. This is an Industrie 4.0 greenfield design, where the user
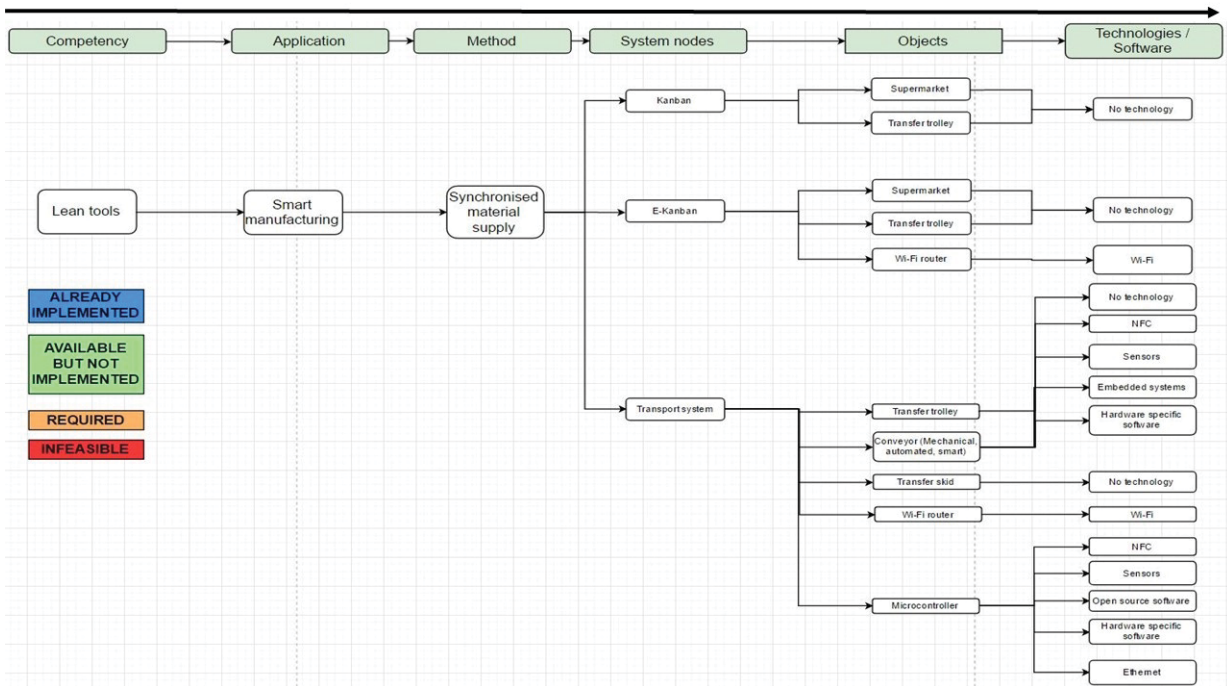
FIGURE 3.5: *Excerpt from greenfield design for teaching lean tools.*
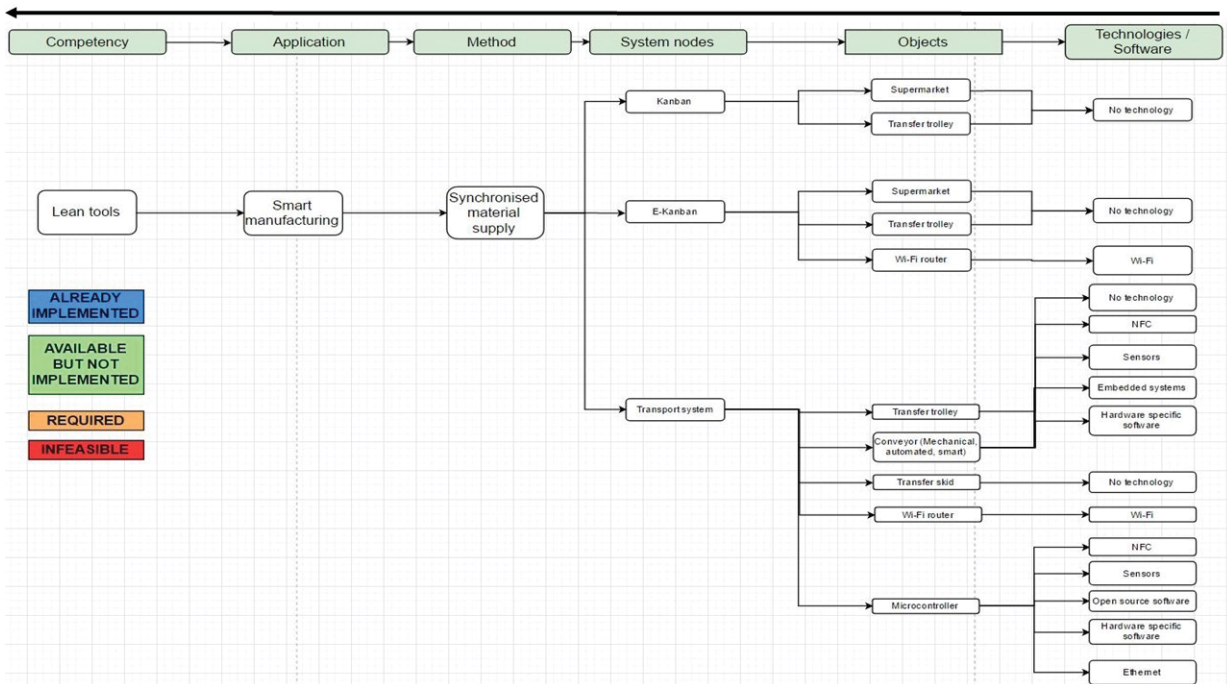
FIGURE 3.6: *Excerpt from Industrie 4.0 redesign for teaching lean tools.*
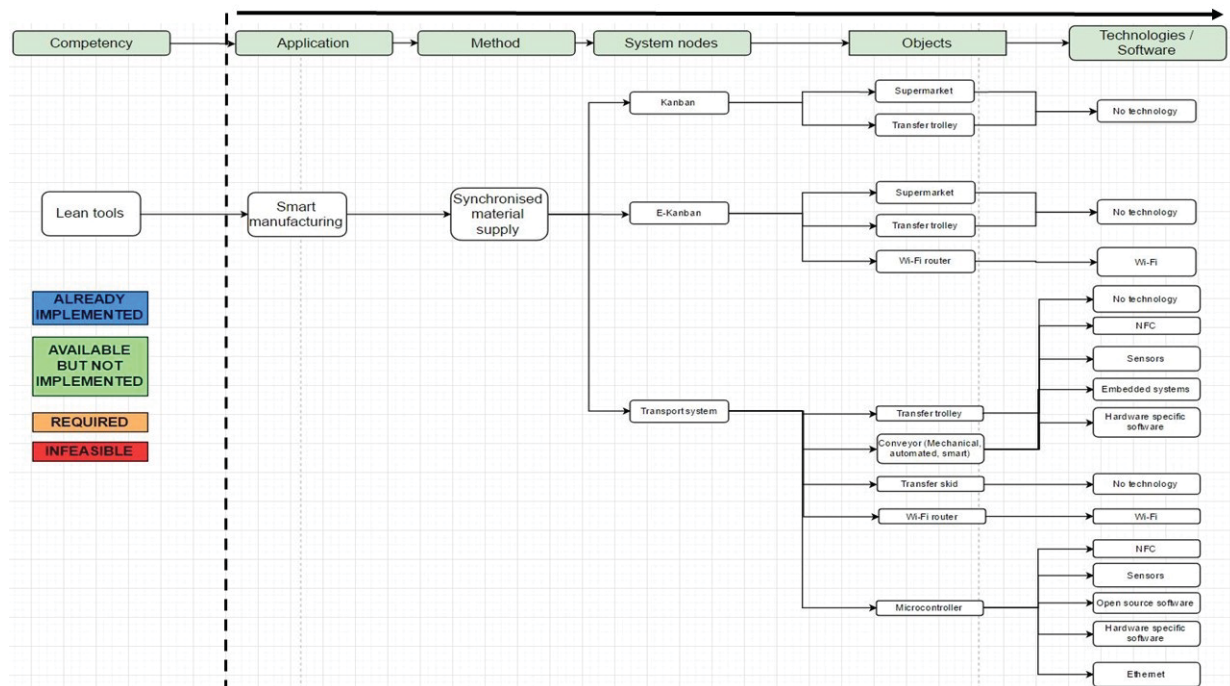
FIGURE 3.7: *Excerpt from Industrie 4.0 greenfield design for teaching lean tools using the smart manufacturing Industrie 4.0 application.*

will start by considering the desired Industrie 4.0 application (on the left of Figure 3.7) and work towards the right of the tree diagram. Again, colouring of elements corresponds to the colour coding key provided. As with the other framework applications, the user can implement a desired Industrie 4.0 application once a direct path, containing only green, blue and/or orange elements, can be drawn from the Industrie 4.0 application to the technologies/software related to the specific Industrie 4.0 application.

3.6 Conclusion

The previous chapter brought forward the problem that there exist no concrete design and implementation frameworks for Industrie 4.0 in learning factories and SMEs. This chapter proposes a generic, and methodological framework for identifying the specific requirements for implementing Industrie 4.0 within SMEs and learning factories. The framework has three applications, the first being the design of a new learning factory with a focus on Industrie 4.0 (greenfield design). The second application is a redesign of an existing learning factory or SME to incorporate Industrie 4.0 (Industrie 4.0 redesign). The third application is the implementation of a target Industrie 4.0 application, either for showcasing purposes or for enhancement of current operations (Industrie 4.0 greenfield design).

CHAPTER 4

ESB Logistics Learning Factory: Industrie 4.0 greenfield design

The ESB Business School at Reutlingen University in Germany, collaborates with the Stellenbosch Industrial Engineering department on selected projects and as such provided an opportunity to test and validate the developed framework. The learning factory at the ESB Business School, the ESB Logistics Learning Factory (ESBLLF), has been in operation since 2008. Being based in an area known for its large textile industry, the learning factory has become a host for seminars and concept demonstrators of industry leading innovations and competency based education. As such, the ESB Business School has a large amount of resources available and has been able to implement high end technological equipment and solutions within their learning factory. A few examples of such high end equipment are a light weight UR10 robot from *Universal Robotics*, smart conveyor from *Gebhardt Fördertechnik*, mobile Baxter robot from *Rethink Robotics*, and a pick by light system from *WIBOND*.

This learning factory was considered as a use case for the developed framework as it would provide one side of the application spectrum, namely a technologically matured environment. A meeting with management of the learning factory revealed that they wanted the addition of three distinct Industrie 4.0 applications. Since the learning factory in question was already in existence and specific Industrie 4.0 applications were desired, an Industrie 4.0 greenfield design was applied in order to best use what was already available for the desired Industrie 4.0 applications.

Currently the ESBLLF has been set-up to manufacture small mobile scooters called Micro scooters, such as the one depicted in Figure 4.1a. Currently there are two variations of scooters being built, a Flexblue and a Flexair scooter. These scooters are produced in multiple stages throughout the learning factory, so as to mimic an actual production line within an SME. These stages are commissioning, kitting, assembly and finally packaging. The commissioning stage was, at the time of performing this use case, a virtual or mock process, as there was no physical process taking place. The process consisted of moving a pallet with a jig on top of it onto a gravity conveyor system. Pallets with scooter jigs were sent from this virtual commissioning station along the gravity conveyor to the kitting station, as shown in Figures 4.5a and 4.5c. At the kitting station, the employee would search for a quick response (QR) code, shown in Figure 4.1b, that matched the scooter variation that had been commissioned. The employee then scanned the QR code using a web camera attached to a central computer, upon which the computer would run a program which sent a text file corresponding to the QR code, to a

57

(a)   ESBLLF scooter.

(b) QR code for associated scooter.
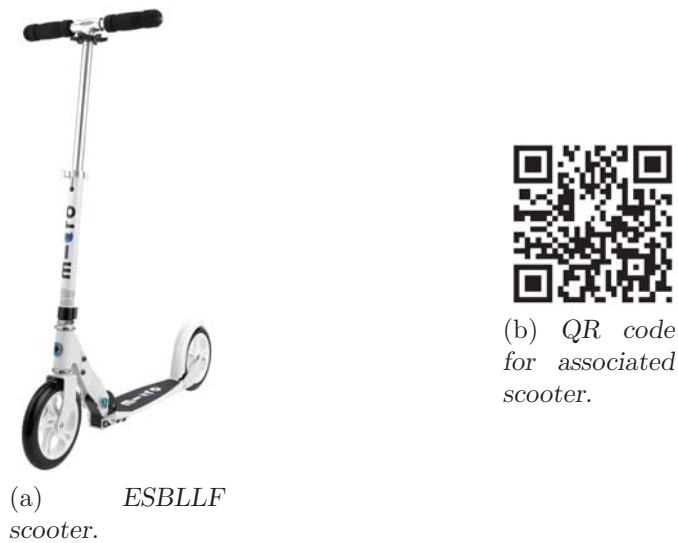
Figure 4.1: ESBLLF scooter with associated QR code card.

pick by light system, informing the employee which parts to pick and place onto the scooter jig. At this same point in time, the employee would press a button, attached under the gravity conveyor, upon which the UR10 robot would place a single handlebar as seen in Figure 4.5b on the scooter jig. Once the kitting process had been completed the employee would move the pallet onto the smart conveyor. Figure 4.2 shows a layout of the main areas in the ESBLLF, including the conveyor system discussed. The smart conveyor has separate modules allowing it to alternate the direction of flow. In the original set-up, before this project's implementations, the conveyor had a counter installed and merely alternated between the two workstations also shown in Figure 4.2. Once a pallet reaches a workstation, the employee at the workstation will remove the palette from the conveyor and place it on his/her workbench and start the assembly process. The employee has two visual guides during the assembly process, one in the form of a video that plays on a tablet attached on the workbench, and the other is instructions on paper worksheets attached on the workbench. Upon completion of the assembly process, the employee will remove the finished scooter from the workbench and place it in a plastic bin underneath the workbench ready for collection and transport to the packing station. An employee from the packing station will fetch the completed products from the assembly stations and move it to the packing station. At the packing station, the employee will ensure that the scooter has been correctly assembled, as well as add some additional items required for home assembly by the customer, before packaging it and placing it in the shipping area ready to be shipped to the customer.

4.1 Mapping the learning factory

The meeting with management revealed that they were interested in incorporating three distinct Industrie 4.0 applications, namely:

1. collaborative work,

2. intelligent transport, and

3. smart manufacturing.
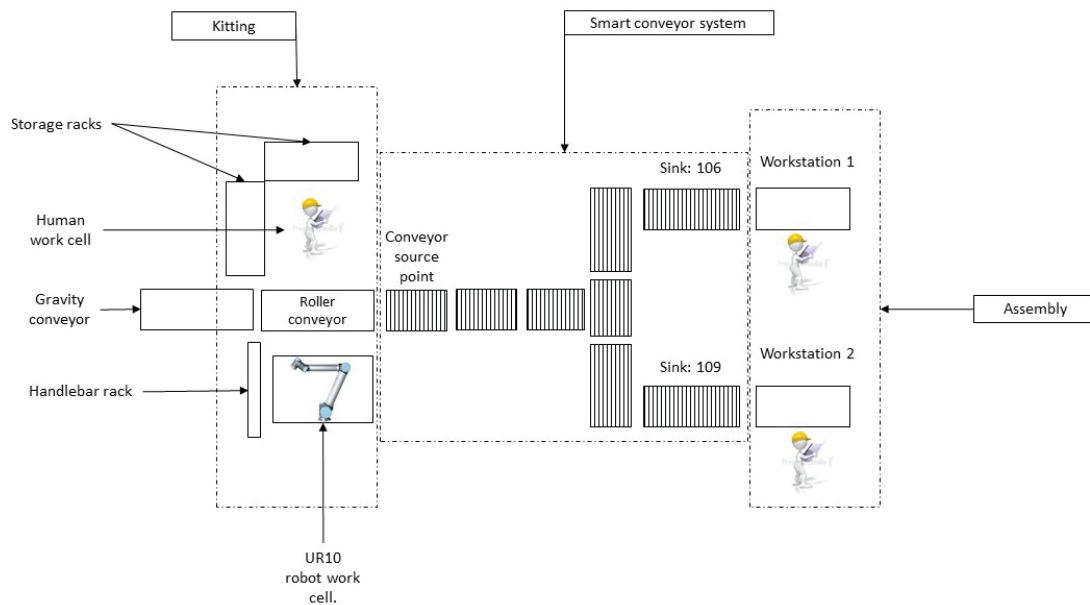
FIGURE 4.2: *ESBLLF layout.*

In the ESBLLF layout in Figure 4.2, three zones are delineated by dotted rectangles. These three zones indicate the areas that would be affected by the incorporation of the Industrie 4.0 applications.

Following the guidelines of the framework, all methods, system nodes and technologies/software that could fulfil the three desired applications were identified. The Industrie 4.0 greenfield design was used since the ESBLLF was already in existence and a requirement was for specific Industrie 4.0 applications to be implemented with minimum investment in new processes or equipment. The initial Industrie 4.0 greenfield maps, corresponding to the three Industrie 4.0 applications, were assessed in terms of elements already implemented or available within the learning factory. An assessment of all three applications resulted in the identification of the minimum additions to the learning factory required for successful implementation. It was found that the biggest effects could be realised through the addition of NFC technologies, connectivity methods such as Ethernet and Wi-Fi, coupled with microcontrollers and Wi-Fi routers. With the addition of these elements; collaborative work, intelligent transport, and smart manufacturing could be incorporated in the learning factory.

4.2 Implementation

The application of the framework to the ESBLLF highlighted the focal areas that should be addressed in order to implement Industrie 4.0 collaborative work, intelligent transport and smart manufacturing. A walk-through of the ESBLLF provided insight into where and how these implementations could be realised.

4.3 Smart manufacturing

Management at the ESBLLF wanted to be able to directly write a client's order in terms of production details to the product, so that a product is self-steered throughout the entire

```
Sector Block   0  1  2  3    4  5  6  7    8  9 10 11   12 13 14 15   AccessBits
  15     63    00 00 00 00   00 00 FF 07   80 69 FF FF   FF FF FF FF   [ 0 0 1 ]
         62    00 00 00 00   00 00 00 00   00 00 00 00   00 00 00 00   [ 0 0 0 ]

   1      7    00 00 00 00   00 00 FF 07   80 69 FF FF   FF FF FF FF   [ 0 0 1 ]
          6    00 00 00 00   00 00 00 00   00 00 00 00   00 00 00 00   [ 0 0 0 ]
          5    00 00 00 00   00 00 00 00   00 00 00 00   00 00 00 00   [ 0 0 0 ]
          4    52 6F 6C 6C   65 72 20 53   69 6C 62 65   72 00 00 00   [ 0 0 0 ]    Pick by light instructions
   0      3    00 00 00 00   00 00 FF 07   80 69 FF FF   FF FF FF FF   [ 0 0 1 ]
          2    31 30 36 78   42 6C 75 65   5F 5F 5F 5F   5F 00 00 00   [ 0 0 0 ]    Conveyor workstation designation
          1    B1 6C 65 78   42 6C 75 65   5F 5F 5F 5F   5F 00 00 00   [ 0 0 0 ]    Variation type details
          0    6B 69 EF 0B   E6 88 04 00   C8 12 00 20   00 00 00 14   [ 0 0 0 ]
```

Figure 4.3: *Excerpt of the RFID data block on the RFID card used for the product variant details.*

production process and can communicate with each process at each stage, co-ordinating it and informing it what processing should be performed on it. This follows the definition of smart manufacturing as outlined in Chapter 3 whereby it is a subset of manufacturing that employs computerised control over processes. As outlined by the applied framework, smart manufacturing can best be accomplished by incorporating RFID and NFC technology.

Standard 1K Mifare RFID cards contain 64 16–bit lines, as shown in Figure 4.3, that can be accessed, read and re-written. This allows production details to be written to the RFID card, which can then be accessed at each production process, via an RFID or NFC enabled device.

In order to accomplish this, an Arduino UNO [8] with an attached MFRC522 RFID shield was used, as shown in Figure 2.20. This set-up enabled writing production details to the RFID card based on customer specifications. The customer will select the type of product, Flexblue or Flexair, as well as the colours of variable items. This will then be written to an RFID card, attached to the scooter jig, in the specified sectors shown in Figure 4.3. The code written as a result of the customer-specific order is then used to steer the product through the required and specific processing steps within the learning factory. The full program code can be viewed in Appendix D

4.4 Collaborative work

In the original set-up, the kitting station was split up into two segments separated by a roller conveyor which forms the link between the gravity conveyor and the smart conveyor. The one side contained the UR10 robot shown in Figure 4.5a, and the other a human work cell, shown in Figure 4.5c. The UR10 robot was being used to pick and place a single common part for both product variations, triggered by the employee who pressed a button to activate the robot. The part being picked was a standard scooter handlebar, shown in Figure 4.5b, and was being placed in a fixture on the scooter jig. The human work cell is a pick an place process, guided by a pick by light, that had the human worker pick up to 12 different parts, depending on which one of the two scooter variations was being produced. An excerpt of the framework applied for the collaborative work application can be seen in Figure 4.4 with the entire framework iteration attached in Appendix B.

In this original set-up, the robot was idle while the human worker performed most of the picking and placing, and as stated previously, was only activated once a button was pressed. To reduce the workload on the human worker, and improve process times by levelling the workload between the robot and the worker, some of the picking and placing work was moved to the robot. It was determined, based on the gripping capabilities of the robot, that there were three parts that could be moved to the robot in addition to the common handlebar part, namely the handlebar shafts, wheels and decks for the scooters. These three parts are shown in Figures 4.6a to 4.6c
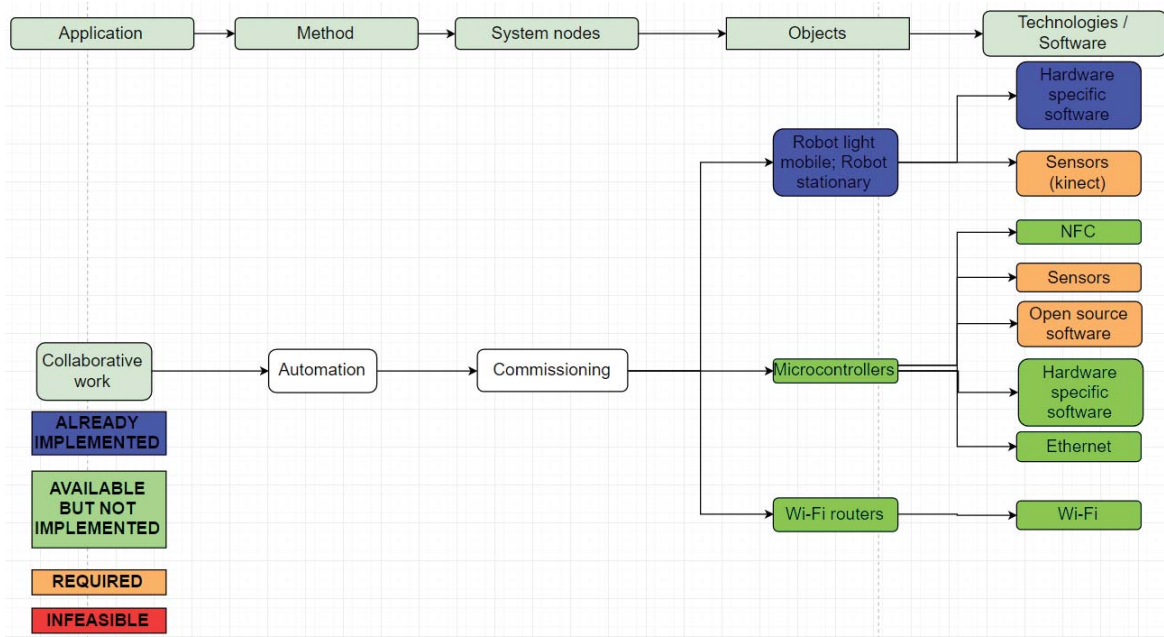
FIGURE 4.4: *Excerpt of the framework application for collaborative work, at the ESBLLF.*

(a) *UR10 robot cell for kitting station.*

(b) *Micro scooter handlebar.*

(c) *Human work cell at kitting station.*

FIGURE 4.5: *Kitting station: UR10 robot cell (a), Micro scooter handlebar (b) and human work cell (c).*

(a) *Handlebar shaft of Micro scooter.*

(b) *Scooter wheels.*

(c) *Deck of scooter.*
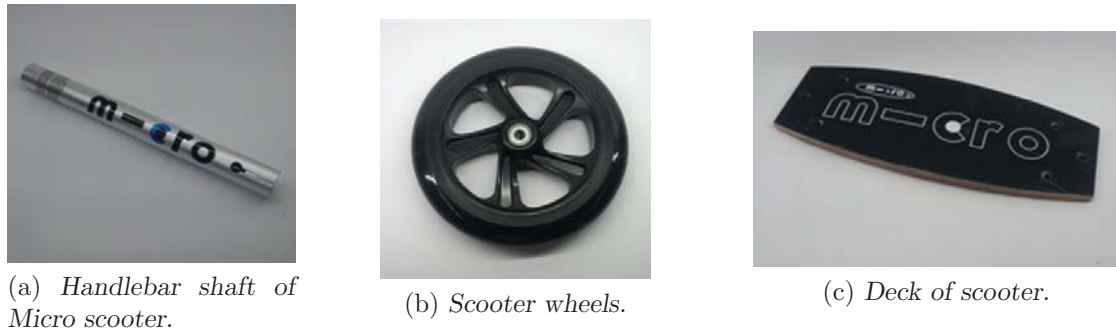
Figure 4.6: *Parts deemed feasible to move to robot work cell.*

respectively. Both scooter variations have their own wheel and deck variants, but use the same handlebar shaft and handlebar. It was thus required that the robot be triggered in some manner to pick the correct parts for the correct product variation.

Using the framework result, NFC in the form of RFID-based scheduling was incorporated, via an Arduino microcontroller equipped with an RFID reader and Ethernet shield. The product variant data is now read from the RFID card in the sector shown in Figure 4.7 using the program written for the Arduino, as provided in Appendix D. The Arduino was attached to the roller conveyor so that it can come into close proximity of RFID cards on scooter jigs, and connected to the UR10 robot through an Ethernet cable and now sends the production details contained on the RFID card to the robot. This implementation allowed true collaborative work, as the robot was programmed to be able to receive production details based on what has been written to the RFID card and can now work conjointly (i.e. collaboratively) with the human worker, as opposed to being in operation only after the worker pushed a button to activate its movement. The information flow can be seen in Figure 4.7. The new UR10 robot work cell can be seen in Figure 4.8. With this new implementation, the UR10 robot was able to pick and place an additional three parts and the work balance between the human and the robot was improved, consequently reducing the workload on the human worker.

4.5 Intelligent transport

The ESBLLF has a smart conveyor made by *Gebhardt Fördertechnik* [29]. The conveyor system has a programmable interface that allows it to be tailored for a specific need. The set-up for the conveyor in the learning factory can be seen in Figure 4.2.

With regards to intelligent transport, the resultant framework application revealed that RFID technology should be incorporated into the conveyor system in order to achieve intelligent transport. Since this was already the method used to convey production details to the UR10 robot, the same RFID system was used to send information to the smart conveyor. A study and analysis of the programmable software of the conveyor was performed to determine how best to incorporate this. It was found that the conveyor system automatically programs specific starting and ending points based on how the conveyor has physically been configured [29]. Each separate conveyor module has its own IP address, and sinks are defined then by their IP address in their own subnet.

Before implementing the RFID technology, the conveyor system sent one product to the left and one product to the right, sink 106 being on the left and sink 109 being on the right, as depicted
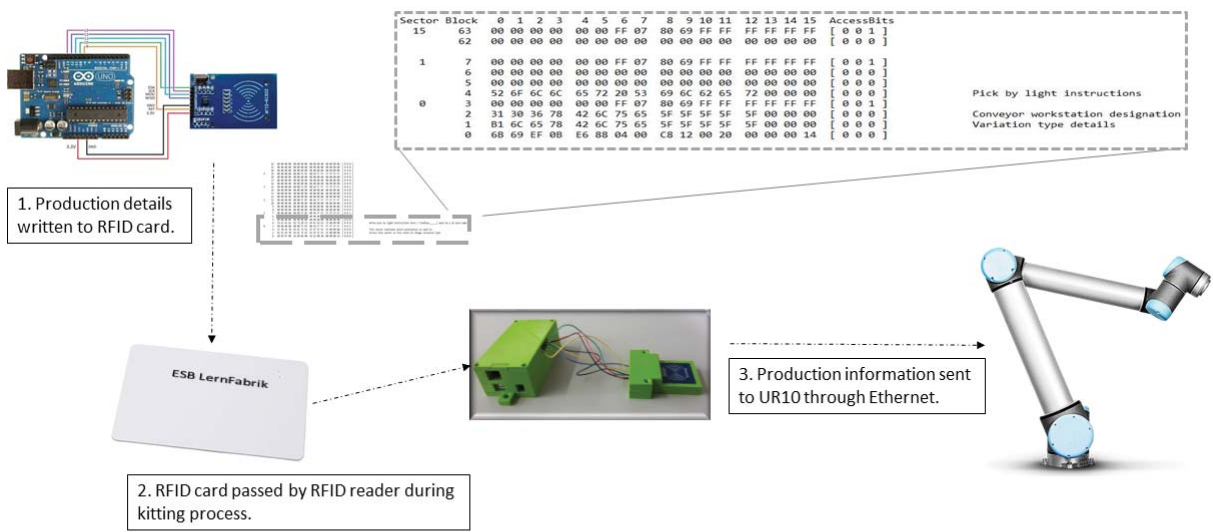
FIGURE 4.7: *Information flow from Arduino to UR10 robot.*
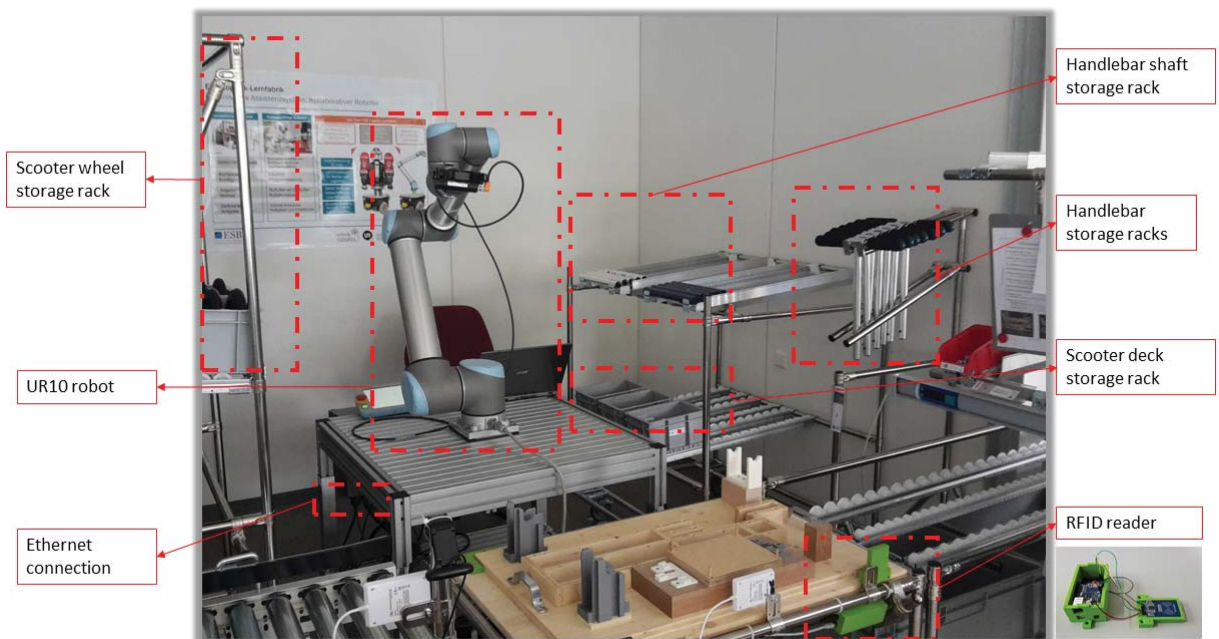
FIGURE 4.8: *New UR10 robot work cell.*

in Figure 4.2. The intended purpose of the conveyor was to send products only to active workstations or to workstations that have been designated for specific work. This is however only conceptual, but an example of such would be, if only certain employees are allowed to work on certain products, then the conveyor would direct products only to where able employees are working. Another application is that certain products can only be assembled on certain workstations. Such allocation requirements could not be achieved in the original set-up since the conveyor was only alternating jobs between the two workstations.

To facilate these allocation rules, the conveyor would require some form of input from the product that informs it which workstation it should be sent to. The user manual indicated that it had an Ethernet connection port on each module, but that the starting point or source of the conveyor would, by default, be the module connected to an external computer. An external computer was then connected, by plugging it into the starting module, through an Ethernet connection, so that information on where to send product variants can be sent to the conveyor system. A program was written to read the RFID information contained on the RFID card, in row 2, shown in Figure 4.7, and send it to the conveyor system through the Ethernet connection. In short, the RFID card of the product is read by an RFID reader, indicating which workstation the product should be sent to, and the IP address of the workstations that the product is designated for is sent to the conveyor system. The product variations (or even a single specific customer order) can now be assigned to specific employees and/or workstations by the now smart conveyor using the information stored on their RFID card.

4.6 Conclusion

The framework was applied to a high end technologically matured learning factory that had many standalone technologies and equipment available, but lacked coordination and connection between processes. The framework aided in the decision making process of incorporating three distinct Industrie 4.0 applications namely, smart manufacturing, collaborative work, and intelligent transport. The successful implementation of each of these Industrie 4.0 applications created large improvements including shorter process times, levelled workloads and improved product customisation options, in the ESBLLF, as well as provided a connection between the processes within the learning factory and can now be used as standalone showcases of Industrie 4.0. The most important benefit defined by management is however, the new ability to showcase Industrie 4.0 applications within the learning factory, adding the potential for hosting Industrie 4.0 demonstrations and seminars.

CHAPTER 5

Stellenbosch Learning Factory: Greenfield design

The previous chapter showcased the application and validation of the developed framework in a technologically-advanced scenario at the ESB in Reutlingen, Germany. This chapter provides further validation of the framework through an application in an environment of a low technological maturity. More importantly, it showcases a second of the three applications of the framework, namely a greenfield design.

The development of the Stellenbosch Learning Factory (SLF), began in 2015, and promises to be an invaluable asset to the Department of Industrial Engineering. Being to a large extent still only a conceptual idea, the aim on the SLF will be rather different than that of the ESBLLF. Whilst the focus of the ESBLLF lie largely on the provision of seminars and demonstrations for industry, the initial aim of the SLF is to provide students of the Industrial Engineering Department with a practical learning environment. Initially, the focus of the SLF will be on a topic highly relevant to its students, namely teaching lean principles. The SLF aims to showcase these principles through the process of manufacturing small model trains, inspired in colour and make-up by the South African Metrorail.

The model train, shown in Figure 5.1, is to be manufactured in two variations, one being a cabin train and the other a driver train. Although the external appearance is identical for both trains, they contain slight variations in their internal composition. To provide students with both a realistic and holistic model of a manufacturing environment that may be experienced in a typical South African industry, the SLF will include all process steps from the customer contact (i.e. a point for order placement), through commissioning and assembly and end in a quality inspection before shipping. The proposed layout for the SLF is shown in Figure 5.2. Since the SLF is physically not yet set up and not operational, and management wishes to teach specific competencies with the aim of also showcasing elements of Industrie 4.0, this learning factory provided the perfect utilisation of the greenfield design application of the framework developed in this thesis.

5.1 Mapping the learning factory

During the planning phase of the SLF, the management team selected three competencies to be taught in the initial operational phase of the learning factory. Since they wish to provide

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Figure 5.1: *Model train built in the SLF.*
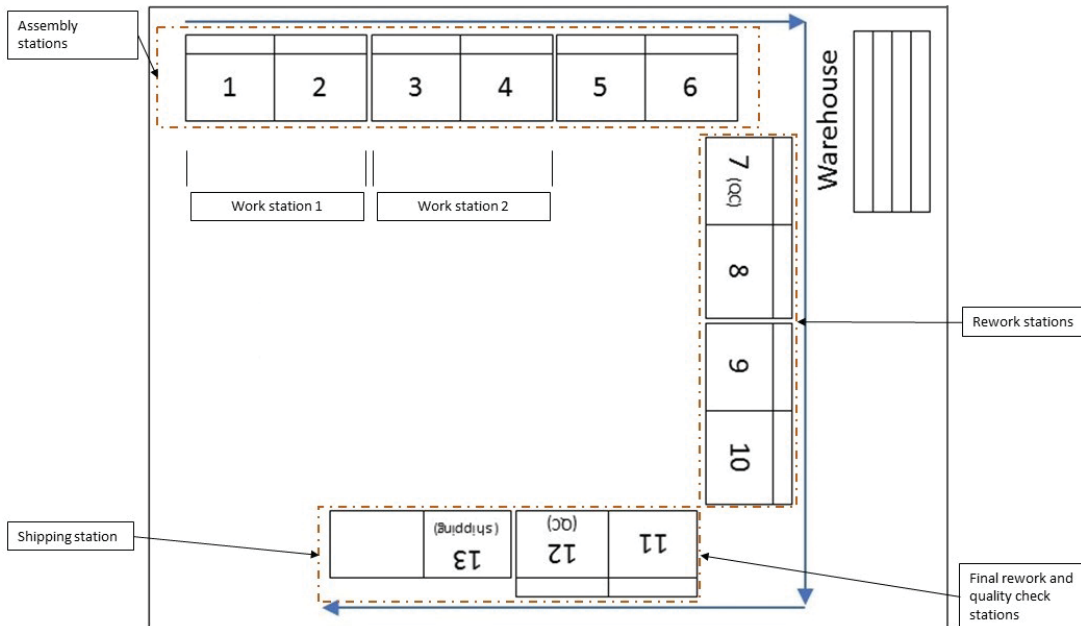
Figure 5.2: *The SLF layout.*

students with the most realistic environment for a South African (and generally low technological maturity level), the competencies to be taught are:

- lean tools,

- visual management, and

- low cost implementations.

Following the guidelines developed in this thesis along with the framework, a greenfield design was executed for the SLF. Starting from the competencies to be taught in the learning factory, the framework was filtered through from the competencies to the technologies/software dimension. This application of the framework would allow for the identification of the minimum methods, system nodes and technologies/software that would be required to successfully implement the desired competencies, as well as show which Industrie 4.0 applications can best be showcased in doing so. The competency maps generated by the developed framework corresponding to the three previously-mentioned competencies were assessed in terms of elements available in the department, in order to identify the minimum overlapping additions required to successfully implement all three competencies. At the time of conducting this use case, the SLF had a few standalone elements already implemented, although there was no overarching cohesive structure in place. All methods, system nodes, objects and technologies/software relating to each of the three competencies, were classified according to:

- already implemented,

- available but not yet implemented,

- required, or

- infeasible.

The elements deemed infeasible for the SLF were largely dismissed on the basis of implementation time as well as cost, since one of the competencies is to showcase low cost implementations. An excerpt of the framework applied to the SLF for the lean tools competency is shown in Figure 5.3. The full application diagram is provided in Appendix C.

After classifying each branch of the framework for each individual competency and identifying the remaining plausible branches, the overlapping elements between the three maps were assessed in order to identify the minimum additional elements required for the successful implementation of all three competencies. Industrie 4.0 applications that were identified as being able to best enhance the three competencies were:

- smart manufacturing,

- smart work sequencing, and

- work data visualisation.

The methods corresponding to these Industrie 4.0 applications and the relevant competencies were also assessed in terms of where the biggest overlap exists. The methods identified for implementation in the SLF, are shown in Table 5.1 corresponding to the relevant competencies to be taught and the Industrie 4.0 applications which can be showcased through their implementation.
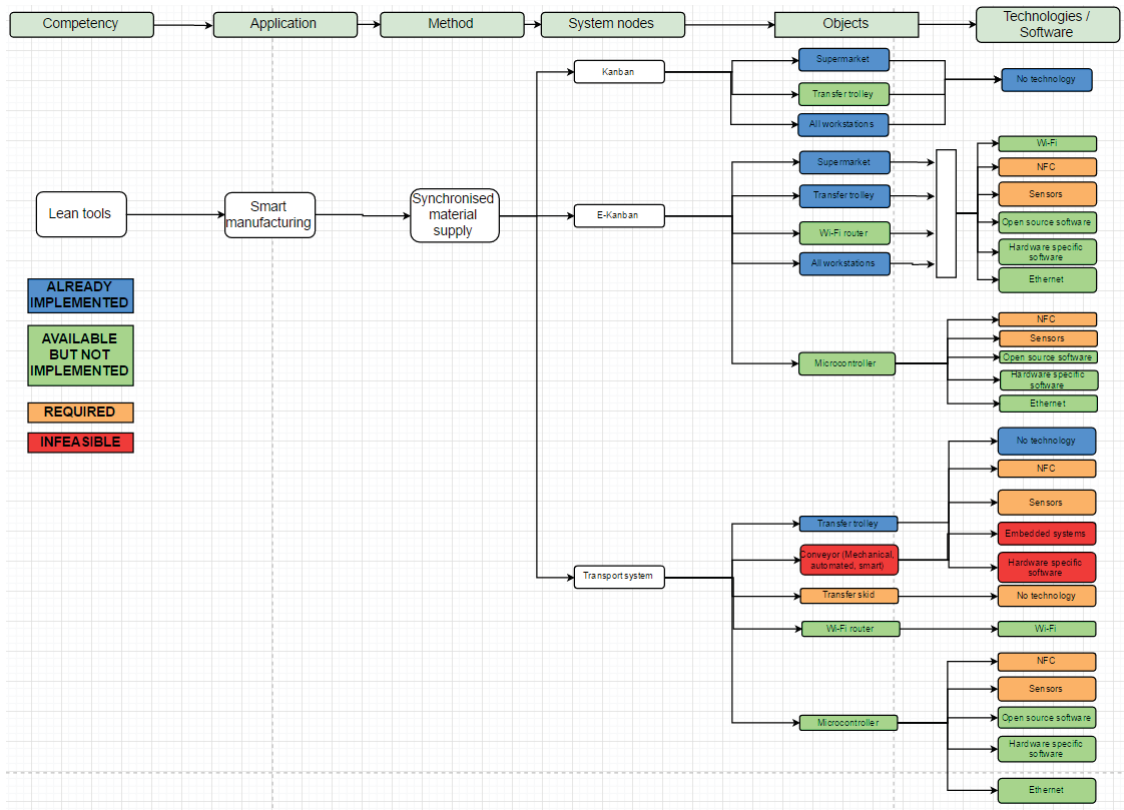
FIGURE 5.3: *Excerpt of the framework application for lean tools, at SLF.*

TABLE 5.1: *Methods to be implemented, with respective Industrie 4.0 application and target competency.*

Competency	Industrie 4.0 application	Method
Lean tools	Smart manufacturing	Synchronised material supply
Visual management	Real time work visualisation	Smart work sequencing (commissioning) Standardisation
Low cost implementations	Smart manufacturing	Standardisation Synchronised material supply Smart work sequencing (commissioning)

The greenfield design application of the framework on the SLF outlined many plausible areas for moving towards an Industrie 4.0 learning factory. These plausible areas, of which an excerpt is shown in Figure 5.3, have been visualised in Figure 5.4. This visualisation is a detailed input–output flow diagram, indicating the requirements for each Industrie 4.0 application and the resulting applicable methods. Each of the Industrie 4.0 applications highlighted are discussed in detail in Section 5.3.
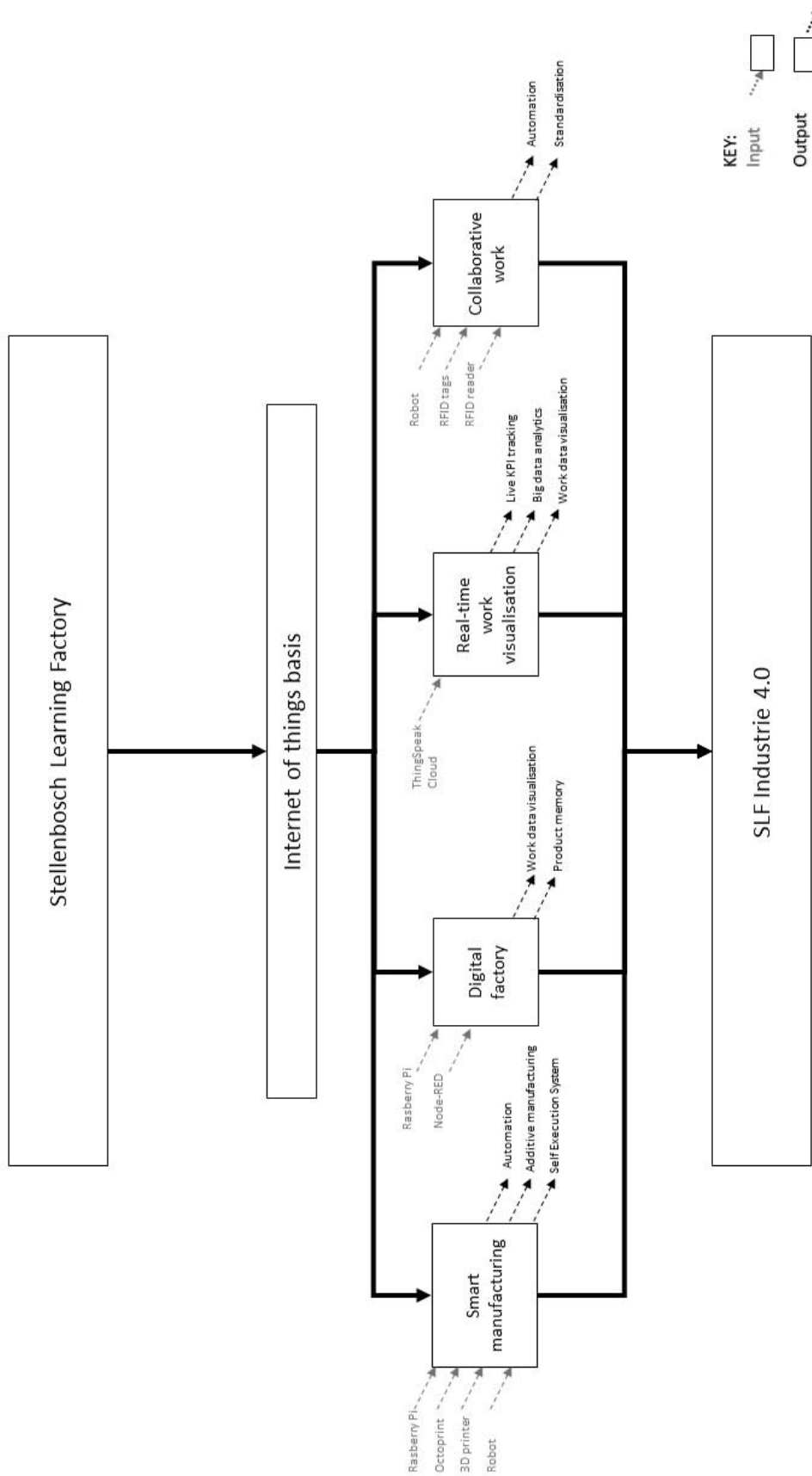
Figure 5.4: *Visualised plan towards an Industrie 4.0 learning factory for SLF.*

5.2 Implementation

The application of the developed framework to the SLF, led to the identification of the focal areas for implementing or enhancing the competencies to be taught within the SLF. Utilisation of the remaining dimensions of the framework, namely system nodes, objects and technologies/software, coupled by an analysis of the SLF in its initial state, enabled the identification of how best to practically implement these elements. Unlike the ESBLLF use case, a requirement for the SLF was to use only the minimum resources required so as to showcase a low cost implementation, whilst also bearing in mind the limited space available to the SLF. The three competencies were therefore considered conjointly, so as to identify the implementations with the biggest overlaps. Since elements as a result form part of multiple competencies, the implementations thereof are discussed holistically rather than individually.

The practical implementation of the three methods shown in Table 5.1, namely smart work sequencing, synchronised material supply and standardisation, required an in-depth analysis of the system nodes, objects and technologies/software required in order to identify the biggest overlap. A pick by light system, as well as an E-kanban system were identified as the best means for showcasing the desired competencies and their related methods.

5.2.1 Pick by light system

A pick by light system is a picking system based on the Lean Production System developed by Toyota [45]. This system acts as a visual guide for the assembly worker in which the manual labour process steps are guided by a lighting system illuminating the materials required for each step as it is performed. Such a system can assist in removing wasteful, unnecessary movements by clearly indicating which materials to pick at what time and in which quantity, thereby also reducing the chances of human error. Since such a system is very relevant for the South African industry, due to language and culture barriers making other means of communication (other than visual) very difficult, it will provide students of the SLF with a very realistic work environment.

As shown in Figure 5.5, a pick by light system was implemented using an Arduino microcontroller [8], seven light emitting diodes (LEDs), and a push button. At each assembly station in the SLF, the employee is provided with boxes containing the various parts required to assemble the model train. For the purposes of this thesis, the pick by light system was implemented at *workstation 1*. The Arduino was programmed using the Arduino programming language written in *C++*. An excerpt of the code written for the pick by light system is shown in Figure 5.6. The full program code is provided in Appendix E.

The Arduino was programmed to contain the assembly instructions for *workstation 1* and which parts to pick in which order. Since *workstation 1* is concerned with assembly of the outer shell of the model trains, there is no difference in work steps between the two train variations. When the assembly worker is ready to commence assembly, he/she can push the push button, which acts as a trigger to the Arduino's program. The Arduino program code executes and illuminates the first box of parts to be picked. After each pick and assembly step, the worker pushes the button and the code runs to illuminate the next part to pick, until all assembly steps have been executed. After the final part has been picked, the Arduino code lights up all the LEDs simultaneously, so as to indicate to the worker that the assembly is complete and the product can be moved to the next workstation, before beginning a second product's assembly.

With the addition of this pick by light system, a new employee's learning curve is drastically reduced, since he/she can now simply follow the standardised work routine set out by the

FIGURE 5.5: *Workstation 1 with pick by light system.*

```
#include <ESP8266_TCP.h>

// ESP8266 Class
ESP8266_TCP wifi;

// Define SSID, Password and Channel that provide for Access Point
#define ssid        "ESP789"
#define pass        "123456789"
#define channel     5

// Connect this pin to CH_PD pin on ESP8266
#define PIN_RESET    6

// TCP Server IP and port
#define serverIP    "192.168.4.1"
#define serverPort  2000

// Pin connected to button to send pick by light information
#define PIN_SEND     52

// Pin connected to replish bins
#define  PIN_REPLENISH 53


//Initialise the LEDs for the pick by light and the replenishment system
const int ledPin[] = {22, 23, 24, 25, 26, 27, 28}; //  pin that the LED is attached to
const int replenishLED[] = {29, 30, 31, 32, 33, 34, 35}; // LED pins for the replenish system


/////////////////////////////////////////// /////////////////// Variables for pick by light function
// Variables will change:
int buttonPushCounter = 0;
int buttonPushCounter2 = 1;   // Counter for the number of button presses
int buttonState = 0;          // Current state of the button, not used
int lastButtonState = 0;      // Previous state of the button
int noofassemblysteps = 5;    // Assembly step counter
int noofbinsonstation = 7;    // Bin counter for station, not in use, but can be added as redundancy
int binquantitycycles = 0;    // No of cycles passed on workstation, not in use, can be used for fixed period replenishment model
/////////////////////////////////////////////////////////
```

FIGURE 5.6: *Initialisation code for client/workstation program.*

illuminating LEDs and no longer needs to identify which parts to use next himself/herself. The worker can now solely focus on the actual assembly process. Process times and work standardisation are drastically improved through the addition of this system.

5.2.2   E-kanban

A kanban system can be explained as a replenishment system in which the supply of components is regulated through the use of an instruction card sent upstream along the production line. The instruction card is always accompanied by an empty container which is to contain the replenished parts. Upon receiving an instruction card, the supplier locates the type and quantity of parts required as indicated on the card, and places them into the empty container. The now replenished container is then sent downstream to where the fill order originated. Such a manual system has various shortcomings including:

- loss or misplacement of kanban cards,

- unnecessary movement of employees to transfer cards,

- changing of parts requires new cards to be printed, and

- cards can be in the way of manufacturing processes.

To nullify the above-mentioned shortcomings, an E-kanban system can be used. This system, enabled through the use of technology, sends replenishment orders upstream by means of an automated electronic signal, thus eliminating the need for the exchange of physical kanban cards. On the basis of its vast benefits over a manual physical system, and being an Industrie 4.0 enhancement tool due to its automated electronic signal, such a system was implemented in the SLF.

An E-kanban system was implemented using a second Arduino microcontroller, along with an additional seven LEDs, an LCD display and a second push button, as shown in Figure 5.7. The parts containers at workstation 1 currently each contain sufficient parts to assemble 10 model trains. Each time the assembly worker completes the assembly of a train, the Arduino programmed for the workstation keeps track of how many trains have been assembled, thereby also providing information on how many can still be assembled corresponding to the amount of parts remaining. Once the stock levels at the workstation reach a pre-determined level of two trains, the Arduino automatically sends an electronic signal to the second Arduino in the warehouse of the SLF. The replenishment level of two was arbitrarily chosen for the implementation but can easily be adjusted in the code written.

The Arduino programming language was used to create this electronic connection between the two Arduinos. A client-server relation was coded, in which the warehouse Arduino is the server, and the workstation Arduino is the client. As soon as the workstation Arduino creates a signal to send to the server's electronic identification code (SSID), the server Arduino's program creates a TCP connection between the two Arduinos. This connection is established independently by the program written, by adding a ESP8266 module to the microcontrollers, and requires no wifi or internet connection to function.

The electronic replenishment signal sent via this connection, the LCD screen in the warehouse lights up and displays the message "Workstation 1 - refill bins" shown in Figure 5.8. The warehouse employee therefore immediately knows that workstation 1 requires replenishment. Along with the message displayed, the first LED corresponding to the first container to be

Figure 5.7: *E-kanban and pick by light system on warehouse storage rack.*

FIGURE 5.8: *LCD screen on warehouse storage rack.*

picked illuminates. The employee removes the container and places it on the warehouse trolley. Similarly to the pick by light process at the workstation, the employee pushes the button after each container removal, before the next LED illuminates. Once all containers have been picked, all LEDs illuminate simultaneously to signal the end of the process. The employee can now simply take the trolley and refill workstation 1. These containers also each contain enough parts to build 10 trains, thus the same cycle commences.

With the addition of this E-kanban system, human error is again removed from the process since the employee can simply follow the steps indicated by the illuminating LEDs, and receives a message telling him/her which workstation to deliver the bins to. Process times are also reduced since the the employee does not need to check a parts list to determine which bins are required, and in addition, the automated electronic signal removes the need for communication between employees regarding when and for which workstation replenishment is required.

5.3 A plan towards an Industrie 4.0 Stellenbosch Learning Factory

As explained earlier, Figure 5.4 indicates the requirements toward achieving an Industrie 4.0 SLF. The implementations discussed earlier in this chapter form the foundation upon which the remainder of the Industrie 4.0 applications can be built. If one considers the 5C framework of CPS discussed in Section 2.3, the solutions implemented in this thesis cover the first three levels of the framework. The workstation and warehouse are analogous to the machines described in the practical example of the 5C framework. Connected by programmed Arduino microcontrollers, the two stations are able to connect and share data (Level 1: Smart connection). This data is converted into a usable form, namely the current stock levels of parts at the workstation (Level 2: Data-to-information conversion). These stock levels are continuously monitored by the server Arduino and a signal sent from the workstation to the warehouse as soon as supplies run low and a refill is required (Level 3: Cyber level). The remainder of the Industrie 4.0 applications
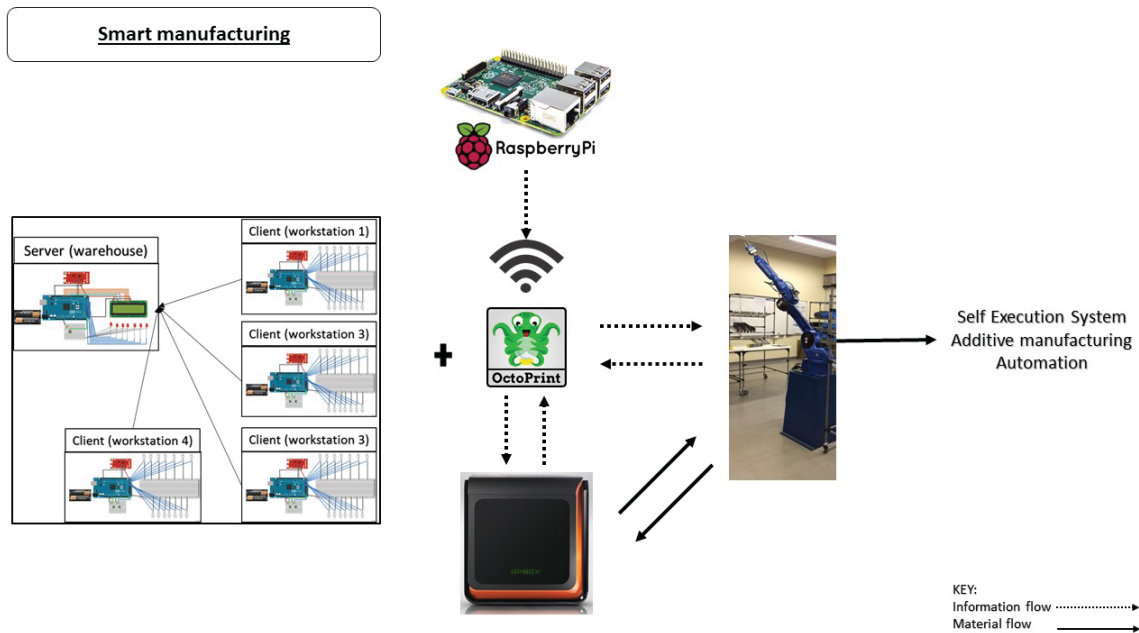
Figure 5.9: *Smart manufacturing for Industrie 4.0 SLF.*

will enable the fulfilment of the fourth and fifth levels. This section will explain each of the Industrie 4.0 applications outlined in Figure 5.4, and how they form part of the Industrie 4.0 SLF.

5.3.1 Smart manufacturing

Further enhancing the SLF and the competencies taught therein using the minimum resources in attaining Industrie 4.0 status, outlined three additional methods that can be implemented. These three methods, self execution system, additive manufacturing, and automation are illustrated in Figure 5.9. On the left hand side of the figure is the base implementation, described in Section 5.2. In the base implementation, normal operation will take place, where the warehouse will provide the workstations with raw materials required. Once material levels in the warehouse are low, a signal will be sent to the the Raspberry Pi PLC [58]. This signal will contain information regarding which material levels are low. The Raspberry Pi PLC will receive this signal and over Wi-Fi, through a program called OctoPrint [54], and send 3D printing instructions to the 3D printer in the SLF. Upon completion of the printing tasks, the OctoPrint program will send a notification to the Raspberry Pi PLC. Once this signal is received by the Raspberry Pi PLC, it will trigger another signal, which will be sent to the robot, triggering a collection action by the robot. Each process described will contribute to fulfilment of smart manufacturing within the learning factory.

5.3.2 Digital factory

The digital factory described in Section 2.3 can be implemented in the SLF by using the same Raspberry Pi PLC as in the smart manufacturing implementation above. The only addition required is a free, open-source program called Node-RED [53]. Node-RED allows wiring together hardware devices, application program interfaces (APIs), and online services. Successfully implementing Node-RED within the learning factory, as indicated in the right hand bottom picture of
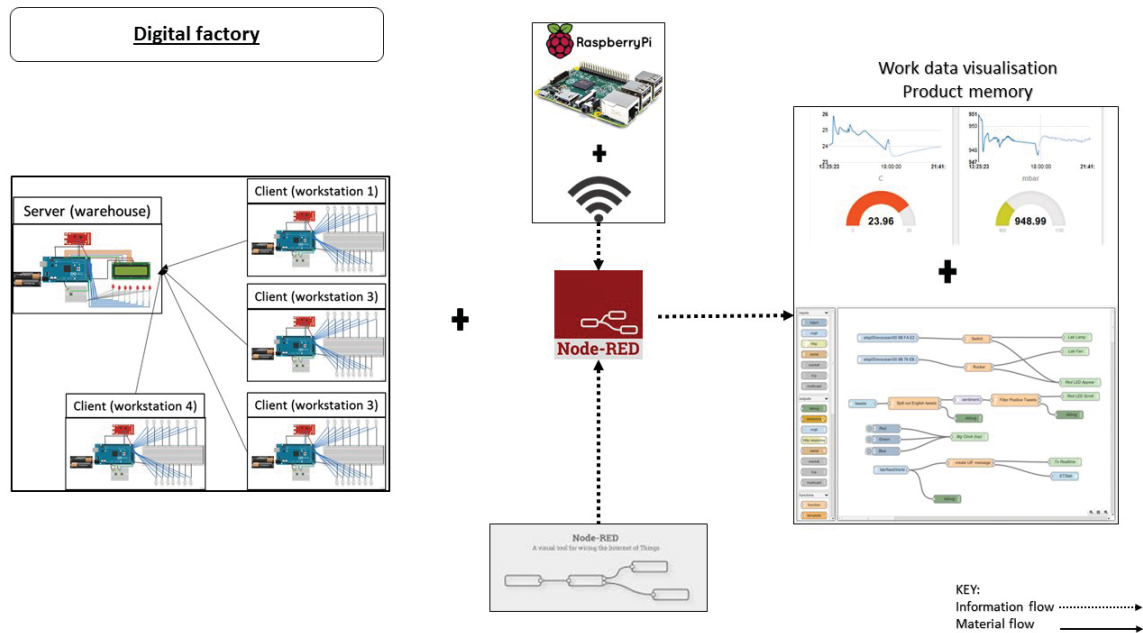
FIGURE 5.10: *Digital factory for Industrie 4.0 SLF.*

Figure 5.10, will allow any user to see live data, from a web browser connected to the Raspberry PI, from each workstation connected onto the Node-RED network. This has again been made possible by the base implementation, as the Node-RED program will utilise the sub-network created by the server (warehouse), through the ESP8266 module described previously, and each workstation connected as clients to the server. The Node-RED program can then be further extended by creating visual representations of the information that is flowing into the program, as illustrated in the top right hand side of Figure 5.10.

5.3.3 Real-time work visualisation

Real-time work visualisation as described in Chapter 3, can be achieved by including the internet as part of the base implementation. In addition, this implementation will require another open-source program called ThingSpeak [73]. ThingSpeak is a data collection web based service. It allows users to send data to a cloud, hosted by ThingSpeak. Data is sent to the cloud via the internet, through an internet enabled device. ThingSpeak uses a mathematical programming language called Matlab to draw the data from the cloud and parse it according to the user specifications. Once the data has been parsed into a usable format, it can be used through various Matlab APIs to produce graphs, make tweets using Twitter [80], and trigger events on other internet enabled devices. A visual representation of the this setup is shown in Figure 5.11. In the SLF, the base implementation can be connected to the internet using the ESP8266 modules. The modules need only connect to an internet enabled access point, an example of such being the university Wi-Fi network. Once the modules have been enabled to connect onto the SU Wi-Fi network, a ThingSpeak program needs to be developed that receives the data from the cloud and presents it accordingly, an example of such would be in the form of KPIs.
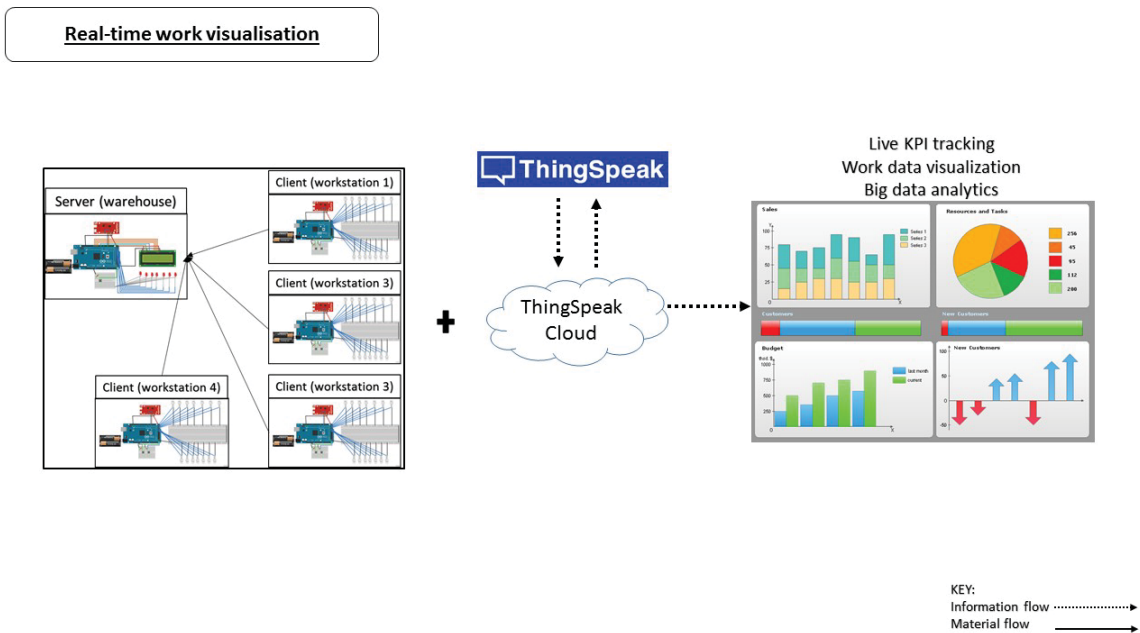
Figure 5.11: *Real-time work visualisation for Industrie 4.0 SLF.*

5.3.4   Collaborative work

Similar to the first use case in Chapter 4, collaborative work can be achieved in the SLF through the use of an RFID based system, as depicted in 5.12. The implementation in this case will be the same as that in the ESBLLF, explained in Chapter 4. As before, the robot will be triggered through an Arduino [8] with an Ethernet shield and RFID MFRC522 module attached, which will read in RFID tags, process the data contained therein, and send it to the robot in the correct format via an Ethernet connection. The robot will then execute precoded programs based on the RFID information received from the Arduino. Programming the RFID cards can be done in the same way as in the first use case, using the programs written for the Arduino, as provided in Appendix E. The Arduino with the attached Ethernet shield and MFRC522 module can be programmed in similar fashion using the program code provided in Appendix E.

5.3.5   Fulfilment of the 5C framework for CPS

As mentioned previously, the solutions implemented in this thesis covered the first three levels of the 5C framework. The digital factory and real time work visualisation implementations described in Sections 5.3.2 and 5.3.3 respectively, will fulfil the final two levels of the 5C framework. Both implementations will provide visual data for the analysis of the user and can act as support for decision making (Level 4: Cognition). The digital factory will, in the envisioned state, act as a digital twin, whereby any changes made in the physical world are directly reflected in the digital world and vice versa. Since the physical learning factory can thus be altered based on the decision support provided to any device through the digital factory and visualisation implementations, it would fulfil the final level of the 5C framework (Level 5: Configuration).
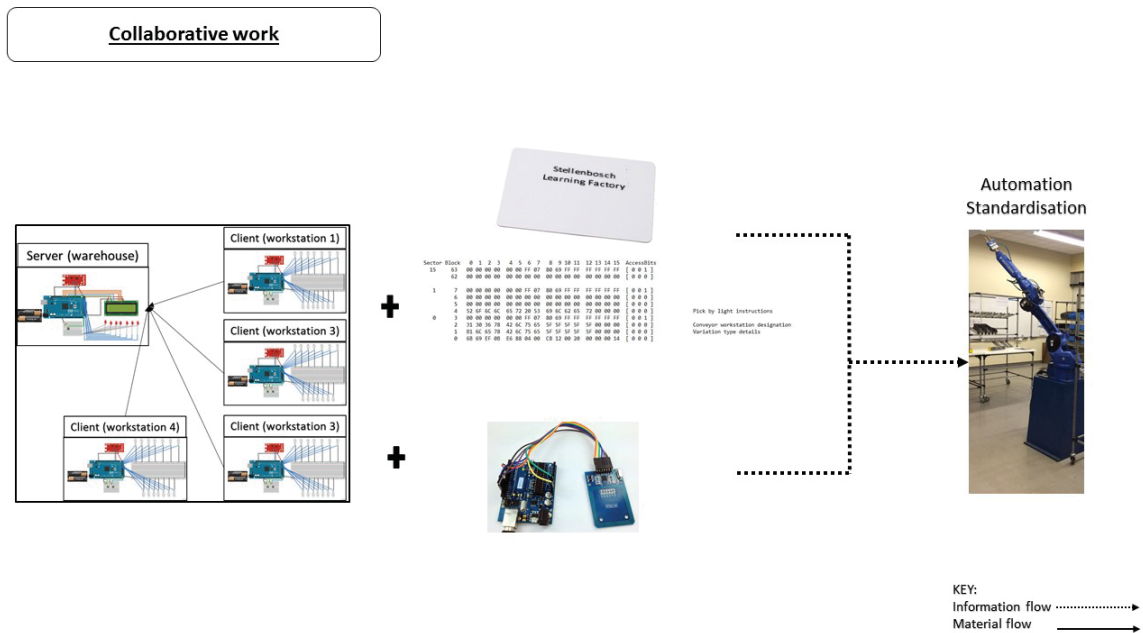
FIGURE 5.12: *Collaborative work for Industrie 4.0 SLF.*

5.4 Conclusion

The aim for the SLF is to showcase lean tools, visual management and low cost implementations, with the enhancement of Industrie 4.0 elements. These competencies were successfully implemented by the addition of the pick by light and E-kanban systems. The lean aspect is covered by the reduction in process times as well as the removal of human error and other wastes inherent to the process previously. With these systems, only the exact parts required, in the quantity that they are required, are picked exactly when they are required. The visual management aspect is included extensively with the addition of the LEDs and LCD display. All work steps are now visually displayed as opposed to the assembly and warehouse employee having to read instructions off of a paper. There is also no need for communication between the two when replenishment is required, since a signal is automatically sent and displayed on the screen in the warehouse. The low cost aspect was covered in that all equipment used to implement the two systems were standard, low cost parts (e.g. small LEDs) and the microcontrollers were programmed entirely by the student using only free, open source software.

Not only was the implementation of the above-mentioned competencies successful and led to vast improvements in the assembly and replenishment processes, but the implementation also provides a basis for many future projects and additions. The replenishment system is currently set to bins containing parts for 10 trains and a reorder point of 2 for demonstration purposes. Using the economic order quantity (EOQ) and reorder point, the current values of 10 and 2 can easily be adjusted for optimisation purposes. At present, the systems were implemented at workstation 1, but the same systems can be easily added to all remaining workstations since the programs were coded in such a way that they can be built on. Since each step is also captured by the microcontrollers, the programs written enable the capturing and analysis of process times which can in future be used to showcase real time data tracking and real time KPI tracking. The addition of these systems provide the SLF with a good starting point for showcasing the desired competencies, but more importantly provide students with the opportunity of adding more elements and improving the SLF even further.

CHAPTER 6

Conclusion

The purpose of this chapter is threefold: First, to present a summary of the work contained in this thesis, secondly to discuss the possible contributions of the thesis, and thirdly to discuss ideas for future work.

6.1 Thesis summary

In this section the development of the framework is discussed to provide a summative overview. Thereafter a brief summary of the topics covered in this thesis, and how they translate to the achievement of the initial thesis objectives discussed in Section 1.4.

6.1.1 Framework development

As mentioned previously, SMEs in today's fast paced environment are forced to adapt to the new technological revolution known as Industrie 4.0 if they wish to remain competitive. Industrie 4.0, the fourth industrial revolution ushered forth by the introduction of the IoT and IoS into the manufacturing environment [37] holds large promise not only for the manufacturing sector, but for all industries world wide. Based on principles of interoperability, virtual representations of reality, decentralised control, real-time data capturing and decision making, in a standardised yet modular service-orientated environment [34], Industrie 4.0 is expected to improve efficiencies and reduce associated costs [38]. Further expected benefits of employing Industrie 4.0 include increased customer service, optimised processes, new areas of employment as well as an increase in revenue.

The need to incorporate Industrie 4.0 thus clearly becomes apparent. The potential benefits, however, do not come without risk. In a study conducted by Koch et al. [38], companies were asked to identify the main challenges brought about by Industrie 4.0. As mentioned, the top two challenges listed by companies, are the unclear economic benefits coupled with excessive financial investments required, and the lack of skills required to operate effectively in this new technologically-advanced environement. Data security is another risk mentioned by various sources in literature, however all experts are in agreeance that these potential risks can be contained, and that Industrie 4.0 should not be a choice, but rather that it is a necessity for future survival.

As noted by Koch et al. [38], low-skilled workers with repetitive jobs in will be replaced by robots Industrie 4.0 as tasks become ever more standardised and automated. Simultenously however, the growing use of software, connectivity, and analytics will increase the demand for
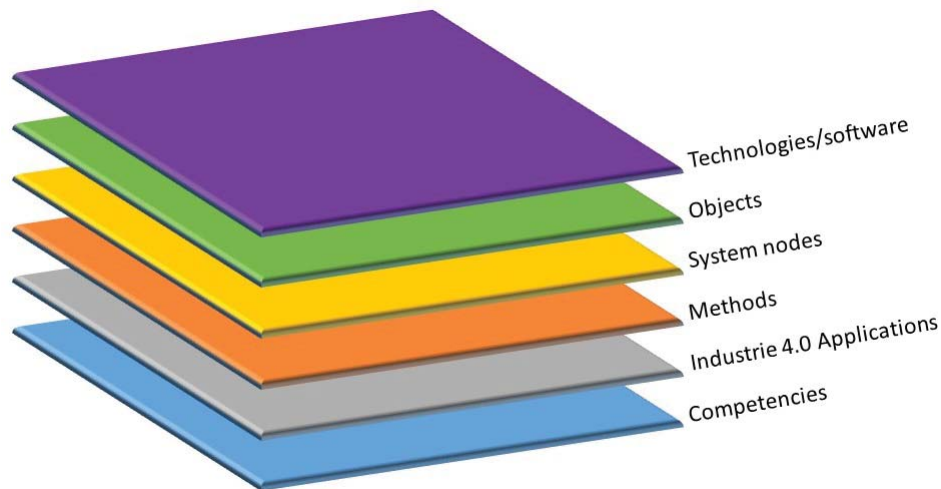
FIGURE 6.1: *Final dimensions for framework.*

employees with competencies in software development and IT technologies, such as mechatronics experts with software skills. As noted by Boese [19], this shift in skills required in industry, will require that education and training be adapted so as to prepare students for future employment in an Industrie 4.0 setting. Learning factories, small scale factories in which production takes place, in order to showcase methods taking place in an actual factory are being implemented world wide with the aim of bridging the gap between education and training, and the real-world experience. Not only do learning factories provide the opportunity for hands-on training, but also allow for the experiemental implementation of new methods, without the associated costs of implementing them into actual production lines in industry. Using learning factories to showcase and test the implementations possible through Industrie 4.0 would thus nullify the top risks identified by companies. By providing industry with a risk free environment in which various Industrie 4.0 scenarios can be tested and showcased will reduce the risk of excessive investments with no guarentee of return. In addition, the an Industrie 4.0 learning factory can provide the platform for training the current workforce in Industrie 4.0 related concepts, as well as better prepare students at university level for such an environment.

After a thorough analysis of literature it however became apparent, that whilst there are various frameworks available for Industrie 4.0, they are insufficient in providing practical implementation guidance for learning factories (or SMEs) wanting to implement Industrie 4.0. The aim of this thesis was thus to bridge that gap, and develop a framework that would provide the user with practical suggestions for implementing Industrie 4.0. An analysis of literature as well as site visits to various learning factory, provided the student with the insight to identify six dimensions required for implementing Industrie 4.0 into a learning factory, as shown in Figure 6.1. The dimensions and the elements within each, are described in detail in Chapter 3.

As mentioned, all possible user states for the framework were considered when compiling the dimensions, resulting in a framework that can be applied in three distinct ways. The first application is a greenfield design, applicable only to learning factories. In this user instance, the framework is applied in the design stage of a new learning factory, that wishes to teach specific competencies whilst incorporating or showcasing Industrie 4.0. Such competencies are discussed in Section 2.10.3. For this application, the framework is followed from the bottom level (competencies) through to the top level (technologies/software). The second user instance is the Industrie 4.0 greenfield design, which applies to both learning factories and SMEs. In this instance, the user, wanting to incorporate specific Industrie 4.0 applications into their current
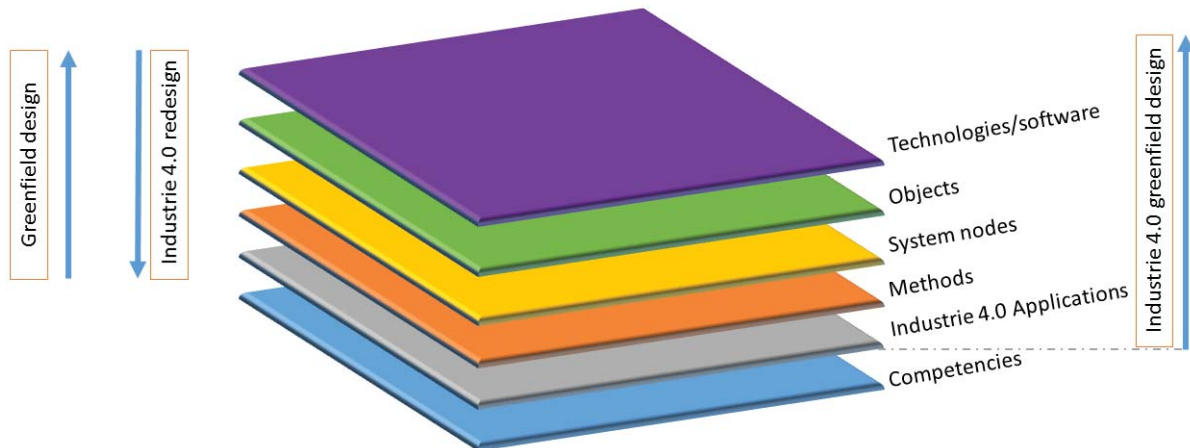
FIGURE 6.2: *Flow of framework applications.*

operations, follows the framework from the second level (Industrie 4.0 applications) through to the top level (technologies/software). The final user instance again applies to both learning factories and SMEs, with a minor variation. In this application, the Industrie 4.0 redesign, a learning factory or SME is redesigned to incorporate Industrie 4.0 with the resources already available. The framework is thus followed from the top level (technologies/software) through to the Industrie 4.0 applications for SMEs, and competencies level for learning factories. The difference can be explained in that the main aim of a learning factory remains the teaching of certain competencies, whereas the end goal for an SME will be the Industrie 4.0 application, since no competencies are taught. These three user instances are shown in Figure 6.2.

A thorough explanation of how to use the framework is provided in Section 3.5. In short, each competency and Industrie 4.0 application was broken down through each of the levels in the development of the framework, providing a tree diagram of relevant methods and objects for each case. These framework expansions are provided in Appendix A. The diagrams corresponding to the specific user instance can be assessed in terms of elements already implemented, available, required, and infeasible. By taking as inputs the desired outputs of a user instance, the framework thus provides a feasible, practical implementation roadmap for the user.

The framework was successfully validated by means of two use cases. The first application in Reutlingen, Germany, was conducted in a technologically-advanced environment. Three distinct Industrie 4.0 applications, namely smart manufacturing, collaborative work and intelligent transport, were implemented, using the Industrie 4.0 greenfield design user instance. The application of the framework identified the most feasible means to implement these Industrie 4.0 applications. They were practically realised through the incorporation of an Arduino PLC programmed by the students using open source software, as well as RFID technologies. These additions proved invaluable, enabling a collaborative picking process between a UR10 robot and human worker (collaborative work), as well as self-steering products. Product IDs were created using RFID tags, and the Arduino programmed to steer the products along the correct conveyor path via the information written to its RFID tag (smart transport), to the specific workstations required to work on that product (smart manufacturing).

In the second use case, the framework was applied in a greenfield design of the learning factory at Stellenbosch (the SLF). In this case, the aim was to incorporate Industrie 4.0 in the design of three desired competencies, namely lean tools, visual management, and low cost implementations. Again, the framework application was used to identify the most feasible options, for the implementation of the desired competencies. These were practically realised with the imple-

mentation of two Arduinos, programmed with add on modules and open source software by the student, and LEDs. These additions enabled a pick by light system that provides the employee with visual assistance in the assembly process (visual management). A network was created using open source software between the two Arduinos, with one acting as a client and the other as a server. This connection was used to implement an E-kanban system, reducing the need for human movement, and decreasing the risk of human error (lean tools). All implementations were done on a minimal budget, using low cost objects and technologies, and all programming done by the student using free, open source software (low cost implementations).

Both use cases received postive feedback from management, and showed vast improvements in the operations within the learning factories, providing good validation for the framework developed in this thesis.

6.1.2   Fulfilment of objectives

Chapter 2 provides a literature study pertaining to Industrie 4.0 and learning factories. In this chapter, the fundamentals of Industrie 4.0 and learning factories were discussed, in fulfilment of Objective I(i)–(iii) and Objective II. Chapter 3 opens with the detailed steps taken in developing the generic framework, in fulfillment of Objective IV. Within these steps, the information from site visits, to learning factories across Europe and in South Africa, were drawn upon and encapsulated into specific groupings, fulfilling Objectives III(i) and (ii).

In Chapter 3, the link between literature and site visits to learning factories was formed, by developing and creating a generic framework that encapsulates the work from Objectives I to IV, in fulfilment of Objective V.

Chapters 4 and 5 contain the documentation of two case studies performed using the developed framework. Chapter 4 contains the documentation of a case study pertaining to the implementation of three specific Industrie 4.0 applications within a technologically matured environment. Chapter 5 contains the documentation of a case study pertaining to the development of a learning factory who wishes to teach specific competencies. Both case studies include detailed documentation on how the framework was applied to the specific case and how the implementations were made. Both use cases were successful in achieving the desired user outcomes, and have been implemented as part of the operations.

This thesis is then concluded in Chapter 6 with a brief overview of the work done in fulfilment of the objectives outlined in Chapter 1.

6.2   Thesis contributions

There are two main contributions of this thesis. The first, clarifying and delineating a part of Industrie 4.0 into tangible and visible criteria. The second contribution is the proposal of a generic implementation and development framework for learning factories and SMEs.

6.2.1   Delineation of Industrie 4.0

The development of the framework in this thesis, enabled the clarification and delineation of Industrie 4.0. Industrie 4.0 was broken down into layers relevant in a learning factory and SME environment, and correspond to the six dimensions of the framework. Each dimension was filled with elements pertaining to Industie 4.0, providing tangible criteria for its implementation.

These criteria are visually displayed in each layer of the full framework dimensions, as depicted in Figure 6.3.
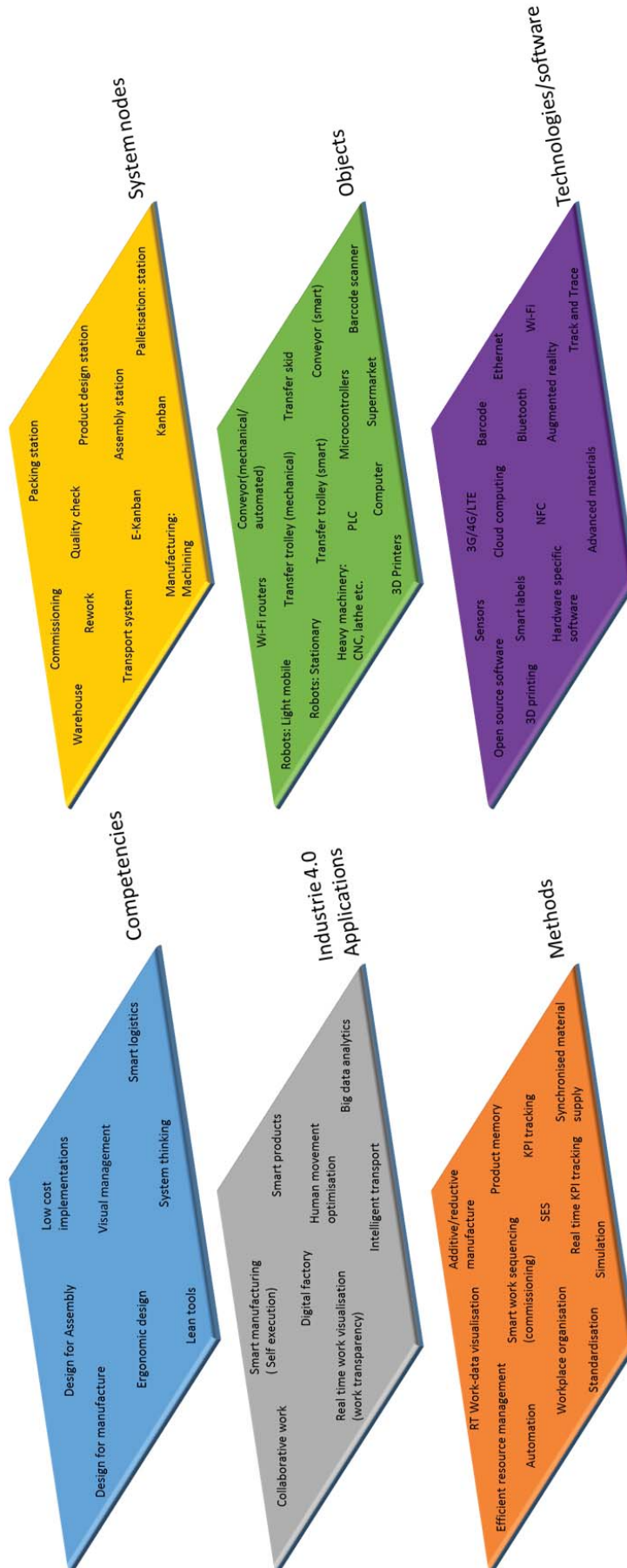
Figure 6.3: *Industrie 4.0 criteria as dimensions in framework.*

6.2.2   Industrie 4.0 framework

Throughout literature there are few frameworks providing decision support for implementing Industrie 4.0. Available frameworks, discussed in Chapter 2 are aimed at classifying and grouping Industrie 4.0 components or providing theoretical effort organisation. For this reason, this framework is the first of its kind in an attempt to provide SMEs and learning factories with decision support for practically implementing Industrie 4.0.

The two case studies in Chapter 4 and 5 were dedicated to testing the framework and using the result as an implementation guideline. The significance of the result of the framework was that management of the first case study, ESBLLF, originally thought it not possible to create a practical and generic framework capable of suggesting implementable Industrie 4.0 applications. This belief was then broken and the head management member provided sound appraisal:

"The work done by the student has been of great significance for our learning factory. The framework and corresponding result applied to our learning factory, can be used as part of the seminars we offer. The implementations made, through the decision support provided through the use of the framework has progressed our learning factory to a new maturity level."

Based on the feedback provided by the head member of the ESBLLF management, it is clear that the value of the framework was realised, and that the implementations made could improve upon, and contribute to their current operations.

The application of the framework in the SLF has established the first Industrie 4.0 applications, and aided in the first steps towards building an Industrie 4.0 learning factory. The implementations made in this thesis can form part of the courses taught to students, as well as be used in future workshops held in the SLF. The low cost of the implementations made, have spurred management of the learning factory on to extend upon the work and concepts outlined in the framework. This can be attributed to the simplicity of the feasible options and alternatives produced by the using the framework. As mentioned, the implementations of this thesis act as a basis upon which simple additions can be built to enable a fully-matured Industrie 4.0 SLF. As depicted in Figure 6.4, the addition of a Rasberry Pi, OctoPrint, Node-RED, RFID tags and reader, as well as a ThingsSpeak cloud would further enable smart manufacturing, a digital factory, real-time work visualisation and collaborative work to be incorporated in the SLF. A 3D printer and robot are already available for the SLF.
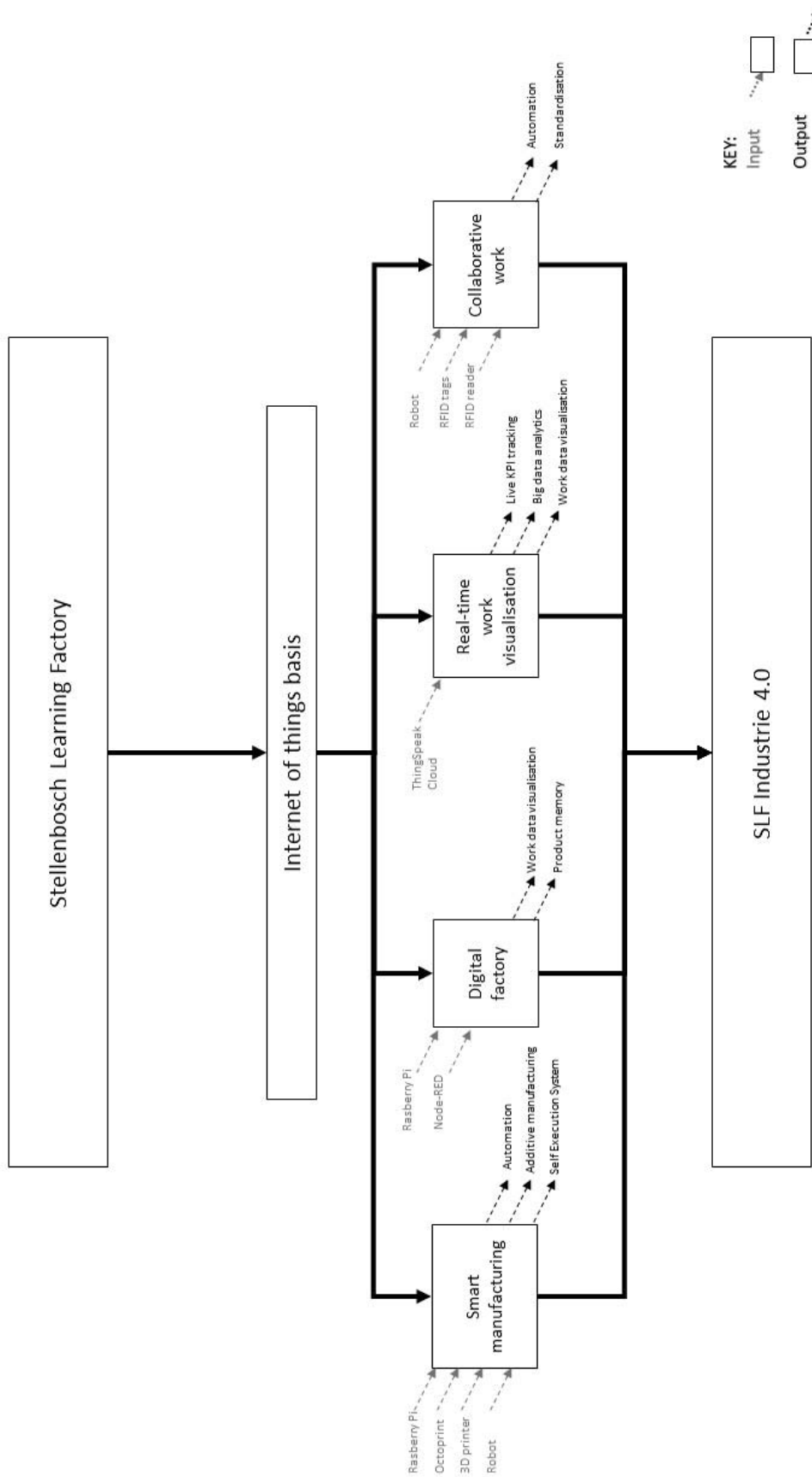
FIGURE 6.4: *Visualised plan towards an Industrie 4.0 learning factory for SLF.*

The application of the framework in the SLF thus provided an indespensible basis for creating an Industrie 4.0 learning factory, and provides future students with a good starting point for the addition of more methods and elements. How to implement these further applications is described in detail in Section 5.3. In closing, it should be noted that although the framework was discussed to be used in only three distinct manners, as outlined in Section 3.5, the framework could be applied in many different ways, where the target implementation could be an element in any of the other dimensions.

6.3 Recommendations for further studies

The following sections provide a discussion on possible future work. Suggestions for future work relate specifically to the development of the framework covered in Chapter 3 and the development of an Industrie 4.0 learning factory in the Stellenbosch Learning Factory, as discussed in Chapter 5.

6.3.1   Suggestion 1: Tailoring of dimensions

The framework developed in Chapter 3 could be improved upon through the introduction of new dimensions allowing the tailoring of the framework for a wider application spectrum. The framework could also be improved through the removal, altering or combining of already existing dimensions. The elements within each dimension, were populated using the current available literature along with knowledge gained from visits to learning factories in Europe and South Africa. Although these dimensions and their elements were sufficient for the successful Industrie 4.0 implementations in the two use cases, further applications of the framework may identify weaknesses or missing dimensions and elements, as well as new ones not yet available at the time of development.

6.3.2   Suggestion 2: Industrie 4.0 Stellenbosch Learning Factory

As mentioned previously, and described in detail in Section 5.3, the SLF can, through application of the developed framework, be extended to include smart manufacturing, a digital factory, real-time work visualisation and collaborative work. By assessing the relevant Industrie 4.0 tree diagrams, the minimum requirements can be identified for implementing these four Industrie 4.0 applications, in addition to the basis implemented in this thesis. This would not only be beneficial to the SLF itself, but may assist in improving and expanding on the developed framework.

6.3.3   Suggestion 3: Further validation of the framework

The framework was developed to be used in three different cases, of which the two extreme cases (an Industrie 4.0 greenfield design and a greenfield design) were used as validation. The third and final use, namely the Industrie 4.0 redesign can be applied to further validate the framework. Since learning factories are representations of real factories and SMEs, it is intended that the framework can also be directly applied in an SME wanting to incorporate Industrie 4.0. The validity of this claim, should therefore also be tested in future work, and will potentially lead to relevant additions and/or alterations to the dimensions and elements within the framework.

6.4 Potential benefits to society

The intent of this thesis was to provide learning factories and SMEs with a decision support framework for incorporating Industrie 4.0. The application of the proposed framework may thus lead to the successful implementation of Industrie 4.0 in both learning factories and SMEs. For learning factories this will provide an improved learning environment as well as the ability to provide Industrie 4.0 workshops for the local industry, to showcase the uses and benefits of Industrie 4.0. For SMEs, the application of this framework, may lead to operational and financial benefits through improved process times, a lean production, and further cost benefits gained from Industrie 4.0. Not only can this improve their financial position, but also aid them in remaining competitive in this fast-paced environment.

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APPENDIX A

Complete framework expansions

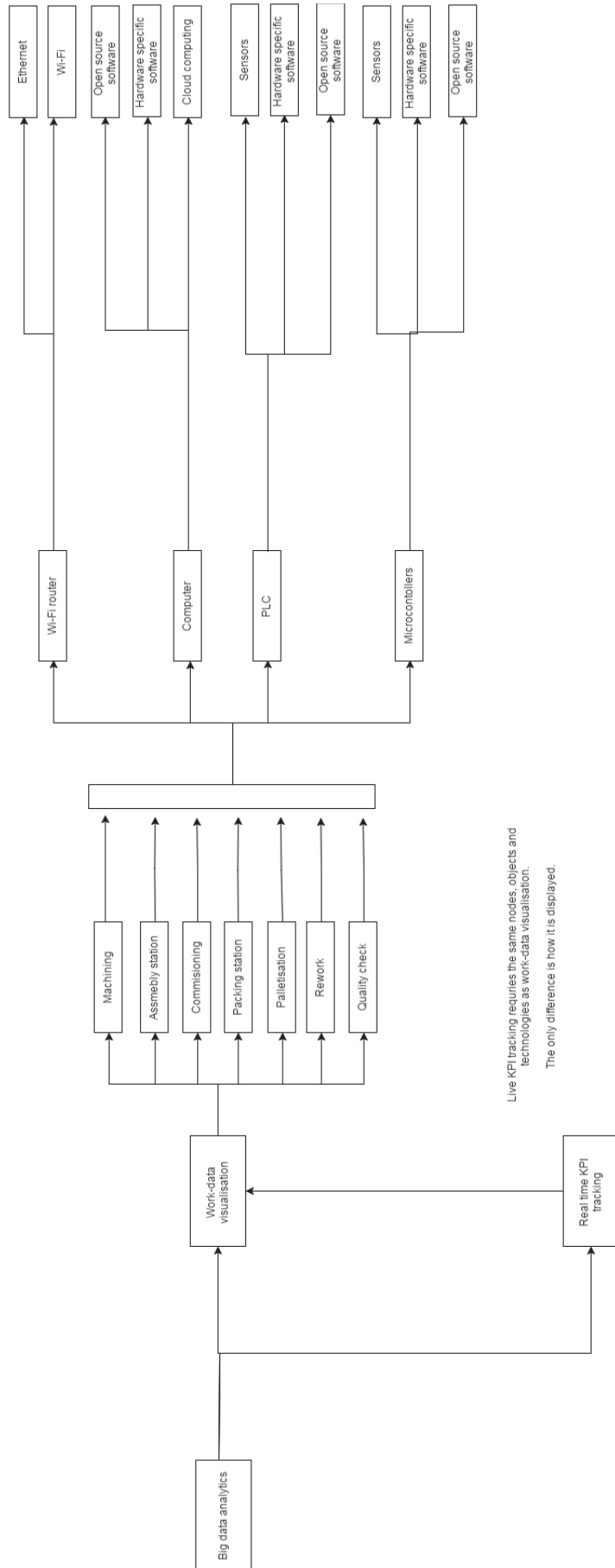The complete framework iterations for each Industrie 4.0 application is shown in Figures A.1 to A.8.

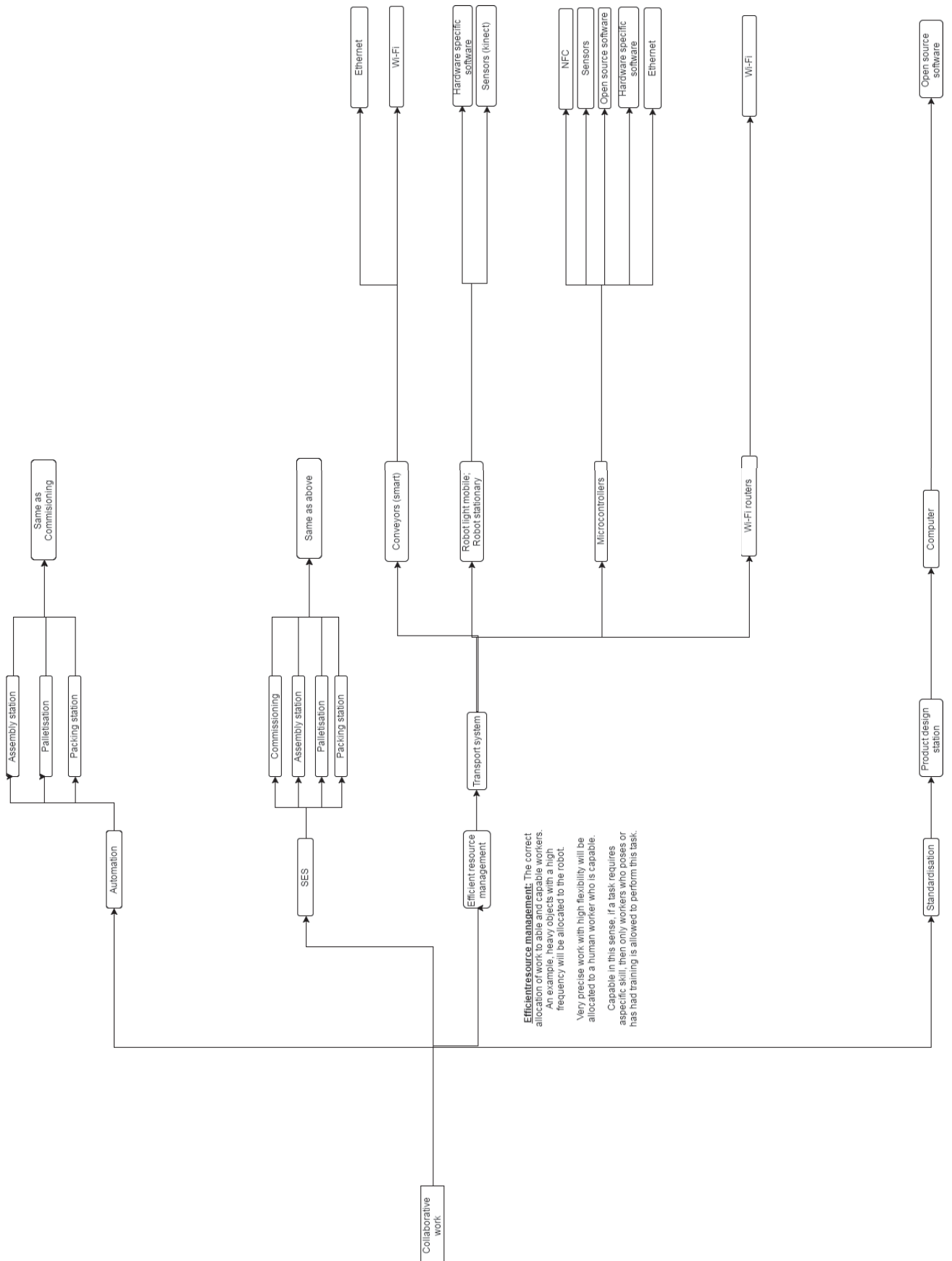Figure A.1: *Big data analytics framework iteration*

FIGURE A.2: *Collaborative work framework iteration*
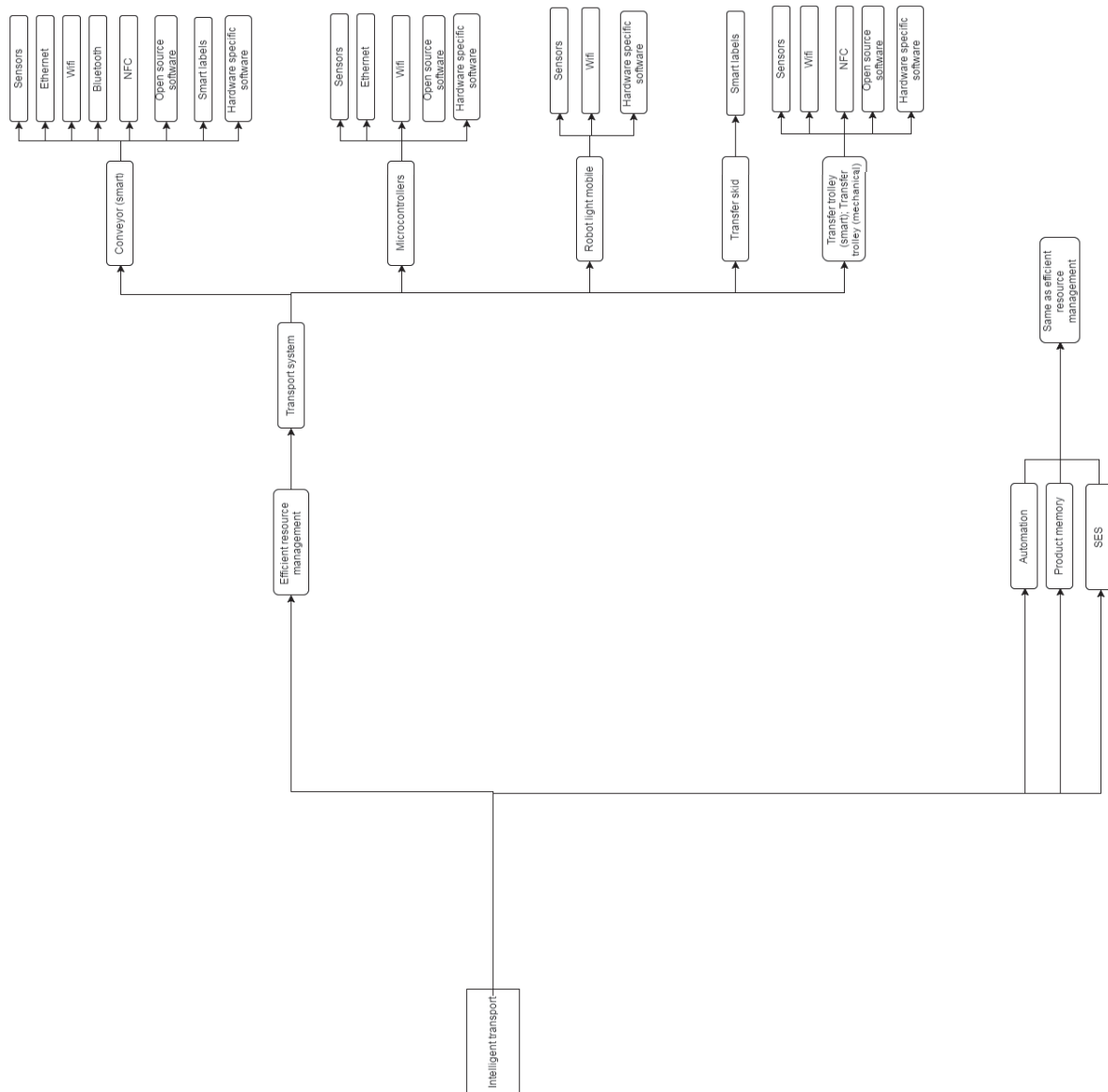
FIGURE A.3: *Intelligent transport framework iteration*
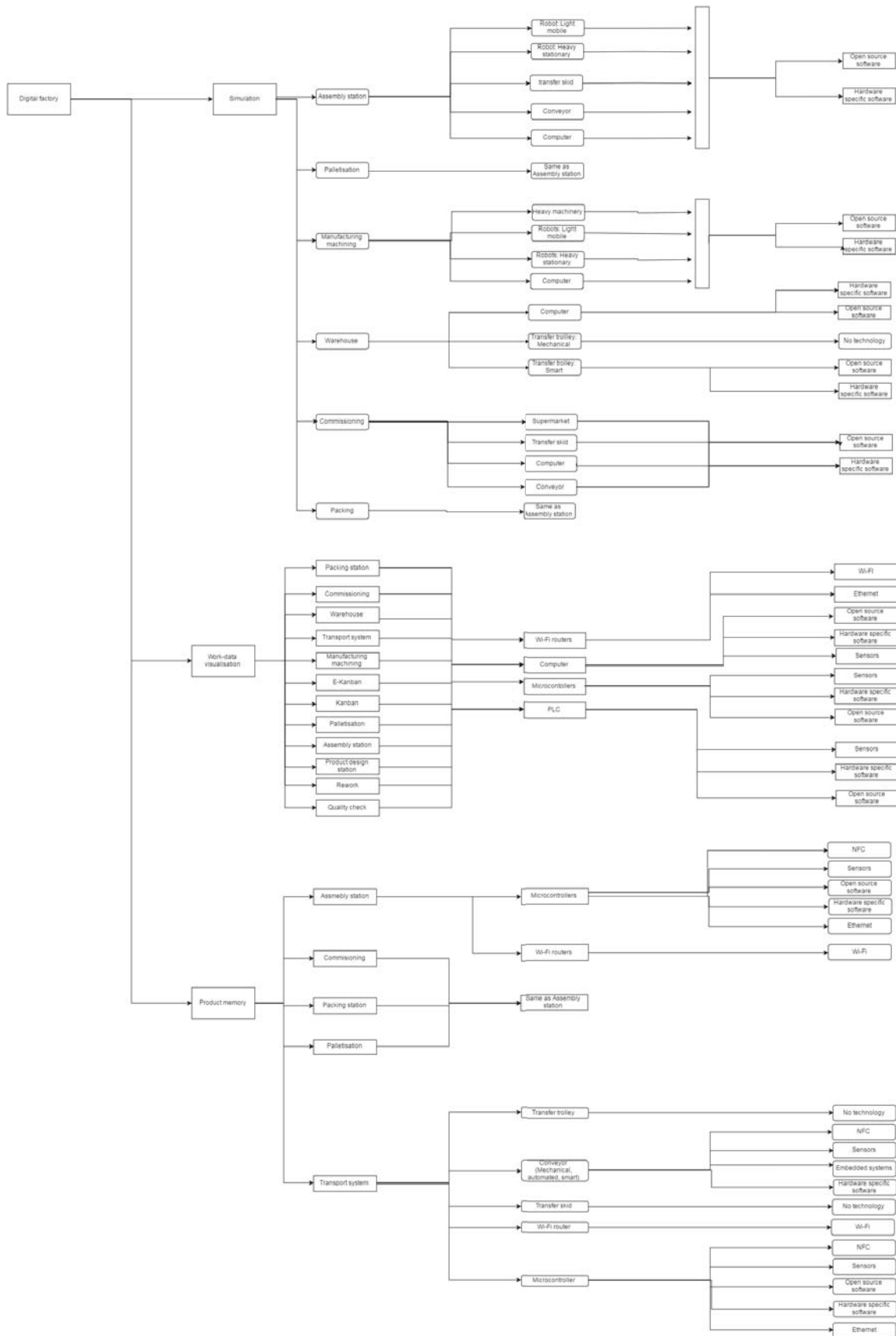
FIGURE A.4: *Digital factory framework iteration*
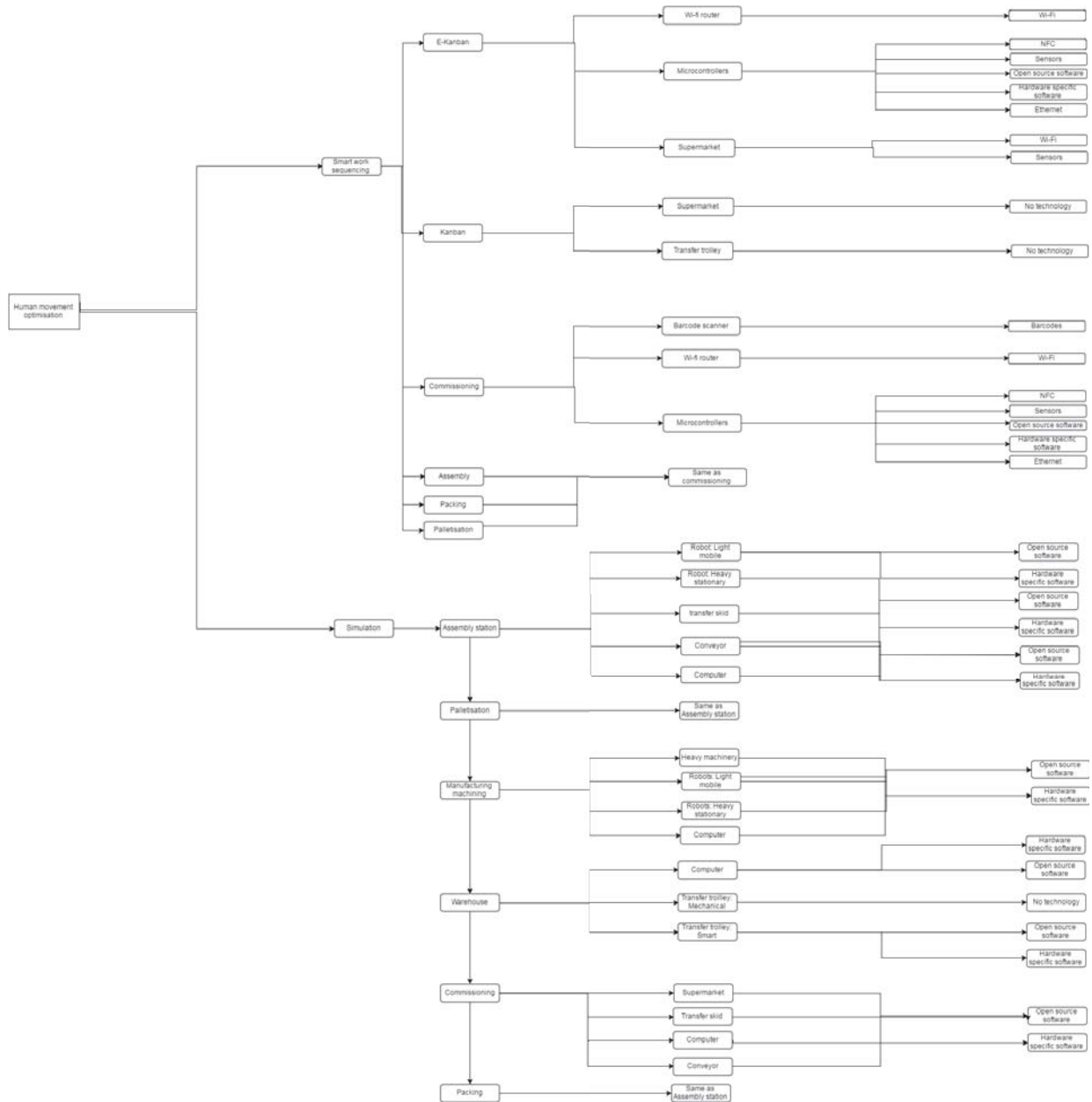
Figure A.5: *Human movement optimisation framework iteration*

FIGURE A.6: *Real-time work visualisation framework iteration*
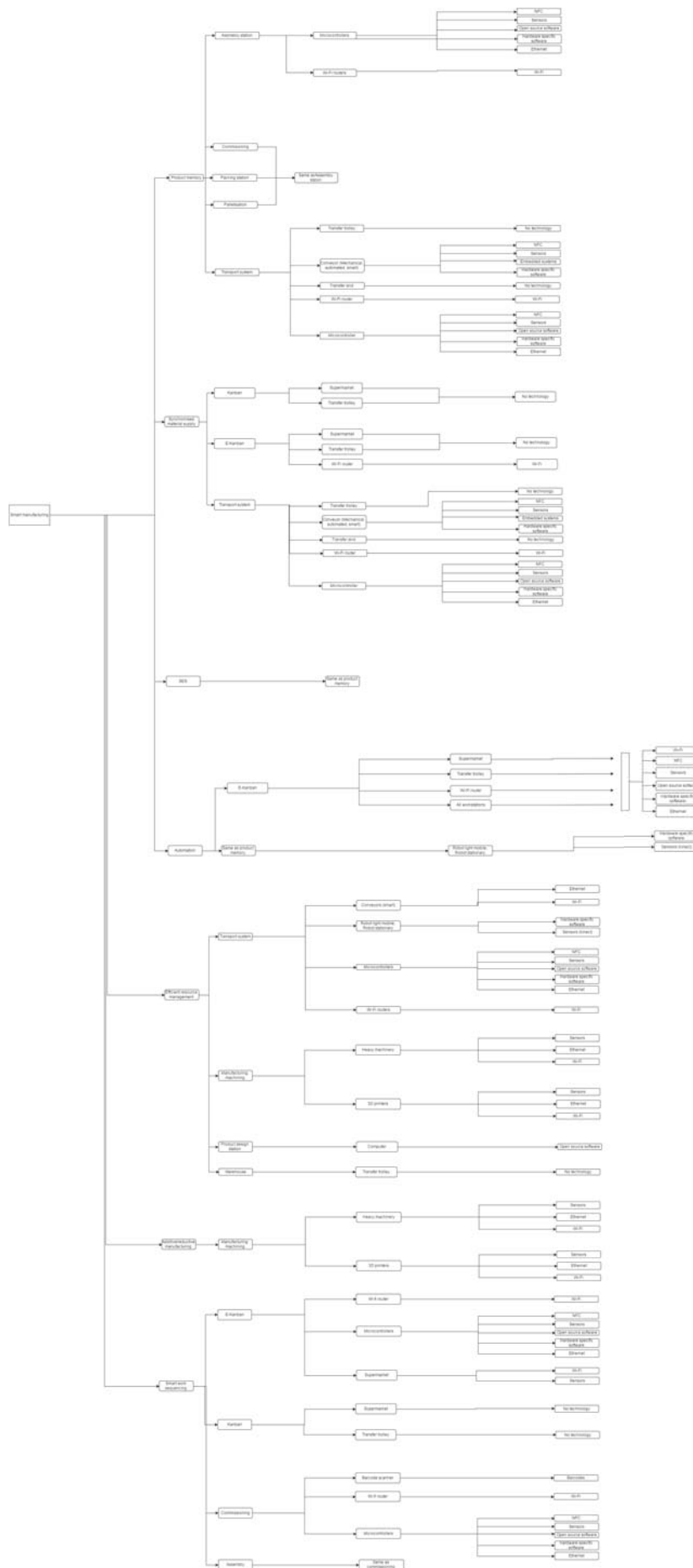
Figure A.7: *Smart manufacturing framework iteration*
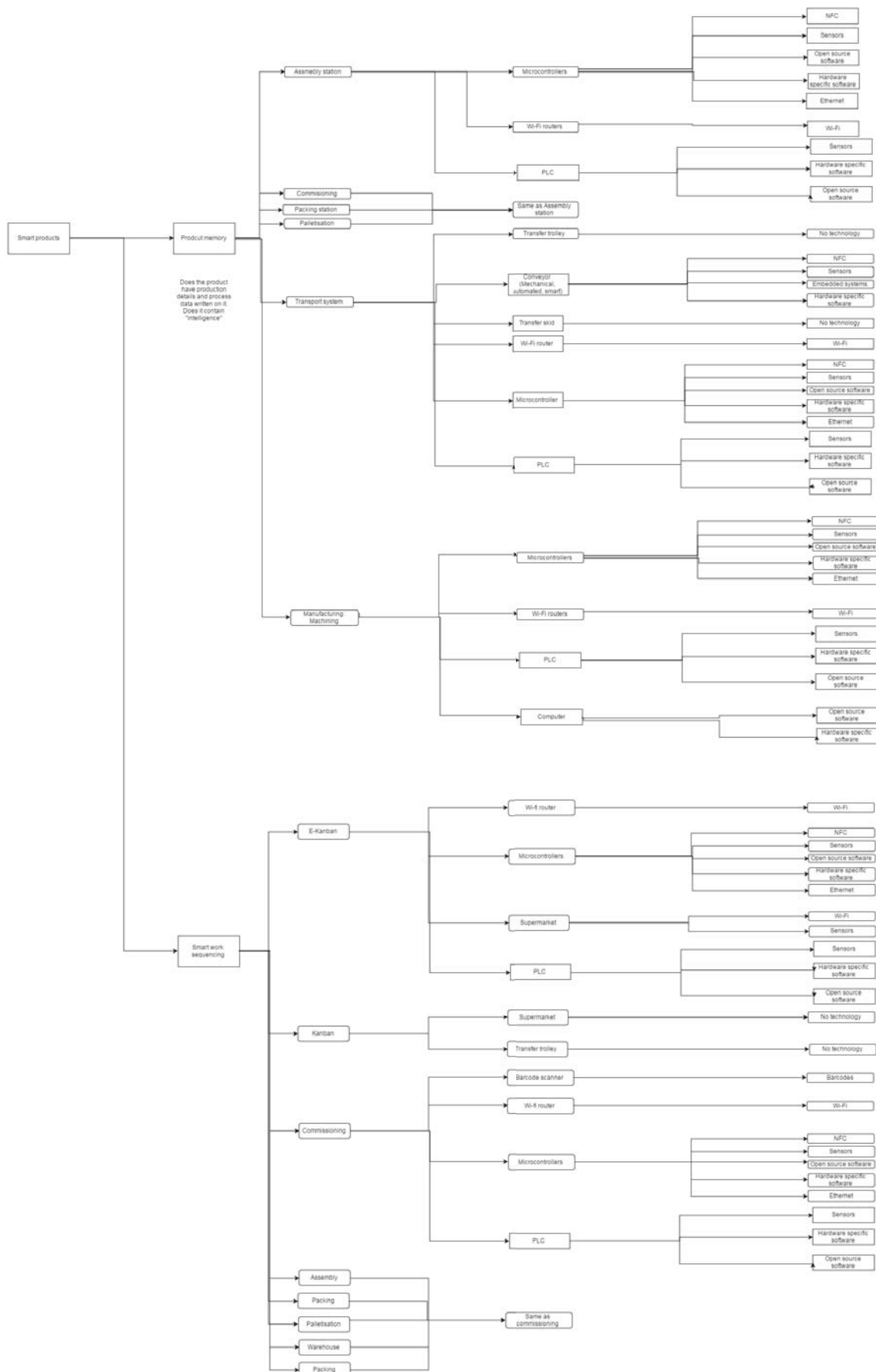
FIGURE A.8: *Smart products framework iteration*

APPENDIX B

ESBLLF framework iteration

The complete framework iteration for the ESBLLF is shown in Figure B.1.

Figure B.1: *ESBLLF framework iteration*

APPENDIX C

SLF framework iteration

The complete framework iteration for the SLF is shown in Figures C.1, C.2, and C.3.

Figure C.1: *SLF framework iteration*

FIGURE C.2: *SLF framework iteration continued*

Figure C.3: *SLF framework iteration continued*

APPENDIX D

ESBLLF implementation code

The Arduino code for the ESBLLF implementations shown in Figures D.1 to D.5.

```
#include <SPI.h>
#include <MFRC522.h>
#include <Ethernet.h>
//-----------------------------------------------------------------------------------
// Ethernet setup
//-----------------------------------------------------------------------------------

// network configuration.  gateway and subnet are optional.

 // the media access control (ethernet hardware) address for the shield:
byte mac[] = { 0xEE, 0xBF, 0xBE, 0x7A, 0xD8, 0x8D};
//the IP address for the shield:
byte ip[] = { 192,168,1,17 };    // be careful with ip adresses, final int can only be 2 no's for some reason
// the router's gateway address:
byte gateway[] = { 0,0,0,0 };
// the subnet:
byte subnet[] = { 255,255,0,0 };

EthernetServer server = EthernetServer(12345); // socket that will be used for communication "12345"


//-----------------------------------------------------------------------------------
// End of ethernet setup
//-----------------------------------------------------------------------------------


//-----------------------------------------------------------------------------------
// RFID setup for RC522 reader
//-----------------------------------------------------------------------------------


//This is the configuration for the Mega board
#define SS_PIN 53                        // Configurable, see typical pin layout above
#define RST_PIN 30                       // Configurable, see typical pin layout above


// Configuration for the UNO board
//#define RST_PIN         9              // Configurable, see typical pin layout above
//#define SS_PIN          10             // Configurable, see typical pin layout above

MFRC522 mfrc522(SS_PIN, RST_PIN);   // Create MFRC522 instance.

MFRC522::MIFARE_Key key;
int dataBlock_2[16];
//-----------------------------------------------------------------------------------
// End of RFID setup
//-----------------------------------------------------------------------------------
```
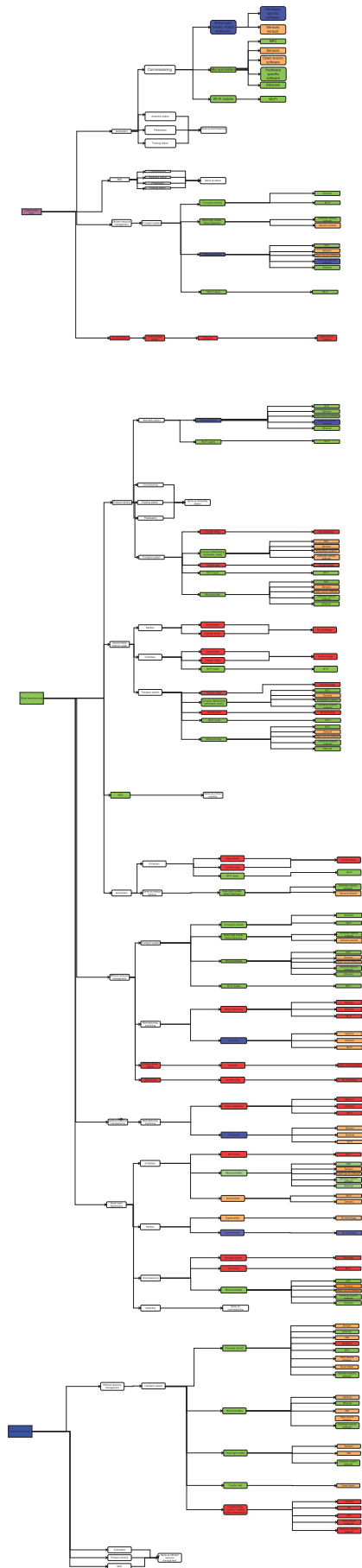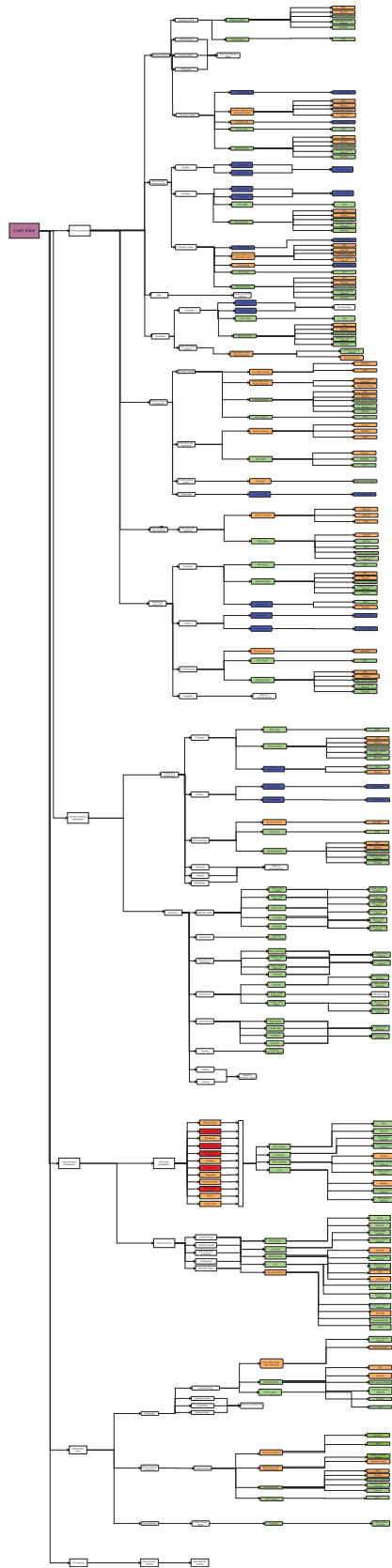
FIGURE D.1: *Code for ESBLLF implementations*

```
void setup() {

  {
    // initialize the ethernet device
    Ethernet.begin(mac, ip, gateway, subnet);

    // start listening for clients
    server.begin();
  }
  Serial.begin(9600); // Initialize serial communications with the PC
  while (!Serial);    // Do nothing if no serial port is opened (added for Arduinos based on ATMEGA32U4)
  SPI.begin();        // Init SPI bus
  mfrc522.PCD_Init(); // Init MFRC522 card

  // Prepare the key (used both as key A and as key B)
  // using FFFFFFFFFFFFh which is the default at chip delivery from the factory
  for (byte i = 0; i < 6; i++) {
    key.keyByte[i] = 0xFF;
  }
}
```

FIGURE D.2: *Code for ESBLLF implementations continued*

```
void loop() {

  // if an incoming client connects, there will be bytes available to read:
  EthernetClient client = server.available();
  if (client == true) {}
  // read bytes from the incoming client and write them back
  // to any clients connected to the server:
  //   server.write(client.read());

  // Look for new cards
  if ( ! mfrc522.PICC_IsNewCardPresent())
    return;

  // Select one of the cards
  if ( ! mfrc522.PICC_ReadCardSerial())
    return;
  MFRC522::PICC_Type piccType = mfrc522.PICC_GetType(mfrc522.uid.sak);
  // Check for compatibility
  if (    piccType != MFRC522::PICC_TYPE_MIFARE_MINI
      &&  piccType != MFRC522::PICC_TYPE_MIFARE_1K
      &&  piccType != MFRC522::PICC_TYPE_MIFARE_4K) {
    Serial.println(F("This sample only works with MIFARE Classic cards."));
    return;
  }

  // In this instance we use the 0 sector,
  // that is: sector #0, covering block #0 up to and including block #3
  byte sector         = 0;
  byte blockAddr      = 1;
  byte trailerBlock   = 3;
  MFRC522::StatusCode status;
  byte buffer[18];
  byte size = sizeof(buffer);



  // Authenticate using key A
  status = (MFRC522::StatusCode) mfrc522.PCD_Authenticate(MFRC522::PICC_CMD_MF_AUTH_KEY_A,
  if (status != MFRC522::STATUS_OK) {
    Serial.print(F("PCD_Authenticate() failed: "));
    Serial.println(mfrc522.GetStatusCodeName(status));
    return;
  }
```

FIGURE D.3: *Code for ESBLLF implementations continued*

```
status = (MFRC522::StatusCode) mfrc522.MIFARE_Read(blockAddr, buffer, &size);
if (status != MFRC522::STATUS_OK) {
  Serial.print(F("MIFARE_Read() failed: "));
  Serial.println(mfrc522.GetStatusCodeName(status));
}

dump_byte_array(buffer, 16); Serial.println();
Serial.println();


switch ( dataBlock_2[0]) {
  case 177:
    Serial.println("Blue scooter with grey holder");
    server.write("b1");
    break;

  case 178:
    Serial.println("Blue scooter with blue holder");
    server.write("b2");
    break;

  case 179:
    Serial.println("Blue scooter with pink holder");
    server.write("b3");
    break;

  case 180:
    Serial.println("Blue scooter with yellow holder");
    server.write("b4");
    break;


  case 181:
    Serial.println("Blue scooter with no holder");
    server.write("b5");
    break;


  case 193:
    Serial.println("Silver scooter with grey holder");
    server.write("c1");
    break;

  case 194:
    Serial.println("Silver scooter with blue holder");
```

FIGURE D.4: *Code for ESBLLF implementations continued*

```
    case 195:
      Serial.println("Silver scooter with pink holder");
      server.write("c3");
      break;

    case 196:
      Serial.println("Silver scooter with yellow holder");
      server.write("c4");
      break;

    case 197:
      Serial.println("Silver scooter with no holder");
      server.write("c5");
      break;



  }


  // Halt PICC
  mfrc522.PICC_HaltA();
  // Stop encryption on PCD
  mfrc522.PCD_StopCrypto1();

}

/**
   Helper routine to dump a byte array as hex values to Serial.
*/
void dump_byte_array(byte *buffer, byte bufferSize) {
  for (byte i = 0; i < bufferSize; i++) {
    dataBlock_2[i] = (buffer[i]);
    Serial.print(buffer[i] < 0x10 ? " 0" : " ");
    Serial.print(buffer[i], HEX);

  }

}
```

FIGURE D.5: *Code for ESBLLF implementations continued*

APPENDIX E

SLF implementation code

The Arduino code for the SLF implementations shown in Figures E.1 to E.7.

```
#include <ESP8266_TCP.h>

// ESP8266 Class
ESP8266_TCP wifi;

// Define SSID, Password and Channel that provide for Access Point
#define ssid        "ESP789"
#define pass        "123456789"
#define channel     5

// Connect this pin to CH_PD pin on ESP8266
#define PIN_RESET   6

// TCP Server IP and port
#define serverIP    "192.168.4.1"
#define serverPort  2000

// Pin connected to button to send pick by light information
#define PIN_SEND    52

// Pin connected to replish bins
#define  PIN_REPLENISH 53


//Initialise the LEDs for the pick by light and the replenishment system
const int ledPin[] = {22, 23, 24, 25, 26, 27, 28}; //  pin that the LED is attached to
const int replenishLED[] = {29, 30, 31, 32, 33, 34, 35}; // LED pins for the replenish system


///////////////////////////////////////// ///////////////// Variables for pick by light function
// Variables will change:
int buttonPushCounter = 0;
int buttonPushCounter2 = 1;   // Counter for the number of button presses
int buttonState = 0;          // Current state of the button, not used
int lastButtonState = 0;      // Previous state of the button
int noofassemblysteps = 5;    // Assembly step counter
int noofbinsonstation = 7;    // Bin counter for station, not in use, but can be added as redundancy
int binquantitycycles = 0;    // No of cycles passed on workstation, not in use, can be used for fixed period replenishment model
//////////////////////////////////////////////////////////////
```

FIGURE E.1: *Code for SLF implementations*

```
void setup()
{
  // Set pin for send command to input mode
  pinMode(PIN_SEND, INPUT);
  pinMode(PIN_REPLENISH, INPUT);

  // We use Serial1 to interface with ESP8266
  // and use Serial to debugging
  Serial.begin(9600);
  Serial.println("Starting Client");
  Serial1.begin(115200);
  delay(3000);
  wifi.begin(&Serial1, &Serial, PIN_RESET);
  //  wifi.begin(&Serial1, PIN_RESET);

  // Check that ESP8266 is available
  if (wifi.test())
  {
    // Connect to target Access Point
    String ip = connectAP();
    delay(5000);
  }
  else
  {
    // ESP8266 isn't available
    Serial.println("Check module connection and restart to try again...");
    while (true);
  }
///////////////////////////////////////////////////////////////////////////////////////////
  // initializes the LEDs as an output:
  for ( int p = 0; p < noofbinsonstation; p++) {
    pinMode(ledPin[p], OUTPUT);                 // Set all the pins to output
    pinMode (replenishLED[p], OUTPUT);          // set replenish pins to output
  }
///////////////////////////////////////////////////////////////////////////////////////////



}
```

FIGURE E.2: *Code for SLF implementations continued*

```
void loop()
{
  // Check for any data has coming to ESP8266
  int dataState = wifi.isNewDataComing(WIFI_CLIENT);
  if (dataState != WIFI_NEW_NONE) {
    if (dataState == WIFI_NEW_CONNECTED) {
      // Connected with TCP Server Side
      Serial.println("Connected");
    } else if (dataState == WIFI_NEW_DISCONNECTED) {
      // Disconnected from TCP Server Side
      Serial.println("Disconnected");
    } else if (dataState == WIFI_NEW_MESSAGE) {
      // Got a message from TCP Server Side
      // handle new message in here

      String message =  wifi.getMessage();
      Serial.println("MESSAGE " + message);
      if (message == "command1") {
        // Do something
        digitalWrite(13, HIGH);
      } else if (message == "command2") {
        // Do something
        digitalWrite(13, LOW);
      } else if (message == "pong") {
      } else {
        // Do something
      }

    } else if (dataState == WIFI_NEW_SEND_OK) {
      // Message transfer has successful
      Serial.println("SENT!!!!");
    }
  }
}
```

Figure E.3: *Code for SLF implementations continued*

```
,
///////////////////////////////////////////////////////////////////////////////////
  // When button for send message was pressed
  if (digitalRead(PIN_SEND)) {
    // Send a message
    buttonPushCounter++;
    pickbylight(buttonPushCounter);
    wifi.send("command1");
    delay(500);                                              // Change to 1 sec if losing data
  }
  else {
    wifi.send("command3");
    delay(1000);
  }
/////////////////////////////////////////////////////////////////////////////////

///////////////////////////////////////////////////////////////////////////////
///Bin replenishment system
///////////////////////////////////////////////////////////////////////////////
 if (digitalRead(PIN_REPLENISH)){
 buttonPushCounter2++;
 pickreplenish(buttonPushCounter2);
 delay(50);
 }
 /////////////////////////////////////////////////////////////////////////////

  // Auto connect to TCP Server Side when connection timeout
  if (wifi.getRunningState() == WIFI_STATE_UNAVAILABLE) {
    // Connect to TCP Server Side
    Serial.println("Connect!!");
    delay(500);
    wifi.connectTCP(serverIP, serverPort);
    delay(500);
  }/* else {
    if (heart_count == max_heart) {
      wifi.send("ping");
      heart_count = 0;
    }
    heart_count++;
  }*/

  delay(50);
}
```

FIGURE E.4: *Code for SLF implementations continued*

```
// Access Point Connection Function that you can loop connect to Access Point until successful
String connectAP()
{
  String ip = "0.0.0.0";
  while (ip.equals("0.0.0.0"))
  {
    ip = wifi.connectAccessPoint(ssid, pass);
    if (!ip.equals("0.0.0.0"))
    {
      break;
    }
  }
  return ip;
}
int pickbylight(int buttoncounter) {
  Serial.println(buttoncounter);
  if (binquantitycycles < 2) {

    //    // compare the buttonState to its previous state
    //   // if (buttonState != lastButtonState) {
    //      // if the state has changed, increment the counter
    //      if (buttonState == HIGH){
    //    }

    // light LEDs based on value of buttoncounter

    //
    if (buttoncounter == 1) {
      digitalWrite(ledPin[0], HIGH);
      digitalWrite(ledPin[6], LOW);
      Serial.println(ledPin[0]);
      Serial.println(binquantitycycles);
      wifi.send("command2");

    }
    //
    else if (buttoncounter == 2) {
      digitalWrite(ledPin[0], LOW);
      digitalWrite(ledPin[1], HIGH);
      Serial.println(ledPin[1]);
      delay(50);
      wifi.send(" ");
    }
    //
```

FIGURE E.5: *Code for SLF implementations continued*

```
else if (buttoncounter == 3) {
  digitalWrite(ledPin[1], LOW);
  digitalWrite(ledPin[2], HIGH);
  Serial.println(ledPin[2]);
  delay(50);
  wifi.send("command2");
}
//
else if (buttoncounter == 4) {
  digitalWrite(ledPin[2], LOW);
  digitalWrite(ledPin[3], HIGH);
  Serial.println(ledPin[3]);
  delay(50);
  wifi.send(" ");
}
//
//
else if (buttoncounter == 5) {
  digitalWrite(ledPin[3], LOW);
  digitalWrite(ledPin[4], HIGH);
  Serial.println(ledPin[4]);
  wifi.send("command2");
}
//
//
else if (buttoncounter == 6) {
  digitalWrite(ledPin[4], LOW);
  digitalWrite(ledPin[5], HIGH);
  Serial.println(ledPin[5]);
  wifi.send(" ");
}

else if (buttoncounter == 7) {
  digitalWrite(ledPin[5], LOW);
  digitalWrite(ledPin[6], HIGH);
  Serial.println(ledPin[6]);
  wifi.send("command2");
  buttonPushCounter = 0;   // reset the buttonpush counter
  binquantitycycles++;
}


}
```

FIGURE E.6: *Code for SLF implementations continued*

```
void pickreplenish(int buttoncounter2) {
  // light LEDs based on value of buttoncounter
  if (buttoncounter2 == 1) {
    digitalWrite(replenishLED[0], HIGH);
    Serial.println(replenishLED[0]);
    Serial.println(binquantitycycles);
    delay(50);
  }
  else if (buttoncounter2 == 2) {
    digitalWrite(replenishLED[0], LOW);
    digitalWrite(replenishLED[1], HIGH);
    Serial.println(replenishLED[1]);
    delay(50);
  }
   else if (buttoncounter2 == 3) {
    digitalWrite(replenishLED[1], LOW);
    digitalWrite(replenishLED[2], HIGH);
    Serial.println(replenishLED[2]);
    delay(50);
  }
  else if (buttoncounter2 == 4) {
    digitalWrite(ledPin[2], LOW);
    digitalWrite(ledPin[3], HIGH);
    Serial.println(ledPin[3]);
    delay(50);
    }
  else if (buttoncounter2 == 5) {
    digitalWrite(replenishLED[3], LOW);
    digitalWrite(replenishLED[4], HIGH);
    Serial.println(replenishLED[4]);
  }
  else if (buttoncounter2 == 6) {
    digitalWrite(replenishLED[4], LOW);
    digitalWrite(replenishLED[5], HIGH);
    Serial.println(replenishLED[5]);
    delay(50);
    }
  else if (buttoncounter2 == 7) {
    digitalWrite(replenishLED[5], LOW);
    digitalWrite(replenishLED[6], HIGH);
    Serial.println(replenishLED[6]);
    delay(50);
      buttonPushCounter2 = 0;   // reset the buttonpush counter
  }
}
```

Figure E.7: *Code for SLF implementations continued*